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GENERAL REPORT ON THE ECONOMICS OF THE PEACEFUL USES OF UNDERGROUND NUCLEAR EXPLOSIONS

by
Oskar Morgenstern
and
Klaus-Peter Heiss

Prepared for
U. S. Atomic Energy Commission
Washington, D. C.

MATHEMATICA

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Since the Plowshare Program was established in 1957 to investigate and develop peaceful uses for nuclear explosives, a large number and variety of applications have been suggested. As a result of the Plowshare research effort, many suggestions have been discarded for technical reasons while others have been more clearly identified as long-range possibilities requiring still more data and further development. Other ideas have now been sufficiently developed and offer enough promise to warrant the type of pilot-scale or prototype experiment needed to obtain precise information in an industrial framework.

By the time such an experiment is seriously considered and proposed, there is a need for some general economic appraisal of the potential value of the application. In the course of research some economic information is usually generated; however, for the most part, the AEC has relied primarily on government agencies responsible for resource development and on industry for information and general economic evaluations. As a result, this information and analysis is scattered throughout different reports, and appraisals have often been made on different bases and with different assumptions and resource information. Since a number of these applications are now approaching a commercial technology level, it seems timely and desirable to make some effort to collect this information, put it on as consistent a basis as possible, place it in the proper economic and resource perspective, and include enough relevant technical and cost information about nuclear explosions, their effects and associated operations, to permit a better and more detailed analysis from an economic point of view.

To these ends, Mathematica Incorporated of Princeton, New Jersey, was engaged to carry out this assignment. They have produced a series of reports covering the various areas of application for peaceful nuclear explosions and a general summary report. These reports are not intended to be definitive economic analyses, since sufficient data is still not available for such analysis. Rather, these studies are intended to serve as a beginning point and a means of identifying on a consistent basis the range of potential of the presently known, most promising applications. It is hoped that they will serve as a useful guide for future economic studies, especially by identifying key technical questions which affect the economics of the applications, such as whether the fractured area of oil shale surrounding the nuclear chimney can also be retorted. It is towards answering these key technical questions that much research and development, including the design of current experiments, is being devoted. Beyond the identification of key technical questions, these studies attempt to define the controlling economic parameters for the different applications, such as the diameter of explosives and concomitantly the cost of very deep drill holes for the gas production stimulation applications.

With the expectation that this information will be of general interest, as well as a guide for the research of those working in Plowshare, the AEC is pleased to make these reports available.

John S. Kelly, Director
Division of Peaceful
Nuclear Explosives

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ABSTRACT

The Plowshare program of the Atomic Energy Commission sets forth to put nuclear explosives to peaceful, economic use. The present report evaluates the major fields of application proposed up to now for such explosives. They are the stimulation of gas and oil reservoirs, production of shale oil, applications to mining, cratering, and a list of various other projects, among them storage of natural gas, waste disposal and water resource management.

These applications were analyzed by MATHEMATICA in five special reports to gather the necessary technical and economic information on each of these uses. This report gives an outline of the general economic problems when evaluating large projects within an economy. An analysis is made of the major costs of nuclear explosives--that is, emplacement costs, costs of the device and costs of safety and estimates of the potential benefits to the economy. The report concludes that there exist substantial economic benefits in each of the four major fields of peaceful uses of nuclear explosives. The report did not set forth to give a preference ordering of these four fields, though definitely these applications have precedence over many of the various other possible peaceful applications. 258 references (auth)

Shale oil production by nuclear explosives was found to hold a tremendous potential for the United States and some other countries.

However, the same application has attached to itself major technological and engineering difficulties in the recovery process of shale oil which will have to be solved. The report concludes that the main U.S. deposits of oil shale in the Green River Formation will be recoverable only by nuclear explosives to any significant extent.

The stimulation of natural gas and oil fields by nuclear explosives was found to be the most straightforward and direct application of completely contained underground nuclear explosions. The additional resources made recoverable by this technique will add significantly to known U.S. recoverable resources of natural gas and, potentially, crude oil. With present expectations and present costs of the nuclear technology, it is estimated that unproductive, tight gas formations can be operated economically by this technology. With experience and technological advances in this field, and implied cost reductions, this technology could recover economically a significantly larger amount of natural gas resources than is the case at present.

The application of nuclear explosives to mining operations was found to be economically feasible if applied to large deposits and at larger yields. Again, substantial additions to economically recoverable U.S. resources, for example in copper, will be made if this technology is developed. The uncertainties of the processes after the nuclear detonation takes place were again found to be of major significance in determining the exact economic benefits. At present, only very particular ore deposits would satisfy the very strict technological requirements for economic production of ores, using nuclear explosives.

Cratering with nuclear explosives in earth moving projects is the most fascinating application the public associates at present with the peaceful uses of nuclear explosives. The potential uses of this technology are of a scale and scope which with conventional means cannot be realized today except at prohibitive costs. The nuclear cratering technology opens up a new set of tools with which the landscape of the earth can be deliberately transformed within a short time to suit economic and technical requirements, for example, the creation of new, artificial harbors at locations chosen by man, the construction of sea level, isthmian canals, the diversion and rerouting of rivers or complete river systems, the cutting of mountain passes, and so on. Cratering with nuclear explosions implies considerable economies of scale: the higher the yield, the larger the scope of the project, the more significant are the economies the nuclear technology will yield over any conventional means.

The considerations of safety are set forth in a separate chapter and reflect the present state of the art and the considerations given to it by the U.S. Atomic Energy Commission. It may prove, after experience and confidence in the new technology have been gained, that nuclear explosives will be applied on a much larger scale and a variety of other projects which at present are excluded a priori due to the lack of information and lack of public confidence. These potential additional benefits were discarded in the present report; but as with the peaceful application of chemical high explosives, unthinkable as to their scope and scale of applications only a century ago, nuclear explosives might prove of similar benefit in these other, added fields of application.

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Chapter 1

INTRODUCTION

PLOWSHARE is a code word used by the Atomic Energy Commission to describe a program for the use of nuclear explosions for peaceful purposes. It is part of the general program to use peacefully the power residing in the atom. Reactors use it in a controlled release of energy. Plowshare, however, embodies the idea to control the uncontrolled release occurring in the form of explosions of widely different magnitude. It may at first seem contradictory to "control the uncontrolled," but we are fairly familiar with this effort in a more conventional form: in mining, road building, construction, and many other uses we constantly set off chemical explosions of varying degree in order to obtain effects which would be very hard, time consuming, and expensive, if not impossible, to obtain otherwise. We have become accustomed to setting off such explosions and when they first became possible, they were quickly recognized for what they represented, namely, to facilitate the exploitation of resources and the accomplishment of work on which technical and economic progress depended. The new power given to the human race through peacefully intended chemical explosions under circumstances over which one could exercise control was hailed as a great step forward, although the dangers inherent in this application were also recognized. There were at first many accidents, most of them due to inappropriate and uncautious handling of the explosive material, but the inherent dangers were overcome and completely overshadowed by the immense advantages obtained from the sudden energy release. As more and more applications occurred, dangers were drastically reduced so that at present among the thousands upon thousands of conventional explosions set off annually all over the world, the number of accidents is reduced to a level which does not exceed the accident rate found acceptable in other industrial processes. Quite on the contrary, because of the awareness of the danger, their rate is probably smaller than in some other industrial activities.

For every new technological advance, there are advantages and there are costs to pay. When the advantages are striking, one is willing to accept significant costs. Sometimes significant costs are indirect, consisting in effects which had not been considered at the time of the introduction of the technology. This happened, for example, with the automobile which we now know produces, in large quantities, poisonous gases that have several adverse health effects upon millions and millions of people. On the other hand, when the railroads were introduced, medical authorities as well as the general public feared bad consequences for the health of passengers; it was believed that the human body would not be able to stand being transported at speeds of 15 to 20 miles per hour without suffering grave physiological damage. It was even proposed that solid fences be erected on both sides of the railway so that the passengers would be spared the devastating influences upon themselves of the fast by-rushing landscape. Thus, in both respects one has been wrong: in the first case in not estimating the dangers properly, in the second assuming dangers which were nonexistent.

Looking at nuclear explosions, it is certainly clear that dangers associated with them have not been minimized; if at all, they have been exaggerated. In many circles the idea prevails that any nuclear explosion is an unlimited catastrophe. That this view is false is easily demonstrated by the fact that in the last twenty years hundreds of nuclear explosions have been set off aboveground and underground in the U. S., the U.S.S.R., and elsewhere without any known accidents of any kind whatsoever attributable to these explosions themselves.

The projects that can now already be envisaged as possible uses of nuclear explosives by means of Plowshare operations, can be classified into two categories.

1. The first group of projects are cheaper to carry out than be conventional methods, which is to say, by methods restricted to the use of chemical explosions; besides, all these nuclear projects are less time-consuming by orders of magnitude than done otherwise.

2. Certain projects are conventionally "unattainable," which is to say, the costs to be incurred would be infinite. They are, obviously, also faster to attain than otherwise.

In the first category Plowshare does what can also be done otherwise, but Plowshare can do it cheaper usually by orders of magnitude. In the second category, the "impossible" is becoming accessible. If the cost reduction in the first category is very significant, as indeed will be the case, for example in the construction of canals, a strong motivation for using the new technology is present. If the value of the otherwise unattainable projects is high, then clearly this is a further substantial strengthening of the motivation for the use of the new means.

The extent of Plowshare operations reaches from primitive earthmoving applications to the production of isotopes and the sophisticated opening up of resources which though known to exist cannot be reached otherwise. In all cases the consequences will be of a very far-reaching nature and have to be examined and estimated in as precise a manner as possible at this stage of our knowledge. For example, a bountiful supply of isotopes, to be created in subterranean, explosively created cavities, can advance technical knowledge and especially the medical art in a very vital manner. Earthmoving of tremendous dimensions may go on with a speed hitherto unimaginable. Resources and treasures deeply locked in the earth may become available in such quantities that the economic structure of individual countries and the balance of nations among each other could be profoundly affected.

The economic problem is generally one of allocating resources in short supply in such a manner that a well-defined optimum of results is assured. It is therefore a question whether the supply of explosive devices is short or, correspondingly, what their price would be, relative to the advantages which can be obtained from their uses. This is an important consideration which indeed raises fundamental questions, but at the present state of the art one rather has to face a more general problem of decision-making, namely, to settle whether or not the new technology shall be used at all.

Costs, at least direct costs, are usually easier to determine than benefits. This is true, in particular, if the former should be expressible in numbers and the latter can be given more in the form of generally expressed advantages of a broad nature, accruing to many over long periods of time. If, however, we consider, as consider we must, among costs also indirect costs, the problem becomes immediately still more complicated. Indirect costs are often hard to face and difficult to allocate.

Regarding the general decision whether or not to use Plowshare at all, a point worth mentioning is of historical nature: no new technology that has ever become available to man has been rejected. There sometimes have been delays in time, and there often was a great deal of initial opposition, occasionally even of an ideological nature. Difficulties arose, partly because of the inherent dangers, as they were understood at the time of the introduction, partly because of the known or assumed direct and indirect effects, not only or even primarily upon the new industries and activities. Sometimes the evolution of a new technology depended on the availability of new materials which could only be developed over time. But sooner or later the new devices were accepted and were introduced on a large scale.

In general one can say that the use of a new technology was essentially due to private initiative. But as regards Plowshare, private industry alone, unaided and uncontrolled by government, can never make use of the new possibilities. This constitutes a novel fact which has to be carefully weighed. The state will always have to be present when a nuclear explosion is being set off, no matter how limited its use may be. In fact, no one else but the Atomic Energy Commission will ever be allowed to detonate a Plowshare device in the United States. Therefore a new form of public-private investment relationship arises; indeed, there are already several promising beginnings of this nature involving close cooperation between the government and private industry, especially in the field of gas stimulation.

It is clear that no matter what the price of the fissionable material be, the state will reserve the right to accept or reject an intended use, if only for reasons of safety or security. Once approved, further influence is possible by variation of the price; but as later chapters in this report will indicate, the advantages of using nuclear explosions are in most instances as such that even considerable variations in price would not offset the economic benefits to be obtained in certain applications. There is thus a very strong motivation for using Plowshare operations, and the other parts of this report will indicate where at present the principal uses lie and what their characteristics are.

While it does not necessarily follow from the historical evidence that any future new possible technology will actually be used, the probability that this will happen is very great. For Plowshare, however, it will be necessary to find new forms of cooperation between private industry and the government, but this will not be too difficult as the illustrations of the principal Plowshare applications listed and discussed below will indicate. The government's involvement will vary significantly from a minimum, as perhaps in mining, to a very considerable degree when, for example, the construction of a new canal connecting the Atlantic and Pacific Oceans is considered. In fact, in the latter case, which is one of the most impressive and immediate probable uses of Plowshare, not only one but several governments are involved simultaneously. Other technologies such as air traffic, railroad traffic, road traffic, etc., all started out with almost no regulations or very few; gradually by virtue of their dimensions and of the speeds involved the government was brought into greater contact with the new fields as a regulatory force. Here, however, the government has to be concerned from the outset.

It should be clearly understood that Plowshare is not concerned with slight, only marginal improvements of known procedures. Plowshare makes desirable changes in our environment possible that could not be contemplated before. It abbreviates the time needed to carry out projects:

All this by orders of magnitude. There are not many occasions in the history of technology where similarly big, discrete steps have been taken.

It would be desirable to order the various projects to be discussed in the following chapters according to feasibility and economic importance viz. their benefits, but we do not do this at present. One reason is that in order to do it competently more information is needed which can only be provided by additional experiments. Each one of these will provide firmer ground for such rankings. When many experiments are called for and these are more costly than the available funds, then also the experiments have to be ranked, which ranking would depend on the presumptive addition to our knowledge, to the future economic advantage of the most important particular project to be advanced by the results of the experiment etc. Such ranking encounters therefore the same kind of difficulty as the one mentioned above. Fortunately it is quite clear, at the present time, that the most important experiments are financially provided for and merely await a green light in order to be executed. They will, in particular, provide invaluable information for cratering applications of Plowshare, where experimental data are most urgently needed. Cratering, as it will be seen, is one area where Plowshare can make perhaps its most dramatic and economically most significant contributions to welfare.

Decisions, which projects to execute and to what extent to pursue them, whether these decisions are made by the government or by industry or in cooperation with each other, fall clearly into a wide category of problems studied at present intensively in advanced modern economics. This is the field of "decision making under uncertainty." In strictly deterministic situations there is virtually no other problem except that of setting preferences and then matching the means to these in an optimal manner. But when uncertainty enters, as enter it must, basically new phenomena appear, especially when uncertainty governs inputs as well as outputs and when conflicting interests of several participants are present.

This report does not examine these issues. To do so first the groundwork has to be laid and this is what the present work tries to accomplish.

It is desirable to list some of the indirect benefits and indirect costs of Plowshare applications.

Benefits: The side effects of a new technology are very hard to estimate, but it is clear that, considering for example a new canal between the Atlantic and Pacific, the following indirect benefits would occur: not only larger ships already in existence, which are now unable to pass through the Panama Canal, could use the new facility at sea level; in fact, much bigger ships than at present envisaged could be constructed. This would in particular be the case if at the same time, by means of nuclear explosives, new harbors could be opened in critical places throughout the world. Their location, of course, is a difficult problem which will have to take into consideration probable trade routes due to demand from heavy population areas; whether new harbors can safely be made in economically convenient places because of low population density; the availability of raw materials to be brought from one place to another where their consumption is assured, etc. From the appearance of new trade routes, indirect benefits always radiate in many directions which cannot be specifically foreseen at the time when the opportunity for new traffic flows is being created. The considerable lowering of transport costs implied would make many heavy industries less bound to their raw material bases, a trend which is already effective in the steel industries of e.g., Italy and Japan. The new opportunities this opens for the creative talents of many regions cannot be doubted, but in quantitative terms they are hard to measure.

Similar considerations apply to the creation of new water resources which also would have most diverse consequences for agriculture and industry. For certain regions in the world the availability of water might bring profound modifications of political economic circumstances. Most Plowshare operations, especially earthmoving, would primarily concern and interest underdeveloped countries where earthmoving is now being carried out in very primitive fashion and where the tremendous transition from hand operations to the immense power of nuclear explosives, bypassing the intermediary state of conventional explosives, is now possible. This is a step of such magnitude that entirely new dimensions of economic activity in those countries have to be viewed. There is also the shortening of time to be considered, which cannot easily be calculated in terms of dollars and cents.

If it should become a concern of a government, for example that of the United States, the indirect consequences of Plowshare could even lead to the condition that the United States could free herself from present dependence on certain foreign resources, say of oil, copper, etc., since it would now become possible to utilize thus far inaccessible resources of this type available within the territory of the United States itself.

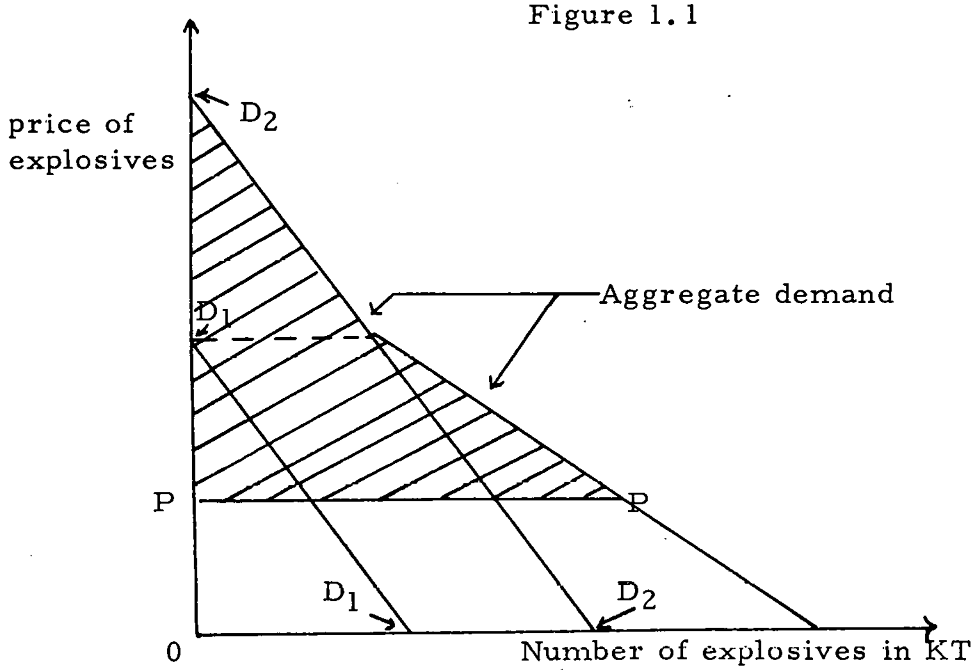
Costs: Indirect costs are also manifold but can be estimated and normally can be controlled. For example, there are social dislocations. If a canal is to be built between Atlantic and Pacific Oceans, population may have to be moved from the region where this canal is going to be established. But such population movements would have to occur even when no nuclear explosives are considered. They may merely have to be somewhat larger. Thus, not all the consequences of the use of Plowshare are to be attributed to the fact that nuclear explosives are involved rather than chemical. Some of the dislocations may be strictly temporary. Another aspect is the possible destruction of landscape, the consequent need for using resources for landscaping etc. But the same problem arises with conventional strip mining or canal construction operations which have been carried on for many decades and where now a control over the landscape destruction is also being imposed. Furthermore, there are indirect effects on world markets, some of which are perhaps unfavorable for other countries. This would be the case, for example, if Plowshare were to be used primarily for strictly political reasons, in order to increase the supply of some raw material in the United States which at present is being imported from abroad. Finally, there are political difficulties which have to be faced; however, most of these arise because of an inadequate understanding of the potential and actual benefits to be derived from Plowshare which easily offset the difficulties associated with this new technology.

An important question is whether the introduction of the Plowshare technology into the economic system and the further direction of efforts within Plowshare will be decided by a straightforward estimate of benefits and costs and, having established the respective overall benefits to the U. S. and individual industries, whether it will be left primarily to individual firms to develop this technology in their particular field. The questions of risk and uncertainty are singularly important when dealing with this particular technology. Risk arises from the known probability distributions of various costs and benefits, while uncertainty, refers to economic events, the possible occurrence of which is not known so that probabilities could be attached to them at present.

Aside from these issues which still fall within the scope of cost-benefit analysis, the question as to the "marketability" of the Plowshare technique raises further issues: applications of Plowshare shots in copper mining, in situ oil shale recovery, gas stimulation etc., may be economic once the technique and uncertainties attached to it are resolved. But are the potential benefits large enough to stimulate the active interest of any given industry or, more specifically, of a particular firm?

The potential demand generated by various industries and the companies comprised in them is a function of the price of the good offered. As the demand is generated by each industry, we obtain the demand at any given price by adding the individual industry demands at the respective prices. If we represent in a diagram both individual and aggregate demands, this procedure, in itself correct, leads to a "horizontal" aggregation of demand functions or, more precisely, an aggregation in the direction of demand, with demand on the abscissa and price on the ordinate.

Figure 1.1



As a measurement of the overall benefit to the "consumers" of the good we may use the area under the aggregate demand function and any given price, this benefit is also referred to as "consumer's rent" and corresponds to the shaded area above the price line $\overline{PP}$ in Figure 1.1. The benefit to the individual industries is similarly measured by the area under the individual demand functions and the given price. Given the benefit to the industries we would, on these grounds, expect sufficient initiative to develop to realize this new good or technology.

The preceding line of thought would be correct if Plowshare were already an established, available technique offered--due to its special aspects--solely by government agencies, so that single firms could not at given costs and expected benefits, develop their demand for nuclear explosives.

This, however, is not yet the case in our particular problem: Today the A.E.C., --though already in participation with private industry--is still in the process of developing this technique for various applications. The "marketable" good to be offered has in many ways yet to be developed; nuclear explosives, ranging in yield from a few KT to several MT and their role within the production process of various other goods still is the subject of current research and, hopefully, of still more extensive research in the future. The development of this new technique has, at present, all the aspects of a collective goods case: i.e., irrespective of whether industry A or B or ... Z decides to cooperate and to go ahead in their particular field or not, benefits of Plowshare will ultimately, at least to a large part, accrue to <u>all</u> possible fields of applications. One industry or even one single firm (e.g., El Paso Natural Gas Company in the case of gas stimulation (cf below pp. 99-124) may be the one to incur the substantial first development risks, and those who follow will benefit from the experience of the initiates.

The principal benefit being a collective one there arises another peculiarity: even if during the developmental phase of Plowshare the technology--still being tested--would not achieve immediate economic profitability, because of the inherent risk and uncertainty, the expected overall benefits warrant and justify further experiments by the government.

To illustrate: Given two industries where the new technology can be applied and given their individual demand functions for that particular technology we now have to aggregate the benefit demand curve vertically. This divergence from the former case is justified when we observe that irrespective of which firm demands 1, 2, or X numbers of experimental nuclear explosions, the benefits of the knowledge gained in developing the new technique invariably accrue to both industries. Thus, if one of the industries decides to acquire the "product," this automatically also satisfies the potential "demand" made by other industries. In non-cooperative situations the costs of satisfying the demand of third industries would be paid for by one industry alone, inhibiting implicitly the development of such a new technology. There may even arise the situation, where <u>none</u> of the individual industries sees an adequate potential of a new technology in its own field as to warrant its development though on a national (or worldwide) level the development of the new technology would be very beneficial. This discrepancy between individual benefits and capabilities and national interests and benefits tends to become large when the number of potential applications increases.

Figure 1.2

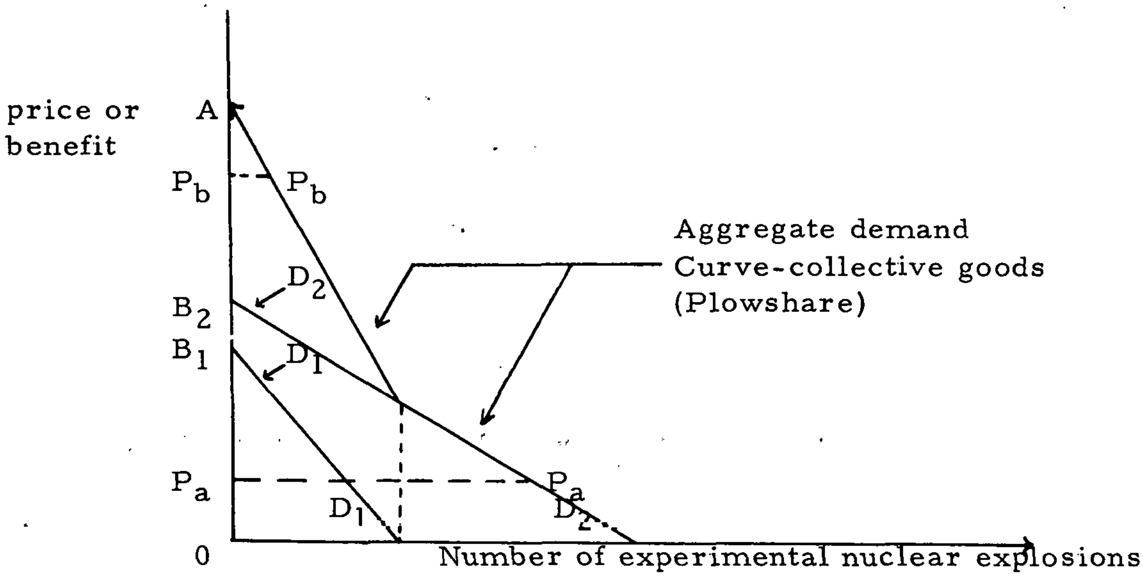


Figure 1.2 illustrates the simplest case, dealing with two industries. As against Figure 1.1 the reader will note that the demand curves for the new technology are now aggregated vertically; the overall benefit curve of developing the new technology is arrived at by adding the benefits of the individual industries and firms. The reason for this procedure is that, once the technological capability has been demonstrated, all concerned industries will benefit from this, irrespective of their participation in that program or not; therefore the name "collective good." In Figure 1.2 D_1D_1 and D_2D_2 show the benefits of their collective good to industry 1 and

2, P_a, P_b show two different prices (development costs) for this collective good, B_1, B_2 and A show the maximum benefit to be derived from this technique by industry 1, industry 2, and within the whole economy. Again the aggregated demand curve is sloping downward as at lower development costs (prices for nuclear explosive experiments) more and more individual firms would go ahead with their own experimental programs, increasing thereby the demand for such shots, and vice versa.

If the development cost of the Plowshare technology per experiment (P_a, P_b etc. along price-benefit axis) is less than the benefits of at least one industry, that is less than B_2 in Figure 1.2, then the structure of the benefits would be such that at least one industry is interested in developing that technique (Plowshare) all on its own. In that case Plowshare techniques may be realized based on the interest of single industries alone.

If, however, the costs to develop the new technique, the costs per experimental program are larger than the benefits each single industry can derive from it, then still a case for developing this technology (collective good) can be made: in case the developmental costs are less than the overall benefits from this collective good (Case P_b) it is still in the national interest to have this technique developed, even though from any particular industry development cost will be regarded as excessive and no individual demand will develop. Examples of such collective goods are easily listed: a missile defense system, solar orbital programs, and many others. The aggregate benefit to be realized by such a development may still outweigh its costs, often by a wide margin.

Finally, if the costs of the development program (i.e. the price of the collective good) exceed not only individual but also aggregate demand benefit functions, then Plowshare should not be developed. An identical argument applies to the various firms within one industry and we do not have to repeat this analysis.

A general conclusion to be drawn from this is rather surprising: if one and the same aggregate demand curve results in one case from a few large industries and/or companies while in another case it results from adding the demand of many small enterprises, the prospects of introducing a new technology with identical overall benefits will seriously be affected by the specific number of industries or firms interested in that technology. When identical overall benefits are to be distributed over an increasing number of beneficiaries, the probability that the development of such a new technology will take place is diminished, assuming that one has to rely on individual interests and assuming constant development costs. Another area of concern is the problem of pricing: if the government controls a considerable part of the costs of such developments, and the benefits to the whole economy of such a program have been established, should those costs be held reasonably low, even below the overall costs to the Government, in order to encourage initiative by individual industries? All these issues give rise to a series of problems of a theoretical nature which still await an adequate, perhaps game theoretical, analysis. The preceding analysis was in a very compressed form. Further elaboration of the theoretical aspects will be presented in a subsequent report.

It is important, however, to realize that a proper evaluation of future Plowshare applications demands a broadening of experimental evidence. Economic and political evaluations of different Plowshare programs have to rest on a firm and broad basis of well designed and well interpreted experiments.

The subsequent analysis of particular industry interests in this report indicates the desirability of further development of Plowshare be it on a national, on an industry, or an individual firm basis.

In the present report only such projects were analyzed which at present are seriously considered to be of immediate relevance and which are technologically far enough advanced to allow at least some economic analysis of their potential. Many other processes can be conceived of, utilizing nuclear explosives at some stage. Such projects will necessarily be developed at some later stage if first nuclear explosives prove to be feasible in the areas analyzed in this study. Still, the present analysis shows that already a vast variety of potential processes are quite technologically advanced and that it is already difficult to get an overall view of the technical and economic aspects of each single process. This general report is itself a summary of conclusions arrived at in five special reports and tries to give some relative weight to each of these fields of applications. Much work remains to be done, but the foundation for it has been laid.

There is reason to be confident that Plowshare techniques will in the future be employed with considerable economic benefits, provided that only economic factors are at work and no other influences delay the peaceful application of this new technology. The benefits lost to the U. S. and other countries in renouncing or delaying this potential development can easily be inferred from the individual potential benefits to be derived from various Plowshare applications.

Even if Plowshare should be rejected for the immediate future, the needs of the human race, in view of its vast and rapid increase in numbers and the developing shortages of resources accessible by conventional means eventually will force the use of this technology upon the world.

Long before this point is reached,the interest of other countries, especially of many underdeveloped nations, will have been aroused, for which there are already now many indications. The President of the United States has declared in 1967: "The United States is prepared to make available nuclear explosive services for peaceful purposes on a nondiscriminatory basis under appropriate international safeguards."* In order to make such services available to the rest of the world,it is obviously necessary first to lay a firm experimental basis at home and to make such applications of this new technology as recommend themselves. In this matter there exists, indeed, a certain urgency: the Plowshare technology is

*Message by President Johnson sent to the Disarmament Conference in Geneva, New York Times, February 22, 1967.

available to any nuclear power. All of them have an interest to apply to it their own needs and to enter the international arena. The U. S. is, to the best of our knowledge, far ahead in the development of the new technology but may lose this important position rapidly unless the additional work is pushed with vigor.

Chapter 2

PHENOMENOLOGY OF UNDERGROUND NUCLEAR EXPLOSIONS

There are basically two types of underground nuclear explosions currently being investigated under the Plowshare Program: First, are the contained explosions which are those that are detonated at such a depth that the force of the explosion does not breach the surface and, in most media, create an underground cavity or columnar-shaped chimney of broken and crushed rock; and second, are the cratering, or excavation explosions, which occur not so deeply so that the force of the explosion not only fractures and crushes the overlying material but also throws it upward and out creating a crater.

For purposes of discussion an underground nuclear explosion can be divided into four phases. Phases one and two are common to both contained and cratering detonations. Phases three and four differ for each type of explosion. The following discussion is based on A. M. Piper and F. W. Stead [1] and G. W. Johnson and G. H. Higgins [74].

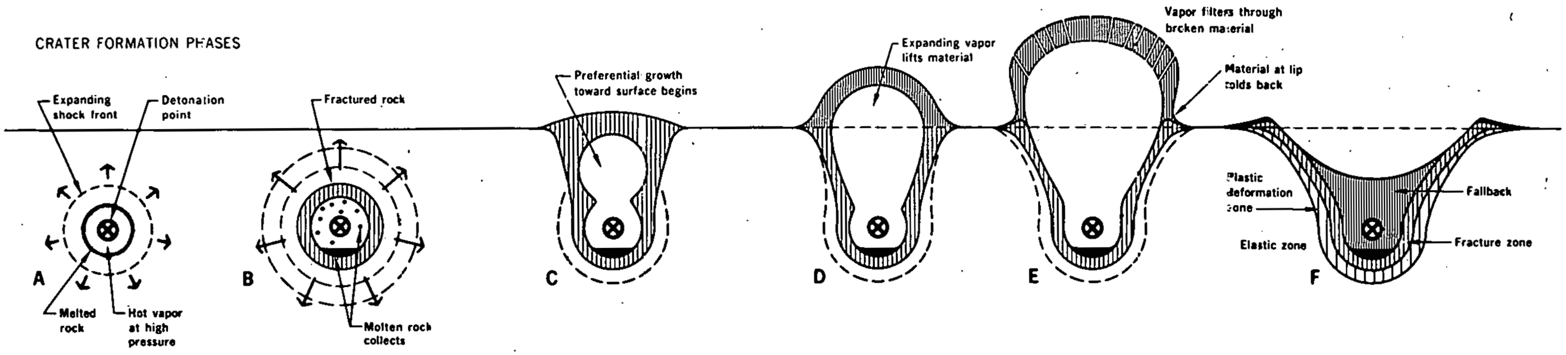
2.1 THE FOUR PHASES OF NUCLEAR EXPLOSIVE EFFECTS

During phase one of either a contained or cratering explosion, the explosion's total energy is released in less than one microsecond. The explosion and the resulting high intensity shock wave vaporize the materials which originally encased the nuclear explosive as well as some of the surrounding medium in which the explosive is emplaced. As a result of the vaporization of this material, and the impact of the shock wave on the surrounding medium, a spherical cavity is created. This cavity is filled with very hot gases which exert intense pressures on the surrounding rock causing the cavity to expand.

During the second phase, the shock wave moves out radially from the explosion, vaporizing, melting, crushing, cracking, and displacing the medium in turn. The wave reaches the surface of the ground very rapidly, whereupon it is reflected back down as a rarefaction wave. These stresses cause the upper layers of the overlying rock to separate and move upward--this effect is called "spalling."

The initial gas-filled cavity continues to expand melting more of the surrounding rock material which lines the borders of the cavity. This concentric shell of molten material is an interface between the rock beyond the shell and the gas sphere which keeps expanding until the pressure exerted by the expanding gas is counterbalanced by the pressure of the surrounding rock (overburden pressure mainly). The radioactive materials created in the explosion are contained in the gas at the initial stages of the explosion. As the sphere cools, the refractory nuclides begin to condense out in the molten rock shell surrounding the gas sphere. The deformation of the surrounding rock may affect up to three times the radius of the cavity formed by the gas sphere (see Figure 2.1).

Figure 2.1



When a nuclear explosion occurs, it initially (A, G) vaporizes, melts, and fractures the adjacent rock and sends out (B, H) a shock wave as the cavity of hot vapor at high pressure expands. If the explosive is buried at the proper depth beneath the surface, when the shock wave reaches the surface (C), the cavity begins to grow preferentially toward the surface. The explosion lifts most of the rock and dirt (D, E), some falling back inside, the rest outside the crater (F). If the explosive is buried very deeply, as the cavity begins to cool (I), (in most types of rock) fractured rock begins to fall into the cavity. This collapse continues upward leaving a column, or chimney, (J) of broken rock.

I II III [redacted] IV [redacted]

SOURCE: Information given by Atomic Energy Commission.

At this point, different phenomena assume importance depending on the depth. In a contained explosion, phase three begins after the pressure of the gas sphere has been balanced by the surrounding medium (or after cratering occurs), the gas sphere cools down, and the molten rock accumulates at the bottom of the cavity. Most of the refractory nuclides, about 65 to 80 per cent or more of the radioactive elements created, become trapped in this congealing rock.

During phase four of a contained explosion, the cavity begins to cool causing the pressure to drop. If the roof of the cavity is not strong enough to support the overlying material, it will start to collapse. This collapsing rock fills the cavity with blocks and pieces of broken rock. The collapse progresses upward forming a cylindrical chimney of broken rock. In a hard rock, such as granite, this broken material occupies more space than does the same amount of unbroken rock; this phenomenon is referred to as "bulking." The collapse continues until a point is reached where the overlying rock is either supported by the collapsed and broken rock or the remaining arch is small enough to support itself so that it no longer collapses. After the collapse ceases, the initial volume of the cavity is found to be distributed in the volume of the voids between the blocks of rubble in the chimney. In a loose rock, such as desert alluvium, there is usually no bulking and the collapse may proceed upward until the surface is reached; a surface collapse forms a subsidence crater which will have approximately the same apparent volume as the original underground cavity.

Phases three and four in the cratering event will lead to the throw-out and crater formation. In phase three of a cratering explosion, the shock wave which the explosion generates in the surrounding rock plays an important role. When it reaches the surface of the ground, it causes the upper layers of the material to spall off (break away) forming a dome on the surface. At this more shallow depth, the rarefaction wave, which is reflected back down, reaches the cavity while it is still expanding, reducing some of the overburden pressure, and thus allowing the gas within the cavity to start expanding preferentially in the upward direction. As the gases expand upward, the surface is pushed upward and out until the dome is breached and the gases begin to leak into the air. With the rapid release of the gases, the pressure thrusting the rock upward is removed. The rock and debris continue to move up and out, traveling along curved flight paths, or trajectories to be deposited on the ground. In phase four of a cratering detonation at the optimum depth, the particle trajectories are such that about half of this material falls back into the crater and the remainder falls on the surface of the ground around the crater. The optimum depth of burial for an explosion of a given yield is that depth which results in the maximum apparent (or visible) crater dimensions. If the explosive is buried shallow or deeper than the optimum, the depth and/or diameter of the crater will be smaller.

After the chimney or crater has been formed and the glass melt and the rocks cool off, the long term phase of temperature dissipation and nuclide decay sets in. Phases three and four may overlap.

It has been discovered by analyzing past cratering experiments that the main mechanism in forming a crater in alluvium is the push of the gases expanding upward. This is partially due to the fact that alluvium has a higher water content than hard, dry rock. The water in the alluvium around the explosion is vaporized and adds to the gas pressure exerted during the cavity expansion phase. In hard, dry rock, such as basalt, the main cratering mechanism appears to be the upward velocity given the rock by the shock and refraction waves from the explosion. Thus, the water content, or hydrogen content in general, of the surrounding medium is a very important factor in predicting the exact dimensions of both cratering and contained explosions.

Chapter 3

COSTS AND DESIGN CONSIDERATIONS OF NUCLEAR EXPLOSIONS

Nuclear explosions are basically cheap, compact, powerful sources of energy. Just how inexpensive energy from a nuclear explosion is compared to other energy sources is illustrated by Table 3.1. The problem confronting Plowshare is how to apply this powerful energy source effectively and economically in peaceful applications. One may say, broadly speaking, that the economics of Plowshare projects is based on the potential cost differential in producing, transporting, and emplacing a nuclear explosive as against an equivalent conventional explosive energy source.

The energy or yield of a nuclear explosive is measured in terms of the amount of TNT required to release an equivalent amount of energy i.e., a 10 KT nuclear explosive releases the same amount of energy as 10,000 tons of TNT.

The main outward effect of fission or fusion reactions is the release of a substantial amount of energy. This energy release is proportional to the number of fissions or fusions of nuclei. The fission of one nucleus produced 179 Mev. (of 2.86×10^4 ergs each, see Table 3.2) of energy, in the form of kinetic energy of fission particles, the energy of fast neutrons and gamma radiation [35]. With this energy is associated an additional amount of 10% of energy released in fissions in the form of residual

Table 3.1--Comparative Energy Costs

Energy Source	Cost Per Million (10^6) Btu
2 Megaton thermonuclear explosive	$ 0.075
Lignite	0.14 - 0.17
Soft coal	0.15 - 0.20
Natural gas	0.20 - 0.15
Water power	0.89
Gasoline	1.50
Electricity ($0.006/kwh)	1.78
Ammonium nitrate	4.50
10 Kiloton thermonuclear explosive	8.75
TNT	125.00

SOURCE: Atomic Energy Commission

radiation, about 22 Mev per fission. Three fourths of this residual radiation energy is converted into heat [35].

The fusion of one nucleus of H^2 (deuterium) releases about one-tenth of the energy of a fission reaction, 95% of the energy being released instantaneously [36]. Explosive energy releases can be also obtained from certain chemical reactions, mainly trinitrotoluene (TNT), ammonium nitrate, fuel oils, and some other chemicals.

Table 3.2--Equivalents of 1 KT of TNT

1. Complete fission of .056 kg (= 56 grams) of U^{235} or equivalent in another fissionable material.
2. Fission of 1.45×10^{23} nuclei.
3. Fusion of 1.45×10^{24} nuclei of H^2 and H^3 (= deuterium and tritium).
4. 10^{12} calories.
5. 4.2×10^{19} ergs.
6. 1.15×10^{6} kilowatt hours.
7. 4.0×10^{9} British thermal units (Btu).

SOURCE: Johnson et al., "Underground Nuclear Detonations," Journal of Geophysical Research, Vol. 64, 10, 1959.

Thus, .056 kg of U^{235} contain a potential energy equivalent of 1,000 metric tons of TNT. However, the cost of a 10 KT nuclear explosive device is about $350,000, whereas the cheapest chemical high explosive material (ammonium nitrate and fuel oil) would cost more than $700,000 at an equivalent 10 KT yield and, finally, 10 KT of TNT would cost about $5,000,000 for the material alone. Moreover, the nuclear explosive of that yield would be about 100,000 times smaller.

In determining the direct cost of a nuclear explosion, a number of factors must be considered: the cost of the nuclear explosive itself, emplacement costs, and transportation charges.

In order to provide some guidance to industry in making estimates to compare the costs of nuclear and conventional techniques for accomplishing a proposed project, the AEC, in May of 1964, announced projected charges for thermonuclear explosives, which charges are expected to apply particularly for excavation applications (see Figure 3.1). Potential users can figure for planning purposes on a charge of about $350,000 for such a 10-kiloton nuclear explosive and $600,000 for such a 2-megaton explosive. The tentative charge would include arming and firing services as well as the explosive itself. However, the charges do not include charges for related services and safety studies. These tentative charges were based on a projection to a time when nuclear explosives will be produced in quantity for routine commercial applications.

The cost figures for nuclear explosives in this report and the five Special Reports by MATHEMATICA, are based on data given by the Atomic Energy Commission. For low intermediate and intermediate yields, the interpolations have been made according to the following function:

$$C = 241,300 + 108,700 \log W \qquad (1)$$

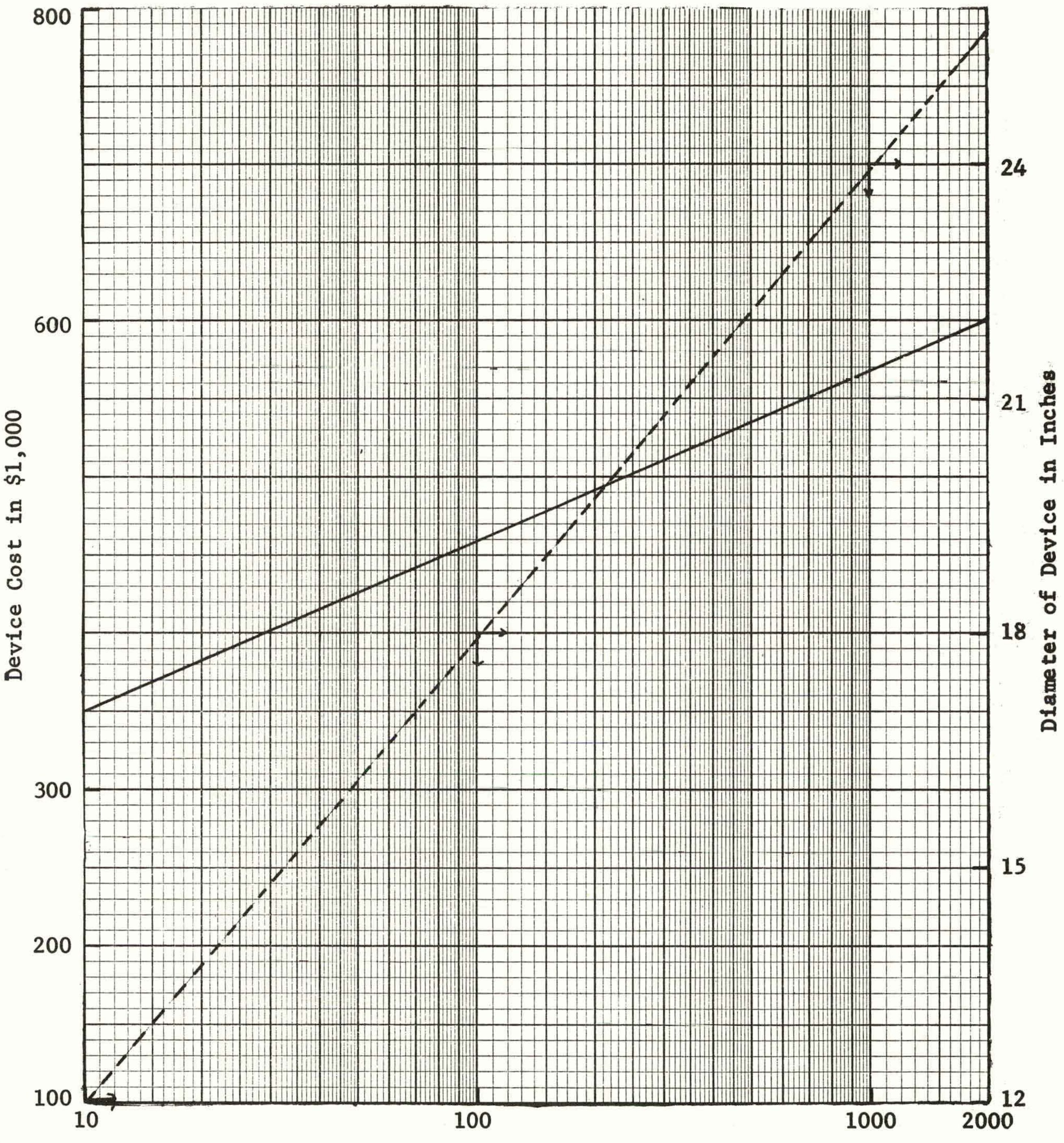
where

C = total cost of the device in dollars

W = yield of the device in kilotons

Important cost items which are not covered by these charges are safety studies, site preparation including construction of holes, transportation and emplacement of the devices, and support. Table 3.3 shows total costs, costs

Figure 3.1--Projected Charges and Diameters of Thermonuclear Explosives as a Function of Yield



10 KT ≥ 12 inches*
100 KT ≥ 18 inches*
1,000 KT ≥ 24 inches*
10,000 KT ≥ 36 inches (not shown)*

* Diameters of Nuclear Explosives

SOURCE: Information given by Atomic Energy Commission.

Table 3.3--Charges for High Explosives and Extrapolated Charges for Nuclear Explosives at Selected Yields

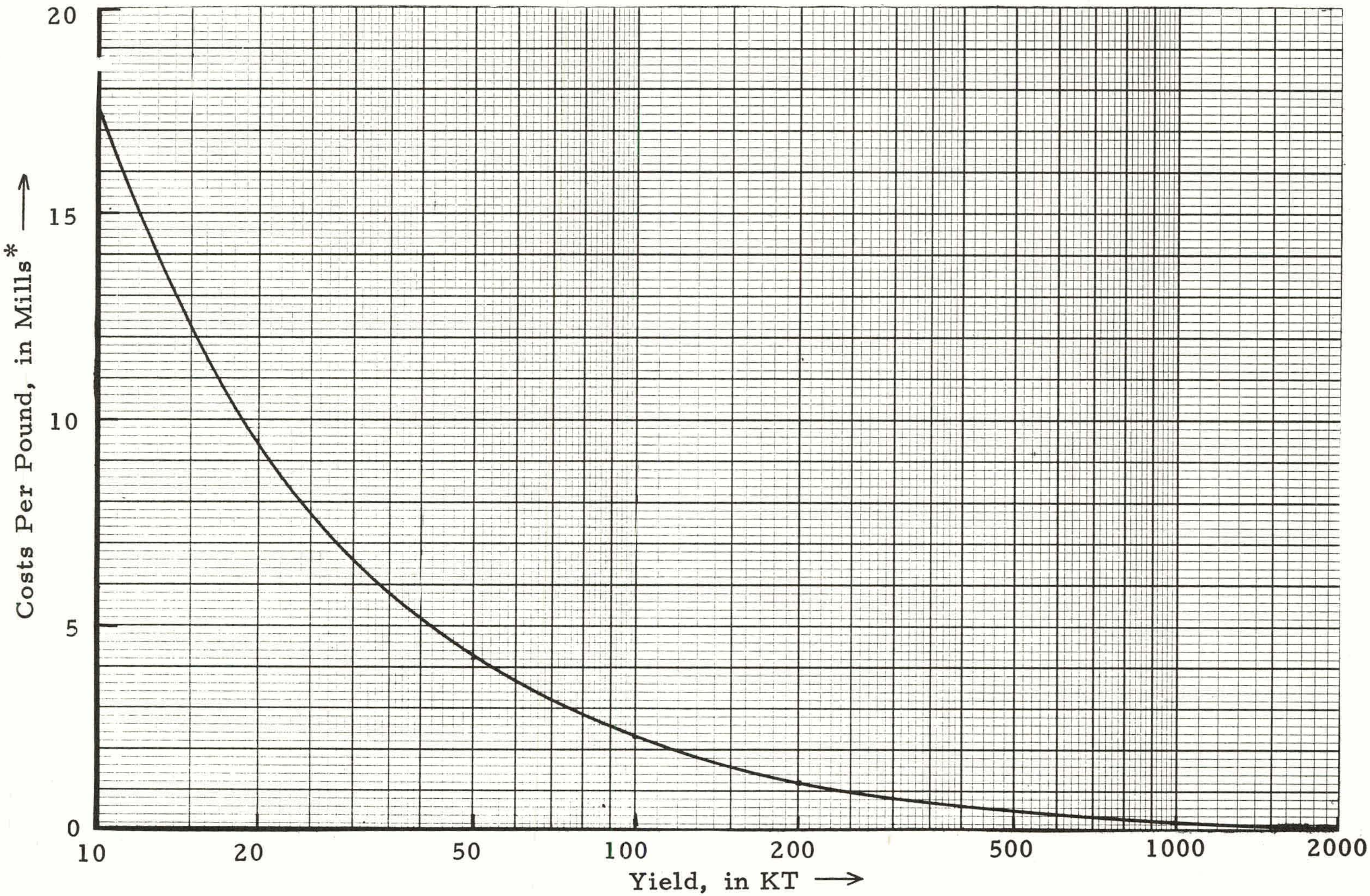
Yield (KT)	Total Cost $ Assumption (1)	Total Cost $ Assumption (2)	Cost per ton Assumption (1)	Cost per ton Assumption (2)	Cost per pound Assumption (1)	Cost per pound Assumption (2)
chemical high explosives (mixture of ammonium nitrate and fuel oil)*						
1.0	$ 70,000 100,000*		$ 70 to 100*		$ .036 to .05*	
nuclear explosives						
0.1	133,000	350,000	1,330	3,500	.67	1.75
1. **	241,000	350,000	241	350	.12	.175
2	274,000	350,000	137	175	.068	.0875
5	316,000	350,000	65.2	70	.032	.035
10	350,000	350,000	35	35	.0175	.0175
20	380,000	380,000	19	19	.0095	.0095
50	426,000	426,000	8.5	8.5	.0042	.0042
100	460,000	460,000	4.6	4.6	.0023	.0023
200	491,000	491,000	2.45	2.45	.0012	.0012
500	535,000	535,000	1.07	1.07	.00053	.00053
1000	570,000	570,000	.57	.57	.00028	.00028
2000	600,000	600,000	.30	.30	.00015	.00015

* [245] Prices for TNT range from $.25 or more to a possible $.15 per pound, depending on the quantities bought. However, the commercial use of TNT is very insignificant. Instead, mixtures of ammonium nitrate and fuel oil are used as high explosives today. The cost per pound of these explosives ranges from $.05 to $.036 and may be as low as $.03. Their explosive effect is somewhat higher than that of TNT.

** The AEC published only projected charges down to 10 KT (= $350,000). In these calculations a constant $350,000 charge was applied to smaller yields, though ultimately the cost price may be lower.

SOURCE: Interview with officials of Hercules Powder, Inc., Wilmington, Delaware, May 19, 1967, and information from Atomic Energy Commission.

Figure 3.2--Costs Per Pound of Explosive Yield at Projected Charges for Thermonuclear Devices (in mills*)



Costs per pound of chemical high explosives: 36 to 50 mills*

* 1 mill = $.001

per ton and costs per pound for nuclear yields ranging from 1 KT up to 2 MT and the comparative costs of a 1 KT chemical high explosive. We have considered two assumptions in connection with yields less than 10 KT down to 1 KT for want of information on costs of these low yields: 1) extrapolation from charges published by the AEC supposing that the log linear behavior holds down to 1 KT, and 2) a constant $350,000 charge for explosives below the 10 KT yield. All of the above costs and projections are based on the charges published at present by the AEC [58, p. 9]. These charges reflected at their time of publication the progress achieved since 1958 in the design, emplacement and technology of nuclear explosions. Further progress has been made and it is plausible that the long run costs of a nuclear explosion (device and firing costs) will approach the costs of the materials used and mentioned in the same publication [58, pp. 8-9]. Based on known prices, each KT in potential yield of fission energy costs $600 per KT (based on U-235 prices) and each KT of potential fusion energy/costs $100 per KT (based on Li^6D costs). For the construction, assembly and delivery of each device an additional amount W_0 has to be allowed for, giving the following potential cost function for nuclear devices:

$$C = W_0 + 600\ W_1 + 100\ W_2 \qquad (2)$$

where

W_0 = (fixed) cost for construction, assembly, delivery, per type of application.

W_1 = fission yield of the device in KT

W_2 = fusion yield of the device in KT

and W_1 should be minimized in order to minimize C and safety costs (radioactivity).

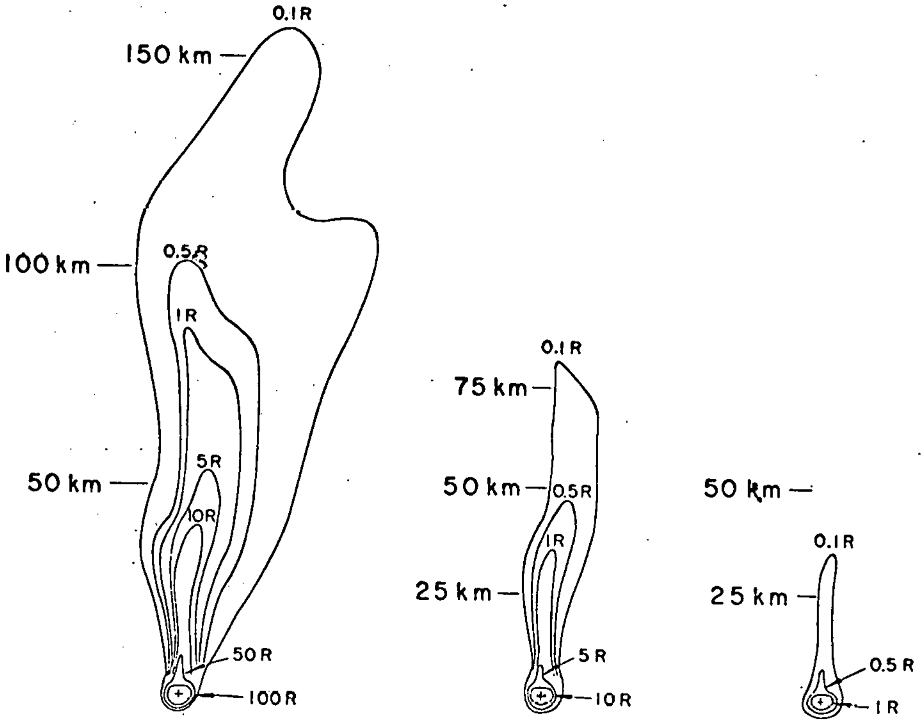
Given the techniques of construction of nuclear devices and given the published charges of the AEC, we may conclude that the cost of nuclear devices as a function of yield includes a large portion of fixed costs. The yield of the fusion device may then be enlarged up to very high yields (in the megaton range) at very small variable costs. Thus while the material of 1 KT of conventional explosives does cost anywhere between $70,000 and $100,000 i.e., $.036 to $.05 a pound, a 10 KT nuclear device is presently charged at $350,000 and a 2 MT device at $600,000 i.e., only $.0175 and $.00015 per pound of explosive energy respectively.

Another comparison given often in this context is shown in Table 3.1 which gives some interesting information on the costs per million Btu (British thermal units) of these various sources. The relevant technical and economic question is whether and how much of that energy can be transformed into effective work in production processes. Thus the costs of water power may be cheaper per Btu than energy released by a 10 KT thermonuclear explosive, but in excavating projects only the explosive device will yield the required work, and do so economically. On the other side, the cost per Btu of a 2 MT device is about 20 times cheaper than the energy cost of electricity; still today it is completely uneconomic to generate electricity or comparable controlled forms of energy by thermonuclear fusion processes. In this sense, Table 3.1 gives only a limited amount of economic information and at the same time serves to outline the difficulties in making an economic evaluation of this new nuclear technology.

The AEC has not yet issued any projected charges for other types of explosives which might be more suited for contained applications. Nuclear explosives can be designed to optimize specific characteristics such as diameter size, level of radioactivity produced, or costs. For example, in underground engineering projects, the question of diameter becomes important as the diameter of the explosive has a direct bearing on emplacement costs. The cost of emplacement is a function of both the depth of emplacement and the required diameter of the hole which is dependent to some degree on the explosive's yield (see Figure 3.1). As drilling costs increase with larger diameter requirements, there is a positive incentive for designing nuclear explosives with as small a diameter as possible. However, other design constraints, such as the question of radioactivity, may outweigh diameter considerations in some underground projects. Thus emplacement costs are a function not only of the yield of the explosive, but also of the purpose of the explosion, safety requirements, depth of emplacement and some other factors. The discussion of the relative weight of emplacement costs is therefore dealt with in Chapter 5 of this report, for each application separately.

Considerable progress has already been made in designing explosives for excavation projects which minimize the amount of radioactivity produced by an explosion, as evidenced by the above mentioned projected charges. Research is currently being conducted both to refine the advances made on the explosives developed for excavation applications and to determine what design properties should be optimized for specific contained applications, including trade-offs between properties when there is a conflict (see Figure 3.3). One of the principal objectives of the Gasbuggy experiment is to determine some of the constraints which may be involved in device design in regard to radioactivity in the gas stimulation application.

Figure 3.3--Estimated Technological Advance to be Made in the Fallout Deposition of Radioactive Debris from a 100 KT Nuclear Cratering Detonation



Technology 1962 (Sedan Event) | Technology 1964 | Future Technology

INFINITE DOSE FROM ARRIVAL IN ROENTGENS (=R)

SOURCE: Nordyke, Milo D., Circeo, Louis J., "Progress in Nuclear Excavation Technology," LRL-Livermore, California, December 1964.

Costs of transporting a nuclear explosive must also be considered in any estimate of the costs of a nuclear explosion. The logistics and costs associated with transporting and emplacing a compact nuclear explosive, when compared with transporting and emplacing an equivalent amount of conventional energy again favor, generally speaking, nuclear explosives from certain yields onwards. The exact break-even point between chemical high explosives and nuclear explosives techniques has again to be determined for each field of application separately and in some cases,high explosive techniques are excluded altogether a priori for engineering reasons alone (e.g., for in-situ shale oil production processes).

If we return to Figure 3.1 and Table 3.1,we see that the crucial question in any such economic comparison will be how much of this new and cheap energy source can be transformed into work.

Much is now known about the phenomenology of nuclear explosions and about the effects that are produced. The major costs associated with carrying out a nuclear explosion have also been identified. Estimates can be made within fairly precise limits for direct costs such as drilling, as shown later on. These costs are known and costs of the explosive and related services are also fairly well established. General cost functions for the nuclear device, transport costs, and emplacement costs will be estimated in later studies. However, it is evident from this rough comparison that nuclear explosives may permit a large set of new techniques to be employed in developing the resources of a nation which up to now were uneconomic or marginal.

Major uncertainties that exist in regard to the economics of Plowshare arise not so much from the costs of nuclear explosions but rather from lack of more precise technical information on the utilization of the effects of nuclear explosions for specific applications and the lack of experiments in each of these fields.

Additional research and experiments are required to define what properties of the nuclear explosive should be optimized for specific applications and what trade-offs should be made; i.e., diameter sizes when emplacement costs are a deciding factor, radioactivity in regard to decontamination costs, etc. Engineering unknowns will have to be solved such as whether the fractured area of oil shale surrounding the nuclear chimney can also be retorted or what the effective well bore radius will be in the gas stimulation application, what the particle size distribution will be within nuclear chimneys for various media and at various yields, whether air or gas injection processes will have to be used in the _in situ_ production of shale oil and what the required pressures will be in such a process etc. It is the solution to this type of problem that will ultimately determine the economics of particular applications. Where these uncertainties still exist, the present study was limited to identify these and show their relative weight in the overall economics of particular applications under various assumptions.

Within these limits, the problem which remains and to which the present study addresses itself is to identify those applications which are economically suitable for nuclear explosions on the basis of individual firms or on a national scale. There is no question that nuclear explosives are a cheap, powerful source of energy in many of the proposed applications. Due restraint, however, will limit effectively the geographical areas where nuclear explosives can be applied safely. Thus, the question of safety may become the controlling parameter in certain types and areas of application.

Chapter 4

SAFETY ASPECTS IN THE PEACEFUL USE OF NUCLEAR EXPLOSIVES

The immediate effect of any nuclear explosion is the production of energy by fission or fusion reactions. The energy thus created is then transformed into heat, kinetic energy and nuclear radiation. The effects produced in these events are varied. Considerable temperature increases occur around the center of the explosion, shock waves emanate in the air or underground, radioactivity (directly created or induced by the neutron fluexes) and secondary effects are induced. If uncontrolled or not predictable, these effects of nuclear explosions could cause such personal, physical and economic damage as to offset any anticipated economic benefits from their peaceful uses. Thus, safety requirements of any Plowshare application do play an important part in determining the range of possible economic uses of nuclear explosives.

Two basic distinctions have to be made when analyzing safety costs: first, an extensive safety study will have to be made prior to any particular Plowshare project, including any possible preventive measures, called for as a result of these studies, and the costs connected therewith; second, safety costs which might arise after detonation, which under efficient project design should be minimal.

Safety studies have to evaluate potential hazards posed by the various effects of cratering or completely contained nuclear explosions, their possible range and whether there would be physical and/or economic damage. These expectations have then to be compared to acceptable, safe threshold levels for the various effects of nuclear explosions, e.g., peak particle velocity variations for seismic effects, pressure increases due to air blasts, expected radioactivity in regard to appropriate guides or standards and so on. The main task of safety studies is to design projects in such a way that nuclear explosives at the yields required can be detonated without entailing safety hazards of any kind exceeding presently adopted safety standards.

Any particular Plowshare project has to consider all of the above effects from the standpoint of safety. According to location, purpose and source of the explosion, the effects most limiting to a particular project may be defined as <u>critical effects</u>. In part, these critical effects and their levels will vary not only with the location of a proposed project but also vary over time: most of the critical effects are a function of the distribution and density of the population in the neighborhood of the project area. In sparsely populated regions it is possible to safeguard the whole population at relatively low cost, if any, against personal, physical and economic damage. Other areas, e.g. large cities, may be excluded a priori because of yield considerations as possible sites for Plowshare applications for obvious safety limitations and safety costs.

Thus a certain set of areas or conditions are excluded for Plowshare projects completely. As the distribution and density of the population changes over time, safety costs and the feasibility of at least some projects will also change.

The main safety costs in Plowshare are thus defined in a rather "negative" way: they occur through the exclusion of a vast set of technically possible applications, due to rigorous safety standards; the main safety costs in Plowshare are, in this sense, the foregone benefits from all projects which, due to safety considerations, will not be acceptable under given conditions. The later parts of this report are therefore by and large limited to the evaluation of safe projects.

The major safety expenditures in Plowshare are connected with the project safety studies and the set of preventive measures to control and minimize the critical effects. Only a minor part, if any, will then be required to compensate actual damages connected with the project. There will also be minor costs associated with the industrial safety program which is a part of every Plowshare project. In the following, the main safety problems are discussed and viewed as a function of:

a. Where the explosion occurs

b. The purpose of the explosion

c. The source of the explosive yield and the yield itself.

The critical effects will vary considerably with each of the mentioned variables, but in each event radiation, air blast and seismic effects will dominate other safety aspects.

Almost every Plowshare project has an estimate of the costs of safety programs or in some cases, of actual safety expenses incurred for those which have been carried out. Examples of estimates of safety costs for large cratering projects are found in the present Canal studies and the Tennessee/Tombigbee study. The Tennessee/Tombigbee study shows that in some instances the costs associated with conducting a project safely will be such as to negate other savings from the project as studied. In Plowshare, all projects so far proposed are conceived of in such a way to guard against any conceivable hazard to any offsite and onsite personnel and offsite property. Such rigorous standards are understandable in this particular case although other industries often operate at much lower, effective safety requirements.

The effects of major concern in Plowshare applications are: radiation effects, shock induced effects, ejecta and air blast effects, and a number of miscellaneous other potential hazards. With regard to radiation effects, an important distinction has to be drawn as to the sources of radiation. By now a large part of the public is in one way or another informed of the possible radiation effects of nuclear explosions. Whether the notions held by the public are founded or not and to what degree they are accurate will not be discussed in this paper. Much less, however, seems to be known of the natural sources of radiation which continuously surround and affect each individual. Such natural background radiation sources include cosmic rays, radioactive materials in the earth and in the waters of the ocean, and radioactive materials within the individual's body (gastrointestinal radiation) caused by food intake and respiration. In addition an individual may be exposed deliberately to a controlled amount of radiation for medical purposes; i. e., x-rays, cobalt treatment, tracers, etc.

The amount of radiation from all past experimental nuclear explosions of all countries contributes only insignificantly to the lifetime radiation dose of an average individual. Moreover, these past shots were of a non-contained nature where the radiation problem was first ignored and then, up to the test ban treaty, only inadequately dealt with. All Plowshare projects as conceived at present are radiologically "contained" in the sense that no substantial amount of radioactivity would be released into the atmosphere even relatively close to the shot point area.

4.1 EFFECTS OF RADIOACTIVITY IN UNDERGROUND EXPLOSIONS ON THE ECONOMICS OF PLOWSHARE APPLICATIONS

Given the nature of radioactive nuclides created in underground explosions, i.e., volatile, intermediate and refractory nuclides with short, intermediate and long half-lives, fission-created, fusion-created and neutron-induced unclides, and given the varying purposes of Plowshare applications, different conclusions as to the economic effects of radioactivity in various Plowshare projects must be drawn.

a. In the case of gas stimulation, volatile elements seem to pose the most serious problem as the refractory nuclides will be trapped in the melt at the bottom of the chimney. Given their nature, volatile elements will readily intermingle with the gas itself and in addition the neutron fluxes produced by either fission or fusion explosions will activate amounts of the hydrogen present in the hydrocarbons surrounding the shot point. Tritium is expected to occur within the chimney at as high a rate as .04 microcuries per cubic cm [13].

Flushing (venting) of two, or more, chimney volumes of gas should remove about 95% of these contaminants. It is estimated the gas thus vented would contain during the initial phases about 3 picocuries per cubic cm. After venting, the contamination of the remaining gas could be lowered by a factor of 10 or more. Dilution with uncontaminated gas would then yield gas, which would satisfy safety requirements. The tritiation problem becomes even more complicated by the uncertainty with regard to the amount of tritiation of H in surrounding hydrocarbons and water [125, 154, et al.].

Research in this area is in progress [58]. Experiments in gas and water containing formations are necessary for further knowledge and accurate evaluation. Through device design and emplacement techniques tritiation could possibly be minimized if not eliminated. Refractory nuclides should not be any problem in gas stimulation and if by any chance refractory particles are produced at the well head they could be easily separated from the gas itself.

b. Oil stimulation and oil recovery from tar sands: Due to the amount of tritium produced in a fusion explosion and, less so, the induced tritiation of the oil in the surrounding medium, considerable contamination of the products could occur, at least within the chimney. Assuming a uniform tritium distribution, crude oil stimulated in tar sands by nuclear explosions should contain about 1 micro-curie per gram of crude oil. Again, most of the refractory nuclides would be trapped in the melt at the bottom of the chimney and would not pose a contamination problem. Conventional crude oil formations contain about three times as much oil per volume as tar sands. This implies an increased quantity of contaiminated products, by a factor of about 3*. Device design, emplacement, and other means discussed previously, might contribute to advances similar to those made and envisaged in cratering explosions.

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* The total amount of radioactivity would remain more or less unchanged. The quantity of radioactivity trapped, however, in oil increases proportionally with the amount of oil present in the chimney.

c. Oil shale: The economic problem here may be less serious than in the previous two cases. The volatile radioactive nuclides could be vented. It is expected that most of the contaminants will be concentrated in the chimney. When heated up during the retorting process, the tritium exchange is accelerated, increasing the contamination of shale oil, though some contaminants will remain in the oil-spent oil shale. Experiments are in progress to learn more about the flux of radioactive products in retorting chimneys.

d. Copper recovery: Radioactivity seems to pose only a small economic problem in copper leaching. Research done at Oak Ridge and reported on by Rawson [13] gave encouraging results. The main problem here is the potential contamination of the leaching liquid which is circulated from surface level. Through ion exchange with the ore, the amount of radioactive nuclides, especially of Cs, Zr, Nb, Ag and Sb would be reduced, and so reduced radioactive contamination of the leaching liquid would follow. Radioactive isotopes in the leaching liquids are expected to be so few as to cause no problem.

e. The contamination of water flows: Apart from contamination by fission products, any fusion device will necessarily increase the possibility of tritiation of the hydrogen contained in adjacent water. Although this is a minor contribution, most of the tritium is produced as a result of the fusion action itself. The tritium created in a fusion explosion would soon combine with the oxygen liberated earlier during the high temperature phase of the explosion and form tritiated water. Tritium also exchanges with the hydrogen of water which further increases the concentration of tritiated water. Tritiated water is chemically identical to non-tritiated water and would flow along the aquifer like normal water and dilute with it. Tritium, in general, does not readily exchange with surrounding media. Decay and dilution are the only means by which radioactivity of tritiated water diminishes. The possible dispersion of tritium in aquifiers is given in Table 4.1 [75, p. 51].

Table 4.1--Tritium Flow Calculations

Flow Rate (feet/year)	Reduction by Adsorption	Decay-time (years)	Distance at which tolerance is reached
5	0	85	425
100	0	85	8,500
100	50%	60	3,000
1000	50%	60	30,000

SOURCE: A.R.W. Wilson, E.B. Pender, E.K. Carter, "An Evaluation, for Australian Purposes, of Proposed Civil Engineering and Mining Applications," Sydney, March 1964.

To diminish or avoid tritiation, methods similar to those used in gas stimulation may prove to be of advantage. However, if the water movement in the aquifier is very quick or the water has to be removed after a short time near the shot point, tritium will necessarily pose problems and will be a critical effect in water management projects. A.M. Piper proposed a method [1, p. 113] to effectively isolate the main center of radioactivity by exploding the device deep enough, such that the explosion center (non-collapsed cavity immediately after the explosion) is completely contained underneath the aquifer proper. Most nuclides would be trapped in the glass melt, and another substantial part could, at least theoretically, be isolated from the circulating water by a blanket of grout or other sealant across the rubble of the chimney at the base of the aquifer system. The problem of placing grout over the glass melt is complicated by the fact that during drill-back the radioactive gases would be present and would have to be removed or the gas sufficiently low in removal volume as to permit escape into the air. Volatile parts could be vented. The scales of most of these explosions are projected in the 10-20 KT range which would not preclude a pure fission explosion, avoiding thereby part of the tritium problem if it cannot be solved otherwise.

4.2 RADIOACTIVE FALLOUT PROBLEMS IN CRATERING EXPLOSIONS

In cratering explosions some radioactivity escapes to the atmosphere, resulting in local or some insignificant tropospheric fallout. Most of the radioactivity because of the deep burial of the explosive is trapped by the overlying material and only a very small percentage escapes to the atmosphere, unlike an explosion which is conducted in the atmosphere where all the radiation produced is released in the atmosphere. The distribution of the radioactivity produced by fission or fusion explosions in cratering applications is as follows:

a. The largest fraction of the radioactivity is trapped underground and in the fallback of the particulates ejected.

b. The activity which escapes, a relatively small fraction, further results in some local fallout in the immediate environment of the crater within an area controlled by the government.

c. A small fraction is injected into the troposphere and results in tropospheric fallout.

The percentages of activity falling under (a),(b) or (c) depend of course on the depth of burial of the device and its yield, and to a lesser extent on the medium. As the yield decreases and the depth of burial increases, or some combination of the two, the amount of radioactivity that escapes and results in local or tropospheric fallout is correspondingly reduced. In the extreme, the explosion will be completely contained. (See Figure 2.1)

Again, various techniques are envisaged to minimize the radioactive fallout problem, if not to eliminate it completely. These include the development of thermonuclear explosives which release a minimum amount of radioactivity, the so-called "clean" explosive, as well as emplacement techniques designed to entrap most of the radioactivity in the immediate vicinity of the explosion.

Moreover, prior to any Plowshare project, the meteorology of the area is carefully studied to determine wind and other atmospheric conditions which would cause any radioactivity released by the explosion to pass over uninhabited or sparsely populated areas, given the airborne radioactivity time to disperse and decay down to very low levels, detectable only by extremely sensitive instruments, before it reached any population.

Because fallout could reach the public via the food chain--i.e. fallout deposited on grass, is eaten by cows, the radioactivity is concentrated in the milk which is consumed by man--a number of measures are taken to avoid this possibility. Detonations can be scheduled for after the grazing season or the cows can be put on dry feed for a few days after the detonation. As the radioactive nuclides deposited on the grass soon decay to stable nuclides, the cows can return to graze in the fields safely within relatively few days.

If milk should become contaminated, it can be removed from the market. As indicated above, the radioactivity fallout soon decays to stable nuclides and the milk from the cows soon returns to normal. At most it is a temporary and manageable problem.

There are costs associated with waiting for the right weather conditions or paying farmers to put their stock on dry feed.

In his testimony to the Joint Committee on Atomic Energy of the Congress of the United States, John S. Kelly gave very encouraging indications as to the further anticipated development [91] which one may expect to occur along the lines mentioned in connection with underground explosions.

The AEC has provided the following information in regard to possible airborne radioactivity from cratering explosions. In order to plan for major excavation projects, the following factors relative to release of radioactive debris should be taken into account. The amount of radioactivity airborne in the cloud and in the fallout is minimized by scavenging during the venting process, by special emplacement techniques, by utilizing minimum fission explosives, and by employing extensive neutron shielding.

Based on reasonable assumptions about these factors, the following information can be used in planning for cratering events of useful magnitudes. For each individual nuclear explosive detonated, the sum of fission products airborne in the radioactive cloud and in the fallout can be expected to be as low as the equivalent of 20 tons. The tritium release may be less than 20 kilocuries per kiloton of total yield, and the sum of activation products airborne in the radioactive cloud and in the fallout may be expected to be as low as the amounts shown in Table 4. 2 .

Table 4. 2--Representative Set of Induced Radioactivities at Detonation Time

(Total in Cloud and Fallout)

Nuclide	Nuclide Production, Kilocurie for Yield of 100 KT	1 MT	10 MT
Na^{24}	200	800	2000
32	0. 1	0. 4	0. 8
Ca^{45}	0. 01	0. 03	0. 06
Mn^{54}	0. 1	0. 3	0. 7
Mn^{56}	6000	20000	50000
Fe^{55}	0. 04	0. 15	0. 3
Fe^{59}	0. 04	0. 15	0. 3
W^{185}	6	10	14
W^{187}	300	500	700
Pb^{203}	1000	7000	20000
Other	15	20	40

Note: This is not a complete list, and the amounts given may be upper limits rather than best estimates.

SOURCE: Based on information given by the AEC.

4. 3 SEISMIC EFFECTS

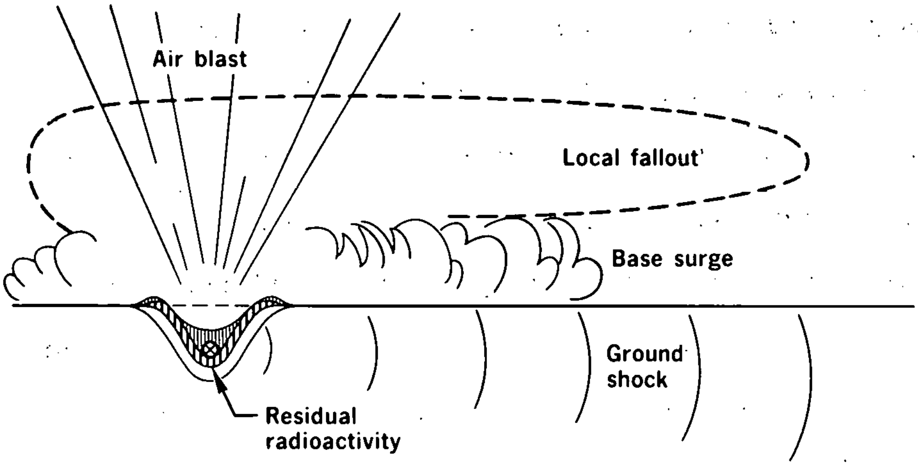
As to the next critical effect, the seismic effects of nuclcar explosions, the predictions of those are based in part on high explosive experiments. Potential damage was found to be a function of particle velocity variations produced by explosions, their acceleration, displacement, amplification, the medium and environment in which the explosion is set off and structural properties of buildings and nearby facilities as well as the medium which serves as their foundation. Experience in earthquakes cannot be projected to estimate seismic damage from nuclear explosions, as the latter are mostly a single wave phenomenon, with the release of a much smaller amount of energy, while in earthquakes the repetitive pattern of shocks tends to aggravate seismic damage at the same peak particle velocities [75,pp. 60 ff.]. It has been observed in certain instances that an 8 - 10 cm second peak particle velocity may result in some minor damage such as the cracking of plaster. However, other factors such as the nature of the medium, the vibration characteristic of the structure, etc., will affect to some degree the impact an 8 cm/second peak particle velocity will have. Table 4.3 gives some of the expected ranges of 8 cm/second induced variations in peak particulate velocity for detonations ranging from 10 KT to 10 MT [75, p. 62] (see also Figure 4.1).

Table 4.3--Range of Ground Shock from Cratering Detonations in Hard Rock

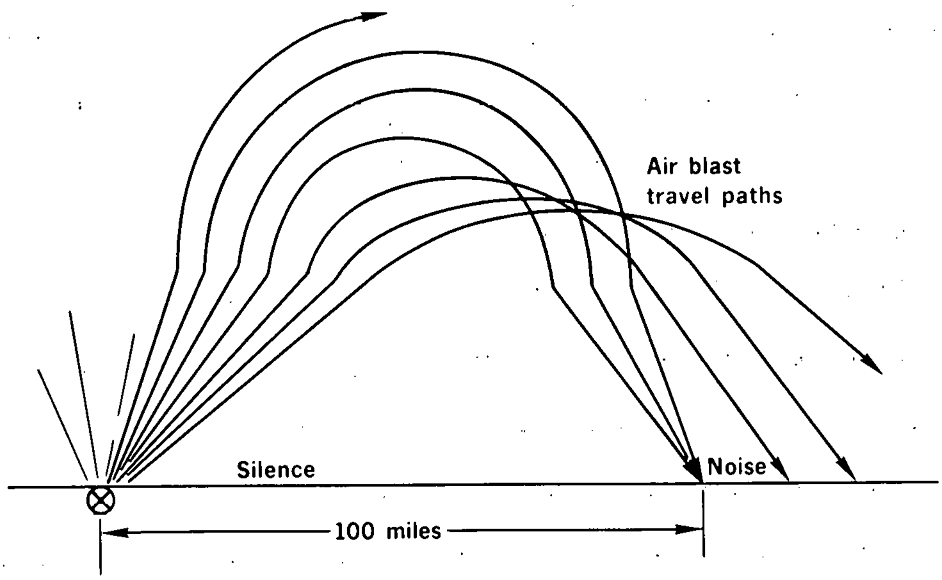
Total Yield in KT	Range of 8 cm/second particle velocities (miles from ground zero)
10	2
100	4
1000	10
10000	23

SOURCE: A.R.W. Wilson, E.B. Pender, E.K. Carter, "An Evaluation, for Australian Purposes, of Proposed Civil Engineering and Mining Applications," Sydney, March 1964.

Figure 4.1



Several aspects of a nuclear cratering explosion, shown here, could be hazardous to man if not properly controlled.

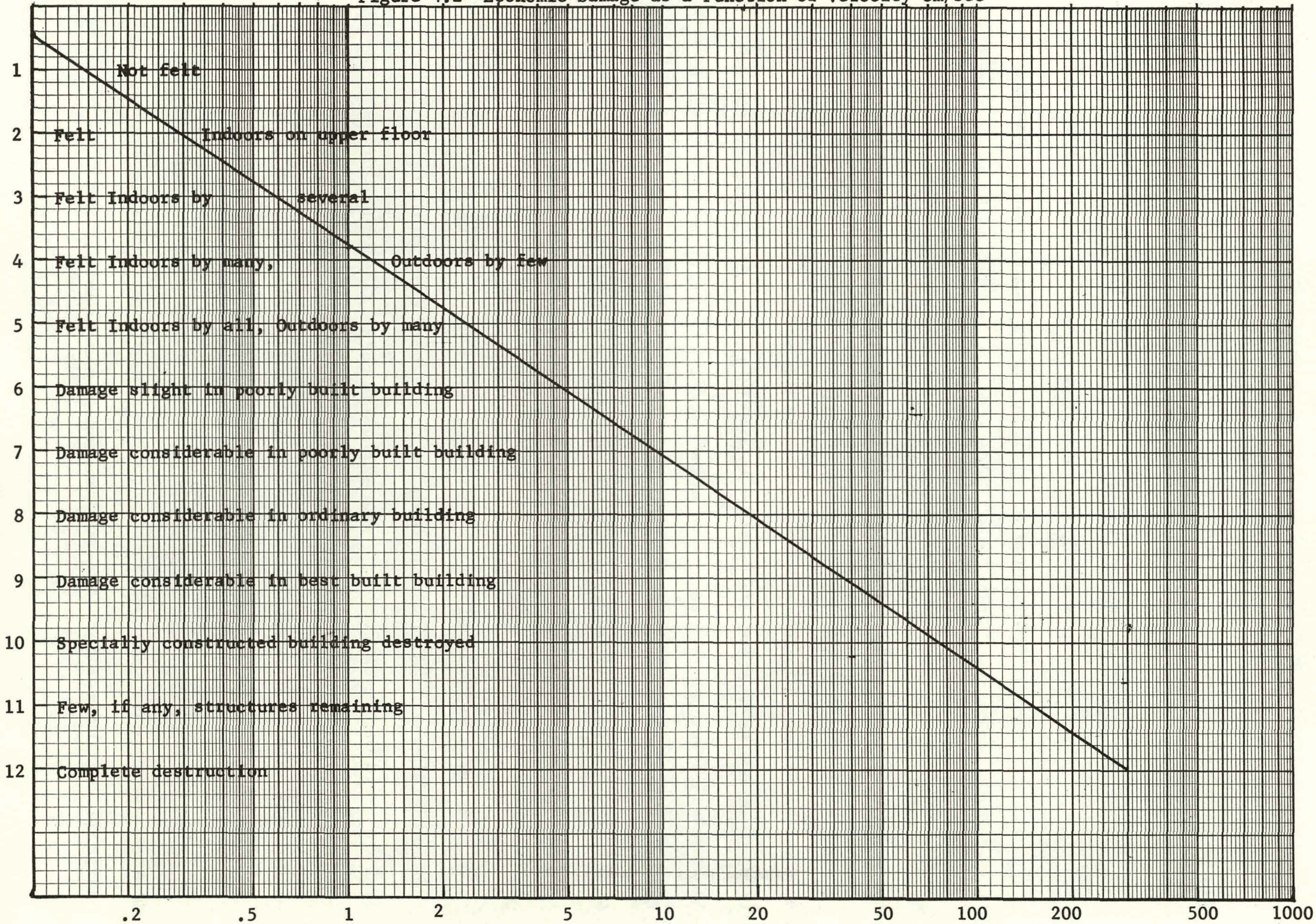


The air blast resulting from the release of energy to the atmosphere during a cratering explosion may be reflected back to earth many miles from the point of detonation.

SOURCE: Information given by the Atomic Energy Commission.

Generally speaking first signs of plaster damage result at 8 cm/second. Many of the proposed Plowshare projects would be acceptable at this threshold level, as productive facilities at or near the sites could withstand substantially larger shocks. Plaster damage and cracks (around 16 cm/second) could all be accepted in most applications. (See Figure 4.2) A 100 KT explosion in hard rock would produce peak particulate velocity variations of 8 cm/second at only 4 miles from ground zero, a yield which could be used in most storage projects proposed, even near large population centers. Pipes and pipelines are seriously endangered only at levels of shock around 30 cm/second, that is, structures which are most likely to occur near or at ground zero of Plowshare explosions. Shock resistant buildings are destroyed at about 60 cm/second; most structures are destroyed at 100 cm/second (see also Figure 4. 2). Any completely contained explosion presently proposed is far under the threshold limits mentioned here at distances exceeding 10 miles. Moreover, it must be pointed out that the above discussion on threshold levels is true only in a most general way. Peak particle velocity is only one of a number of criteria which must be evaluated in predicting or evaluating potential seismic change. Seismic effects depend to some extent on the medium in which the explosion is set off and propagated. Some uncertainties still exist as to the predictability of seismic effects (Project Dribble/ Salmon Event and another recent military shot in Alaska). Shoal, Clearwater, and to some extent, Salmon, seem to confirm present predictions. Still, a severe limitation to some industrial applications is imposed by the potential seismic damage, if an explosion would have to be set off near

Figure 4.2--Economic Damage as a Function of Velocity cm/sec



population centers or structures of particular value or dubious shock resistance. Potential seismic damage is minimized

a. in remote, unpopulated areas,

b. at lower yields,

c. by preventive measures (e. g. , special casing techniques for well bores in completely contained explosions to minimize seismic damage to an emplacement hole.

4.4 EJECTA AND AIR BLAST EFFECTS

Other effects from nuclear cratering explosions are ejecta and air blast (see Figure 4. 1 [78, 79] . In the Sedan event, maximum impact occurred about 2-1/2 crater radii (460 mm). A structure located 900 meters from ground zero was substantially damaged by an alluvium block. Due to the fact that such ejecta would be limited to the area controlled by the government, the damage by ejecta should be negligible, i. e. , in most cases ejecta will be a non-critical effect in Plowshare projects.

A more serious effect of cratering explosions is the air blast induced by the explosion which again varies with the depth of burial and the yield of the explosion. The air blast gives rise to problems similar to those of the "sonic boom" effect. The air blast in cratering explosions is directed upwards in a conical pattern emerging from the crater and is considerably less than that produced by surface level or atmospheric explosions [75, p. 57] for close in air blast (about 100th of an above ground shot). Under favorable conditions (unstable atmosphere, particular wind directions and surface temperature inversions) air blast over pressures may increase. As a blast wave hits structures, the difference in air pressure may cause structural damage. Most of the damage will result in store and household window breakage. This damage threshold can safely be set at 2 millibars. Past experience has shown that household windows begin to break at about 3 millibars, at typical frequencies involved in explosion produced air blasts. Again, depending both on physical distance and yield of the explosion 10 millibars appears to be a reasonable safety limit in relatively remote areas [75, p. 55].

A particular phenomenon in the propagation of airblast is intermediate and long-range propagation by focusing mechanisms in the upper atmosphere (refraction by vertical temperature gradients and wind movements). Damage close to the detonation (5 - 30 miles) results from the generation of a direct blast wave and it is known as the close-in blast. The distance of the overpressure is scaled as the 1/3 power of the yield of the device and is fairly independent of wind and weather conditions out to a range of 5 miles. Beyond that distance, refraction effects predominate and meteorological conditions govern the blast overpressure.

Intermediate range blast is due to the tropospheric refraction of the blast wave back toward the ground at ranges of 30 to 100 miles resulting from a layer where the sound velocity is greater than at surface. The higher velocity is produced by either higher temperature or greater wind speed or a combination of both. The troposphere is usually associated with a layer of jet stream winds.

Long range blast peak overpressures are also experienced at 80 to 150 miles from a detonation and are due to the refraction of the blast wave in the ozonosphere at 100,000 to 150,000 feet of altitude. They depend strongly on weather conditions in the ozonosphere and may vary by a factor of 100 from the most favorable to the worst time of the year [75, p. 59 and p. 247].

Because of the great uncertainties introduced in intermediate and long-range air blast by the effect of shot environment and meteorological conditions, it is difficult to predict the overpressures from a nuclear detonation.

What can be done is to indicate the maximum and minimum overpressures expected downwind under the most and least favorable weather conditions and the average overpressures expected upwind.

The safety criteria for air blast damage will depend on the area involved. Nevada experience has shown that large plate glass windows begin to break when the airblast peak overpressure is 4 millibars (one millibar is approximately 0.015 psi), on towns such as Las Vegas, Nevada, or St. George, Utah. Claims of cracking plaster have been made when pressure amplitudes were only 3 millibars in Project Dribble-Salmon Event, although most claims for plaster damages may have been unjustified. A damage criterion of 10 millibars would appear reasonable in remote areas which are thinly populated but for a highly populated area, 2 millibars might be established as the safety criterion. In general, in order to control this potential hazard from nuclear cratering explosions, we must determine the character of the airblast signal, the effect of the meteorological conditions on its transmission to long ranges and the response to airblast loading of typical structures.

Thus, to assure safety from airblast effects, it is necessary to choose, according to meteorological conditions, the limits of yield, detonation times and numbers of simultaneous detonations. These considerations, however, lead directly to the concept of Maximum Permissible Yields. Maximum Permissible Yields would then be dependent not only on seismic limitations as a function of the distance to population and industrial centers, but also depend on such factors as weather conditions and wind directions. This dependence implies a classification of the yield of detonation as to the probability of safe detonation, which decreases with increasing yield. We will come back to this at the end of this chapter.

4.5 MISCELLANEOUS OTHER EFFECTS

Any number of other potential critical effects were mentioned at one stage or another of Plowshare and previous nuclear experiments. Some effects which do exist in atmosphere or surface explosions are eliminated in Plowshare explosions. Others are still present.

1. Prompt radiation (neutron and gamma) thermal radiation and temperature increases.
2. Fire risks from hot ejecta in cratering explosions.
3. Dust clouds in cratering explosions.

To 1: In all present Plowshare applications any such radiation is absorbed by the rock cover surrounding the explosion. In this sense all Plowshare applications are "contained," whether cratering or not.

85% or more of the total energy released in a nuclear explosion results in temperature increases within and around the cavity of the explosion, [48, p. 7]. These temperature increases do not, however, constitute serious hazards in most Plowshare applications. In oil shale recovery they might even considerably improve the prospects of recovery. In cave mining applications high temperatures would pose no problem as the heated (fractured) rock cools off relatively quickly to the boiling point of water through heat transfer throughout the chimney and the fracture system. Furthermore, the mining would take place only some time after the explosion (to allow for major radioactive decay) which also would enhance mining conditions.

Thermal radiation, which in surface and atmospheric explosions can cause considerable eye damage at large distances (focusing effect of the eye lenses) will not occur in Plowshare explosions as the nuclear fireball will be contained underground.

To 2: This effect will only occur in cratering explosions and even there, only in particular circumstances (dry glass, bush and woods). Additional costs may be caused by preventive measures to be taken. No technical difficulties exist.

To 3: The dust cloud (in cratering explosions only, though ground surge occurs also in some completely contained explosions) reduces visibility at some distances in cratering explosions. The choice of adequate meteorological conditions and other preventive measures would minimize any potential damage. Moreover, it is not likely that the dust cloud would extend beyond the region under government control.

4.6 ECONOMIC IMPLICATIONS OF SAFETY REQUIREMENTS

As already mentioned, it is difficult to assign any specific cost equivalent to safety effects in Plowshare projects. Too much information is still lacking about possible decontamination techniques, airblast propagation, dust cloud development, etc. At present in each Plowshare project, extensive safety measures are taken as shown for example in [80, 81, 82, 83]. Donald Edwards, Director of the Safety Evaluation Division at the Nevada Test Site, estimated the average safety costs in nuclear explosion experiments to amount to about $500,000 per experiment in the 10 to 20 kiloton range (single, off-site experiments). This figure has to a large extent a fixed cost character and does not increase appreciably with the increase in the yield of the explosive. In repetitive, commercial applications one and the same kind of device, this cost figure would be below $100,000 per explosion. A substantial part of this cost figure goes into labor costs for personnel employed in each experimental shot. Another substantial part goes for instrumentation. Many of the instruments used in single experimental explosions in a large scale commercial application could be reused in subsequent detonations. The set of instruments required comprise telemetry detectors, portable radiation instruments, air samplers, fallout trays, and meteorological devices (see, for example, [82]). Additional instruments would comprise ground monitors, remote dose rate recorders, film badges, air cloud tracking devices and instruments to sample milk and water [81]. Air traffic, if necessary, will be rerouted by a Federal Aviation Agency Air Space Advisory project (for project Sulky, see [83]).

Other equipment comprises directional survey and logging trucks, miscellaneous building tools, miscellaneous hand tools, drill rigs and associated equipment. One also has to dispose of certain quantities of solid and liquid radioactive wastes. All of the equipment used near or at shot point has to be checked for contamination after the explosion is executed. The same holds for all personnel involved in experimental shots [80]. An industrial safety program is carried out as part of any Plowshare project. In the Salmon Event the main source was from vehicle accidents [80, pp. 34 ff.]. Total working days lost due to accidents in the Salmon Event were ten man working days. Precautions also included fire protection. A four-wheel drive fire truck, 49 portable fire extinguishers and radio-equipped pickup trucks were included in the equipment.

As seen from the above short list of some of the equipment used in experimental shots, it is evident that most of the equipment used in each single experiment can readily be used again in later nuclear explosions. As to the Nevada test site itself (the Salmon Event occurred near Hattisburg, Mississippi), most of the equipment which is associated with area surveys is permanently installed there or is of a portable character to be reused at the various explosion centers. In some of the Plowshare applications,conditions similar to those prevailing at the Nevada Test Site would be found. For example, in the oil shale application an area similar in size to that of the Nevada Test Site may involve up to 30,000 nuclear explosions to fully bring the reserve into production. The charge for the nuclear explosives alone in oil shale would exceed twenty billion dollars. Any safety program connected with that area of development should be just a fraction of the nuclear charges themselves. Similar conditions hold for Isthmian Canal projects where, again, a number of detonations are planned for a single area. It is evident that the direct safety costs in such large scale developments would be smaller after the first safety programs have been installed.

Costs connected with the eventual decontamination of the products themselves (oil, gas, copper) may also prove to be a significant factor. But, as of now, it is not even known whether and to what extent each of these products would be contaminated. No specific cost figure can, therefore, be given for any of these products until we know more about the extent of contamination and techniques proposed to limit or eliminate contamination.

Where safety considerations do significantly affect the economics of any Plowshare application (especially cratering applications), is in the yield ranges approaching Maximum Permissible Yields; that is, depending on the location, from 10 KT yields upwards.

The scaling law of nuclear cratering explosions warrants some additional considerations for its effects on technical requirements and safety costs. It is shown in the report on cratering that with larger required yields (increasing navigational prism) the total direct costs of nuclear canal projects are regressive as the number of devices required decreases at constant canal length. This effect is due to increasing crater dimensions (increasing radius, half width, half spacing) which reduces both total device cost and total emplacement costs. The limit, implicity, is in all those projects not the direct cost,that is the costs of the device and emplacement, but safety costs. And as not very much is known about this relationship, device yields are tailored to technical minimum requirements. Should safety costs considerations prove to be less important then larger canals, cuts, harbors and so on could be made at less total cost and, of course, considerably less cost than any comparable conventional project.

To bring this line of thought to its extreme, that is if no technical restrictions were imposed, and safety considerations did not arise, that is safety costs were 0, then one single nuclear charge, deeply emplaced (at "optimum" depth of burial) and of an extremely high yield (250 MT to 1000 MT depending on route and scaling law) would be the most economic and fastest solution. This is, of course, not the case and safety costs do arise and play a dominant role in all these considerations. There exists an important trade off as direct costs would be substantially reduced and benefits from various projects of larger scale increased. This warrants more knowledge on potential safety costs than is known today.

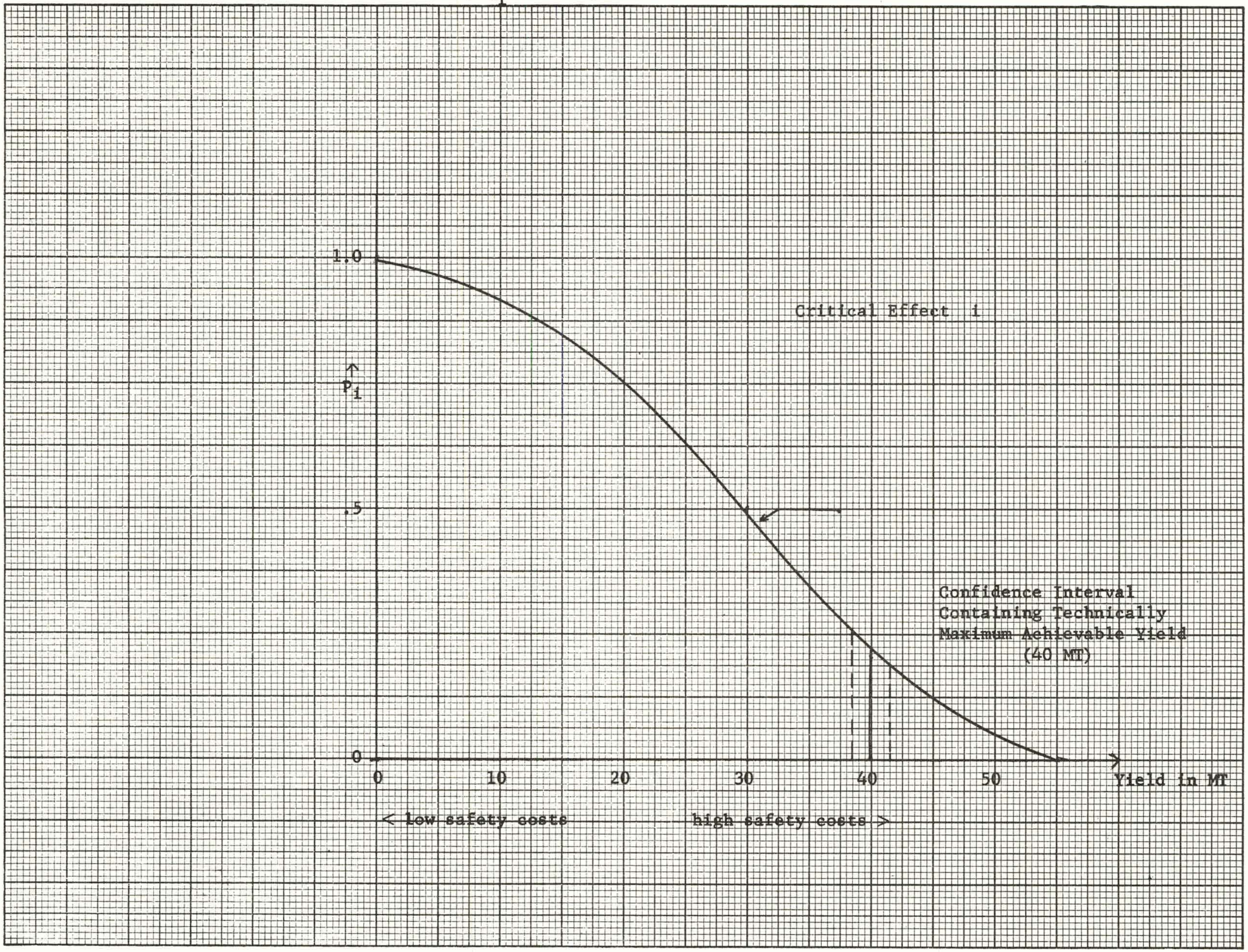
This leads to another final remark on how best to approach a possible "quantification" in terms of costs of the safety problem. Associated with each single critical effect is a certain technically known safety threshold which is, or to some degree has been developed and which has associated with it a certain confidence interval within which this limit falls. Such thresholds (least upper bounds) exist for seismic damage, damage from radiation, from ejecta, dust clouds, airblasts.

Furthermore, all of the mentioned critical effects increase at higher yields, but are at each yield also a function of other, exogenous variables, e.g., wind direction, climate, geographic location, geological factors. From this we may deduce a certain range within which, independent from these exogenous variables, we know beforehand that up to that particular yield a nuclear explosion can always take place safely, at any time. For example, ejecta and dust clouds from a nuclear explosion buried at 4000 feet will not occur at all up to a relatively large yield. From a given yield onwards, however, any particular effect will have associated with it particular limitations as to required wind direction, minimum necessary distance of evacuation, or even political considerations (e. g. , Limited Test Ban Treaty). That is, with each particular hazard we may, over the range of all potential yields, associate a probability function stating whether at that yield the explosion can be made safely at all times (probability 1) or is limited to certain seasonal or climatic conditions or certain geographic requirements (probability less than 1 and larger than 0), or can for technical or safety considerations not be made at all. The technical maximum achievable yield may intersect this probability function in which case the range is further restricted (see Figure 4. 3). However, not enough information (or experience) is available to attempt any detailed quantification of this safety function.

The economic implications of these safety limitations express themselves not only in safety costs directly but also in additional costs of each project falling under such limitations due to the delay in time of the construction or production schedule. Of all Plowshare applications analyzed it is the cratering schedule of certain Isthmian Canal studies where most likely these safety considerations will approach, if not exceed, the Maximum Permissible Yield.

The presently ruling axiom of adjusting projects to minimum required yields is done more out of expediency and uncertainty than informed, rational judgment and if a 1, 500 feet wide canal costs less

Figure 4.3--Probability p_i that Explosion at Place x and Time t is Feasible



in total direct costs than its 750 feet counterpart, this safety "axiom" is worth further, more detailed, analysis. As the present safety considerations go back to 1959 - 1962 knowledge, while in the meantime considerable progress has been made, e. g., with regard to fallout problems, these safety limitations may be considerably reduced.

Chapter 5

SUMMARY AND CONCLUSIONS OF THE ECONOMICS OF THE PEACEFUL APPLICATION OF NUCLEAR EXPLOSIVES

5.1 THE ECONOMIC POTENTIALS OF SHALE OIL PRODUCTION BY NUCLEAR EXPLOSIVES

The largest single reserve of hydrocarbons known to exist anywhere in the world is given by the oil shales of the Green River formation in the western part of the United States. With available conventional techniques only an insignificant part of these resources could be tapped, and that only at great cost and under considerable technical uncertainties. It is on this basis that the Oil Shale Advisory Board came in 1964 to the negative conclusion that such an oil shale industry would not be competitive under conditions as they were at that time.

In the MATHEMATICA report on oil shale [154] a new technology is discussed which was first proposed in 1959, but which has been developed mainly since 1964: the _in situ_ production of oil from shale by large underground retorts created by nuclear explosives. The first part of that report describes this new process, the second part gives an analysis of the United States and the world endowments with crude oil resources and oil shale deposits, and finally, the third part deals with expected cost estimates of this new technology as compared with present crude oil prices and potential costs of conventional shale oil production. We may conclude that even under the most optimistic estimates a shortage in crude oil reserves will develop within the next generation (up to the year 2000), if the energy demand is supplied as it has been up to now, i.e., by fossil fuels and within this, again, mainly by oil and gas.

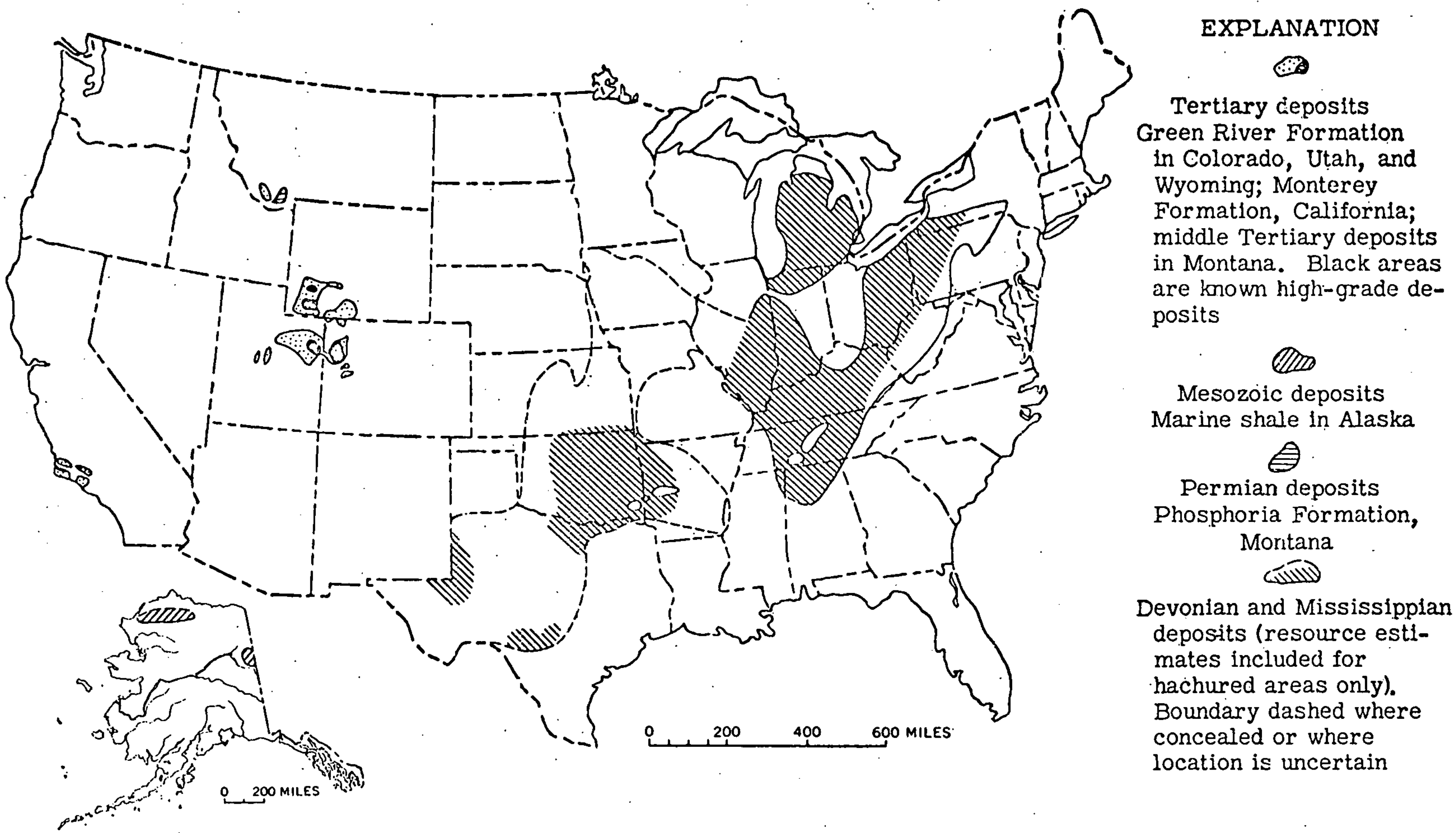
Thus shale oil reserves are important for at least two reasons:

a. As potential extensions of U. S. oil reserves, once serious shortages in the crude oil section develop.

b. As potential competitors with conventional oil supplies at prices below even "ultimate" conventional crude oil prices at present production rates.

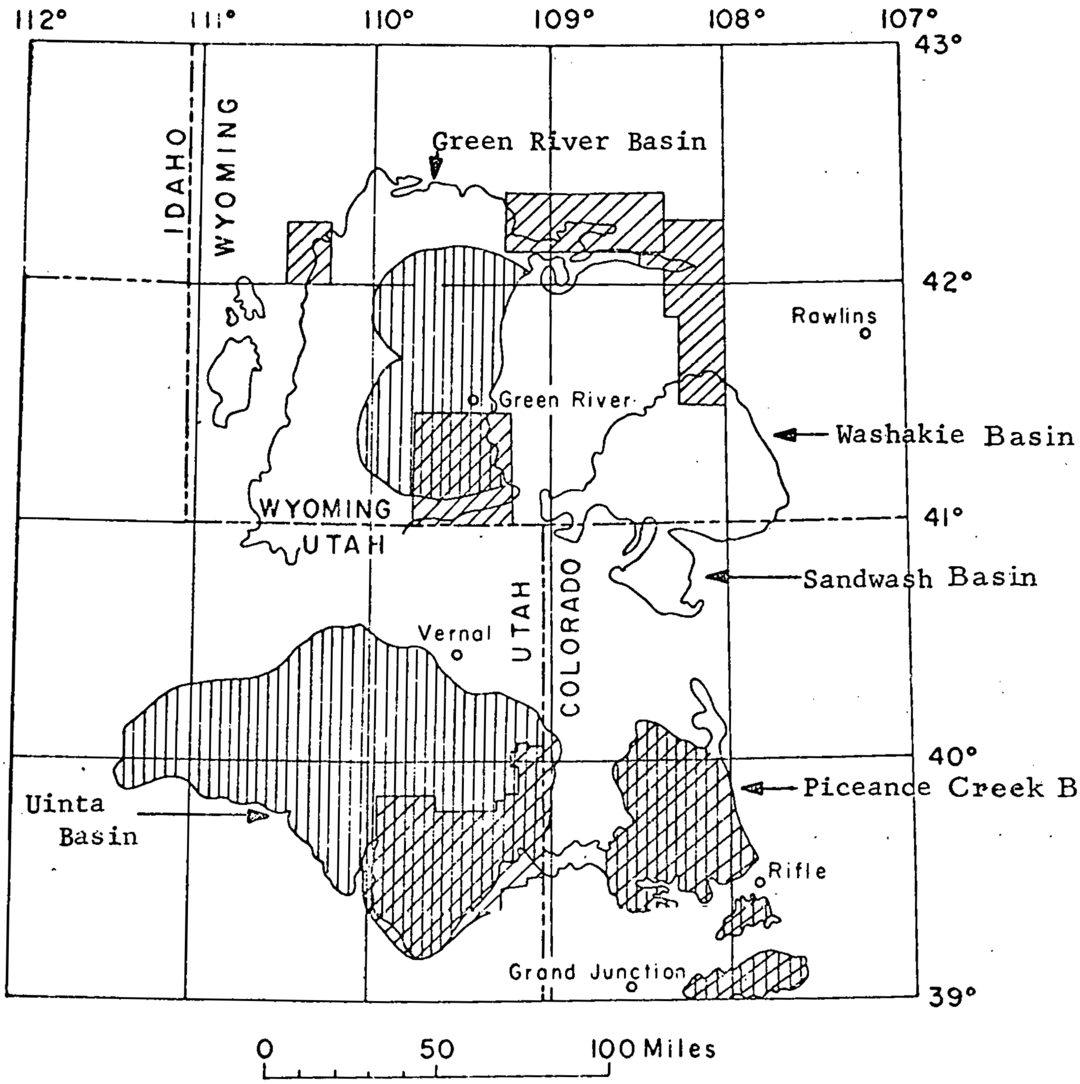
Deposits of oil shales are known to exist in Colorado, Nevada, Utah, Wyoming, Indiana, Kentucky, Pennsylvania, West Virginia, and other states [30, 113, 121, 122]. The geographical distribution is shown in Figure 5.1 [30] while Figure 5.2 shows the main U. S. oil shale deposit in more detail. In a broad generalization we may define two major areas of oil shale basins in the U. S.: the Green River formation in the Rocky Mountains (See Figure 5.2), the largest proven oil shale deposit in the world, and the area of the Devonian and Mississippian shales of the Eastern and Central United States [30, 91, 113, 123, 124, et al.]. In addition to these reserves there exist high grade oil shale

Figure 5.1--Principal Reported Oil-Shale Deposits of the United States



SOURCE: Duncan, Donald C., and Swanson, Vernon E., "Organic-Rich Shale of the United States and World Land Areas," U. S. Department of the Interior, GSC 523, 1965.

Figure 5.2



Location of areas that have been mapped in detail and in which oil-shale resources have been evaluated. Diagonal ruling indicates areas mapped or being mapped by the U.S. Geological Survey, at scale 1:62,500 or greater. The vertically lined areas indicate oil shale resources which have been partly evaluated and are presently being drilled to determine thickness and quality of the oil shale.

SOURCE: Donnell, John R., "Geology and Oil Shale Resources of the Green River Formation," Quarterly of the Colorado School of Mines, Vol. 59, No. 3, July, 1964.

deposits in Alaska (up to 140 gallons of shale oil per ton of oil shales), but the extent of these deposits and their characteristics are yet unknown. Undiscovered* oil shale deposits also exist in other parts of the U. S., though these are in most cases thin formations and therefore not suited for the nuclear *in situ* recovery technique. Estimates of overall oil shale resources of the U. S. and the world are given in Tables 5.1 and 5.2, while Tables 5.3 and 5.4 compare U. S. and world oil shale reserve estimates to the overall fossil fuel resource base (see also Figure 5.3.)

The estimate of 170Q** of total potential U. S. resources in 10-100 gallons grade shale which underlie the United States may appear to be extremely high. However, an intensive search for oil shales, comparable to those made for crude oil, has not been made and these estimates may again prove, as in the history of crude oil reserves, to be conservative. In countries where crude oil is or was scarce, conventional shale oil operations are maintained, mainly in China (Manchuria, Kuan-tung), Brazil Paraiba Valley), U.S.S.R. (Estonia, lower Volga, Siberia), Congo

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* The term "undiscovered resources" is used in various Department of the Interior publications. These columns refer to resources which are expected to exist but the exact extent of which has not yet been determined.

** 1Q = 10^{18} British thermal units. This is a large amount of energy; by comparison the total U. S. energy consumption in 1960 was 0.06Q. The conversion factors used throughout this report are:

Natural Gas	1 cubic foot	=	1,000 Btu
Crude Petroleum and Shale Oil	1 barrel	=	6,000,000 Btu
Coal	1 short ton	=	25,000,000 Btu

Table 5.1--Shale Oil Resources of the United States in Q****

Deposits	Known Resources				Possible Extensions of these Reserves		Total Reserves Including Unappraised and Undiscovered	
	Recoverable Conventionally	Marginal and Submarginal ***		Potentially Recoverable with Plowshare				
		10-100	5-10**		10-100	5-10**	10-100	5-10**
Green River formation	.5	11.5	12.	12.	12.	12.	24.	24.
Devonian and Mississippian	none	1.2	1.2	large	4.8	10.8	6.	12.
Marine-Alaska	small	small	small	some	2.7	large	2.7	large
Associated with Coal*	-	-	n-e	n-e	n-e	n-e	1.9	1.3
Other*	-	-	-	-	-	-	135.0	802.7
Total U. S. Energy Consumption in 1965	.48	12.7	13.2	12.	19.5	22.8	170.	840.

* unappraised or undiscovered

** 10-100 gallons shale oil per ton of oil shale and 5-10 gallons shale oil per ton of oil shale

*** under conventional techniques

**** 1 Q = 10^{18} British thermal units (Btu)

n-e = not estimated

SOURCE: Duncan, Donald C. and Swanson, Vernon E., "Organic-Rich Shale of the United States and World Land Areas," U. S. Department of the Interior, GSC 523, 1965.

Table 5.2--Shale Oil Resources of the World Land Areas in Q

Continents	Known Resources			Possible Extensions of Known Resources		Total, including Unappraised and Undiscovered**	
	Recoverable Conventionally	Marginal and Submarginal*					
		10-100	5-10	10-100	5-10	10-100	5-10
Africa	.06	.54	small	n-e	n-e	504	2,700
Asia	.12	.5	n-e	22.2	n-e	700	3,500
Australia	small	n-e	n-e	n-c	n-e	126	600
Europe	.18	.3	n-e	1.8	n-e	165	840
North America	.48	12.7	13.2	20.4	24	318	1,560
South America	.3	4.5	n-e	20	24	252	1,260
Total	1.14	18.7	13.2	63.6	48	≈ 2,000	10,500

* under conventional techniques

** see note to Table 5.1

SOURCE: Derived from: Duncan, Donald C., and Swanson, Vernon E.: "Organic-Rich Shale of the United States and World Land Areas," U. S. Department of the Interior, GSC 523, 1965.

Table 5.3-- U. S. Resources of Fossil Fuels
(Energy Equivalents in Q = 10^{18} Btu)

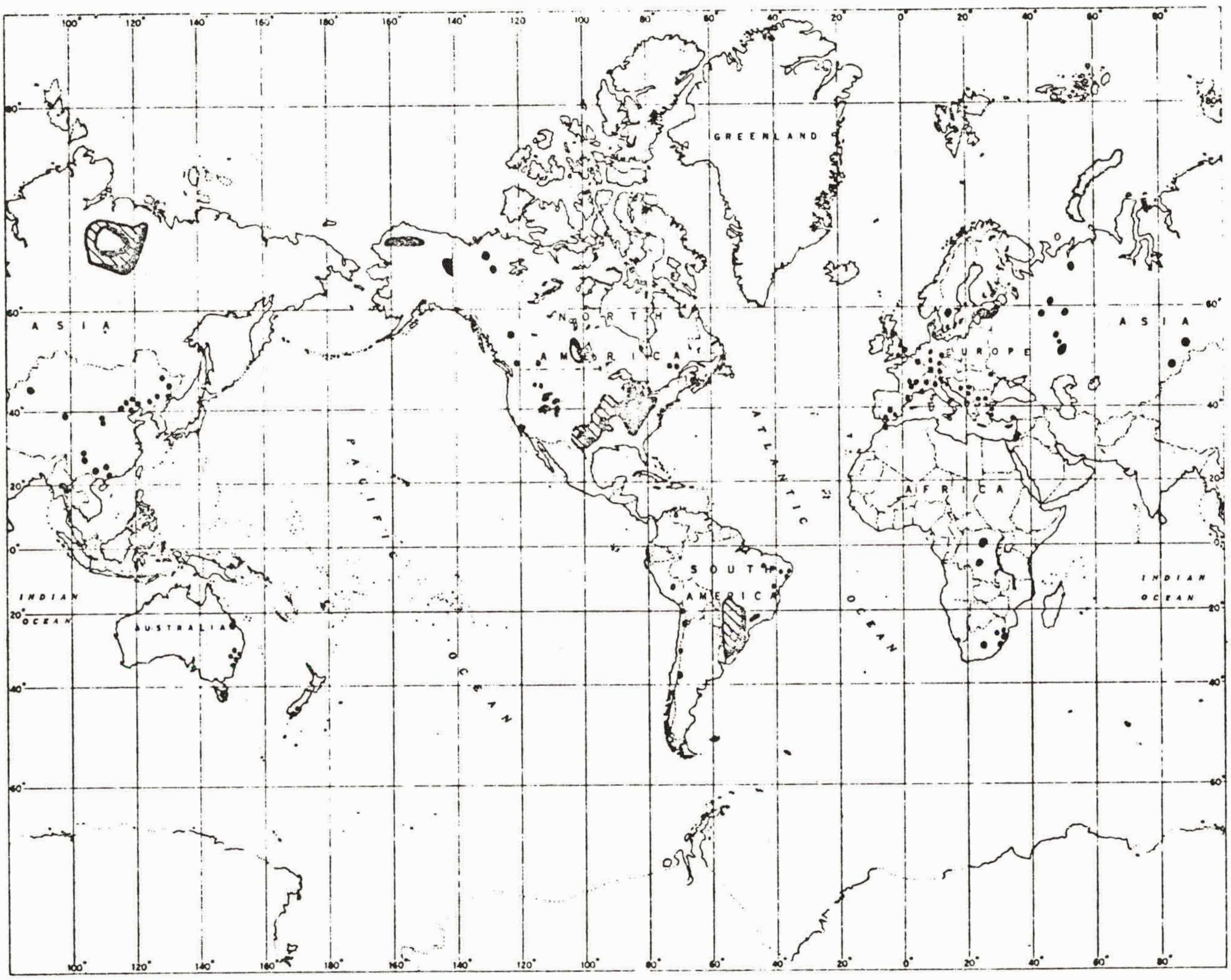
	Known Recoverable Resources (= Reserves)	Undiscovered Recoverable Resources*	Known Marginal Resources	Undiscovered Marginal Resources*
Coal	4.6	n-c	29.	55.
Petroleum	.28	1.15	.2	1.7
Natural Gas	.3	1.3	n-c	.9
Natural Gas Liquids	.03	.14	n-c	.3
Oil in Bituminous Rock	.01	n-e	n-e	.1
Shale Oil	.3	n-e	11.6	23.2
Potential Oil Shale figures (if Plowshare successful)	[12.0]	[n-e]	[12.0]	[large]
Total Q	5.5	2.6	41.	81.

U. S. Consumption in 1960 = 0.06 Q

* See footnote, p. 74.

SOURCE: U. S. Department of the Interior, "The Oil Shale Problem," A synopsis prepared for the opening meeting of the Department of the Interior, Oil Shale Advisory Board, July, 1964.

Figure 5.3--Principal Reported Oil-Shale Deposits of the World



SOURCE: Duncan, Donald C., and Swanson, Vernon E., "Organic-Rich Shale of the United States and World Land Areas," U. S. Department of the Interior, GSC 523, 1965.

Table 5.4-- World Resources of Fossil Fuels
(Energy Equivalents in Q = 10^{18} Btu)

Source	Known Recoverable Reserves	Undiscovered** Marginal Resources
Coal	18	320.
Petroleum	1.7	23.
Natural Gas	2.0	21.
Natural Gas Liquids	.2	3.2
Oil in Bituminous Rock	.2	6.1
Shale Oil	.9	79.
Revised Shale Oil Figures	[12.0]	[170-800]*
Total Q	23.	452.

* potentially for U. S. alone

** see note to Table 5.2

SOURCE: U. S. Dept. of the Interior, "The Oil Shale Problem," Oil Shale Advisory Board, July, 1964. (Chart derived from this.)

Republic (K.) and other countries [86, 93, 94, 149 et al.].

How conventional methods compare to nuclear in situ techniques is analyzed in detail in [154]. The main conclusions for conventional techniques are:

a. All cost figures on shale oil production so far published are extrapolations from experimental results or pilot plants. Of these figures H. Steele's are the most widely quoted:

Table 5.5--Conventional Shale Oil Production Costs (per barrel)

	H. Steele 1963	H. Steele 1965
Mining	$ 1.003	$ .832
Shale Preparation	.096	.090
Retorting	.289	.212
Viscosity Break	.129	.120
	$ 1.517	$ 1.254

SOURCES: Steele, H. B., "The Prospects for the Development of a Shale Oil Industry," Western Economic Journal, Vol. 53, Dec., 1963.

Oil Statistics Bulletin and Canadian Oil Reports, "Shale Oil... On the Threshold?" Oil Statistics Company, Babson Park, Mass., 1966.

b. Serious external diseconomies are not reflected in these conventional shale oil estimates.

c. The upper limit of economic conventional operations (with regard to resource utilization) is about 70-100 feet thick oil shale formations. Even there over 25 per cent remain underground.

d. The crude oil price could be lowered substantially below the present level without seriously affecting U. S. production, except marginal relative unproductive wells. Thus shale oil costs should be substantially below the present crude oil price in case "price competition" sets in. This in itself could have a beneficial effect for the rest of the U. S. economy.

The costs of nuclear in situ shale oil production can not be stated in one single cost figure, even if experiments in this field had been made. The economics of the nuclear in situ retorting technique will roughly depend on the following parameters:

a. The percentage of shale oil recovered by the in situ retorting technique from the rubble chimney;

b. The extent of the rubble chimney in oil shale formations and its particle size distribution;

c. The extent of control over the burning front in fragmented oil shale which determines retort size and compressor requirements.

d. The amount of shale oil recovered from the fractured zone around the chimney;

e. Extent of radioactive contamination of shale oil;

f. The thickness of the oil shale formation;

g. The grade of the oil shale.

The minimum thickness and minimum grade of the oil shale formations where the nuclear in situ technique will be applicable is again a function of the parameters under a, b, c, d, and e. Very crucial at least in one of the techniques (in situ burning at the top of the nuclear chimney), will be the investment in air compressors (see among others, [200]) and the maximum controllable burn-area in such nuclear plants. Single nuclear chimneys, especially at low and low-intermediate yields, do not give the best economic results. The basic assumptions in our analysis, based on Lekas [117] are:

a. An area of 25-50 acres per retort, i.e., a maximum controllable burning front of 50 acres.

b. Four to 20 retorts which are combined to one plant such that production of the plant extends up to ten years.

c. A daily production of 75,000 barrels in 25 gallon grade oil shale, and 45,000 barrels in 15 gallon grade oil shale (i.e., constant speed of burn within retorts).

Figure 5.4 shows total investment costs as a decreasing function of the thickness of the oil shale formation as fewer and fewer retorts can be combined in plants of equal capacity (75,000 barrels a day) with higher yield explosives. The weight of the fragmentation cost is evident. This is still true if the capital costs are related to barrels produced (Figure 5.5). Power cost and labor cost are assumed to be constant, per day, which results in constant costs per barrel of shale oil produced as long as the capacity of the plants is held constant at 75,000 barrels a day. Figure 5.5 shows these operating costs and interest charges of 6 per cent on capital invested. Some changes in the technical parameters of Lekas' oil shale plant would affect favorably the economics of shale oil production. There exists no reason why the plant capacity should be held constant at 75,000 barrels a day (or 45,000 barrels per day in 15 gallon oil shales). If in thicker formations an equal amount of retorts with identical areal extent and identical daily burning rates (2 feet) would be combined to our plant, the fragmented shale per plant would be increased considerably, extending

Figure 5.4

Total Plant Investment Costs of 75,000

Barrels/Day Nuclear <u>In Situ</u> Retorting Plant

75% Recovery Rate

25 Gallon Grade Shale Oil

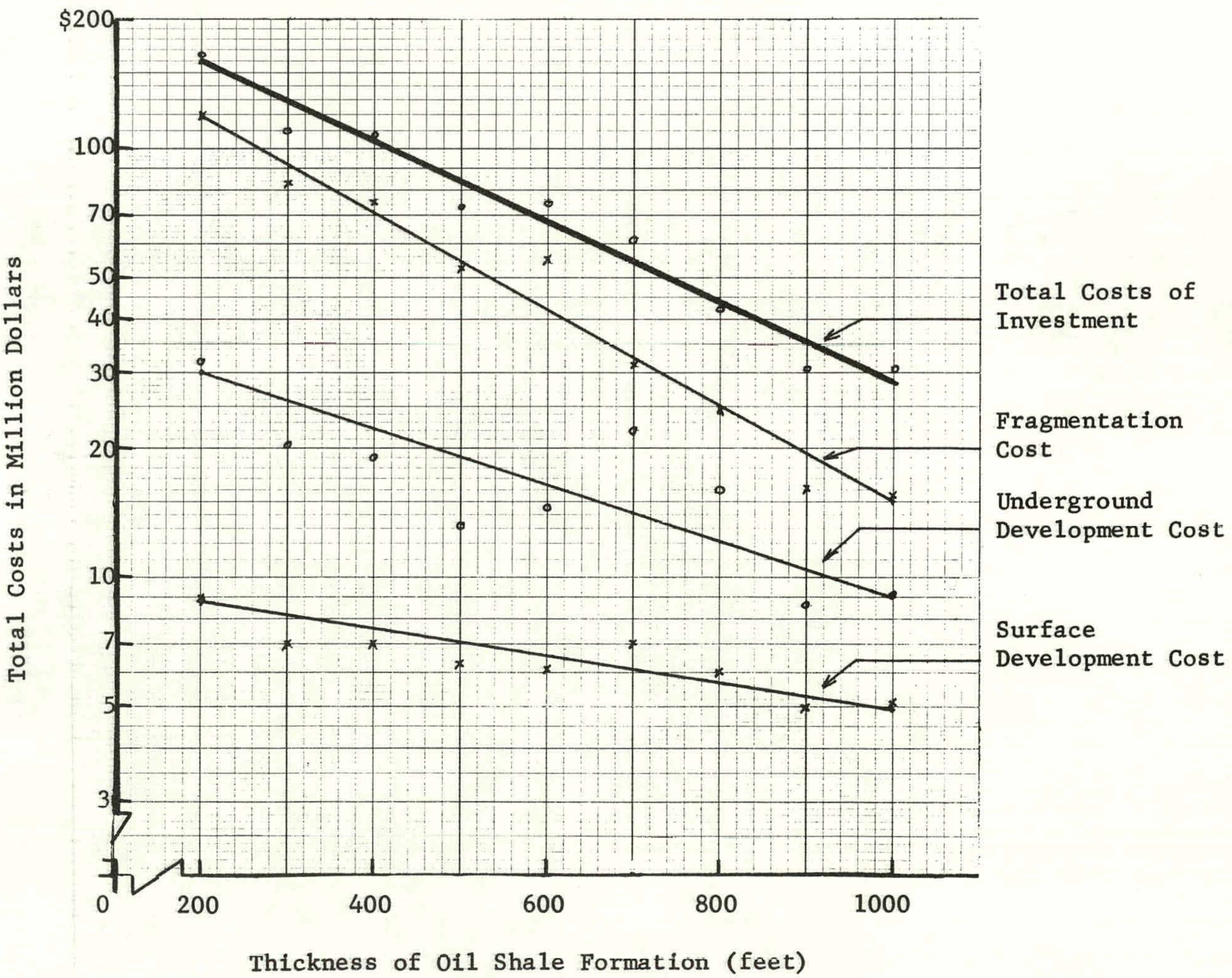
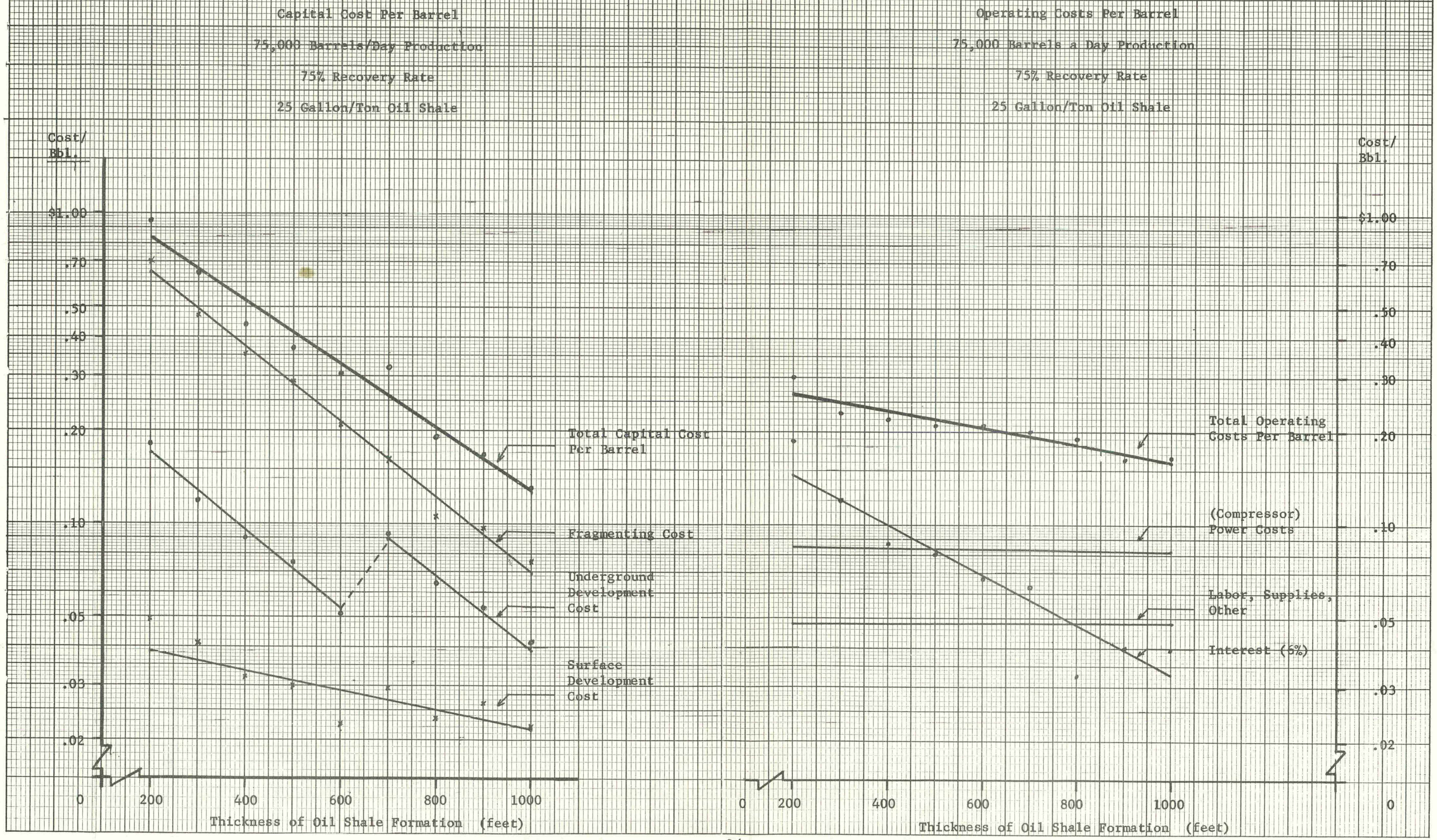


Figure 5.5

COSTS PER BARREL OF SHALE OIL IN 75,000 BARRELS/DAY NUCLEAR IN SITU PLANT



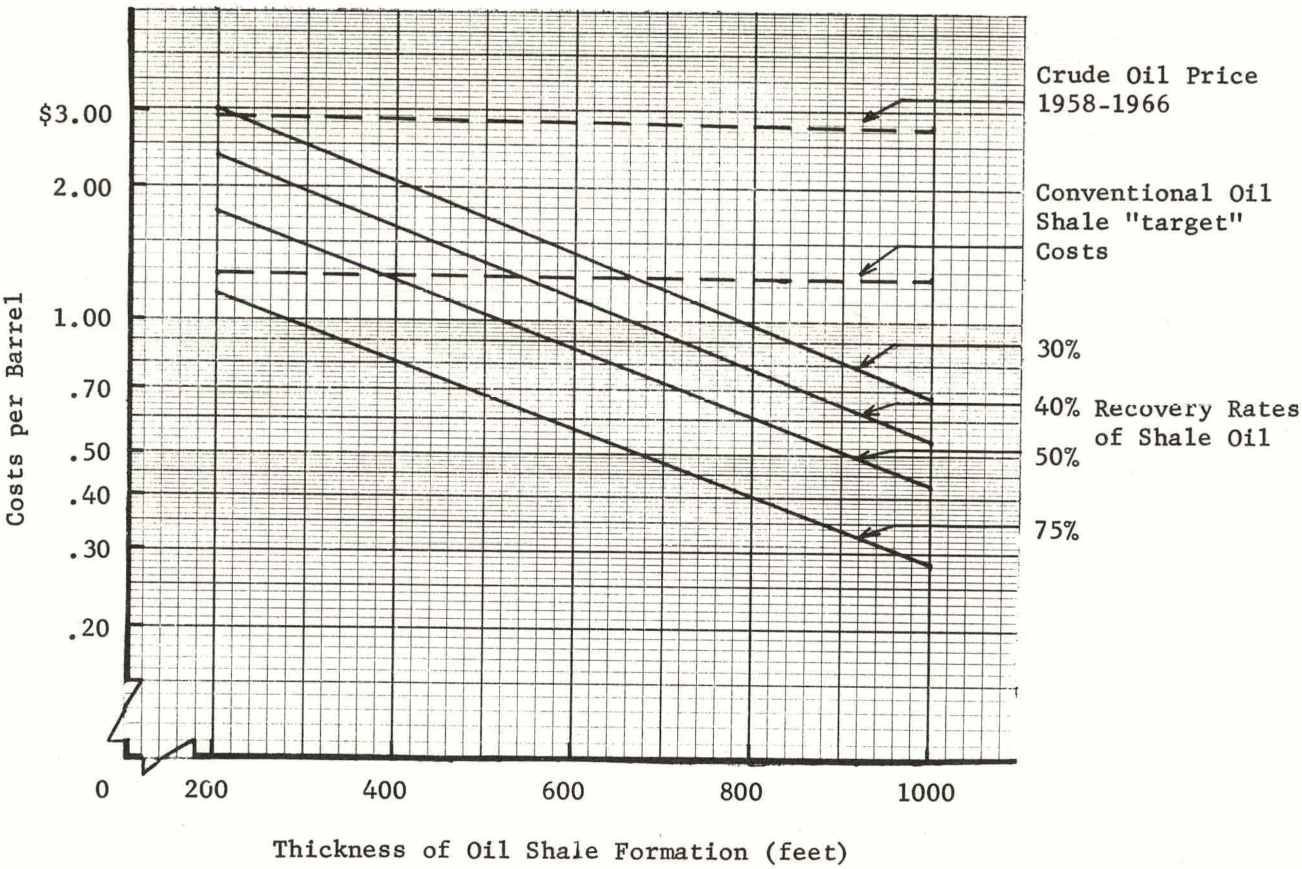
the plant life and lowering the capital cost per barrel of shale oil produced beyond the savings already inherent in Lekas' figures. If retorting times are reduced as envisioned in [115] by about 50 per cent due to advanced retorting below the actual burning front, the daily capacity could be doubled at more or less identical development costs, i.e., reducing overall costs by 30 per cent or more. Additional production of shale oil may be derived from the fractured regions around the retorts (50 per cent to 60 per cent of the total plant area) during the retorting of the chimney, and later on by secondary recovery in those areas, which may in part use existing plant facilities (mainly wells drilled, the collection system and the compressors). These possible wind fall profits are all not reflected in the present analysis and no figures can be attached to any of these items as too little is known on the actual retort techniques themselves.

By varying the recovery rate below the 75 per cent figure assumed, we see that a large "safety" margin is available if the in situ process should work at all within limits now mentioned (see Figure 5.6). At a 75 per cent recovery rate shale oil can be produced economically below a $1.25 cost estimate down to an oil shale thickness of about 100 feet. This would comprise all formations in excess of present mining operations at Rifle (70 feet, possibly 100 feet). The present crude oil price at the well-head ($2.90) would allow an economic shale oil operation in formations thicker than 200 feet at a recovery rate as low as 30 per cent. A 30 per cent, 40 per cent, 50 per cent recovery rate of shale oil would

Figure 5.6

Costs Per Barrel Shale Oil as a

Function of the _In Situ_ Recovery Rate

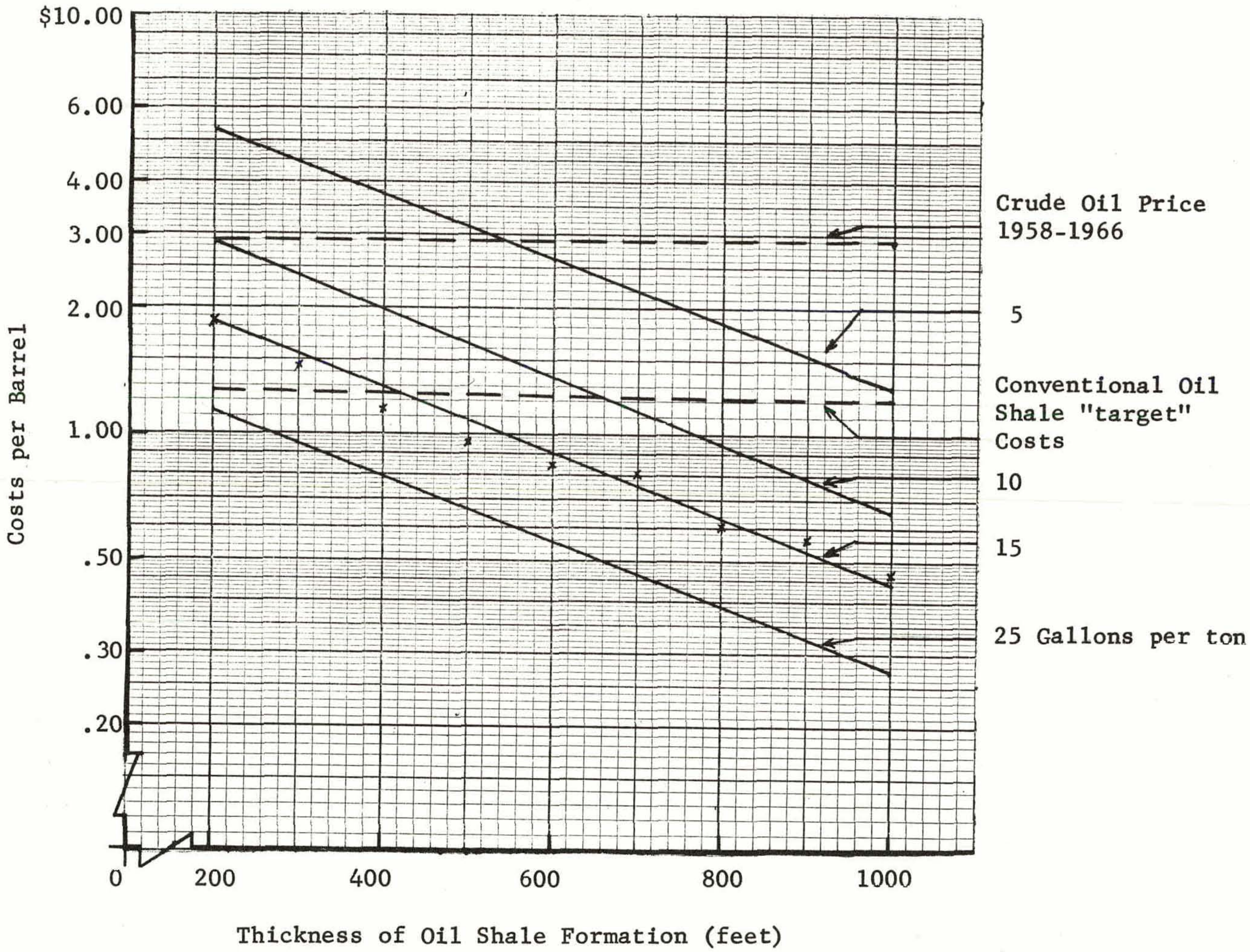


allow the operation to break even with a $1.25 cost price in formations of about 650 feet, 550 feet, and 350 feet respectively. This assumes that other technical parameters of Lekas are correct. Given that the main part of the Piceance Basin exceeds 1,000 feet in thickness, (up to 2,000 feet and more of 25 gallon shale) the recovery rate of 75 per cent is not essential to an economic plant operation even if we assume a $1.25 cost price as an upper limit. The crude oil industry today operates at a recovery rate of about 35 per cent and including secondary recovery, 50 per cent at best. Present experience at the Laramie retort indicates that higher recovery rates, even in excess of 75 per cent, are feasible in oil shale. Equally, the nuclear in situ technique would allow one to exploit oil shale formations below the 15 gallon grade requirement generally advanced at this time. If we assume again that Lekas parameters are fairly accurate, including the assumption of 75 per cent recovery rate, we may vary the grade of the shale, assuming all other factors as given in [117]. Cost savings by different plant design for lower grade shales may be feasible, but are not considered here. In addition, Lekas' 15 grade shale oil cost figures fit the 15 gallon grade cost function extremely well based on an extension of the 25 gallon data above (Figure 5.7). Thus, formations down to 5 gallon grade could be recovered economically at a $1.25 cost in formations exceeding 1,000 feet in thickness, other parameters being equal. Oil shale of less than 15 gallon grade is not likely to burn. However, as pointed out in [154], such oil shales might be retorted by the hot gas

Figure 5.7

Costs Per Barrel Shale Oil as a

Function of Oil Shale Grade



x : Lekas 15 gallon grade plant "data" while 15 gallon curve is an extension of 25 gallon curve injection method. For this process, again, the cost figures cited in the previous tables and figures do not apply except for nuclear fragmenting costs. Similar break even points are given for 10 and 15 gallon shale at 650 feet and 400 feet respectively.

A major uncertainty in the costs of the nuclear <u>in situ</u> shale oil production are compressor requirements, compressor investment cost, and compressor operating cost. The air or gas inflow determine the rate at which the oil shale is retorted. The required pressures and rates have not yet been determined at which enough energy is delivered to retort successfully the rubble chimneys. The air or gas rate and the necessary pressures will differ from chimney to chimney, mainly as a function of the water content of the oil shales. A difference in air and gas requirements in such processes causes a substantial difference in compressor investment cost and operating cost, at present, the most variable cost item in the estimates on <u>in situ</u> retorting. Appendix II of [154] shows air compressor requirements for a single 200 KT chimney at 3,000 feet depth. Cases II and IV are based on a preliminary draft on such a retort process [242].

While Lekas' shale oil costs were arrived at assuming a 3,000 scf (standard cubic feet) air requirement per ton oil shale rubble and a 5 psig pressure in the chimney, Cases II, III, and IV assume different technical parameters. They are:

Case I: Assumes technical requirements in air compressors as stated by Lekas, that is a 3,000 scf air per ton of chimney rubble, a pressure requirement of 50 psig, a recovery rate of 75 per cent, a C-value of 325 in the Boardman equation, multiple shots of 200 KT adequate for a ten-year plant life.

Case II: Assumes air requirements of 7,100 scf, operating pressure of 50 psig, a 70 per cent recovery rate, a C-value of 325, a single 200 KT shot, and a one- to two-year plant operation.

Case III: Assumes 7,100 scf in air requirements, an operating pressure of 1,000 psig, a 50 per cent recovery rate, a C-value of 325, a single 200 KT shot, and plant life of one to two years.

Case IV: Assumes 7,100 scf in air requirements, an operating pressure of 1,000 psig, a 50 per cent recovery rate, a C-value of only 275, a single 200 KT shot, and a one- to two-year plant life.

The difference in the C-value and the cost increase induced thereby is shown in the difference between the costs of Cases III and IV. The linear dimensions of the nuclear chimney as predicted in Case IV are about 40 per cent lower than those assumed in all previous cases.

In line with these and the other differences stated, we observe that air compressor investment costs would rise from the original 5-6 cents in Case I to 8 cents, 18 cents, and 34 cents per barrel of shale oil respectively in the best possible operations.

A similar increase is observed in air compressor operating costs which from the original 8.5 cents rise to 22 cents, 76 cents, and $1.25 in Cases II, III, and IV (see Figure 5.8). Thus, the overall increase in compressor costs per barrel of oil shale in a single 200 KT chimney would be from expected minimum costs of about 13 cents (Case I, Lekas) or 30 cents (Case II) to 94 cents in Case III and $1.59 in Case IV, making the in situ retorting process uneconomic in the latter case (see Figure 5.9). It is important, however, to remind ourselves that the Lekas estimate was made for a multiple detonation, large-scale project with a planned life of nearly ten years while Cases II, III, and IV are only single 200 KT detonations with a respective plant life of two years only. Thus, the cost increases in Figures 5.8 and 5.9 may be on the higher side and may not be so drastic in large-scale projects. However, basically compressor requirements are proportional to the rubble mass and should, therefore, not show considerable economies of scale.

Figure 5.8 shows air compressor operating costs in the four cases and their influence on total operating costs as presented earlier; Figure 5.9 shows air compressor investment costs under the four sets of assumptions, total air compressor costs, and their influence on total production costs per barrel of shale oil. As shown in Figure 5.8, the air compressor operating costs in Case IV exceed by themselves the "target" price for conventional shale oil production, assumed to be the competitive limit of either conventional or nuclear shale oil production. Thus, if the

Figure 5.8

Total Operating Costs per Barrel

As a Function of Air Compressor (=AC)

Operating Costs

(four cases, see text)

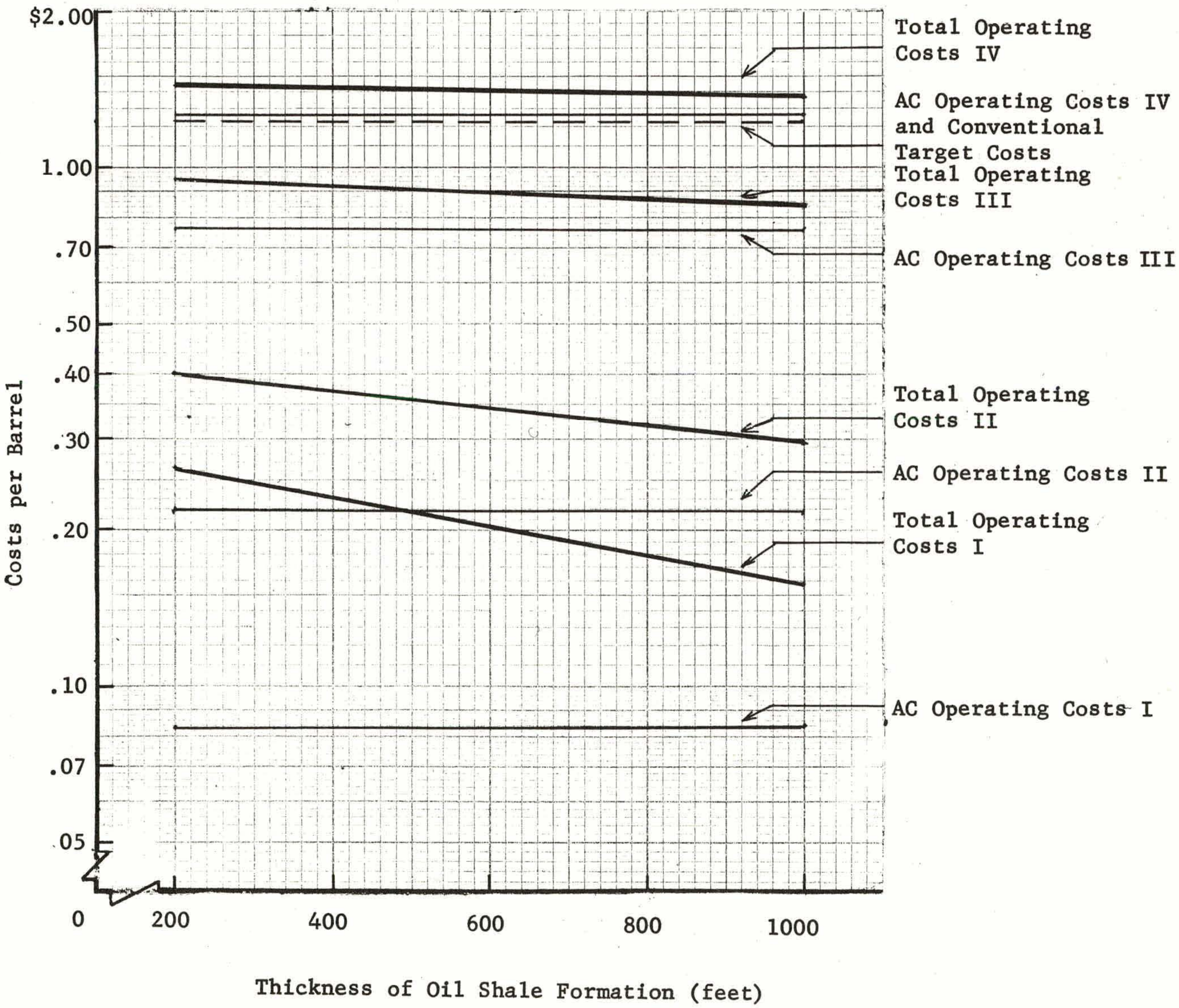
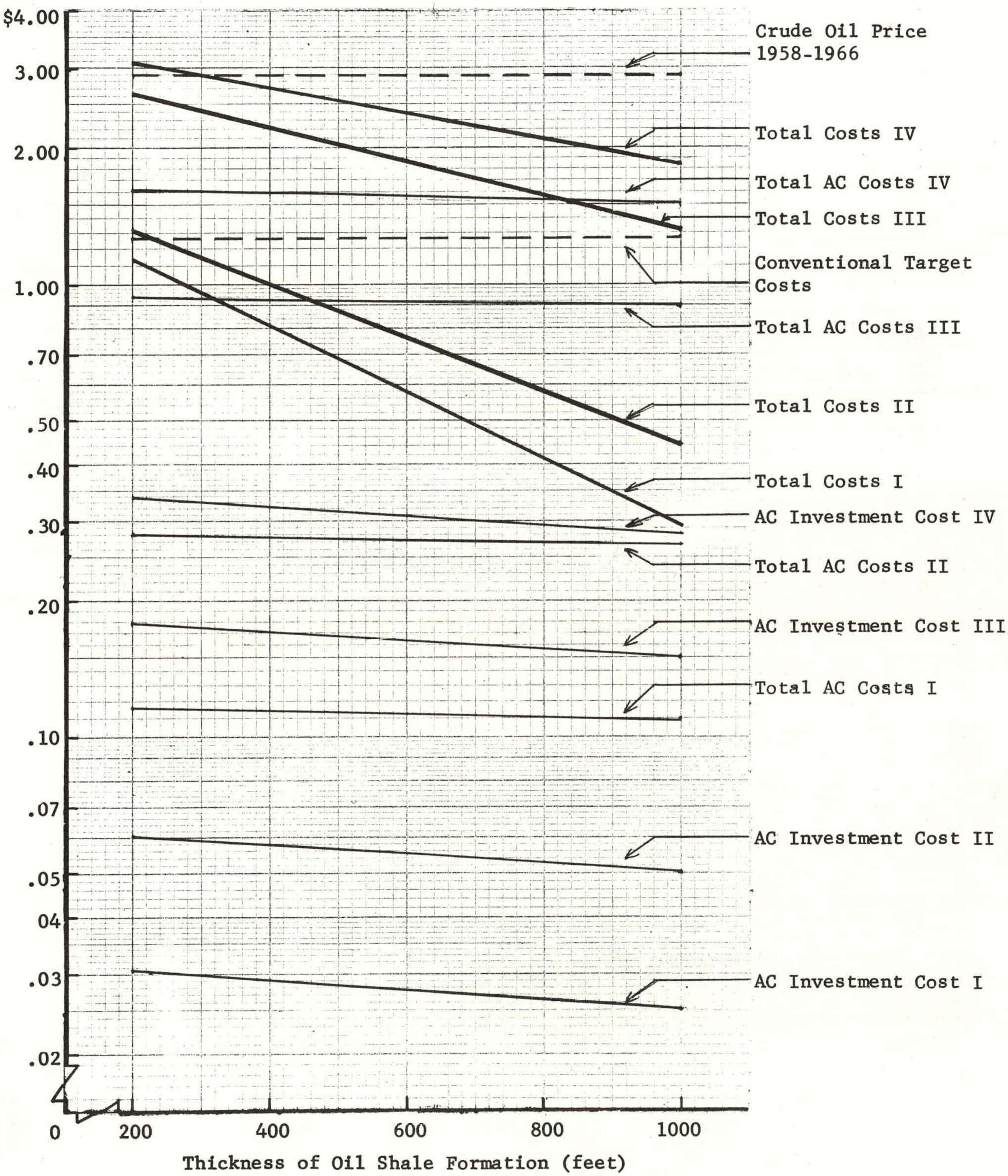


Figure 5.9

Total Costs per Barrel of Oil Shale
As a Function of Air Compressor (=AC) Costs.

(four cases, see text)



technical requirements of Case IV hold then the nuclear in situ production of shale oil would be uneconomic under present market conditions.

The air compressor operating costs in Case III still exceed the cost estimates of Lekas for total in situ shale oil production costs over a wide range. If to air compressor operating costs the investment costs are added, then the total shale oil production cost in Case III would in general exceed the $1.25 limit price for the in situ method. But while total costs in Case IV are unacceptably high, Case III would be at least marginally competitive, especially in the thicker oil shale formations, where conventional recovery methods are known to be relatively inefficient. On the other side the cost differences of Cases I and II are negligible if compared to the other two cases. Thus, we may tentatively conclude that among the most crucial parameters in the economics of in situ shale oil production using nuclear explosives are the pressure requirements within the chimney in order to retort effectively the shale oil. Though, under favorable other assumptions, 1,000 psig air pressure requirements would by themselves make this process at best only marginally competitive or a slight change in other parameters; for example, the 70 per cent recovery rate or lower grades would already exclude this process due to excessive costs if such extreme pressure requirements prove necessary. High pressures may be called for in water-rich formations ("wet" formations) using the in situ combustion method. In addition, the ignition of the rubble causes, in this case, added difficulties. A process avoiding combustion of the material altogether, for example by hot gas injection, might prove to be more efficient in such cases.

In "dry" formations the 50 psig pressure requirement may suffice, especially as air pressure drops across the rubble zone nuclear chimneys have been very low [117].

The main findings are:

1. Crude oil resources both of the United States and the world, are limited and if related to present production levels,serious scarcities will develop within the next generation (35 years). This conclusion takes account of substantial additions to crude oil resources during this period and increasing Gross National Products.

2. The main organic matter reserves of the United States and the world are in the form of oil shales and coal deposits. Oil shale deposits may equal expected coal deposits in energy content. At least in the long run these two resources will be the main base of fossil fuels and organic material production. The known, measured oil shale and reasonably inferred resources in Colorado alone exceed "known and measured" United States crude oil resources by a factor of 100 and total maximum expected recovery of crude oil resources by a factor of 10.

3. The expected technical parameters in nuclear <u>in situ</u> retorting of oil shale would allow a shale oil production at substantially lower costs than present crude oil production. This is mainly due to:

a. the elimination of finding costs, as the shale deposits discussed here are known and measured. The only open question is their ultimate extent, not their location. There may, of course, exist additional oil shale deposits not yet discovered.

b. increasing economies of scale in the thick oil shale formations of the Green River area for nuclear <u>in situ</u> methods.

c. substantial external economies due to a reduction in labor requirements and water requirements and a near exclusion of waste disposal problems by the nuclear <u>in situ</u> retorting process.

d, the present crude oil industry enjoys a 27.5 per cent depletion allowance which is reflected in the extent of their operations and in part in crude oil prices. In the present analysis no such allowance was made for shale oil production costs, though potentially shale oil production by any <u>in situ</u> production method might be entitled to an identical allowance.

4. The nuclear <u>in situ</u> retorting method would enable the U. S. economy to expand petroleum production at will without substantial cost increase.

5. The extension of petroleum supplies for the U. S. by this new technology would be in excess of 100 years allowing for a 3 per cent

annual expansion of total petroleum demand. Even if the crude oil reserves estimates should be changed to 3, 4, ... times this figure the difference with the oil shale opportunities remain formidable. Potentially, this expansion could extend to 200 or more years within the U. S. This compares with the time horizon of proven crude oil reserves of ten years only.

6. The nuclear _in situ_ method would not discriminate against private industry or any firm that wants to participate in such an undertaking and is able to do so financially.

Against these expectations stands mainly the fact that no nuclear _in situ_ retorting experiment has yet been conducted. Such experiments could lead to substantial changes in expected costs in both directions, cost-savings and cost-increases. In particular, this study found that variations in the technical parameters could be such that the nuclear _in situ_ process would still be economically feasible down to a recovery rate of 30 per cent of the shale oil present. Similarly, if present parameters are confirmed, the nuclear _in situ_ process could be extended by various processes economically to recover shale oil from very low-grade deposits (five gallon per ton grade instead of 25 gallon per ton grade oil shales) extending thereby substantially the exploitable oil shale reserves.

Uncertainties as to compressor requirements were found to be the most serious variable in expected shale at production costs.

The nuclear in situ technique would be mainly applied in formations exceeding 100 feet in thickness. This is due to the discrete size of any nuclear explosion and the fixed costs incurred independently of the yield of the explosive. Thus, the nuclear in situ technique does not directly compete with most conventional mining-retorting techniques developed by some firms at present.

If the nuclear in situ technique proves to be successful and confirms expectations anywhere in the neighborhood of present figures, a substantial shale oil industry could develop within the U. S. and ultimately replace crude oil production at an annual rate of 10 to 15 billion dollars per year of gross output. In addition, this technique would constitute one of the first forms of production in which the fusion energy would be utilized with advantage for peaceful purposes, as up to date fusion processes are not yet controllable to such an extent and scale as to allow an economic transformation of the fusion energy released into economic work through reactors. Whether and when this will ever be possible, we do not yet know. In the meantime the explosive release of this energy may be put to work through Plowshare.

These projections do not take into consideration possible social costs which arise in the form of possible destruction of landscape, pollution, etc. Such costs are difficult to estimate, but at any rate it must be recalled that ordinary oil refineries also have this effect and as the oil industry would be called upon by increasing demand to expand its operations, so would these rise.

Even if there were no other uses for peaceful nuclear explosives, these considerations alone would justify a substantial research and development program of the peaceful application of nuclear explosives far in excess of present efforts. If the expected technical parameters advanced so far for this method hold, the 10 billion dollars gross output of the crude oil industry could be replaced or added to by shale oil at 25 to 50 per cent of present costs. To what extent these parameters are realistic has to be tested by experiments.

5.2 THE ECONOMIC POTENTIALS OF GAS (AND OIL) STIMULATION BY NUCLEAR EXPLOSIVES

The special report on gas stimulation [125] describes the technical and economic potentials of gas stimulation by nuclear explosives. The report shows that there exists a fairly firm body of information which, however, will have to be enlarged and improved by experiments specifically related to gas stimulation to confirm the statement that gas stimulation can become one of the first technically and economically feasible applications of the peaceful uses of nuclear explosives.

As in the case of shale oil recovery, the potential in gas stimulation has to be evaluated and weighed against the generally available knowledge of fossil fuel energy resources in the United States and the world, and the particular prospects of gas stimulation by nuclear explosions within the overall fossil fuel balance. The evaluation of the U. S. fossil fuel reserves by present techniques was shown in Table 5.3 in Section 5.1, page 77 which was compiled by the Department of the Interior [derived from 24, p. 6].

A similar breakdown of world reserves was shown in Table 5.4, page 79, with all the faults such a table necessarily has [derived from 24, p. 10].

Both tables give some insights into the overall United States and world energy situation if the present structure of energy supply is somehow maintained, i.e., over 90 per cent of total energy demand is supplied by fossil fuels. We have estimated that at least 12 Q will be added to "known recoverable reserves" if Plowshare and the subsequent recovery techniques in oil shale prove to be successful. This will overthrow any of the predictions ever made regarding the fossil fuel energy base of the United States.

A case similar to the one that can be made for oil shale can very likely be also made in the case of gas stimulation. During the last decades, U. S. production and estimated U. S. proved reserves followed a path similar to the one found in the oil industry: production expanded considerably, proved reserves were expanded too, but the relation between the two figures is more and more narrowing down as is evidenced by Table 5.6 [20, p. 406]. Figure 5.10 gives a graphical representation of Table 5.6.

As in the case of the American Petroleum Institute's estimate of crude oil reserves, the table below gives a very conservative estimate of recoverable gas reserves. Other estimates were also advanced [9, 11, 25, 27, 28 et al.].

Table 5.6--U. S. Natural Gas Production and Proved Reserves in TCF**

Year	Withdrawals during year	Estimated Proved Reserves end of Year*	Reserves as Multiple of Current Production
1945	4.8	147.8	30.8
1950	7.1	185.6	26.1
1955	10.2	223.7	21.9
1960	13.3	263.8	19.8
1964	17.0	281.3	16.6

* Report of the Committee on Natural Gas Reserves of the American Gas Association for year ending December 31, 1961.

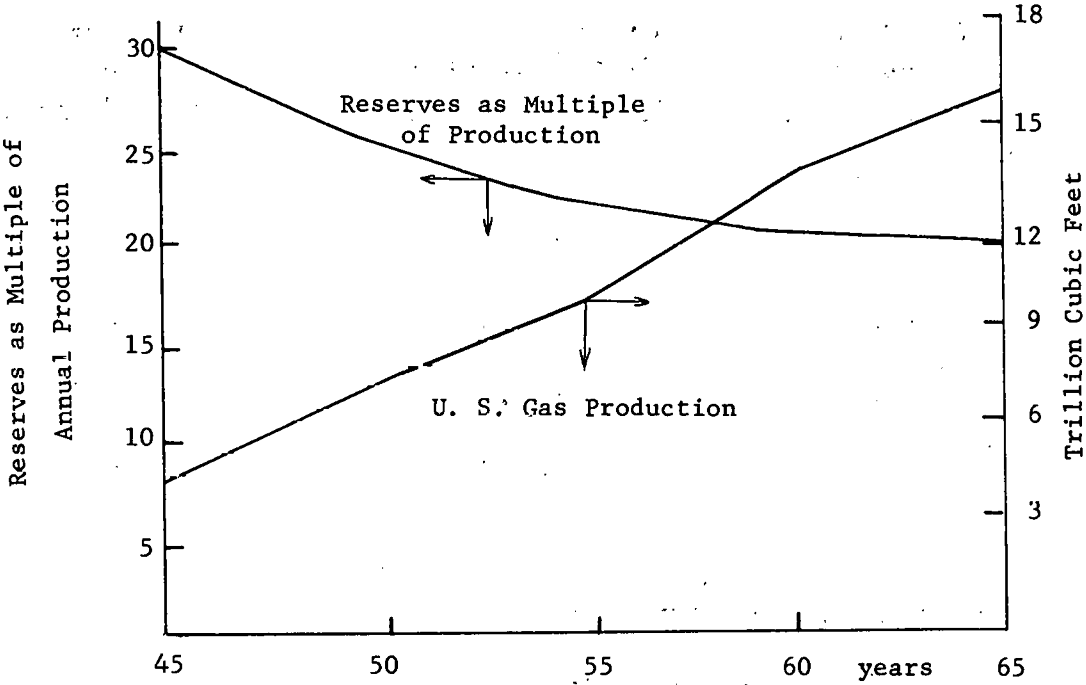
** TCF = trillion cubic feet

SOURCE: Landsberg, H. H., Fischman, L. L., Fisher, J. L., "Resources in America's Future--Patterns of Requirements and Availabilities," (The Johns Hopkins Press), 1962, and American Gas Association, 1965.

The highest estimate on recoverable gas reserves so far advanced is that of T. A. Hendricks [11]. The reliability of such estimates was discussed in [125]; here we cite only the estimate as given in [11] (see Table 5.7).

For conventional production methods in gas fields, T. A. Hendricks' estimate of gas "economically recoverable" might be a very high estimate given that it is "based" on crude oil recoverable reserves of 400 billion barrels. Once, however, nuclear techniques are developed which would stimulate low permeability gas fields, fields which per well would yield less

Figure 5.10--U. S. Gas Production and Reserves as Multiple of Production



U. S. Exploratory Activity and Gas Discoveries

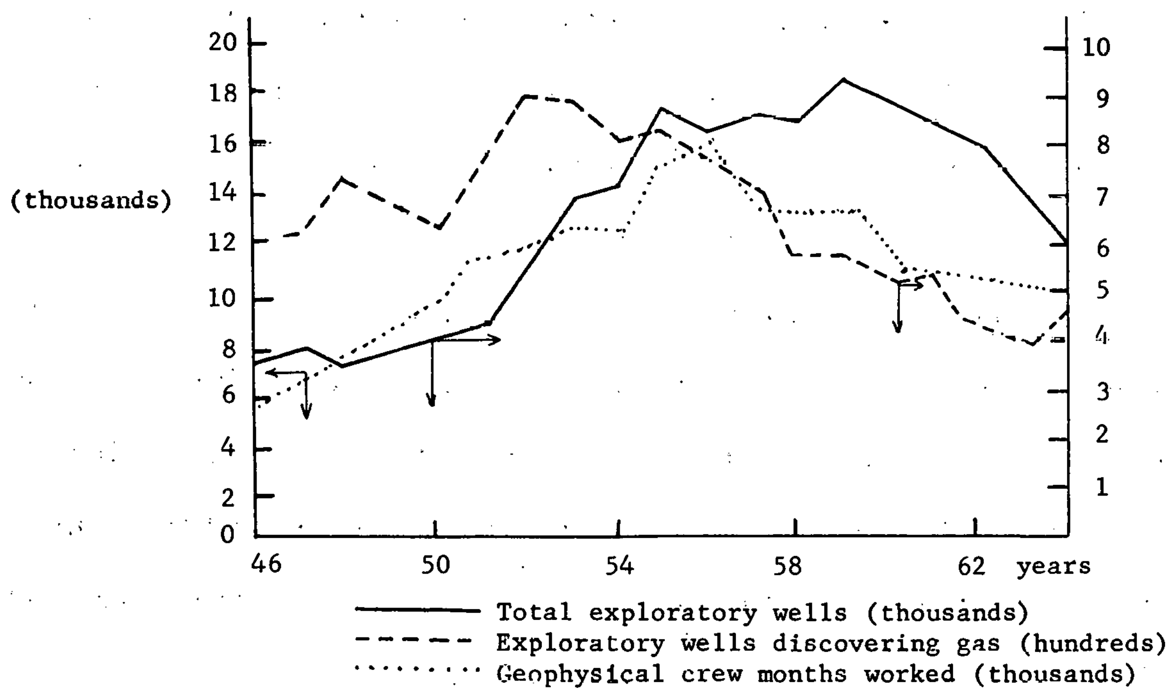


Table 5.7--Oil, Gas, and Natural Gas Liquids in Place in the United States before Production Began

	Crude Oil Billion Barrels	Natural Gas TCF	Natural Gas Liquids Billions Barrels
Total in Place	1,600	4,000	120
Total in Place to be found by exploration	1,000	2,500	75
Economically Recoverable	400	2,000	60
Submarginal	1,200	2,000	60
Approximate Production through 1961	68	230	7

SOURCE: Hendricks, T. A., "Resources of Oil, Gas and Natural Gas Liquids in the United States and the World," U. S. Department of the Interior, GSC 522, 1965.

than 250 MCFD* with conventional techniques, the total gas recoverable will add significantly to present estimated recoverable reserves. T. A. Hendricks' estimate can well be classified as reflecting "associated" gas estimates, given his estimating procedure. Known quantities of "non-associated" gas do exist in at least two areas extending over thousands of square miles in the United States, often in geographical association with oil shales. These reserves occur mainly alongside and south of the Rocky Mountain oil shale basins (in very sparsely populated areas) and in the "black shales" along the Alleghenies, where the thick formations again

* MCFD = 1 thousand cubic feet per day.

occur in relatively sparsely populated areas. The gas reserves are located in such a way that:

a. Plowshare techniques could readily be applied.

b. The main centers of demand (East Coast, West Coast, area around the Great Lakes) are relatively close to one of the areas.

c. Resources in both areas are very large by present production rates, though in the future gas demand might expand considerably.

For both the Rocky Mountain and Appalachian areas reliable estimates as to their overall potential are missing. With regard to the Rocky Mountain area we know the approximate extent of the gas-bearing basins [10, p. 23] (see Table 5.8 and Figure 5.11).

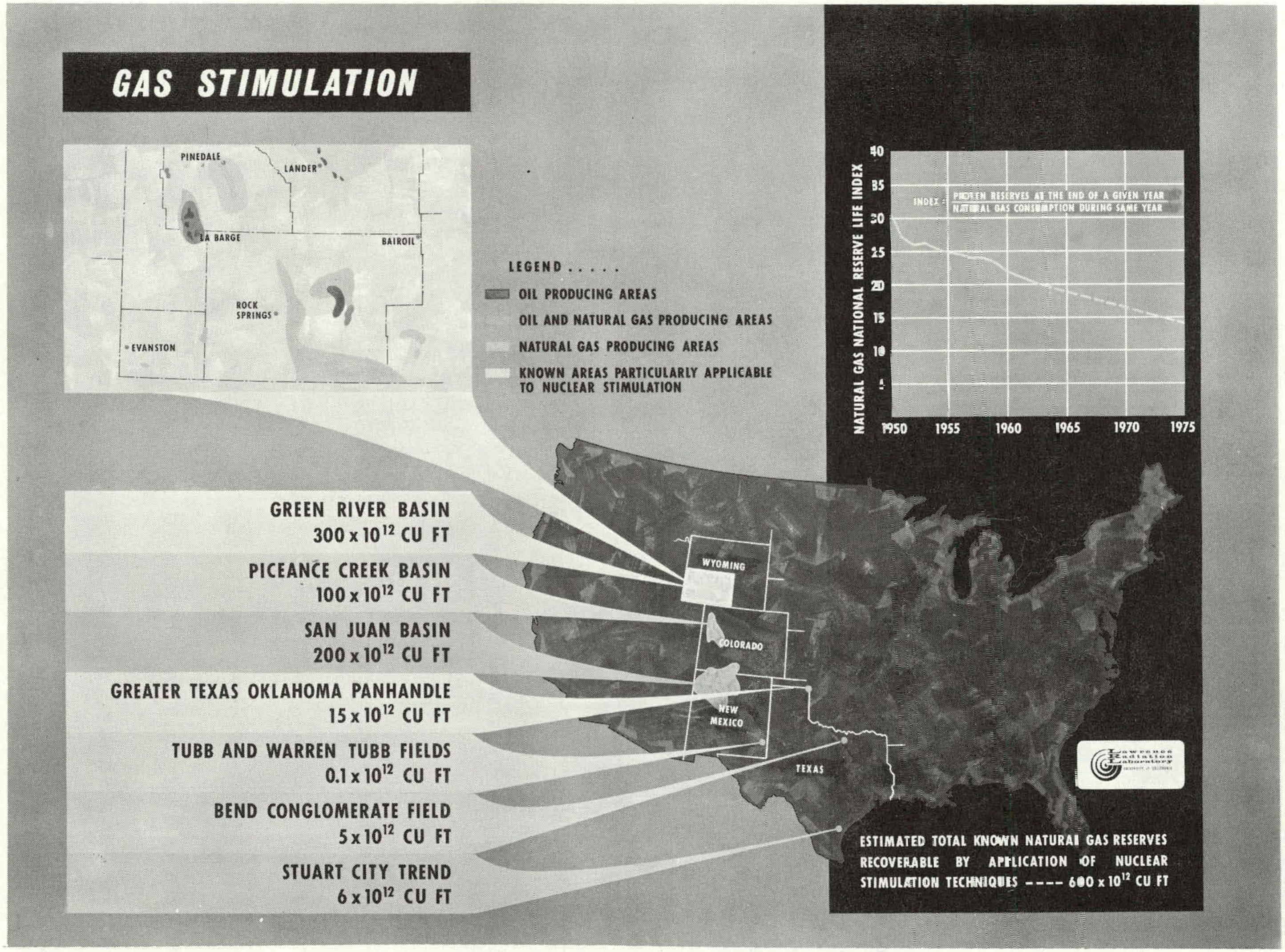
Table 5.8--Extent of Rocky Mountain Potential Gas-Bearing Formations

Basin	Area with Production Potential (square miles)	Number of Gas-Bearing Formations	Thickness of Potential Gas-Bearing Sandstones (feet)
Uinta	8,900	4	1,700
Piceance	3,900	4	1,200
Green River	19,000	7	2,500
San Juan	10,600	8	10,000
Paradox	25,000	n-e*	n-e
Wind River	4,000	n-e	n-e

n-e = not estimated

SOURCE: "Project Gasbuggy," Feasibility Study by the El Paso Natural Gas Company, U. S. Atomic Energy Commission, U. S. Bureau of Mines, LRL, May 1965, pp. 8 and 23.

Figure 5.11



SOURCE: Figure on Gas Stimulation and Estimated Known Natural Gas Reserves Suitable to Nuclear Stimulation, UCRL-Livermore, Graphic Arts, Neg. No. GLC-669-8254, PNE-798.

Estimates of total gas in-place reserves, if derived from a basin-by-basin evaluation are very likely to seem extremely large when compared with existing estimates of gas in-place reserves.

The figure cited most often in connection with gas stimulation by Plowshare techniques (in the Rocky Mountain area) is 320 TCF [7, 60]. This amount is equal to the American Gas Association's total figure on known, recoverable reserves (see above). This 320 TCF estimate seems, however, to be very conservative. Other estimates were advanced, one in the neighborhood of 600 TCF for three of the major basins alone [52, 253] (see Figure 5.11). This figure itself, if taken as an estimate for the whole Rocky Mountain area, is again on a more conservative side, as it does not include other major basins in that area.

Since such tight formations could not be brought into production economically up to now, such reserves were not included in many of the previous estimates in the first place and well data are scarce for the same reason.

Given the areal extent of the potential gas fields cited in Table 5.8 and all the well data available in that area, one could obtain a more precise estimate of gas in-place reserves. As long as such an evaluation is not made, one is left only to speculation. Thus, at an average gas occurrence of 10 BCF* per square mile (= 1 section in nuclear stimulation) at total depth the Rocky Mountain Area should contain resources of about 700 TCF

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* BCF = Billion cubic feet (10^9 CF).

gas in-place, such that about 300 TCF might be recoverable by nuclear stimulation.

Furthermore, at an average 50-60 BCF per square mile of gas in-place at total depth (i.e., comprising all formations that occur at different depths) the Rocky Mountain Area would yield an approximate gas in-place reserve of 3.5 - 4.2 QCF*. A 50-60 BCF per square mile would be a very high average quantity of natural gas for entire basins and thus would constitute an upper limit to the potential in-place resources. On the other side the 50-60 BCF estimate of gas in-place in <u>all</u> formations may be compared to some known, measured values of gas in-place in <u>single</u> formations: about 200 BCF per square mile in the Fort Union Formation in the Pinedale Unit Area (Green River Basin) [10], about 30 BCF in the Pictured Cliffs Formation (Gasbuggy) [10], 1.0 BCF in the Mancos B formation in Blanca County (Piceance Basin) [16]. Not all of these formations produce economically with present techniques because of their tightness or low reserve figures per section.

The 700 TCF estimate would more than double the present estimate of gas reserves in the U. S. The potential resources are, however, considerably higher and could be in the range just cited (about 4 QCF), though one has to treat such figures with very large qualifications. T. A. Hendricks estimates a similar total of 4 QCF in-place resource for the U. S. [11, pp. 20 ff.].

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* QCF = Quadrillion cubic feet (10^{15} CF)

The Devonian and Mississippian black shales (Figure V in [125] Central and Eastern regions) might come close to the Rocky Mountain potential. At present gas is produced there mostly from the sandstone overlying the black shales as some gas presumably escaped from the lower black shales and is now trapped in the higher formations. A substantial part of the gas (and shale oil) is, however, still contained in the tight, low-yield black shales [61]. The same is true for the fields in the Mississippian region.

For nuclear stimulation relatively thick formations are required, or a sequence of overlapping, thinner formations which can be connected by nuclear stimulation. Such gas-bearing formations also occur in the lower part of the Appalachian basin along the Kentucky-West Pennsylvania line [61] and possibly also in the Mississippian region, the shale oil content of these regions and its potential recovery by Plowshare techniques are analyzed in [154]. The potential methane yield of the total organic reserves in these formations was estimated by E. B. Shultz as 8 QCF for better grade deposits and an additional 16 QCF for lower grade deposits, i.e., a total of 24 QCF in these basins [31].

Not all of these 24 QCF, however, are suitable to nuclear techniques. Much of the organic rich oil shale does occur in thin formations [30]. A substantial part of the gas (and shale oil) are present in the thick formations (i.e., exceeding 100-200 feet thickness). The exact potential of nuclear stimulation in these areas is not known. But of the total 24 QCF estimate, 4 QCF might well be suitable for nuclear stimulation (subjective estimate). In energy equivalents the cited figures (700 TCF, 4 QCF, and potentially 8 QCF) do correspond to .7 Q*, 4 Q, and 8 Q respectively**, while present total annual U. S. energy consumption is about .06 Q, with natural gas accounting for about 0.015 Q of this demand. Of these above estimates, about 50 per cent were recoverable by nuclear stimulation and if one allows for a 3 per cent long run expansion of gas demand (the present mid-1966 rate of expansion is 6 per cent [32], considerably higher than the long-term average), then these supplies could cover demand for the next 18 years, 55 years, and 75 years respectively. Present reserves recoverable by conventional techniques would last, at the same 3 per cent rate of expansion, for scarcely 15 years.

In addition to being used in these formations, gas stimulation by nuclear explosives might well develop to such an extent that even those fields which at present are developed only by conventional techniques (hydraulic fracturing) would be able to utilize, at least in part, the nuclear stimulation technique, local conditions permitting. This would then affect the ultimate recoverable reserve figures (mainly the south-central region of the United States). No estimate of possible benefits in this area can be made at present.

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* 1 Q = 10^{18} British thermal units (Btu).

** Estimating 1 MCF as equivalent to one million Btu [59, p. 271].

The nuclear stimulation technique would also allow for a more elastic production schedule. Due to the fact that the whole chimney volume has nearly infinite permeability, it can serve as a potential storage container for gas when irregular withdrawals of gas from the chimney occur. In conventional gas wells, production is only determined by the natural gas flow induced by the pressure differential between the area immediately around the well and the surrounding gas-bearing formation. If withdrawal at the well is interrupted, the gas flow is interrupted, and the induced gas flow starts only after production has been resumed. Additional gas flow from the surrounding medium occurs mainly if gas is actually withdrawn from the well. During the initial phases of the well history, this would imply a postponement of revenue by about 20 years (the average life of a conventional well).

In the case of nuclear stimulation, the storage space within the nuclear chimney would still allow the gas to flow from the higher pressure in the surrounding formation to the relatively low pressure within the nuclear chimney. When production is resumed, the gas in the chimney can then be withdrawn at an increased rate. In May 1966 about 90 M^2CF^* of natural gas were stored underground [32]. Though gas storage itself should be as near as possible to the centers of demand (i.e., at the end of the gas transmission systems), the storage capacity of the nuclear chimney would never-

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* M^2CF = one million cubic feet.

theless allow more elastic production schedules and in some cases directly allow for demand fluctuations. Nearly identical arguments hold for the stimulation of oil wells, though the extension of these reserves are less spectacular than those anticipated in oil shale and even gas stimulation.

As to the potential costs of gas stimulation by nuclear explosives and the resulting benefits to individual firms, four specific cases were analyzed in [125] based on [5, 10, 15, 16, 17, 28, 51] and gave, overall, encouraging results. The benefits of using nuclear explosives in gas stimulation at present costs seems to lie not so much in potential cost reductions but in making additional natural gas resources accessible to the U. S. at present costs in tight formations which today are not utilized due to the lack of gas flow.

As no nuclear explosive experiment has been made in media containing hydrocarbons in general and gas in particular, any statement made so far in this section is bound to be subject to considerable uncertainties. Relative to some other Plowshare projects there are, however, no industry uncertainties regarding the technology of recovery and processing after the nuclear effects did take place. Once the uncertainties concerning nuclear explosions in hydrocarbons are cleared away, in particular the extent of contamination, then in the case of gas stimulation no further technical problems exist.

The term "uncertainty" does not refer to possibly large, catastrophic events. Enough is known by now regarding the general effect of underground nuclear explosives to exclude any such event. The existing uncertainties are of a different kind and concern areas of design and engineering which will ultimately influence quite extensively the economics of gas stimulation (see Figure 5.12 derived from [5], [15], and [17]. There do exist uncertainties as to:

a. the extent of fracturing in the surrounding rock (i.e., the induced permeability increase).

b. the extent of tritiation of the gas and possible decontamination techniques and costs. Substantial tritiation may be avoided, or contaminate about one chimney volume of gas (or more).

c. the ultimate of reduction in the diameter of the nuclear device and the associated cost saving due to a reduced diameter of the emplacement well.

d. the charges for the nuclear explosives in completely contained, commercial applications.

The expected rate of return in nuclearly stimulated wells will mainly be a function of the gas in-place of the tight formation and the expected gas flow from this formation after the explosion took place. Figure 5.12 shows the expected increase of deliverable natural gas beyond conventional production for 34 BCF, 50 BCF, and 100 BCF per section; the conventional well is assumed to produce from a 100 BCF section.

Given the expected gas flows there remain still a variety of technical and economic parameters which will influence the effective rate of return of

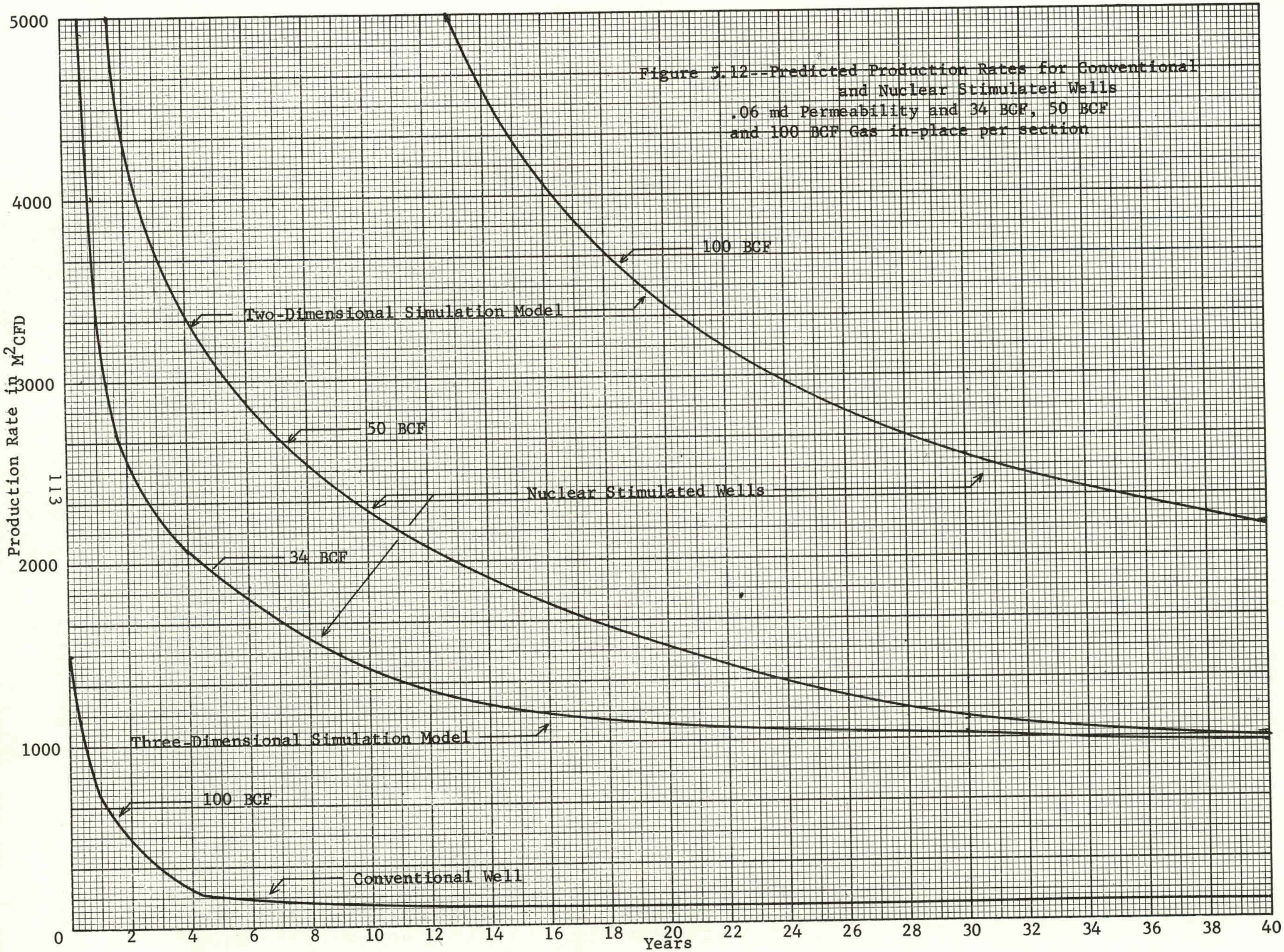

Figure 5.12--Predicted Production Rates for Conventional and Nuclear Stimulated Wells
.06 md Permeability and 34 BCF, 50 BCF and 100 BCF Gas in-place per section
Production Rate in M^2CFD
Years
0
1000
2000
3000
4000
5000
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
100 BCF
Two-Dimensional Simulation Model
50 BCF
Nuclear Stimulated Wells
34 BCF
Three-Dimensional Simulation Model
100 BCF
Conventional Well

such wells. In [125] four hypothetical cases are analyzed assuming in each of them (i) a low and (ii) a high increase in permeability by nuclear stimulation. The stimulated production capacities of the wells shown (in Case I expected production figures are entered) are evaluated at fifteen cents per MCF at well-head. Operational costs are assumed to be $7,200 per well per year* [e.g., source 17], and the "net revenue" is discounted to present worth at a 6 per cent rate, assuming that revenue is collected around the end of the year. The 6 per cent rate was chosen as a minimum internal discount rate for gas companies in risk-free investments. In the early stages of a new technique, a 10 per cent rate would be more likely in projects of this nature [51, p. 9]. The 6 per cent rate allows for minimum opportunity costs a gas company would incur in risk-free investments.**

The potential royalties to the Federal Government are 12.5 per cent of the gross-production value. In the Rocky Mountain area up to 90 per cent of the prospective gas-producing area is government owned, thereby giving rise to royalty payments. The treatment of royalties and taxes on profits when establishing real costs is at least controversial. The most consistent way to treat such items, in our opinion, is to regard them as side payments funded out of profits. Of course taxes and royalties are expenses to the firm. But the inclusion of taxes on profits and royalties as costs (and for that matter, of subsidies as revenues) can lead to serious

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* A relatively high figure. Operational costs per nuclear well may be much lower.

** Gas transmission companies are restricted to a profit rate of about 6 per cent per year.

3

misallocations of national resources, in addition to theoretical inconsistencies when making economic evaluations. A further revenue would accrue to the Federal Government through income tax levied on the (potential) profits. As large amounts of the gas in-place would, without nuclear stimulation, never be produced by techniques now available, we may regard these revenues as net additions to Federal revenue.

The discounted net income from the productions of Cases I to IV is compared in Summaries 1 and 2 (Tables 5.10 and 5.11 on pages 121, 122 below) to present costs and (potentially lower) future costs of nuclear well stimulation. All of the following tables are derived from data in [5, 10, 15, 16, 17, 28, 51, and 254]. (Roman numerals indicate Case I, Case II, Case III, and Case IV.) The built-in assumptions in the figures differ widely from case to case. The depth of emplacement, for example, ranges from 2,700 feet to 7,500 feet, the permeability and porosity are somewhat different in each formation, and with increasing depth the potential gas pressure differential is increased. None of the four cases would produce economically with present techniques. Assumed initial and stabilized production rates of the wells for the four cases are shown in Table 5.9; Case I was predicted by a steady state flow model, Cases II, III, and IV by radial, two-dimensional, unsteady state flow models, and Case IV-C, shown in Figure 5.14 is based on a similar, but three-dimensional simulation model.

The discounted net income would then have to cover the following initial investment costs in commercial applications:

Table 5.9--Gas-Well-Deliverability in MCFD*

		Deliverability			
		Initial	Stabilized	Average	Production
		low**	high**	low**	high**
Pictured Cliffs (San Juan Basin)					
(I) 10 KT, 160 Acres,	20 years	1560	2580	480	510
10 KT, 640 Acres,	20 years	1180	1650	840	1060
30 KT, 640 Acres,	20 years	1360	2000	930	1200
MANCO 5-B (Piceance Basin)					
(II) 40 KT, 640 Acres	20 years	1000	2800	550	750
MESAVERDE (Piceance Basin)					
(III) 100 KT, 640 Acres	50 years	4000	5000	1200	1600
(IV) 100 KT, 640 Acres	50 years	5000	5000	2300	3200
MESAVERDE (San Juan Basin)					
100 KT, 640 Acres	20 years	2000	3600	1100	1400

* MCFD = 1000 Standard Cubic Feet per Day

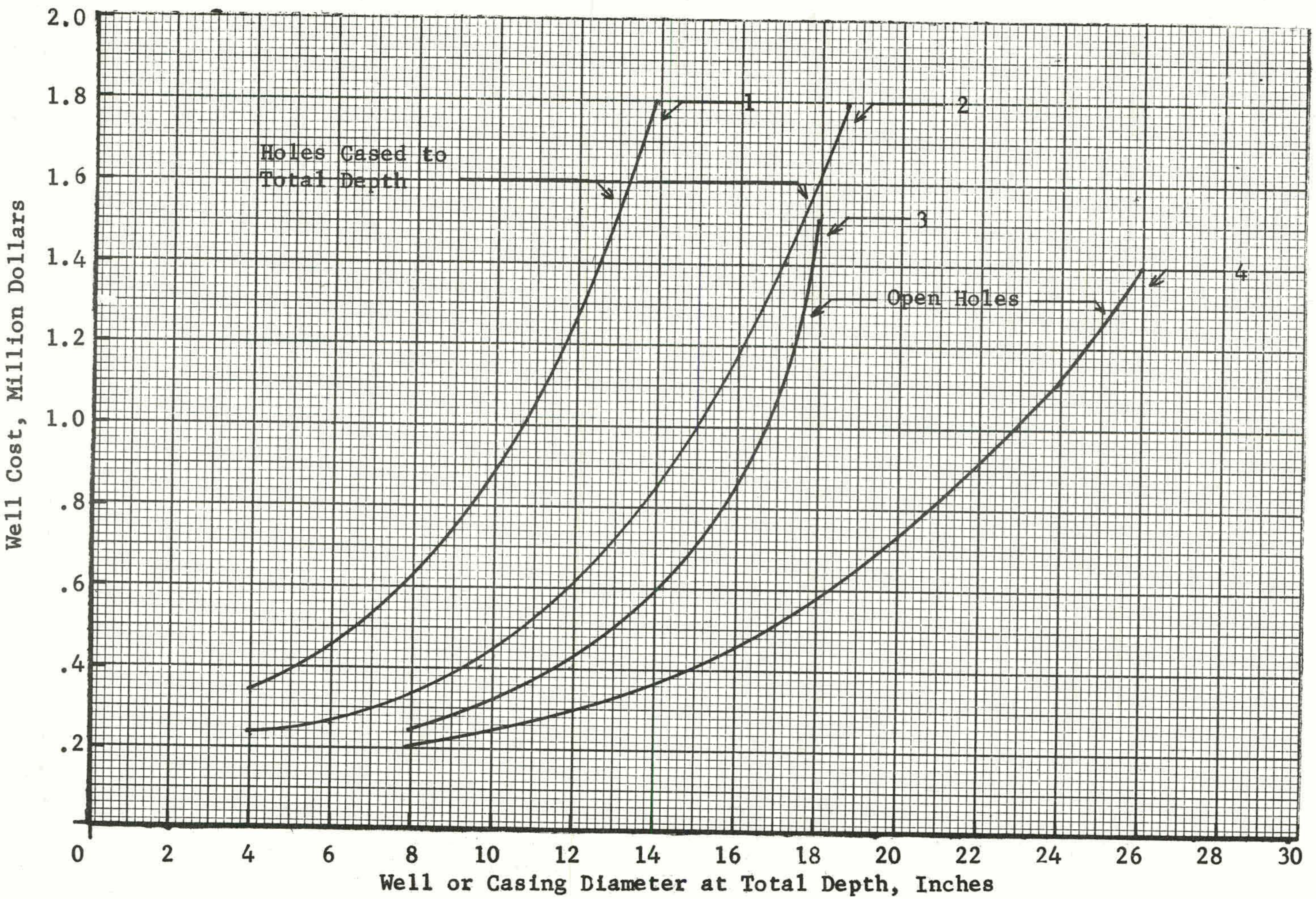
** Based on $C_f \approx 3$ (low) and $C_f \approx 7$ (high)

SOURCES: Austral Oil Company, CER Geonuclear Corporation, Continental Oil Company, El Paso Natural Gas Company

a. The costs of the device at projected charges for nuclear explosives (see Section II of this report).

b. Drilling costs for the emplacement hole which, at present, are a main part of the costs in nuclear stimulation. Many of the tight formations in the Rocky Mountain area do reach to 10,000 feet. These drilling costs are in general a function of the depth of emplacement, the diameter of the hole and the hardness of the rock. Figure 5.13 gives an estimate of these costs in Rocky Mountain areas [51, 1. 17]. To realize the full potential benefits of nuclear stimulation at such depths it would be desirable to restrict the diameter of the explosives up to 500 KT yield to a maximum of 12-18 inches. There are indications that considerable progress is possible (i.e., below the diameters shown in previous Figure 5.12, [51, p. 15]). Cases III and IV of [125] demonstrate one possible way to lower emplacement costs, i.e., by a simultaneous, vertical emplacement of two devices. In formations where vertical connection of more gas-layers is called for, such an emplacement might prove to be more economic than a single, higher-yield shot. There exist, however, at present costs a trade-off between lower emplacement costs when two devices (of smaller diameter) are used and the lower cost of one single device with similar total yield ($850,000 versus $460,000 in case of 2 x 50 KT and one 100 KT shot). After the explosion has been set off, re-entry wells (= production wells) have to be drilled. Whether the existing emplacement well could sometimes be utilized (and to which extent) is uncertain. Re-entry wells are

Figure 5.13--Emplacement Costs Versus Diameter Size of Nuclear Explosive



All Curves: Total Depth = 10,000'
Surface Casing to 1000'
No Severe Lost Circulation
No Testing, Usual Logging

Curves 1 and 3: Intermediate Casing to 7000'

Curves 2 and 4: No Intermediate Casing

normal gas production wells and their costs are those generally anticipated in gas industry. In addition, the depth of the re-entry wells would be somewhat less than the original emplacement well (by about the height of the chimney above shot point). At depths to 10,000 feet these re-entry wells should cost about $150-200,000.

c. Miscellaneous other costs [51, 10, 16, 17].

Given the present uncertainties as to how much of the initial gas will be tritiated and to which extent this will pose a problem, it is difficult to attach any specific cost figure for detritiation of the gas. It may turn out that the contamination of the gas can be held to a very low level or avoided altogether. On the other hand, a substantial part of the gas might be seriously contaminated and a variety of proposals exist to deal with this particular decontamination problem. The costs of each procedure differ and are in some cases not even known. Present opinions in this field are too divergent to allow any particular cost estimate. However, there exist enough reasons to expect that the cost of decontamination can be held low. The uncertainty regarding the extent of tritiation is one main area which could be adequately assessed by experiments in nuclear stimulation. The safety aspects in this case are extensively discussed in Chapter 4 of this report, pp. 46 f.

Other costs occur in large scale commercial operations [51, p. 14 among others]. Allowance has to be made for engineering and inspection costs, miscellaneous construction costs, well testing, communications, other support operations, and finally, the industrial safety program. In large scale applications these miscellaneous costs might be held to $100, 000 per well [51].

For purposes of this study safety costs are estimated to amount to another $100, 000, giving overall miscellaneous costs of about $200, 000. Operational costs of the wells were included earlier. Both figures may be quite different from those assumed here in either direction.

Tables 5.10 and 5.11 summarize the results of Cases I to IV of [125]. At present costs and a 6 per cent internal discount rate, high production in Case III nearly yields a break-even; in both high and low productions of Case IV a considerable profit is realized in excess of the 6 per cent. In Case III there are 50 BCF underground at 7, 500 feet: this case would be in the neighborhood of a 6 per cent profitability given all the particular characteristics of the formation as shown in [125]. This rate of return is slightly exceeded if in the same field 100 BCF are present and a relatively low increase in permeability occurs. If all the optimistic estimates are realized, a high payoff is to be expected in Case IV, even if royalties have to be paid (Case III is still uneconomic if substantial royalties are to be paid). Figure 5.14 shows the cumulative gross income of Case IV under different predicted gas flows, the operating costs per well (shaded areas), and the cumulative net income; the present initial investment costs for Case IV are shown with $1.9 million and the cumulative capital costs were calculated on the basis of 6 per cent per annum interest

Table 5.10--1. Summary of Cases I to IV at Present Costs

	Total Net Income, i.e., 0% Discount		Present Worth of Net Income, 6% discount Rate		Costs of Devices	Costs of Emplacement	Miscellaneous Costs
	low	high	low	high			
Case I	384,000	418,000	230,000	240,000	350,000	200,000	200,000
Case II	390,000	680,000	250,000	480,000	410,000	150,000	200,000
Case III	2,830,000	4,076,000	1,250,000	1,880,000	850,000	600,000	200,000
Case IV	6,295,000	8,433,000	2,534,000	3,499,000	850,000	600,000	200,000

	Costs of Re-entry Well	Balance Over Total Net Income, 0% discount rate		Balance Over Discounted Net Income, 6%		Potential Royalties to Federal Government Discounted at 6%	
		low	high	low	high	low	high
Case I	150,000	-516,000	-482,000	-670,000	-660,000	31,000	32,000
Case II	100,000	-470,000	-180,000	-610,000	-380,000	33,000	62,000
Case III	280,000	+950,000	+2,146,000	-680,000	-50,000	227,000	306,000
Case IV	280,000	+4,365,000	+6,500,000	+604,000	+1,570,000	388,000	508,000

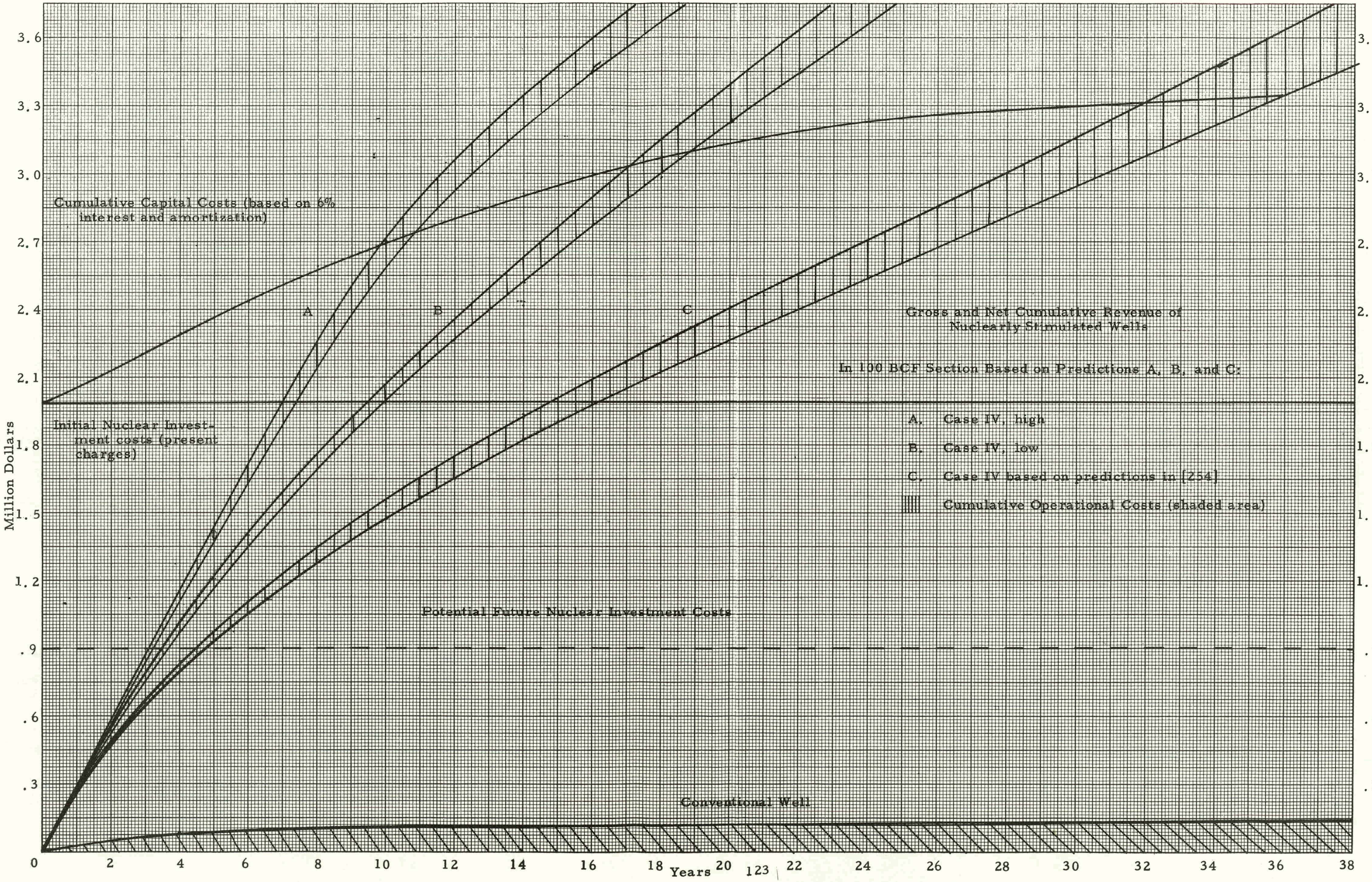
Table 5.11--2. Summary of Cases I to IV at Potential Long Range Costs, Excluding Costs of Device

	Total Net Income 0% Discount Rate		Present Worth of Net Income, 6% Discount Rate		Costs of Emplacement	Costs of Re-entry Well	Miscellaneous Costs
	low	high	low	high			
Case I	384,000	418,000	230,000	240,000	150,000	(150,000)	100,000
Case II	390,000	680,000	250,000	480,000	100,000	(100,000)	100,000
Case III	2,880,000	4,076,000	1,250,000	1,880,000	280,000	(280,000)	100,000
Case IV	6,295,000	8,433,000	2,534,000	3,499,000	280,000	(280,000)	100,000

Cont'd.	Balance Over Total Net Income,* 0%		Balance Over Present Net Worth,* 6%	
	low	high	low	high
Case I	-16,000	+18,000	-170,000	-160,000
Case II	+90,000	+380,000	-50,000	+180,000
Case III	2,220,000	3,416,000	590,000	1,220,000
Case IV	5,635,000	7,773,000	1,874,000	2,839,000

* Costs of device not included.

Figure 5.14



Cumulative Capital Costs (based on 6% interest and amortization)
Initial Nuclear Investment costs (present charges)
Potential Future Nuclear Investment Costs
Conventional Well
A
B
C
Gross and Net Cumulative Revenue of Nuclearly Stimulated Wells
In 100 BCF Section Based on Predictions A, B, and C:
A. Case IV, high
B. Case IV, low
C. Case IV based on predictions in [254]
Cumulative Operational Costs (shaded area)
Million Dollars
Years
3.6
3.3
3.0
2.7
2.4
2.1
1.8
1.5
1.2
.9
.6
.3
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38

and the amortization of the capital by the net income flow for Case IV-C, the lowest prediction shown in Figure 5.14, based on gas-flow predictions in [254]. Case IV-C has an effective rate of return of slightly more than 6 per cent; Case IV-B perhaps as high as 15 per cent.

However, from the above analyses, and Figure 5.14, it is also evident that initial investment costs play a decisive role in determining whether a certain gas formation can be stimulated economically.

Only a slight change in interest rates, or a relatively minor increase in investment costs would exclude many potential tight gas formations from nuclear stimulation. One important parameter will be the estimated quantity of gas in-place, as shown in Figure 5.12.

Another, equally important parameter will be the ultimate required initial investment for nuclear stimulation which again brings on a set of various potential developments: a reduction of the required diameter of nuclear explosives for gas stimulation, whether and to which extent the emplacement hold can be used as a re-entry well, the long-run charges for nuclear explosives in commercial applications, and, also, the elimination of same existing uncertainty as to the effective stimulation of gas formations by such explosions. This will require a number of carefully planned experiments.

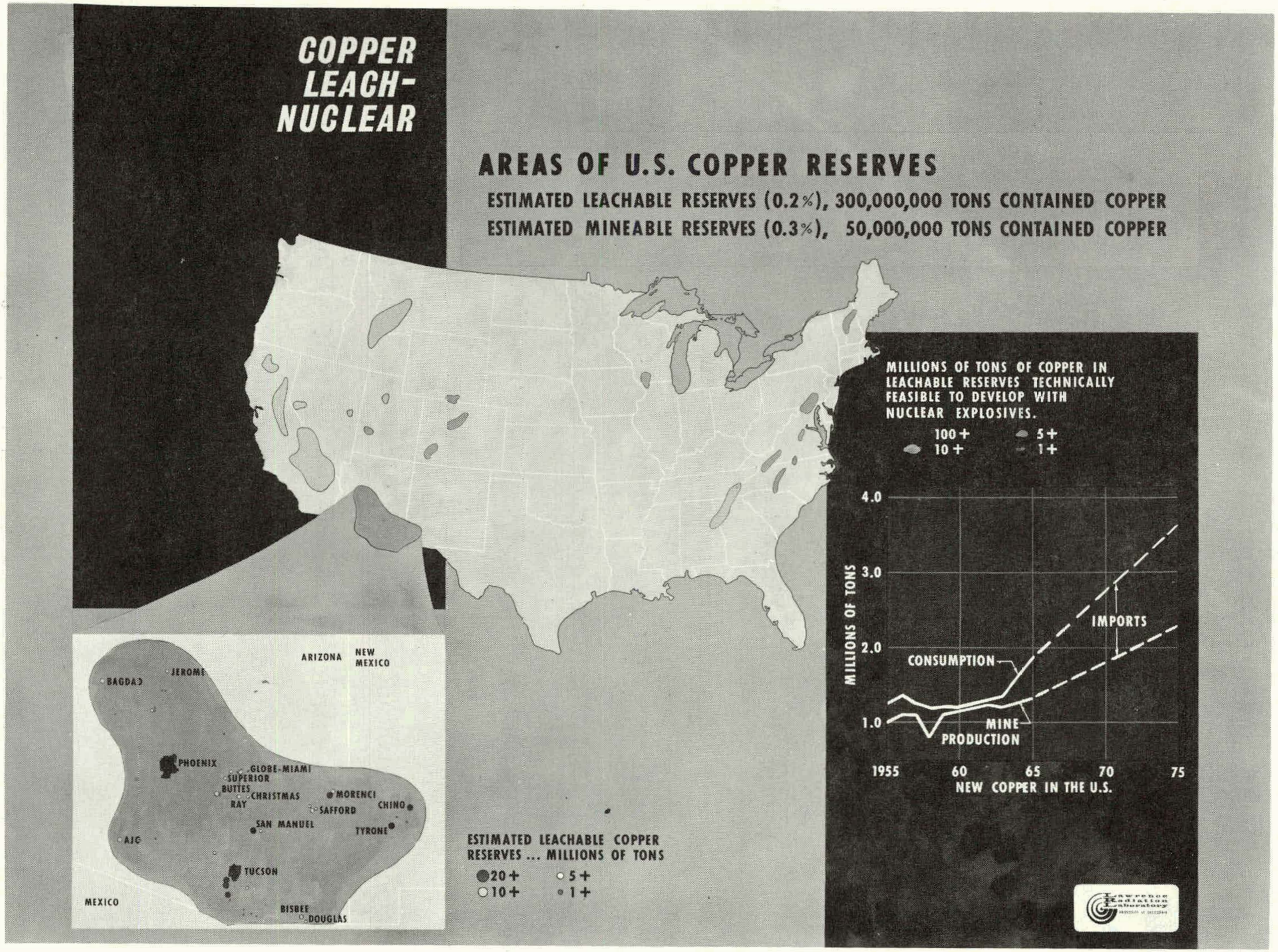
One tentative estimate of such a long-run initial investment is shown in Figure 5.14, based on potential long range costs shown in Table 5.11, including somewhat reduced charges for the nuclear explosives. At this reduced initial investment cost all cases shown in Figure 5.14 would be economic, with considerable rates of return. Another potential procedure would be to calculate for each formation upper limits to the changes for nuclear explosives under which that formation could still be recovered economically at some agreed upon rate of return. At present, however, the uncertainties on predicted gas flows from nuclearly stimulated gas wells are yet such as to make any calculation of this kind very difficult. Again empirical knowledge through experiments is needed.

5.3 THE ECONOMIC FEASIBILITY OF MINING APPLICATIONS BY NUCLEAR EXPLOSIVES

The application of nuclear devices as a substitute in such processes seems to be very attractive from the economic point of view, and appears to be one of the major prospective fields for peaceful uses of such devices.

The MATHEMATICA report on mining applications [179] concentrates only on copper mining applications (see Figure 5.15 [174]) although nuclear explosions could be utilized in mining operations of other non-ferrous metals with only minor modifications. In copper mining applications three different processes are considered: a) <u>in situ leaching</u> of copper ores, b) mining of copper ores by <u>block caving</u>, and c) <u>strip mining</u> of copper ores. The first two processes propose contained underground nuclear explosions, while <u>strip mining</u> would involve underground cratering explosions. All three processes were proposed to recover additional, known copper resources in an economic way.

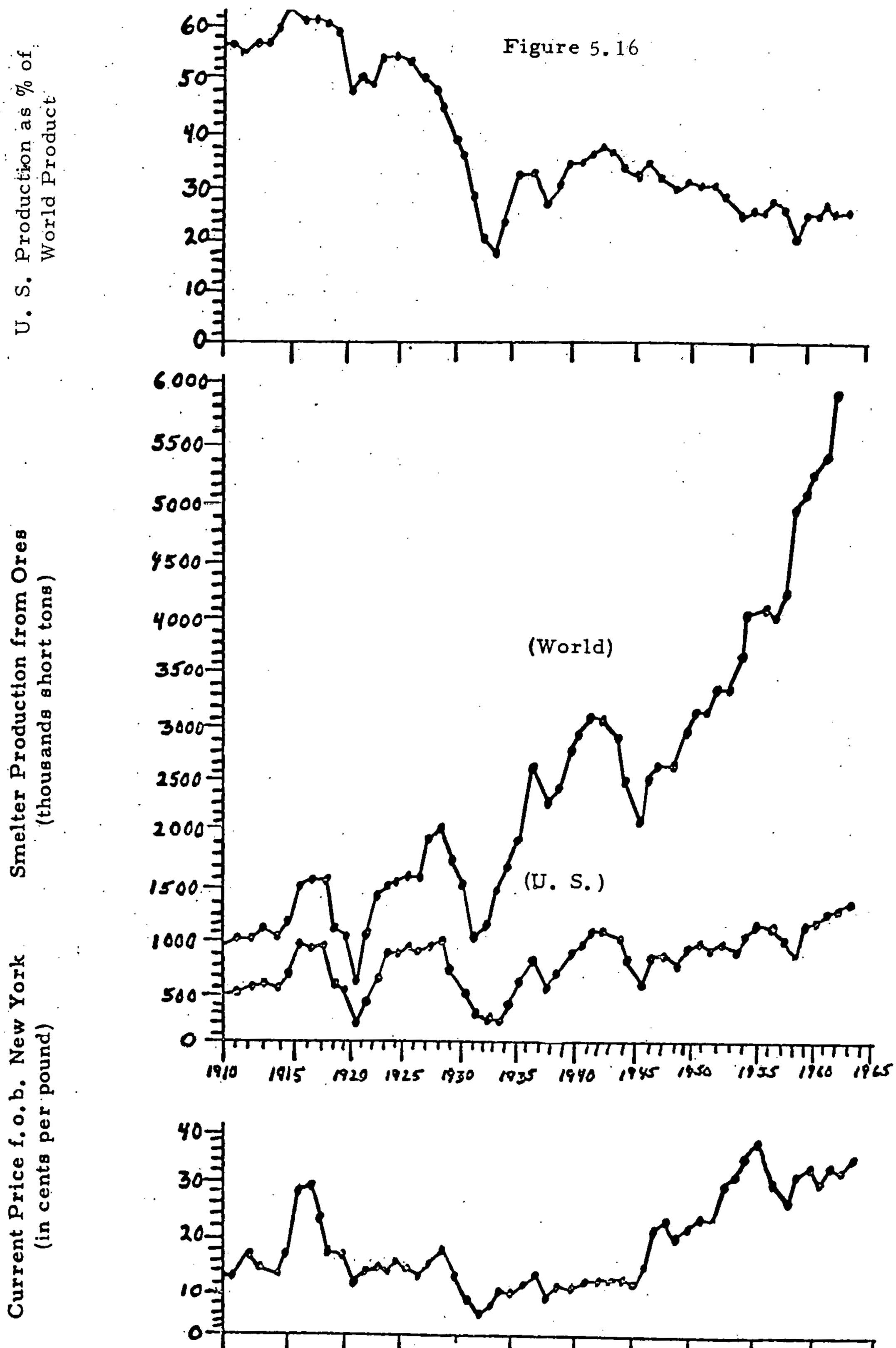
Figure 5.15



SOURCE: UCRL, Livermore, Graphic Arts, Neg. No. GLC'669-8253, PNE-776.

The potential extensions of economic U. S. copper reserves have to be compared with present consumption and available reserves. The resource estimates vary widely and may lie somewhere between 35 to 100 million tons of copper content in ores exceeding .5% grade. Present (1965) apparent U. S. consumption of primary refined copper is 1.5 million tons per year (about equal to expected 1967 production, see Figure 5.16). At only a 2 per cent rate of growth, by the year 2000, the annual consumption of copper will be 3 million tons and the cumulative consumption will then be 80 million tons. With a ten-year reserve requirement in the year 2000, this would require reserves of 120 million tons up to the year 2000. This means that catalogued copper reserves, mineable with present techniques at more or less present costs, will be exhausted.

On a world-wide basis (see Figure 5.17) a similar situation holds: at a 4 per cent growth rate, the annual world consumption will be 25 million tons and cumulative consumption about 500 million tons by the year 2000. A 5 per cent growth rate would imply a cumulative consumption of 635 million tons over the same period. At a 30 per cent increase in production costs, copper could be mined down to a .5 per cent grade by conventional methods and would extend present recoverable world reserves from about 200 million tons to somewhere around 600 million tons of copper content. This will be just adequate to cover cumulative consumption up to the year 2000, at increased costs.

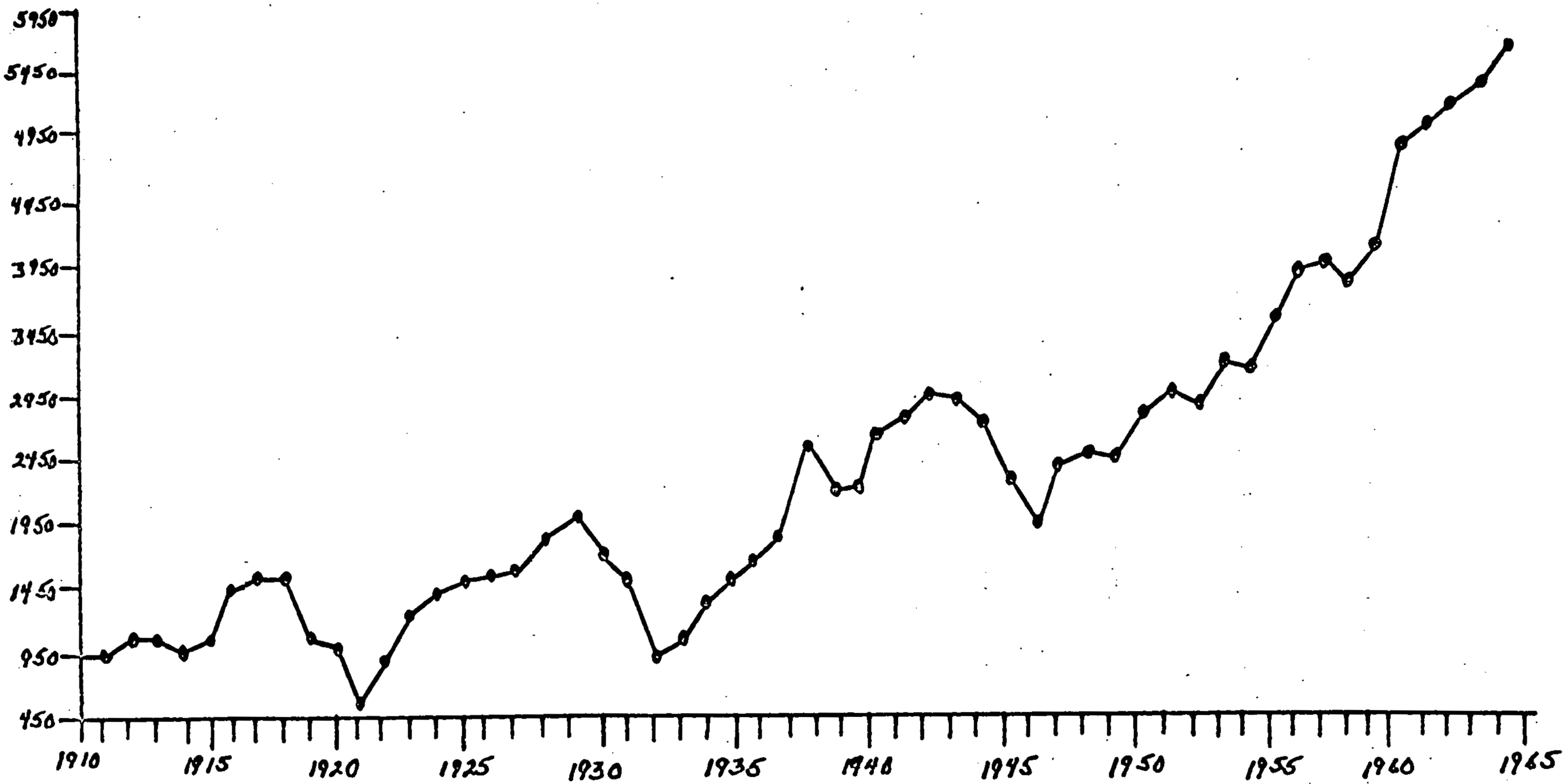


SOURCES: 1910-1962: A. D. McMahon, "Copper, A Materials Survey," Bureau of Mines, IC-8225, 1965, p. 157.

1963-1965: USBM.

Figure 5.17

World Smelter Production
(thousands short tons)



SOURCES: McMahon, op. cit.
USBM.

Most present projections seem to regard the year 2000 as some final barrier. Such an artificial restriction is, of course, completely arbitrary: this period now covers 33 years, a short period in the economic development of a nation, and is equally distant in time as the year 1934.

Though Plowshare should not be justified on the basis of "long-term" considerations alone, we observe that Plowshare could make an additional 350 million tons of copper content accessible to the U. S. at costs in the neighborhood of present figures or at slight increases. This extension of U. S. resources would cover adequate consumption levels for at least an additional two generations and therefore reach well into the 21st century.

These considerations are distinct from others, concerning the application of such new techniques in the copper mining industry. The structure of U. S. production and distribution of copper and the particular situation of world production may cause a postponement in the application of large scale nuclear processes, where conventional operations are still adequate for a controlled expansion of copper production.

As was pointed out in [179] a small number of companies control a very large fraction of the copper market. In addition, the major copper producers are also affiliated with large plants where the bulk of the new copper is fabricated into sheets, strips, rods, tubes, wires, and various extended and rolled shapes. More than 50 per cent of the total volume of

Table 5.12--World Copper Reserves and Major Production Figures

Country	Ore Reserves (1960) Copper Content (000 short tons)	Production 1963 (000 short tons)
North America		
Canada	8,400	461.
Cuba	200	
Haiti	75	
Mexico	750	
United States	32,500	1,210.*
TOTAL	41,925	
South America		
Bolivia	55	
Chile	46,000	660.
Peru	12,500	
TOTAL	58,555	
Europe		
Austria	60	
Bulgaria	300	
Finland	750	
East Germany	500	
Ireland	280	
Norway	500	
Poland	11,400	
Spain	4,500	
Sweden	700	
USSR	35,000	600.
Yugoslavia	2,750	(estimated)
TOTAL	56,740	
Asia		
China	3,000	
Cyprus	200	
India	100	
Israel	250	
Japan	1,200	
Philippines	1,000	
Turkey	580	
TOTAL	6,330	
Africa		
Angola	40	
Republic of the Congo (K.)	20,000	298.
Zambia	25,000	648.
Southern Rhodesia	475	
Kenya	20	
Mauritania	460	
South-West Africa	525	
Uganda	210	
Republic of South Africa	900	
TOTAL	47,630	(six countries) 3,880.)
Oceanic: Australia	1,200	
GRAND TOTAL	212,000	4,944.**

* U.S. production in 1965 was 1,356 and in 1966 equal to 1,421 thousand tons of copper [244].

** Production in 1965 was about 6 million tons [243].

SOURCES: McMahon, op. cit., p. 44.
O. T. Mouzon, Resources and Industries of the United States, (New York, 1966).

copper fabrication is done by affiliated fabricators. It would seem possible that the price of the fabricated copper product could be increased to reflect the high open market price of copper and the profits to the industry could be large even with the 38 cent price set for refined copper.

The copper industry is one where there exist strong incentives for control of the quantities produced for the purpose of maintaining a high price. The dominant position of a few companies makes such control more than a remote possibility. Indeed, in the history of the industry there have been several instances where organized efforts at price control have been made [see 179], although they ultimately collapsed, bringing forth severe crises.

The economic analysis in [179] of the in situ leaching, cave mining, and strip mining of copper ores using nuclear explosives gave mixed results. The nuclear in situ leaching of copper ores seems at present costs to be most attractive on large, low grade, leachable copper deposits. This conclusion rests, however, on various qualifications which might prove unnecessary after experiments have been made.

The typical economic analyses that have come to our attention in copper mining involve a calculation of the value of the copper that can be recovered, followed by a calculation of the costs involved in such recovery, such as costs of the nuclear device, costs of leaching, and costs of obtaining copper from the pregnant liquor, including capital costs. Such studies indicate substantial profit potential. These studies have not involved the calculation of "discounted profit" which would be considerably lower. Two basically different comparisons were drawn in [179]: first, whether the *in situ* leaching method combined with nuclear explosives yields such profits when compared with average U. S. mining costs of high grade copper and, second, whether this leaching method yields profits substantially in excess of conventional methods if applied to new, identical deposits, that is, deposits of generally low grade which would be added to present copper production and which determine marginal costs of copper production. Even without technological uncertainties there do not appear to be any opportunities to make profits in the first case, i.e., if compared to average production costs. On the other side, in case of expanded copper production in lower grade, deep, and/or small deposits of suitable mineralization the nuclear technology may yield decisive advantages if technical uncertainties are removed by experiments.

In the first case it was assumed in [179] that the goal of the entrepreneur is to maximize the value of his discounted profits from a specified ore deposit. A consideration of vital importance, which has been omitted from economic analyses that have come to our attention is the substantial difference in recovery rates obtainable by conventional methods and by *in situ* leaching. Indeed, this difference is so important for the national economy that a continuation of conventional methods might be desirable even at very low costs of nuclear devices, due to the higher recovery rates in conventional mining methods.

We shall assume that the time horizon is the same for the two methods and that discounting would have a roughly proportionate effect on the two. We can then simplify the analysis without seriously distorting the comparison.

The following notations will be used:

R: total amount of ore (lbs.)

y: grade of ore

r_1: recovery under conventional methods (assumed to be .86)

r_2: recovery via in situ leaching (assumed to be .5)

c_1: cost per pound of copper obtained by conventional methods

c_2: cost per pound of copper obtained via nuclear explosion, in situ leaching, etc.

p: price per pound of copper (assumed to be \$.38)

s: cost saving per pound of copper obtained by in situ leaching ($s = c_1 - c_2$).

The value of total (undiscounted) profits before taxes obtained by conventional methods is then:

$$R \; y \; r_1 \; [p - c_1] \tag{1}$$

The value of total (undiscounted) profits before taxes obtained by <u>in situ</u> leaching is:

$$R\ y\ r_2\ [p - c_2] \qquad (2)$$

For the leaching <u>in situ</u> to be more profitable, it is necessary that the profits (2) be larger than (1), i.e.:

$$R\ y\ r_2 [p - c_2] > R\ y\ r_1\ [p - c_1] \qquad (3)$$

It is easy to simplify (3) to:

$$c_2 < \frac{r_1}{r_2}\ c_1 + p\ (1 - \frac{r_1}{r_2}) \qquad (4)$$

According to Mr. Franklin D. Cooper's estimates, the cost per pound of copper obtained from ore of .7 per cent content is approximately 15 cents*

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* Though the 15 cents cost per pound of copper estimate dates back to 1958, this cost figure is still in close agreement with present average costs.

The costs in some new mines are, of course, considerably higher, but this is in part due to the cost accounting procedures, particularly with regard to depreciation costs. A distinction between legitimate depreciation cost procedures for tax purposes, with their built-in investment incentives, and real costs for company-internal decision making is rarely made by industry. This leads then to disproportionate cost differences of old mines (as low as 10 cents and less) and new mines (as high as 28 cents), which reflect, at least in part, inadequate cost accounting procedures.

for mining, milling, concentrating, smelting, refining, and marketing. Using $c_1 = \$.15$; $p = \$.38$; $r_1 = .86$; and $r_2 = .5$, we obtain the condition that for leaching to yield more profit than conventional methods, it must be true that:

$$c_2 < 1.72\ c_1 - .72\ p = -.0016 \qquad (5)$$

In other words, the cost of obtaining copper via leaching must be negative to make it preferable. Even if the copper were obtained free, it would not be profitable to do so. The reason for this seemingly paradoxical result is that the loss of copper due to a 50 per cent recovery by leaching rather than 86 per cent recovery by conventional methods is so large that it should never be incurred for relatively high grade ores. Note that condition (5) is independent of the size of the deposit. From (5) we have also to conclude that with any increase in the copper price the right-hand side decreases more and more. This is explained by the increased value of the copper that remains underground.

Condition (5) can be restated in another form which allows some further generalizations:

$$c_2 = c_1 + s < 1.72\ c_1 - .72\ p, \text{ or}$$

$$s > .72\ (p - c_1) \qquad (6)$$

That is, the cost savings per pound of copper obtained by leaching must be at least 72 per cent of the profit per pound of copper obtained by conventional methods. If now, due to a favorable mineralization of the copper or advanced <u>in situ</u> leaching techniques, the recovery rate is raised above the 50 per cent rate here assumed, and if marginal production costs of 20 cents per pound are substituted for the average production costs of 15 cents, the inequality in (6) gives the following results:

Case a: $r_2 = 50\%$, $c_1 = 20¢/lbs.$, $r_1 = 86\%$, $p = 38¢/lbs.$

$$c_2 < \frac{r_1}{r_2} c_1 + (1 - \frac{r_1}{r_2}) p \quad \text{or}$$

$$c_2 < 1.72 \times .20 - .72 \times .38 = \$ .07$$

Case b: $r_2 = 60\%$, $c_1 = 20¢/lbs.$, $r_1 = 86\%$, $p = 38¢/lbs.$

$$c_2 < \frac{r_1}{r_2} c_1 + (1 - \frac{r_1}{r_2}) p \quad \text{or}$$

$$c_2 < 1.43 \times .20 - .43 \times .38 = \$.12$$

Case c: $r_2 = 70\%$, $c_1 = 20¢/lbs.$, $r_1 = 86\%$, $p = 38¢/lbs.$

$$c_2 < \frac{r_1}{r_2} c_1 + (1 - \frac{r_1}{r_2}) p \quad \text{or}$$

$$c_2 < 1.23 \times 20 - .23 \times .38 = \$ .16$$

While a recovery rate of 50 per cent still yields uneconomic results if compared with an 86 per cent recovery in conventional methods and marginal costs of 20 cents, Cases b and c, i.e. recovery rates of 60 per cent and 70 per cent, yield required nuclear costs of 12 cents and 16 cents respectively. Based on our cost estimate of conventional techniques, this yields an equivalent cost of non-nuclear operations in the nuclear process of about 10 1/2--11 1/2 cents (see page 140 below). Adding to this cost figure the nuclear costs of fragmenting of 7.4 cents (see page 140) down to possibly 2 cents (100 KT devices, .56 per cent copper), at a 60 per cent recovery rate the nuclear *in situ* leaching method is marginally attractive at larger yields (100 KT and more) while with a 70 per cent recovery rate the nuclear method clearly would yield economic advantages when all uncertainties are removed. It is frequently alleged that under normal conditions a net profit after taxes is approximately 25 per cent of the average selling price [161, p. 68].* With a 50 per cent tax on profits, the above "normal" price-cost ratio is 2. Thus, the savings per pound of copper obtainable by leaching would have to exceed .72 c_1 in the first part of our analysis to make this alternative attractive. The total costs per pound of copper obtained by nuclear fracture, leaching *in situ* precipitation, electrowinning, and marketing under the above "normal" price-cost ratio would have to be *approximately one-fourth* of the cost per pound obtained by conventional methods.

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* This is the "Notman formula."

The analysis on higher grade copper ore deposits indicates that in deposits where conventional and nuclear methods are both applicable at the stated costs, the nuclear in situ leaching method will only be applied if the recovery rate of this process is sufficiently large, exceeding perhaps 60 per cent. This is a rather severe requirement which may be met only in particular cases. As we already said, this rate will depend on, among other factors, the mineralization of the copper, the particle size distribution within the nuclear chimney, and acid consumption.

The second comparison to be drawn, that is whether the nuclear in situ leaching method yields profits substantially in excess of conventional methods if applied to new, low grade deposits yields somewhat different results. If we consider ore deposits of approximately 0.3% copper content at the current (38 cents per pound) price of copper, conventional mining and processing methods are not considered sufficiently profitable to justify their use for these low grade ores. It is argued here that the relevant economic question is not whether there is some potential profit available, but rather whether there is more profit per pound that is obtainable by conventional methods. Only if the cost per pound of copper obtained by nuclear fracturing, in situ leaching, precipitation, and electrowinning is lower than the lowest cost of obtaining additional pounds of copper by conventional methods will the prospect have an appeal to the entrepreneur. For purposes of comparison, the figure of 20 cents per pound is taken as representative

[171, p. 291].* The non-nuclear costs per pound** have been estimated to be:

c_2 - non-nuclear	
leaching and precipation	6 - 7 cents
electrowinning	3 1/2 cents
freight and marketing	1 cent
total non-nuclear	10 1/2 - 11 1/2 cents

This leaves about 9 cents per pound for all costs associated with nuclear fracturing. We shall assume that a 50 KT detonation fractures 2.4 million tons of ore. The total amount of copper recoverable is then:

$$.003 \times 2.4 \times 10^6 \times .5 = 3600 \text{ tons}$$

$$\text{or } 7.2 \times 10^6 \text{ lbs.}$$

The device is assumed to cost $430,000; the emplacement costs are assumed to be $100,000. These costs amount to 7.4 cents per pound. No mention has yet been made of the costs of the required safety program. To compare with the 20 cents per pound conventional cost, the safety program must amount to no more than 1.6 cents per pound of copper or a total of approximately $115,000 per 50 KT device. It seems unlikely that this cost could be met, at least until more experience has been obtained.

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* The author quotes a recent study showing median cost for 1960-62 of 17 1/2 to 20 cents.

** These non-nuclear costs have to be added to the direct nuclear costs of the process in order to get total costs per pound of the nuclear *in situ* process.

However, this conclusion is only valid as long as copper can be produced by conventional methods at 20 cents per pound. As we pointed out before, there exists a variety of known deposits where the costs of a conventional recovery are considerably higher than 20 cents. This is due to the low grade of those deposits or their large depth or their relatively small size which does not allow the large capital investment of conventional mining operations. The U. S. Bureau of Mines has identified at least 18 known deposits containing reserves of 16,000,000 tons of copper potentially suitable for nuclear <u>in situ</u> leaching in Arizona, Alaska, Idaho, Washington, and Utah [173]. In addition to these deposits the U. S. Bureau of Mines estimates that other billions of tons of suitable copper ore deposits exist in Arizona, New Mexico, and Nevada [173]. For these deposits, which could be exploited as the rich deposits now mined are gradually exhausted, the above comparison has to be modified. None of the deposits just mentioned can be developed and mined at a 20 cent cost per pound, while the nuclear <u>in situ</u> leaching costs are at least in the neighborhood of this cost figure.

Also, larger deposits of low grade ores would permit a fracturing of the deposit with higher yield devices which again lowers considerably the nuclear fracturing costs per pound of copper. How these costs change at different yields is shown by the following figures:

Table 5.13--Direct Nuclear Costs Per Pound of Copper

Yield in KT	Ore Fragmented, in million tons	Grade of Ore in %	Costs of Device in $	Approximate* Emplacement Costs	Costs in ¢ per lb. Recovery 50%	60%	70%
20	1.3	.36	380,000	100,000	10.26	8.54	7.32
		.50			7.38	6.15	5.27
50	2.4	.36	425,000	120,000	6.31	5.26	4.51
		.50			4.54	3.78	3.24
100	4.0	.36	460,000	150,000	4.24	3.43	3.03
		.50			3.05	2.54	2.18

* Assumes an emplacement depth of 2,000 to 2,500 feet.

These costs do not include safety costs and do not allow for the fact that most likely the nuclear fracturing of the ore would have to be done at the beginning of the mine development and therefore constitute initial investment costs. The only other alternative, at present, would subdivide the mine development into three or four major phases. The nuclear fracturing would in this case be made at the beginning of each phase, with at least some risk to existing aboveground and underground mining facilities.

Nevertheless, with 100 KT explosives in both cases the nuclear costs are substantially below the 9-cent margin for all nuclear costs in order to be competitive with the 20-cent cost figure for conventional production costs of higher grade deposits. This finding is in part at least also confirmed by the "Project Sloop" study [246].

The mining of copper by nuclear block caving is uneconomic except in very special cases. Mining by nuclear block caving compares unfavorably not only with average copper mining costs in the U.S. but also to alternative techniques, mainly conventional or nuclear strip-mining, and conventional mining by block caving in case of incompetent ore bodies.

Available cost data show that the nuclear cave mining method is cost saving only in particularly competent ore deposits, when compared to conventional cave mining. In most ore deposits a combination of nuclear and conventional cave mining processes would be the most economic solution if these methods are feasible at all. The main difference between conventional block cave mines and nuclear mines are according to S. M. Hansen [151, 167] three:

a. nuclear operations require no undercut level;
b. larger development units and a more flexible mine layout;
c. a different sequence in mine development; the nuclear process requires all permanent underground workings to be constructed after the nuclear detonations.

Given available cost data [among others see 155], we concluded in [179] that the nuclear cave mining method is cost saving only in particularly competent ore deposits, when compared even to conventional cave mining. In most ore deposits a combination of nuclear and conventional cave mining processes would be the most economic solution if these methods are feasible at all.

Let c_3 be the cost of one pound of copper by nuclear cave mining and r_3 the recovery rate in this process: Then equation (4) becomes

$$c_3 < \frac{r_1}{r_3} c_1 + p \left(1 - \frac{r_1}{r_3}\right) \tag{4a}$$

which in our case, at identical recovery rates ($r_1 = r_3$) reduces to the inequality

$$c_3 < c_1 \tag{7}$$

i.e., a simple cost comparison of the two processes, in a first approximation. If condition (7) is fulfilled then one would in addition have to consider the difference of time required in nuclear and conventional cave mining operations and alternate processes.

In the case study performed by Anaconda [155] an orebody of 564×10^6 tons of 1.25 per cent copper was considered. This orebody is from 150 to 1,000 feet thick and the overburden equals 200 to 1,800 feet in thickness. The stripping ratio is 3:1 as compared with the conventional average of about 1.7:1. About 30 per cent of this orebody (188×10^6 tons) are highly competent, while the remaining 376×10^6 tons are moderately competent or soft. A total yield of 1,400 KT in the form of low intermediate (20 KT - 200 KT) would be used to fracture the competent part of the orebody.

The costs for mining and development in the case of block cave mining are:

	Block Caving			
	Conventional		Nuclear	
	Incompetent	Competent	Incompetent	Competent
Development and mining costs per lb. of copper	$.0711	$.0920	$.0928	$.0768
National average in Conventional processes		$.0406		

The further processing costs of copper being equal, neither the conventional nor the nuclear methods yield any cost savings over the national mining and development cost average. The conclusion further strengthened if we observe that in the above block caving figures the main haulage drifts and loading cross cuts were assumed to exist already [155, p. 16] and that no allowance is made for radiological, seismic, or thermal hazards which might arise. If no other production processes were available (e.g., open pit mining), and all other U. S. deposits exhausted, then only the highly competent ore zone would be mined by the nuclear method (¢7.684 per pound as against ¢9.20 per pound in mining and development costs), while the incompetent area would be developed by conventional block caving.

Under the most favorable conditions the nuclear block cave mining process still exceeds the average mining and development costs of copper by ¢3.02 which exceeds the recent price increase of copper (¢2.0) by more than 50 per cent.

In the long run, i.e., over the next generation, when present more favorable deposits are exhausted and deeper deposits have to be mined, the nuclear cave mining method may be applied in solid competent rock if strip mining operations and in situ leach operations were uneconomic. Such conditions would most likely be met in very deep, high grade copper ore deposits and only after some further increase in the price of copper occurred.

The most favorable application of nuclear explosives is given in strip mining operations if present knowledge on explosions of this type can be extended to larger yield projects. Strip mining by nuclear explosives implies cost savings over conventional mining methods. This again would lead to a variety of favorable effects: a) cost reductions of copper ores mined at even double the average stripping ratio* of present U. S. strip mining operations; b) a potential increase to a 10:1 stripping ratio at present marginal costs of copper production, and c) an addition to U. S. copper resources in excess of 50 million tons of copper content.

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* The ratio of tons of overburden to tons of underlying ore to be mined is called the stripping ratio. The present U. S. average ratio is around 1.7:1. In the MATHEMATICA special report on copper mining [179], two cases are analyzed with stripping ratios of 3.2:1 and 11:1. For technical parameters on craters, ejecta and air blast from multiple changes in a horizontal square arrangement see the recent studies by C. A. Rappleyea at Sandia Corporation [209].

As in the case of mining by block caving the modified equation (4)

$$c_4 < \frac{r_1}{r_4} c_1 + p\left(1 - \frac{r_1}{r_4}\right) \tag{4b}$$

where c_4 are the costs of nuclear strip mining operations, reduces to the condition

$$c_4 < c_1 \tag{7a}$$

as the recovery rates r_1 and r_4 are equal. The cost comparison reduces, to be more exact, to a difference in mining and development costs and capital investment connected with it, as all other, subsequent operations are identical in both conventional and nuclear mining.

If concentrating, smelting, and refining costs for both, the conventional and nuclear processes are assumed to be equal, then a considerable cost advantage of the nuclear strip-mining process over average U. S. copper mining costs may be achieved. The cost figures shown in Table 5.14 [179] are based on a 1.25 per cent grade copper ore deposit and a 3.2:1 stripping ratio with 35 per cent of fallback from areal nuclear cratering explosions.

Table 5.14--Cost per Pound of Copper
(in dollars)

Nuclear		U. S. Average
Stripping and Mining	.0249	.0406
Capital Investment	.0183	.0544*
Milling	.0266	
Melting and Refining	.0320	.0600*
Costs per pound	.1018	.1550

* These two figures cover capital investment costs, milling costs, melting, and refining costs.

SOURCE: Based on: ANACONDA - Company - Mining and Research Department, "Nuclear Mining Feasibility Study," UCRL-13104, Butte, Montana, LRL, February 1965.

An additional advantage of the nuclear strip mining process is given in the considerable time difference in the completion of the mine (dead-time):

	Time Requirements in Years	
	Nuclear	Conventional
Stripping (dead-time)	13	30
Mining (100, 000 t a day)	19	19
	32	49

The 40 per cent reduction in the time required to mine completely the ore-body by the nuclear method reduces depreciation costs of the equipment, total interest charges on capital invested and increases the present value of revenue realized on future markets. The difference in capital costs due to decreased capital replacement costs is about 20 per cent as shown in

Table 5.14. The value of discounted revenue is considerably increased by the reduced stripping time: at a 10 per cent internal interest rate and average production periods of 23 and 40 years respectively, the ratio of the present values of revenue is about 4:1, and at a 5 per cent discount rate the ratio still exceeds a 2:1 ratio.

The difference in nuclear stripping costs alone to average U. S. stripping costs in open pit operations (at a 1.7 stripping ratio) is $.0157 ($.0406 - .0249, from Table 5.14). This cost saving per pound of copper and the additional benefits due to reduced investment costs ($.0037, from Table 5.14) and time savings should suffice to equalize any costs incurred due to additional safety requirements regarding radiation, seismic, and thermal hazards in nuclear processes.

Though it is not possible to construct a general model based only on these two case studies, we may nevertheless say that the economics of strip mining by nuclear explosives look more favorable than either nuclear <u>in situ</u> leaching operations or mining by nuclear block caving. In the particular case of strip mining we see that the cost advantages of nuclear versus conventional explosives become effective and the more so the higher the stripping ratio is. Whereas in strip mining a stripping ratio of slightly more than 3:1 gave marginal results for conventional open pit mining, a nuclear strip mining operation may allow economic operations down to a stripping ratio of 10:1 or more, depending on the particular orebody, in case additional copper reserves have to be developed at present prices.

However, we must realize that economic stripping ratios, conventional as well as nuclear, are complicated functions of each individual situation. With decreasing grade of the ore the marginal stripping ratio is of course reduced. Under conventional operations the second orebody analyzed could not be mined economically, while the nuclear method would allow costs in the neighborhood of $.20, i.e., the minimum cost of additional copper production in the U. S. in 1964 to the present. The potential additional costs regarding safety are at least in part covered in this application by the time saving connected with nuclear strip mining. In the second case analyzed in [179], the reduction in stripping operations would be more than 50 per cent from 40 years (conventional) to 18 years (nuclear). To both dead-times a constant mining period of 7 years has to be added. Most of the western part of the U. S., where the majority of prospective copper ore bodies lies, and Alaska are sparsely populated areas. This tends to minimize both major safety hazards of cratering explosions: the seismic shock effects and air blast effects. Both may be very serious near populated areas. With an increase of population in these areas, over time the potential safety costs become more and more relevant (see Chapter 4 of this report and [209]).

The analysis of strip mining by nuclear cratering explosions assumes, of course, that there are no other, e.g. political, objections to strip mining as such and in particular on the scale at which nuclear strip mining would occur. Some of such objections might lead to the imposition of costs which are not considered here at all.

5.4 THE ECONOMIC FEASIBILITY OF CRATERING BY NUCLEAR EXPLOSIVES

The use of nuclear explosives in large earth moving projects is perhaps the most obvious and natural extension of the use of high explosives made in such enterprises. The first applications proposed for the use of nuclear explosives dealt, therefore, with nuclear cratering and some of the most spectacular projects were proposed in this particular field. This led to a misleading identification of the Plowshare program exclusively with cratering projects, both in the public mind and even within high political decision making groups. This restriction does not, of course, reflect the whole scope of Plowshare, a program within which cratering applications are just one of several potentially very large technical and economic enterprises; cratering applications of nuclear explosions may not even rank first in their beneficial impact on the U. S. and other economies. This should be evident by now from the preceding chapters.

It is a very difficult undertaking to evaluate the national or worldwide benefits of nuclear cratering. Even the evaluation of the benefits of each single project poses serious problems of a theoretical and practical nature.

In such cases, it is instructive to compare the new technology to available conventional techniques and costs. This very often omits a large variety of external effects on the economic system, which are especially large in this particular case due to, among other things, a "technological multiplier" effect on means of transportation, the location of industries, the development of untouched resources in remote areas. But if the new technology seems feasible even on a cost comparison basis alone, i.e. without considering indirect net advantages, then this justifies so much more the introduction and support of the technological advance, in this case nuclear cratering.

The potential fields of application of the nuclear cratering technology are of such a variety and open such large, new construction possibilities beyond anything technically and economically feasible today, that one has to be careful in not overlooking the economic details of any such enterprise. In scope some of the potential projects are of a scale never accomplished before: the diversion and reversal of river systems on a continental scale, the feasibility to create sea-level canals of dimensions technically required for large scale shipping, the removal or cutting of adverse mountain ranges to facilitate overland traffic flows, the creation of artificial, deep harbors at locations deliberately chosen by man, and many more projects. In the following we limit ourselves just to the comparison of expected costs of the nuclear cratering technology to the costs of conventional excavation, where such conventional excavation is feasible within given economic limits. Some projects of nuclear cratering would have to be justified on the basis of expected benefits of the construction alone, in particular when the project could not be realized by any conventional method. Wherever feasible, however, the nuclear technique has to yield cost advantages over conventional excavation, independent of the benefits expected which in any case should exceed the costs of the project.

One of the main problems is to define the limit where one would change from conventional excavation to nuclear excavation. The other area of important research is the question of maximum permissible yields, already touched upon in Chapter 4 of this report. In the following the direct costs of nuclear cratering explosions are summarized, based on the published charges for nuclear explosives (see Section II) and emplacement costs, a comparison of chemically high explosives and nuclear explosives is made, the costs of conventional excavation and the direct nuclear costs are compared, and finally, some remarks are made on conventional and nuclear construction requirements of the Isthmian Canal project.

5.4.1 Emplacement Costs of Nuclear Explosives for Cratering Applications

As in the case of completely contained, underground nuclear explosions, emplacement costs are a major part of the total costs. However, their overall weight is substantially reduced in the case of cratering applications as the depth of emplacement is now reduced to optimum depth of burial (= ODOB) which varies with yield and rock medium. The cratering DOB is, of course, less than the minimum depth of burial for complete containment of a device with identical yield. At 10 KT the DOB ranges between 260 and 400 feet, at 10 MT between 1,500 feet and 2,200 feet and at 100 MT, a hypothetical yield which would exceed the total maximum permissible yield in most geographical areas, the DOB would range between 2,600 feet and 4,000 feet [178, pp. 67-72]. These emplacement depths are less than comparable depths of emplacement for completely contained nuclear explosions, which may ultimately reach down to 10,000 feet or more [125, 154, 179]. As nuclear emplacement costs are a function of depth of burial and the diameter (yield) of the devices, this explains the reduced weight of emplacement costs in nuclear cratering applications. While in completely contained nuclear explosions [125, 154, 179], emplacement costs did amount to 50 per cent and even more of the total costs connected with nuclear development techniques, in the most advanced nuclear cratering projects, emplacement costs now amount to only about 10 per cent of direct nuclear excavation costs [see data in 180, pp. 6-1ff, 191, pp. 33 ff].

Emplacement costs as calculated in Table 5.15 are based on a variety of very particular specifications and assumptions. The reader is here referred to MATHEMATICA's Special Report on Cratering Applications [214]. An item which will considerably vary, according to the scheduled number of devices, is overall mobilization costs per emplacement hole. This item is relevant when calculating nuclear emplacement costs for the Isthmian Canal project as the equipment is transported only once to the emplacement site and after the emplacement of all devices (250-300) called for demobilized and returned to the U. S. The devices in the

Table 5.15

Total Direct Costs of Nuclear Cratering Explosions

Yield (in KT)	Emplacement Cost per ft.	Emplacement Costs at ODOB (Total) in $1000	Cost of Device in $1000	Total Costs in $1000
10	60	24	350	374
15	61	26	369	395
20	61	28	380	408
25	62	31	393	424
30	62	32	402	434
35	62	33	409	442
40	63	35	415	450
50	63	37	426	463
60	64	39	435	474
70	64	41	442	483
80	64	42	448	490
90	65	44	454	498
100	65	45	460	505
150	66	51	478	529
200	67	56	491	547
250	68	60	502	562
300	68	63	511	574
350	69	66	518	584
400	69	68	524	592
500	70	73	535	608
600	76	83	542	625
700	82	93	551	644
800	87	102	557	659
900	92	111	562	673
1000	96	119	570	689
1500	114	157	586	743
2000*	128*	189*	600*	789*
2500	139	217	611	828
3000	149	244	619	863
3500	157	267	626	890
4000	165	290	633	923
5000	178	331	643	974
6000	190	370	652	1,022
7000	203	410	659	1,069
8000	208	435	666	1,101
9000	212	456	671	1,127
10000	216	477	676	1,153
15000**	233**	570**	695**	1,265**
20000	246	646	709	1,354
25000	257	714	719	1,433
30000	266	774	728	1,502
35000	274	828	735	1,563
40000	281	878	742	1,620
50000	294	982	752	1,734

* Changes above 2 MT have been extrapolated from the published AEC charges (see Section of this report).

** 15 MT seems at present to be the maximum permissible yield for technical and safety reasons. The concept of maximum permissible yield and its dependence on location, time, climate, etc. are analyzed in Chapter 4 of this report.

Isthmian Canal would range from 100 KT to 10 or 15 MT, giving rise to a variety of required emplacement systems, and a variety of emplacement costs; overall, the Isthmian Canal emplacement costs should be much closer to "domestic" rates than "overseas" rates, given the repetitive use of drill equipment at the emplacement site.* Thus, in the following Table 5.15, emplacement costs are calculated for various yields from 10 KT to 50 MT (larger than the 35 MT yield of maximum U. S. nuclear explosive yield), based on the domestic rates. "Overseas" rates in single operations could "slide" anywhere between those figures and an additional 100 per cent or more, mainly due to mobilization costs. Mobilization costs become especially prominent in smaller diameter emplacement holes.

There exists also a trade-off between yield of nuclear device, diameter of the device and the cost of the device; the smaller the diameter the larger the cost of the explosive device at identical yields. Table 3.1 of Chapter 3 was used in calculating emplacement diameters (and costs) of Table 5.15. If different diameters are considered,the trade-off between additional device costs and savings in emplacement costs will decide the issue.

As for the effect of differences in the scaling law, a 1/3.4 vs. 1/4 scaling would influence emplacement costs only as far as it would require smaller sized yields, (Table 5.15 is based on the consequences implied

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* The data of the 1964 Isthmian Canal Studies are preliminary, even with regard to technical questions. Thus the cost estimates in that study are only a first, rough summary. In [214] costs per foot of linear cut at various yields and for various media are derived, based on our own estimates and assumptions on technology, emplacement, and device costs.

thereby), smaller diameters, smaller optimum DOB and reduction in device and emplacement costs (≈10 per cent). Thus the figures in Table 5.15 represent rather an upper bound to the direct costs, i.e., emplacement and device costs.

5.4.2 High Explosives versus Nuclear Explosives

If we compare nuclear costs to various conventional techniques, the obvious, but not necessarily relevant, comparison to make is between nuclear and high explosives. Though the A.E.C. published only projected charges for 10 KT upwards, the direct comparison between nuclear and high explosives warrants much lower yields for establishing a "break-even" point in the costs of the two techniques. Table 5.16 and Figure 5.18 summarize the results arrived at in [214]. Table 5.16 indicates the total costs of nuclear devices versus chemical high explosives.

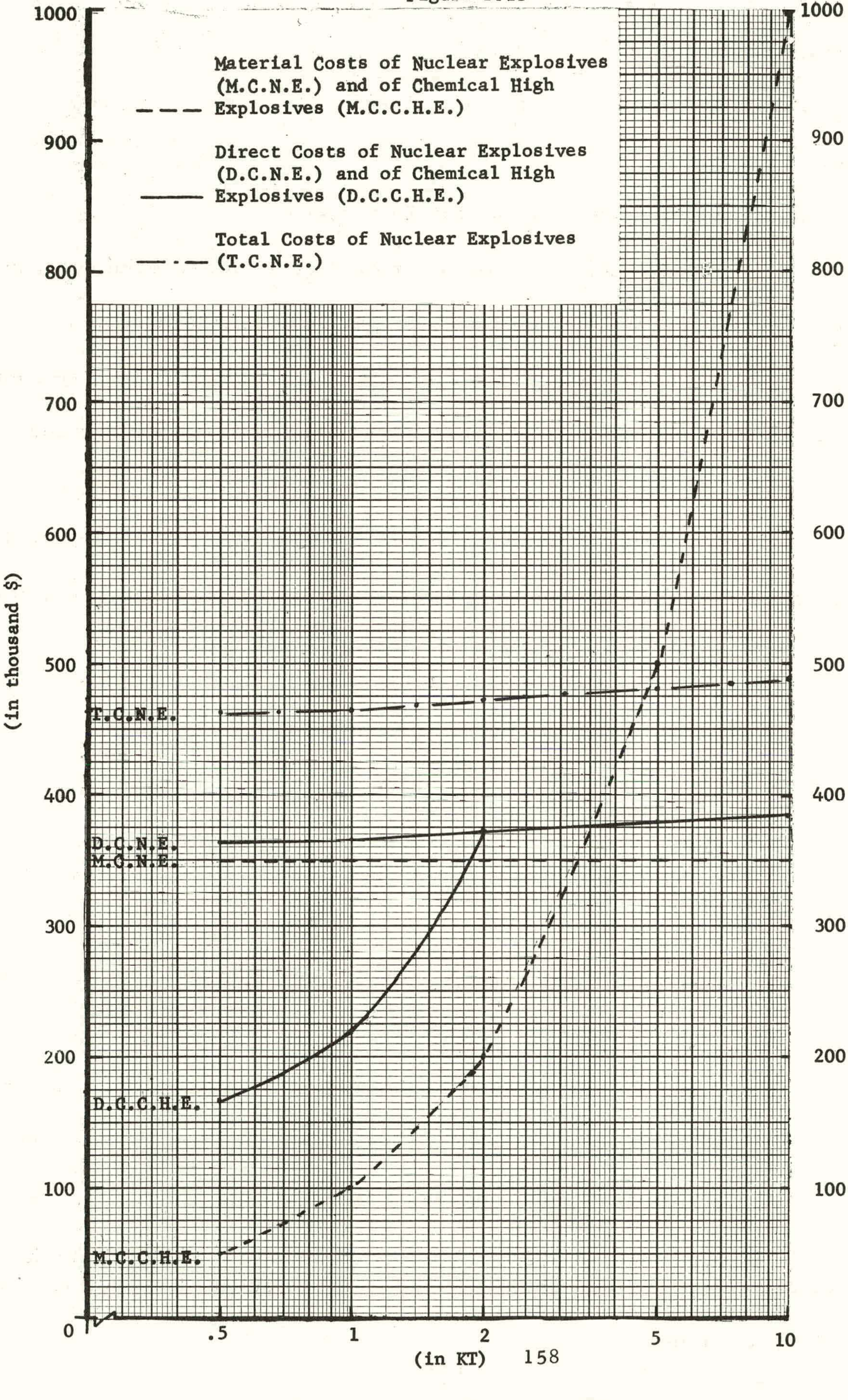
Table 5.16--Total Costs of Nuclear Explosives Versus Chemical High Explosives (in dollars)

Yield (in KT)	Direct Costs of N. E.		Safety Costs*	Total Costs of N. E.		Direct Cost of Chemical H. E.
	Assumption 1	Assumption 2		Assumption 1	Assumption 2	
.5	247,000	356,000	100,000	347,000	456,000	158,000
1	248,000	357,000	100,000	348,000	457,000	208,000
2	283,000	359,000	100,000	383,000	459,000	360,000
5	328,000	362,000	100,000	428,000	462,000	**
10	364,000	364,000	100,000	464,000	464,000	**

* The total amount of $100,000 was assigned for safety costs due to the lack of detailed information and reasons outlined in Section 4 of this report.

** not feasible

Figure 5.18


Material Costs of Nuclear Explosives (M.C.N.E.) and of Chemical High Explosives (M.C.C.H.E.)
Direct Costs of Nuclear Explosives (D.C.N.E.) and of Chemical High Explosives (D.C.C.H.E.)
Total Costs of Nuclear Explosives (T.C.N.E.)
T.C.N.E.
D.C.N.E.
M.C.N.E.
D.C.C.H.E.
M.C.C.H.E.
(in thousand $)
0
100
200
300
400
500
600
700
800
900
1000
.5
1
2
5
10
(in KT)

Due to these safety considerations, the break-even point has moved upward and probably would lie in the neighborhood of the 2 KT yield under assumption 1 and about 4 KT under assumption 2. Considerations on the true emplacement costs for chemical high explosives, the difference in transportation costs that have not been included and the true percentage of safety costs to be charged to nuclear devices would again lower this range.

Figure 5.18 shows the different break-even points for the costs of the device, direct costs and total costs of nuclear explosives and chemical high explosives under assumption 2 which is the most conservative one. The direct costs of high explosives for single spherical detonations are shown only up to 5 KT, as beyond this range no conceivable economic use of this expensive technique is foreseeable. The material costs of high explosives alone, at 5 cents per pound, break even with total costs of nuclear explosives around 5 KT. This would not allow for transportation and emplacement costs of chemical high explosives and shows the severe economic limitations of chemical high explosive techniques.

5.4.3 The Costs of Conventional Excavations versus the Direct Costs of Nuclear Excavation

Each single large earth-moving project has specific technical problems, mainly determined by the particular geology, topography of the terrain and climate, among others. These conditions will determine the optimum set of equipment to be used in each single earth-moving project and one can not generalize such costs without substantial qualifications.

However, certain lower bounds for the costs in excavating various media may be established and this we will try to do in this section.

Problems of equipment system selection, and scheduling of their respective capacities are sidestepped here. We assume that the costs stated below refer to optimum equipment selection, i.e., to minimum achievable costs. Substantial contributions to scheduling and equipment selection problems can be made by mathematical techniques and they could produce substantial cost savings over the usual "trial and error" methods of equipment scheduling and selection.

Particular conditions which affect substantially the costs of conventional earth-moving projects are [182, pp. 1-2].

1. Type of material to be excavated (sand, clay, sandstone, rocks).

2. Accessability of the excavation site (available road system, railroad system, shipping routes for equipment transport). Similar considerations are equally important in nuclear excavation projects.

3. Vegetation along excavation site (grassland, woods, jungles).

4. Climatic conditions: they affect equipment, personnel, and the "downtime" during excavation, i.e., time when equipment and/or personnel cannot operate (permafrost, temperate, tropic climates, etc.).

5. Altitude: at higher altitudes air pressure diminishes, liquids gasify easier, and the horsepower of the equipment is diminished (increase in energy requirements). None of these considerations affects nuclear device yields themselves, though they might affect the requirements of drilling equipment.

6. Vertical profile of earth section to be excavated (determines equipment selection and, basically, whether wet or dry excavation is to be applied).

7. Distance of earth transportation required and haul grade of material (determines type of transport equipment). Similar considerations result in nuclear excavation projects with regard to the particle size of the material after cratering explosion.

Again we have to refer to [214] for all the specifications underlying the analysis. Tables 5.17 and 5.18 do summarize the most optimistic, i.e. lowest, conventional excavation costs and based on these the cost comparison to nuclear explosive techniques are made.

The cost comparison of conventional and nuclear explosives now reduces to the task of finding "break even" points for the costs of both techniques: at increasing yields the costs per cubic yard diminish substantially. Of some importance are the technical assumptions made for predicting the linear dimensions of nuclear craters and these are given in [214]. In establishing nuclear excavating costs, the most conservative assumptions with regard to scaling and spacing of nuclear explosions were made (1/4 scaling and 1.3 spacing up to yields where the depth of the navigational prism is still a limiting factor). Though the 1.3 spacing is more favorable with regard to the nuclear costs of a linear cut, the potential costs arising from "conventional" crater lip adjustments outweigh these advantages if linear crater lips are required.

Table 5.17--Costs per Cubic Yard of Earth Excavated for Various Equipment Systems

Equipment	A,* C, E	B, D G, H	F	I, J, K, L, M, N + above 250 ft.	O, P + above 250 ft.	I, J, K, L, M, N O, P below + 250 ft. and + 100 ft.
Drilling + Blasting	--	.078	--	.078	.073	.078
Shovel	--	.154	--	.128	.106	.106
Wheel Excavator	--		.031	--	--	--
Bulldozers	--	.031	--	.013	.013	.013
Hoppers	--	.021	.010	.010	.020	.020
Conveyor Belts	--	--	.016	.278	.020	.020
Trucks	--	.310	.289	--	.207	--
Crushers	--	--	--	.078	--	--
Stackers	--	--	--	.021	--	--
Barges, Tugs	--	--	--	--	.053	.063
Trains	--	--	--	--	--	.040
Dredges	.26-.28	--	--	--	—	--
Totals	.26-.28	.594	.346	.606	.487	.312
+ 20%	.05-.06					
Overhead	.05-.06	.119	.069	.121	.097	.067
	$.31-.34	$.713	$.415	$.727	$.584	$.374

* The letters A, B, ..., P refer to the various sections of Route 25-A of the Isthmian Canal Studies.

Table 5.18--Costs Per Cubic Yard in Large Conventional Excavation Projects at Different Depth and/or Different Media

Elevation		Medium	Costs/cubic yard
Min.	Max.		
+250 <	≤ + 1000 feet	hard rock	$.72 \leq c_1$
+20 feet <	≤ + 250 feet	intermediate	$.40 \leq c_2 < .71$
-60 feet <	≤ + 20 feet	alluvium and	$.30 < c_3 < .40$

Where c_1, c_2, and c_3 are the expected costs of conventional excavation in hard rock, intermediate, and soft material respectively.

Based on these technical parameters and the costs listed above for nuclear devices and emplacement costs, we calculated the following direct costs per cubic yard, shown in Table 5.19.

Table 5.19 yields various interesting results:

1. The costs per cubic foot of linear cut are regressive up to yields between 300 and 500 KT and then remain more or less constant up to yields presently known to be feasible (≈ 10MT). This implies that canals of larger width and depth can be created at less or equal direct costs than their lower yield counterparts.

2. There exists, based on present knowledge of cratering explosions, a difference in the costs of nuclear excavations in different media, similar to the one observed in conventional excavation.

3. Even by comparing direct costs only, there still remains a complementary use for conventional excavation techniques below yields of approximately 10 KT, i.e., relatively narrow cuts at low elevations where larger counterparts are not desired or not feasible. This 10 KT or below range may turn out to be high when additional knowledge on exact crater scaling is gained. However, at 10 KT and with our conservative assumptions, excavation jobs in the 10 KT range ($ .30, $ .50, $ .85 per cubic yard of earth moved for alluvium, sandstone and basalt respectively) correspond nearly exactly to the lowest possible conventional excavation costs.

4. The costs per volume of linear cut are even slightly less than the volume excavated in one single cratering explosion, though the spacing

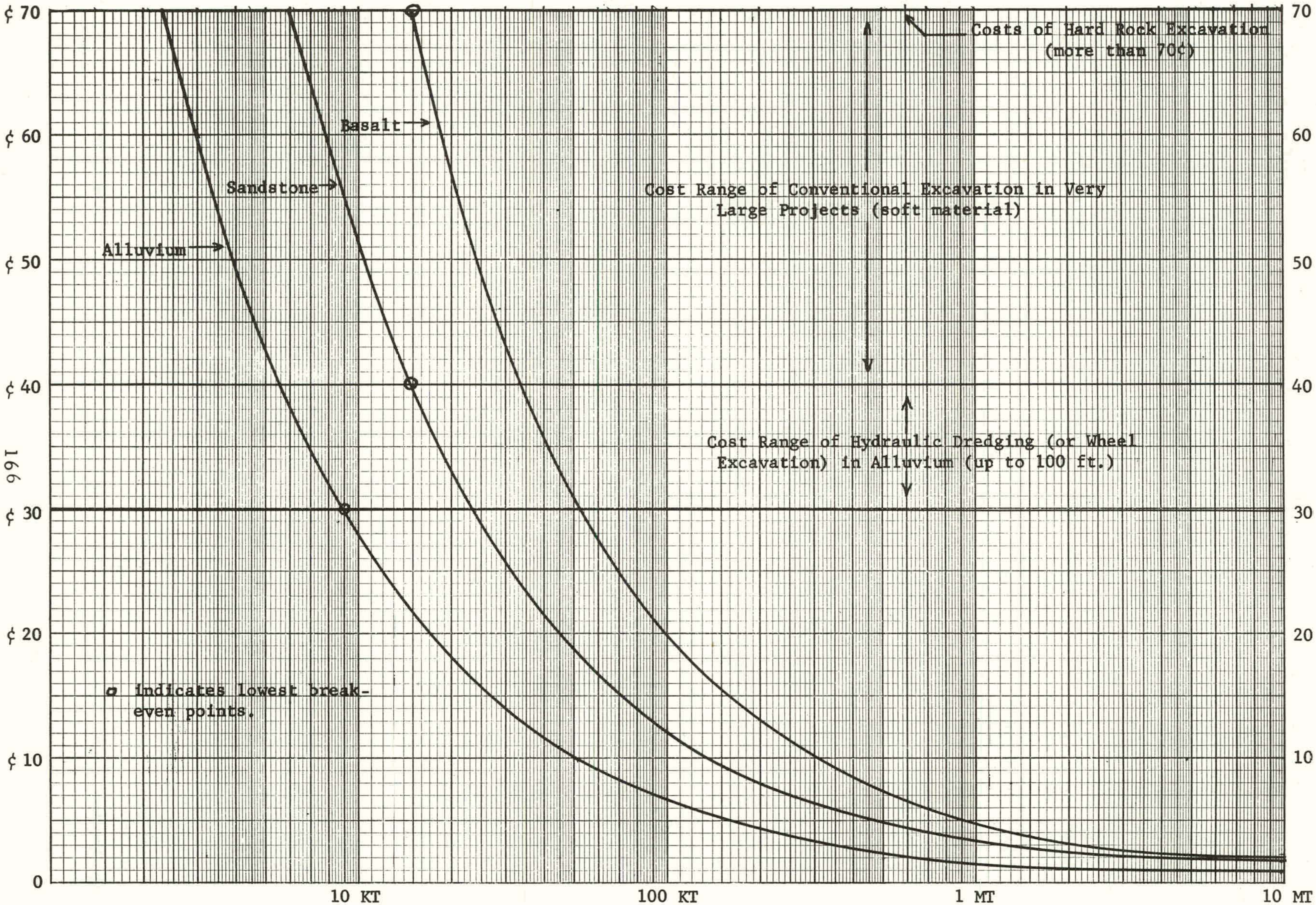
Table 5.19--The Direct Costs of Nuclear Row Charges

	Costs per foot of linear cut			Cost per cubic yard of earth removed		
	Alluvium in $	Sandstone in $	Basalt in $	Alluvium in ¢	Sandstone in ¢	Basalt in ¢
10KT	$ 838	$ 1022	$ 1208	¢30.13	¢51.09	¢85.46
15KT	800	973	1155	23.48	39.56	66.93
20KT	770	936	1106	19.61	33.03	55.40
25KT	754	922	1087	17.12	29.18	48.84
30KT	738	900	1064	15.31	25.99	43.60
35KT	724	880	1042	13.88	23.43	39.45
40KT	712	869	1027	12.80	21.72	36.49
50KT	693	845	1002	11.14	18.89	31.75
60KT	679	826	979	9.95	16.82	28.36
70KT	666	810	958	9.06	15.29	25.66
80KT	654	795	942	8.31	14.06	23.61
90KT	644	785	929	7.73	13.09	21.96
100KT	636	774	918	7.23	12.21	20.57
150KT	603	735	870	5.61	9.48	15.92
200KT	580	707	836	4.66	7.90	13.28
250KT	563	685	812	4.05	6.84	11.51
300KT	550	669	793	3.61	6.09	10.26
350KT	538	655	776	3.27	5.52	9.29
400KT	528	642	761	3.00	5.06	8.53
500KT	514	624	740	2.61	4.41	7.42
600KT	504	613	725	2.34	3.95	6.63
700KT	499	608	719	2.23	3.63	6.10
800KT	494	601	712	1.98	3.35	5.64
900KT	490	597	705	1.86	3.14	5.27
1000KT	488	595	704	1.75	2.97	4.99
1500KT*	476*	580*	687*	1.40*	2.36*	3.98*
2000KT	470	682	678	1.19	2.11	3.40
2500KT	466	676	673	1.06	1.88	3.02
3000KT	464	674	670	0.96	1.71	2.74
3500KT	461	669	665	.89	1.57	2.52
4000KT	462	671	789	.83	1.47	2.45
5000KT	462	670	788	.74	1.31	2.19
6000KT	462	671	796	.68	1.21	2.02
7000KT	466	676	795	.63	1.12	1.86
8000KT	464	673	792	.58	1.04	1.74
9000KT	461	668	787	.55	.98	1.63
10000KT**	460**	666**	784**	.52**	.92**	1.54**
15000KT	455	661	778	.42	.75	1.25
20000KT	454	658	774	.36	.64	1.07
25000KT	454	659	775	.33	.58	.96
30000KT	454	660	777	.30	.53	.88
35000KT	455	661	778	.28	.49	.82
40000KT	456	662	780	.26	.46	.72
50000KT	462	671	789	.23	.42	.69

* See first footnote to Table 5.15.

** See second footnote to Table 5.15.

Figure 5.19--Costs Per Cubic Yard of Nuclear Versus Conventional Excavation in Large Projects

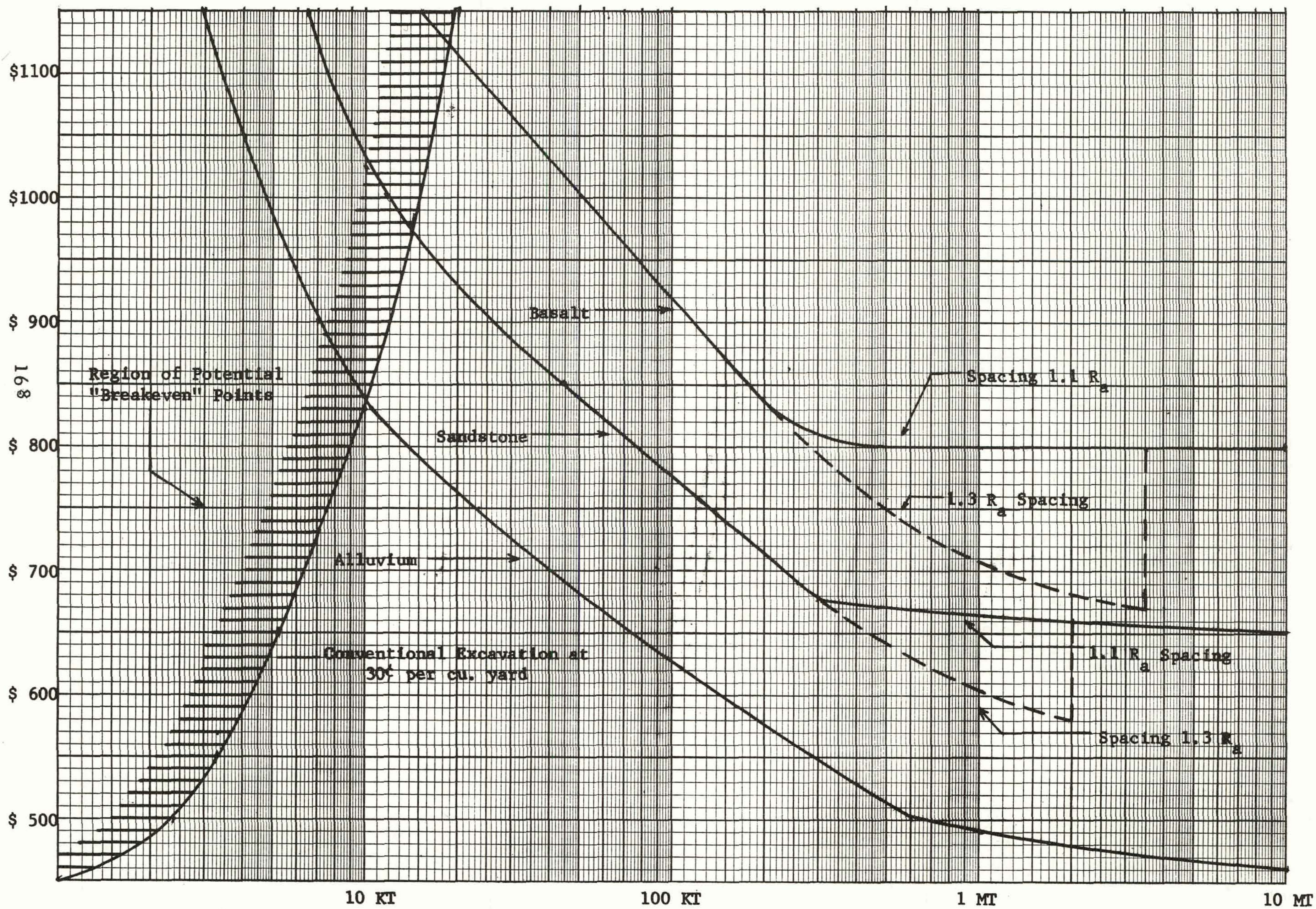


is only 1.1 or 1.3 times the radius (see Figure 5.20). This is due to volume gained by somewhat increased linear dimensions (r, d) in row charges and the volume gained through "crater-connection."

5. The per cubic yard costs of nuclear cratering are such that they would allow for substantial safety costs due to the various hazards of cratering explosions (see Chapter 4), such that from presently available information, safety costs may influence decisively the choice between various alternative nuclear routes (to lower maximum required detonation yields) but will hardly ever be such as to give priority to conventional excavation at yields above, say, the 100 KT range.

6. The most economic solution of nuclear construction projects tends either to relatively high yields (around 200-300 KT or more) or, if such dimensions are not desired, to a combination of nuclear and conventional excavation techniques as contemplated at present for Route 25A of the Isthmian Canal Studies. This is, however, a deliberate limitation to uniform canal dimensions and may have to be justified by some other argument than uniformity of canal width at the lower and higher elevations. A wider, deeper nuclear canal is feasible at these low elevations at significantly less costs than both, its smaller nuclear counterpart or conventional excavation.

Figure 5.20--Costs Per Foot of Linear Cut



5.4.4 Conventional Construction Requirements of the Isthmian Canal and Nuclear Excavation

In order to make a direct comparison between nuclear and conventional excavation, we will analyze here only Route 25, and, in part, Route 17 of the various Isthmian Canal projects. The complete conventional excavation of Route 25 would take at least 10 years under present schedules. It would be divided into substantially different complementary sub-projects: a) Dry Excavation project and b) Wet Excavation project. The equipment requirements in both sub-projects are substantially different.

a. *Dry Excavation:* Dry excavation, would mainly deal with the removal of earth and rock above 20 feet of elevation. In dry excavation again various systems of machinery are available and in various segments this equipment may differ substantially according to the particular geographical structure. However, according to the Engineering Manual [187] the following rough estimates of equipment requirements for conventional dry excavation can be made: Overall 3.7 billion cubic yards have to be excavated by this method. Allowing for one year mobilization time and one year demobilization time of the equipment, this means an annual removal of 455 million cubic yards per year or 63,000 cubic yards per month, allowing for 600 working hours per month. This compares to an overall earth-moving capability of about one billion cubic yards per year in 1965 within the United States, i.e., about 50 per cent of the overall United States earth-moving activity. The basic equipment requirements were outlined in [214].

b. Wet Excavation: Excavation of 20 feet above sea level or less would be done by wet excavation, i.e., utilizing hydraulic dredges. The quantity of earth to be removed by wet excavation is 1.56 billion cubic yards which would be moved in about 9 years, i.e., a yearly rate of production of 167 million cubic yards per year in addition to dry excavation. This would involve the movement of 622 million cubic yards per year of 60 per cent of the total earth movement activity during 1965 within all of the United States, (about 1 billion cubic yards). According to the Engineering Manual, even a single large excavation unit requires 15-18 months from the day it is ordered to the day it will be installed on the excavation site within the U. S. The Isthmian Canal project, however, would involve more or less the simultaneous construction of fifty-four '65 cubic yard' dredges, six '35 cubic yard' dredges and about 1,000 '85-ton' trucks or as substitutes for it, 180 miles of 54" conveyor belts in addition to 80 'D-8' bulldozers. The 180 miles of conveyor belts would be constructed on a more continuous basis, i.e., extended over more years of construction time. However, the dredge requirements certainly would pose a major construction problem though I am convinced that United States industry has the capability of producing them within an 18 to 24 month period. This would be in addition to the other requirements of United States industry, especially strip mining requirements and other large earth-moving projects. Not included in the above equipment requirements are 4 large wheel excavators which are supposed to be available during at least the same time period. The present conventional Isthmian Canal schedule allows only for a one year mobilization time. This can only be realistic if the orders for the required equipments go out at least two years before the actual excavation begins at the Isthmian Canal site.

Nuclear excavation would under present plans extend over a similar period, allowing for a more realistic 3 to 4 year mobilization time and 6 years of actual operations, i.e., much more in line with mobilization time requirements. This relates to time estimates of Route 17. The construction time along Route 25 is again 10 years of which, however, only 3 years are required for the drilling and casing of emplacement holes and 2 years at most for the emplacement and detonation of the nuclear charges. While, in case of emergency, the nuclear time requirements could be substantially reduced (more or less to the drilling and emplacement time requirements) the conventional excavation of the Isthmian Canal would hardly allow any reduction in construction time due to scheduling problems. From an emergency standpoint one could go even so far as to emplace the nuclear charges along any route for an alternative canal in case any existing shipping route through the isthmus should be destroyed by adverse influences. In such emergency situations, the actual construction time would be reduced to the detonation schedule of the charges. Safety requirements under such conditions would be substantially lowered, thus reducing the detonation schedule to a few days at best. It is obvious that conventional excavation could never compare with this new, though extreme potential.

The general conclusion, therefore, is that the Isthmian Canal would increase substantially the machine building requirements in U. S. industries for at least 2 years (by 50 to 100 per cent) and in particular branches extensions of capacities would be necessary. We are also convinced that these requirements could be met, but certainly would impose a serious initial strain on this particular industry with a successive slump after the completion of the project. All these considerations hold in addition to the substantial cost savings anticipated in the previous paragraphs of this chapter.

As to the selection of the most economic route in nuclear excavation, it is not obvious that either Route 25 or Route 17 are those to which the choice should be restricted. Many criteria do affect the selection of such routes, among others the length of the route, maximum elevation, total costs, number of nuclear devices used, total yield of explosives, long term slope stability problems, maximum single yields of detonations etc. Table 5.19 gives a ranking of nine different routes and is based on Luke Vortman's work in [178]. As shown in Table 5.19, either Route 25 or Route 17 are consistantly the most economic ones. While Route 17 may be regarded as very economic, if maximum permissible yield questions are neglected, both Routes 17 and 25, do extremely poorly with regard to maximum yields required. The maximum yield required may, under the 1/4 scaling law, well exceed maximum permissible yields along Routes 17 and 25. Thus the choice of the optimum nuclear route may well differ from those most contemplated at present, i.e., Routes 17 and 25.

This discussion indicates that the computation of optima requires the consideration and measurements of many variables, and, if executed in detail, is far from trivial, especially when uncertainties (in data and of other kind) are introduced as they must be.

5.5 OTHER PROJECTS ON THE PEACEFUL USE OF NUCLEAR EXPLOSIVES

5.5.1 Underground Gas Storage

Most of the natural gas used in the United States is produced in areas remote from the large consumer markets. Because the high pressure pipelines which move the gas to the consumer markets cost hundreds of millions of dollars to construct, it is economically necessary to operate these pipelines as near to maximum capacity as possible, in order to minimize pipeline gas costs. For many years purchasers buying gas in large volume have been developing gas storage facilities near the point of use. The major form of gas storage in the United States today is underground, either in depleted gas or oil fields from which the hydrocarbons have been exhausted, or by injecting gas into a subsurface water-bearing rock formation (aquifer storage). Storage at high pressures underground is not only safer than other methods (such as the use of refrigerated containers to hold liquified natural gas), it is also substantially cheaper. Moreover, these underground reservoirs are of a size to permit storage of the large quantities of gas needed to satisfy a major portion of the winter season requirements. The majority of this kind of gas storage is in depleted gas reservoirs [241].

Since many market areas are not favored with potential naturally occurring reservoirs, a possible method by which underground gas storage sites could be formed is through the creation of an underground nuclear chimney [125].* This application of the peaceful use of underground nuclear explosions falls within the Plowshare program. It requires a detonation of a 10KT to 100 KT device at the scaled depth in excess of 400 feet/$KT^{1/3}$ in a relatively impermeable medium. The rubble-filled chimney and the surrounding system of fractures would be expected to have gas capacity of the order of 20,000 MCF per kiloton of yield at a pressure of 2100 psi [234]. Depths to contain 50 KT explosions or gas at desirable pressure probably range from 2000 to 4000 feet. This is typical of many natural underground storage sites in use, although many in the midwestern states occur at a depth of less than 2000 feet, and a few are much deeper.

Surrounding the nuclear chimney after an underground shot is a zone of crushed and fractured rock of increased porosity. The probable extent of the zone and the amount of the increase in porosity are still unknown. Project Gasbuggy, the join experiment of the USAEC, the U. S. Department of the Interior, and the El Paso Natural Gas Company for nuclear stimulation of a "tight" gas field (to be conducted in the near future) should provide measurements of these important parameters. In the meanwhile, only conservative estimates of the potential storage volumes can be computed which underground nuclear explosions provide, based on the chimney volumes. These are relatively well determined, apart from the magnitude of the effect on storage volume of the geological medium in which the explosion

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* See Section I of [125], also [34].

occurs. As an example, consider the proposed Project Ketch [239] in which it was estimated that a 24 KT explosion at 3300 feet depth would produce a chimney with a storage volume of about 2.2×10^6 cubic feet. The general formula for the volume is:

$$V = \frac{4}{3} R^3 \quad \text{cubic feet for the chimney volume (void space)}$$

where $R = \dfrac{CW^{1/3}}{(\rho h)^{1/4}}$ is the chimney radius in feet*

and
W = yield of nuclear device in KT
ρ = average bulk density of overburden (=2.5)
h = depth of burial in feet
C = lithology factor

To obtain the Ketch estimate above, assume $\rho = 2.5$ and $C = 260$. Additional void space, ranging from 10 to 50% of the chimney volume will be created by fractures in the chimney wall rock.

In order for the method to be of general economic value, the cavity or chimney must not only offer a large enough storage volume; it must also contain the storage gas at the desired pressures without leaking.** Two further considerations present themselves. The radioactive materials formed in the cavity, which may mix with the storage gas, must be removed. If so, this must be done at a cost which does not impair the value of the storage reservoir. Flushing the first few chimney volumes may be sufficient to reduce radioactivity.

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* See, however, [188] and [189].

** Whether this is the case depends on the depth and the geology of the site. No experience in using nuclear chimneys as gas storage wells is known to us at this time.

The second concerns the flow rate allowed by the cavity. Here the picture is very favorable. As Witherspoon points out [234], one can regard the chimney as an enormous tank from which one should be able to obtain very high rates of production. Similarly, injection of the gas into the chimney will not be a problem so long as appropriate compressor facilities are available.

Economic Appraisal

In the United States there are today 4-5 trillions of cubic feet of storage capacity in the underground gas storage facilities of the major gas companies, according to a survey conducted in the winter of 1965-66 by the American Gas Association [241]. Table 5.20 (from reference [239]) shows the regional distribution of gas storage compared with population and sales. If only those areas with no storage or limited storage were developed to the same degree on the basis of population, this would add 4 trillion cubic feet of new storage capacity. The additional storage capacity would presumably reduce the cost of supplying gas to the market areas if it were available on the same cost basis as conventional gas storage. In the future, increased demand for gas may result in an increased demand for gas storage facilities with the consequence that the nuclear method may become attractive even for regions which at present have unused underground facilities. Two factors are at work here. First, the economies of scale in using nuclear explosives: The AEC projected charges for the explosives are proportional to the logarithm of the yield, while the storage volume is roughly proportional to the yield. Second, the nuclear method appears to be competitive in cost per MCF of gas* delivered with conventional underground storage

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* See Table 5.21.

Table 5.20--Regional Distribution of Gas Storage, Utility Sales, and Population

Producing Regions	Percentage of National Total: Population	Utility Sales of Gas	Gas Storage
Southwest States (6)	12.5	24.2	9.6
Pacific States (5)	11.8	14.7	6.2
Mountain States (8)	3.9	6.0	6.7
Consuming Regions with Storage			
Appalachian States (5)	16.5	16.3	34.4
North Central States (5)	16.6	17.3	31.4
Plains States (6)	6.7	8.6	7.8
Consuming Regions with Little or No Storage			
New England States (6)	5.8	1.7	0.0
South Atlantic States (6)	13.2	6.0	1.6
Middle Atlantic States (3)	13.0	5.2	2.3

Southwest States	- Alabama, Mississippi, Texas, Louisiana, Oklahoma, Arkansas
Pacific States	- California, Hawaii, Oregon, Washington, Alaska
Mountain States	- New Mexico, Colorado, Utah, Montana, Nevada, Wyoming, Idaho, Arizona
Appalachian States	- Ohio, West Virginia, Pennsylvania, Kentucky, Tennessee
North Central States	- Michigan, Indiana, Illinois, Wisconsin, Minnesota
Plain States	- Kansas, Missouri, Iowa, Nebraska, North Dakota, South Dakota
New England States	- Massachusetts, New Hampshire, Vermont, Maine, Connecticut, Rhode Island
South Atlantic States	- Maryland, Virginia, Georgia, North Carolina, South Carolina, District of Columbia, Florida
Middle Atlantic States	- New York, New Jersey, Delaware

SOURCE: Project Ketch, Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and Lawrence Radiation Laboratory, September 1966.

methods, and accordingly will be attractive to gas distributors who require large volume additional storage capacity. The main expected use for the nuclear chimneys, however, is where suitable aquifers or depleted gas fields do not exist [240]. Table 5.21 (from reference [239]) is a sample calculation of the cost of developing nuclear gas storage reservoirs which shows the slight differences in total investment cost when the yield is varied. But as the storage volume is approximately proportional to yield, the average annual cost per MCF of gas delivered and the average annual cost per MCF of turnover show substantial savings when the yield is increased.

In practice, for a given geographic location, the limitation on yield is likely to be the seismic effect. Since the gas storage facility is needed near population centers to serve the large consumer markets, it is to be expected that the maximum acceptable yield will be that which falls short by some preset margin of causing damage to structures. To some extent this effect may be compensated by increasing the depth of the shot at an increased cost of emplacement. Damage is measured mainly by "peak particle velocity" produced by the explosion. At one time, the Bureau of Mines recommended a criterion of 5.08 cm/second (2 in./second) as the dividing line between safe and damage zones. Today an 8 to 10 cm/second peak particle velocity threshold is used in planning any (experimental) nuclear shot, which results in approximate zones of radius of 3 miles for 100 KT shots in tuff, and 5 miles for 100 KT shots in granite [46]. Caution is mandatory in making predictions of the extent of seismic damage, however, as the Salmon Event near Hattiesburg, Mississippi produced damage complaints at 22 miles from ground zero

Table 5.21--Cost of Developing Nuclear Gas Storage Reservoirs

	Yield of Nuclear Explosives		
	24-KT	50-KT	100-KT
Reservoir Development	$	$	$
AEC Charge for Nuclear Explosive	390,000	425,000	460,000
Safety Studies and Precautionary Measures	400,000	400,000	400,000
Site Preparation	50,000	50,000	50,000
Emplacement Hole	125,000	150,000	175,000
Property Acquistion and Claims Investigation	80,000	100,000	120,000
Chimney Re-entry	75,000	75,000	75,000
Chimney Cleanup	40,000	50,000	60,000
Other Facilities	40,000	50,000	60,000
	1,200,000	1,300,000	1,400,000
Gas Storage Facilities			
Cushion Gas	36,000	86,000	160,000
Transmission Line	150,000	150,000	150,000
Compressor Horsepower	165,000	220,000	375,000
	351,000	456,000	685,000
TOTAL INVESTMENT COST	1,551,000	1,756,000	2,085,000
Average Annual Fixed Charges (11.29-11.00%)	175,000	198,000	235,000
Operating and Maintenance Costs	13,000	17,000	23,000
	188,000	215,000	258,000
Average Annual Cost/Mcf Deliverability	2.09	1.43	1.03
Average Annual Cost/Mcf Turnover	0.50	0.24	0.16

SOURCE: Project Ketch, Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and Lawrence Radiation Laboratory, (Updated version, August 1967).

Table 5.22--Comparative Costs and Performance for Recently Developed Conventional Underground Storage Fields in the Columbia Gas System Against Nuclear Storage Fields

	Year Developed	Investment Cost of Facilities $000	Annual Cost to Own & Operate $000	Annual Turnover Mcf	Peak Day Deliverability Mcf	Maximum Deliverability Mcf	Annual Unit Cost per Mcf: Of Turnover $/Mcf	Annual Unit Cost per Mcf: Of Peak Day Deliverability $/Mcf	Annual Unit Cost per Mcf: Of Maximum Deliverability $/Mcf
Columbia Gas System Storage Fields									
Field A	1957	4,893	635	4,200,000	73,000	238,000	0.15	8.70	2.67
Field B	1958	5,520	646	2,500,000	80,000	114,000	0.26	8.07	5.67
Field C	1964	12,295	1,583	1,400,000	110,000	475,000	0.21	14.39	3.33
Field D	1960	23,032	2,627	13,985,000	255,000	340,000*	0.19	10.30	7.73
Field E	1964	18,913	2,263	12,195,000	240,000	580,000*	0.19	9.43	3.90
Field F	1967	18,519	2,112	8,400,000	110,000	280,000	0.25	19.20	7.54
Field G	1967	2,195	300	800,000	22,000	90,000	0.38	13.64	3.33
Nuclear Fields Foreseeable Cost Basis									
24 KT Field		1,551	188	375,000	90,000	90,000	0.50	2.09	2.09
50 KT Field		1,756	215	875,000	150,000	150,000	0.24	1.43	1.43
100 KT Field		2,085	258	1,600,000	250,000	250,000	0.16	1.03	1.03

SOURCE: Project Ketch, Report on proposed experimental shot by Columbia Gas System Service Corp., USBM, USAEC and Lawrence Radiation Laboratory, (Updated version, August 1967).

with peak particle velocities of 0.4 cm/second. Further details of the seismic limitation are to be found in Chapter 4 of this report.

5.5.2 Water Resource Applications

During the remainder of this century the availability of an adequate supply of water of suitable quality for its various uses is likely to be a pressing problem for many regions of the United States, not to mention large areas of the rest of the world. Although there is no shortage of water on a continent-wide basis, the increasing demands of the growing population are reflected in the more intensive usage of the water resource, and in some regions by the high cost of treatment due to pollution. In most parts of the country, spring rains and thaw of snow release the greatest fraction of the annual water supply, often in flood proportions. The potential to divert, capture and store this water in conventionally constructed surface reservoirs is limited by the number and size of suitable reservoir sites and the runoff pattern. Tables 5.23 and 5.24 contain projections of how much additional surface storage capacity will be necessary by the end of the century to meet the water requirements in each of 22 regions. In the regions marked with an asterisk little or no excess supply is expected to be available after 1980; with a double asterisk no excess after 2000. The additions from 1954 to 1980 are 82% of the total storage available in 1954; from 1980 to 2000, i.e. in 20 years, the further additions require 123% of the 1954 storage. This gives an idea of the gravity of the situation.

While there are some conventional ways of increasing the water supply, these are limited in scope. Many clearly involve operations which are accessible for nuclear means. De-salination is mainly

Table 5.23--Withdrawal vs. Remaining Supply (bgd)

River Basins	1954	1980	2000	Supply Remaining (1954)
New England	6.3	18.0	30.3	67.
Delaware and Hudson	14.7	35.7	58.7	32.**
Chesapeake Bay	7.1	20.8	36.0	52.
Southeast	11.2	39.2	73.2	212.
Eastern Great Lakes	11.2	32.4	58.2	40.**
Western Great Lakes	13.0	37.9	65.4	42.**
Ohio	22.0	67.2	110.7	110.
Cumberland	.2	.5	1.9	17.
Tennessee	3.7	11.8	24.4	43.
Upper Mississippi	8.4	22.5	39.9	62.
Lower Mississippi	4.5	8.7	15.9	49.
Upper Missouri	27.9	33.9	47.2	19.*
Lower Missouri	1.3	2.6	6.4	23.
Upper Arkansas-White-Red	8.4	12.1	16.5	11.
Lower Arkansas-White-Red	3.8	7.1	11.4	77.
Western Gulf	22.7	43.0	78.9	46.
Upper Rio Grande and Pecos	8.9	10.2	10.7	(-)*
Colorado	26.7	27.6	30.0	3.2*
Great Basin	12.6	13.1	13.3	3.7*
Pacific Northwest	24.7	34.9	60.4	143.
Central Pacific	50.0	60.2	69.1	47.
South Pacific	10.8	19.3	28.5	.4*
U. S.	300.3	558.9	888.4	1100.

SOURCE: U. S. Senate Select Committee on National Water Resources, August 1950, Committee Print No. 32.

Table 5.24--Present vs. Required Minimum Storage
(1000 acre feet)

River Basins	1954 Present	1980 (add to 1954)	2000 (add to 1954)
New England	9.0	2.4	6.1
Delaware and Hudson	3.1	5.8	12.0
Chesapeake Bay	.9	4.3	14.5
Southeast	16.4	9.8	21.5
Eastern Great Lakes	.5	8.5	20.0
Western Great Lakes	1.2	34.0	50.0
Ohio	5.7	8.5	16.0
Cumberland	6.4	.3	.8
Tennessee	15.0	.1	.4
Upper Mississippi	4.3	5.8	17.0
Lower Mississippi	4.5	8.5	18.0
Upper Missouri	74.8	30.0*	30.0
Lower Missouri	1.2	2.3	4.9
Upper Arkansas	7.3	8.0	13.0
Lower Arkansas	26.8	9.6	14.6
Western Gulf	11.2	25.5	34.0
Upper Rio Grande and Pecos	3.3	7.4*	7.4
Colorado	35.1	14.5*	14.5
Great Basin	4.1	6.5*	6.5
Pacific Northwest	28.9	10.8	14.7
Central Pacific	16.4	25.5	27.8
South Pacific	1.8	.6*	.6
U. S.	278.0	+228.8	+344.0

SOURCE: U. S. Select Committee on National Water Resources, August 1960, Committee Print No. 32.

important for areas near the oceans and surely has a great future, especially if carried out by means of nuclear energy (mostly combining such operations with the generation of electric power).

Two types of application of nuclear explosives for the creation of improved water storage have been suggested. First, the construction of dams and reservoirs by means of the nuclear cratering method. Second, the improvement of flow and storage of water underground by creating a deeply buried nuclear cavity: either through connection of separated aquifers, undercutting of perched water bodies, the use of nuclear craters for recharging aquifers or construction of underground water storage facilities. Artificial recharge can be accomplished by non-nuclear means, for example, by means of seepage basins excavated conventionally or by drilled recharged wells. It is important, however, that the time scale of large scale operations be considered when capital costs are calculated, and here nuclear explosives may offer a significant advantage (Keller [237]). A related application in the second group is the underground disposal of fluid wastes.

The formation of a nuclear crater, as described in Chapter 2 of this report, offers an opportunity for surface storage of water which may collect in or be pumped into the crater. In addition the nuclear cratering technique may also be applied to canal construction. The building of dams, reservoirs and canals by nuclear technology is covered in Section 5.4 of this chapter. In this type of application, the principal economic features are (i) that the time for construction can be considerably shortened compared with conventional excavation (ii) that the needs for unskilled and semi-skilled labor are much less (iii) that the method is capital-intensive and the labor costs per unit are high. Keller [237] has pointed out that, in very large construction projects associated with water management, delayed benefits from the project may entail large social costs.

In the second type of application--the creation of nuclear cavities underground for increasing water flow or storage capacity--the approach is a distinctive one which does not lend itself easily to economic comparisons. There does not appear to be any alternative way for reaching the same objectives for most of the proposed schemes. On the other hand the disadvantages associated with the groundwater proposals are that the technology of groundwater management is still in a very early stage so that the Plowshare application involves a high investment risk. Further, the need to avoid contamination of groundwater is a potential burden on the proposed undertaking which is not measurable until further experiments reveal the extent of the hazard. Careful geological surveys in the vicinity of the underground nuclear tests have shown that the safeguarding of the water supply from radioactivity (at least in arid Western states) is hardly a problem; nevertheless, it must be expected that state and municipal governments will establish strict guidelines once the method becomes practical. Meeting these guidelines will add to the cost of the technique.

Besides its unique advantage of creating deeply buried void space either for more or less permanent storage or for increasing the flow of groundwater, the nuclear cavity has other advantages compared to surface storage of water. Evaporation loss is reduced. The cost of distribution can be substantially less when local geology permits the nuclear wells to be placed close to the industries or farms which need water in large quantities. Particularly in the case of certain industries (the new oil shale industry may become one such) which need water in remote regions and which do not require very high quality water, the "nuclear well" may have great advantage. Lastly, the percolation of water through some permeable strata may filter the water and actually reduce the cost of purification.

There are three specific methods of applying Plowshare to the improvement of groundwater utilization. First, the recharge of the groundwater. Natural recharge occurs through stream beds and runoff; artificial recharge can be accomplished by means of basins, pits, wells, etc., which have permeable connections with underlying aquifers. In areas where heavy drafts have been made on the groundwater without compensating recharge, the regional water tables have fallen. Lowered water table means greater distance of pumping water to the surface, which adds a major component to the cost of the water supply system. In some areas of the United States a more serious consequence of depleting groundwater supplies is the encroachment of saline water into the fresh water aquifers. In Long Island for example, there are currently over 1000 wells in operation to return used water to the aquifers in an attempt to maintain a higher pressure gradient in these coastal aquifers and keep the sea water out. A contained nuclear explosion, at a depth which locates the rubble chimney beneath an impermeable overlayer can be used for recharge purposes. A cased well is drilled into the chimney to conduct the water underground--the chimney acts like a gigantic injection well. On behalf of the U. S.

Geological Survey, A. M. Piper has recently conducted a preliminary canvas of the eleven groundwater provinces, and numerous potential aquifer recharge sites have been suggested [225]. Not all of these would be suitable for Plowshare technology, but there remain many for which the local benefits are likely to prove substantial.

The other two methods of applying Plowshare to groundwater management will be mentioned briefly here; greater detail can be found in MATHEMATICA's Special Report [238]. The second method is to reduce the impedance of recharge by "caliche" formations over the aquifer, which causes loss of rainwater through evaporation. A series of subsidence craters* resulting from relatively small (10 KT) underground nuclear explosions could hold the runoff waters long enough to allow recharge to occur. In this method, it is proposed to use a large number of small explosions; hence the cost of drilling, emplacement and the actual devices is relatively high. The third and last method consists of using a nuclear explosion to breach a naturally occurring geological fault which separates two or more aquifer systems. A typical case of the natural fault preventing greater groundwater use occurs in Miami, Oklahoma. When usage of wells began in 1900, water pressure was so strong that the wells flowed on land surface without pumping. By 1960 the pressure head had dropped so that pumping levels were 750 feet below the surface. Several nuclear rubble chimneys could breach the fault and induce an increase in head between the two areas.

In addition to the applications to groundwater management, there is also the possibility of creating underground reservoirs by the

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* The subsidence crater is formed when the collapse of broken rock above the shot point extends all the way to the surface.

detonation of a nuclear explosion in an impermeable stratum. A 100 KT shot has been suggested [255] for the area near Ashland, Oregon. The rubble chimney would hold 600 acre-feet of water and would supply nearly 60 per cent of the community's needs, at a cost which is not greatly in excess of the cost of a comparable surface reservoir, if a site were available. The comparison is, once again, probably idle since that alternative does not exist in the locality.

Although it has not been possible to present detailed cost-benefit calculations for the application of Plowshare technology to water resource improvement, there are numerous proposals of potentially large benefit which deserve further research study if only because the needs for larger and better quality water supplies are an urgent national --and international--problem. Until experiments in the relevant environments for the water resources improvement schemes are carried out, the full extent of the costs and benefits in the nuclear technology will not be known. It seems, however, certain that at least in the long run (of only 2-3 decades) the needs will become so pressing that the United States will have to fall back on the immense possibilities which Plowshare offers in this regard. Even if costs should be higher than what the public is now accustomed to, the need for water will override any considerations which are now being advanced.

5.5.3 Waste Disposal

a. Types of Waste Disposal Problems. The disposal of sewage and industrial effluents has received much attention in recent years as the streams, rivers and lakes of the United States have suffered increasingly from pollution. In some areas, population increases with no compensating change in the sewage disposal facilities result in a worsening quality of the water resource. In other areas, sewage and chemical wastes from industry combine to destroy the wildlife and/or the pleasing surface aspects of lakes and rivers. The problem is spreading at a rate which threatens to outstrip the best efforts of the anti-pollution fighters.

In 1959 municipalities spent about $100,000,000 [215] on water treatment. By today this figure may have multiplied five. But still not enough is being done. Advanced chemical techniques for the treatment of water are often so costly that they will be applied only to drinking water. (About 1% of all water in public and private use.) Of all water returned to streams, rivers and lakes after industrial use, about 30% is still untreated [215]. So long as the total amount of water being used remains a small percentage of the water resource, there is no problem providing that extremely harmful materials are excluded. But at the present accelerated rate of withdrawals of fresh water and returns of polluted water to the system, it is probably becoming necessary that <u>all</u> the major rivers and lakes should be "cleaned" and put into proper mineral balance and biological balance. Such a program will be vast, requiring the annual expenditure of billions of dollars ([231], p. 10).

A particular problem is the safe disposal of radioactive wastes. Although not large in volume, these are too dangerous to dump into the nearest waterway and hence must be diluted in advance to safe levels or buried underground. The groundwater in the vicinity must be constantly surveyed to prevent excessive radiation dosages entering the food chain. By 1959 a total of $200,000,000 capital had been outlaid on radioactive waste burial in the U.S. (mostly at Hanford, Washington and Oak Ridge, Tennessee) and an annual amount of $6,000,000 for maintenance was necessary ([230], p. 203). Some of the long-lasting radioactive material, after a process called "calcination" which converts them into a powder, has to be stored in long metal cannisters, which are buried in huge underground vaults. Others are diluted to appropriate levels and the fluid effluent is then injected hydraulically into a permeable layer thousands of feet below ground surface. Proposals for the use of abandoned salt mines have been considered in connection with the management of radioactive wastes, but long-distance transportation may prove to be a prohibitive cost and public menace. If Plowshare could provide a large, safely removed underground storage area for these "hot" wastes at reasonable costs, there would be interest in development of the new technique of waste disposal.* The geological structure and hydrology of the terrain in the vicinity of the reactor or chemical processing plant (separator) would have to be known, and the cost of obtaining this information included in the economic evaluation of the method. The details of this proposal and related methods for the disposal of other waste fluids will be discussed below.

b. The Use of a Contained Nuclear Explosion for Waste Disposal. For the purposes of this project one of the most important features of underground explosions is the large increase of permeability of the rock

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* At the present time the disposal or storage of radioactive wastes in the chimney created by an underground nuclear explosion is not considered feasible by the U.S. AEC due to the affects of seismic shock on the plant which produces the wastes. In the event that disposal or storage sites underground are planned <u>before</u> a future plant is built, these considerations may be changed in favor of the Plowshare method.

medium surrounding the shot point (particularly above shot point) [1]. Through the fractures which the explosion engenders for six or seven times the distance of one cavity radius, a waste fluid may flow into the permeable stratum selected for the purpose. This stratum must be bounded below by an impermeable rock and should be well isolated from aquifers which are directly connected to the water supplies of the region. The fission products from the explosion (such as Strontium 90) would be partly contained in a pool of radioactive glass which characteristically forms at the bottom of the chimney, and partly dispersed through the rubble and cracks in the surrounding formation. Its rate of transport through a permeable stratum is 40 times slower [1] than that of the water which carries it, so that only a minute quantity of the radioactivity released by the explosion would ever find its way into the environment. When radioactive wastes are to be injected into the nuclear chimney, the problem is, of course, more serious, but it is still quite conceivable to find a geological formation in which the containment is adequate. For this purpose the use of relatively impermeable formations may be required, sacrificing storage volume but gaining permanent security from radioactive contamination of the environment [68].

In the case of non-radioactive waste disposal it is possible to consider the project a part of overall water management. The use of low-yield nuclear explosions for groundwater recharge has been proposed [221], and in this connection the basic purpose is similar, i.e., to improve the quality and quantity of the local water resource. It is not yet known whether the problems of managing the fission products can be solved in a water application. With the disposal of sewage and chemical wastes there is a trade-off between conventional processing costs and the risk of radioactive contamination of water supplies, but much more information is required before definite evaluation of the alternative can be made.

Todd discusses several artificial recharge programs in [222]. Costs vary widely and the range for his selected examples is $2.00 to $50.00 per acre-foot. The single largest recharge project cost half a million dollars in El Rio, California, and involved a gross area of 125 acres. Three recharge pits operated by Los Angeles County Flood Control District cost $45.00, $3.50 and $19.50 per acre-foot of water recharged. The total volumes of water involved (during twelve months) were respectively 1000, 6100 and 2500 acre-feet. According to E. F. Renshaw quoted in [222] the maximum value per acre-foot of water for waste disposal in the U.S. was $2.56 in 1950. Even allowing for today's higher prices, it does not appear that the use of nuclear technology is commercially competitive in this method. But to carry out a further analysis, we must also consider the alternative methods of treatment and disposal of wastes, and their costs.

c. The Problem of Dispersion vs. Disposal. From the point of view of the riparian* municipality, fluid wastes which are removed from the area by the river are <u>disposed</u>, but from a regional point of view--taking the whole river basin as a convenient region--they are only

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* river bank

dispersed and diluted. Much effort has gone into the economic study of water management recently, and a number of proposals have been made to achieve an equitable distribution of the user costs associated with the avoidance of pollution in public bodies of water. See for instance [232].

The burning of solid and gaseous wastes is an inexpensive way of disposing of a major fraction of many waste materials--from the narrow point of view of the firm or municipality doing the burning. So long as the dispersion is effective, there is no problem; but sooner or later industrial and population concentrations will cause air pollution. At such time, the wastes are no longer disposed of, public health is threatened, and legislation comes into being to limit the quantity of harmful waste substance released through burning into the atmosphere. Again, as with the fluid wastes, disposal is really dispersion; and the limits of the environmental capacity to absorb and dilute the wastes are rapidly approached under a system of "free" dispersion.

In the case of wastes which are extremely dangerous there has been for some time a rather tight control on their release to the environment. The various unwanted radioisotopes produced at Oak Ridge and Hanford [230] having half-lives of more than a few days must be first stored; then they may be released if the radioactive decay is sufficiently advanced or, more likely, they are reduced in bulk and permanently stored by burial. In one method [233], the radioactive wastes are reduced to solids using a pot calcination process. The "pot," a steel cylinder, six to eight feet tall and eight to eighteen inches in diameter, becomes the permanent container for the calcined product. It is sealed and stored underground. The pot itself is designed to last for twenty or thirty years under stable environmental conditions. Although the method is expensive, it appears to be well within the feasible range as far as the system costs are concerned. Studies carried out at Oak Ridge showed that, for a reactor plant the various steps required for the management of radioactive wastes from power reactor fuel processing would cause a total incremental cost of 9.03 mill* per kwh--or about 1% of the total reactor fuel cycle cost. These steps included interim storage of the wastes as liquid in tanks, pot calcination to produce relatively smaller volumes of thermally stable solids, and finally shipment of the pots to the place of permanent disposal.

The principle in the above-mentioned treatment and disposal of radioactive wastes is quite different from dispersion. On the contrary, they are concentrated into compact containers, isolated from the biosphere and temporarily or permanently stored in isolation. The major reason for the applications of the method in the case of radioactive wastes is the high cost of "treatment." Unlike most other industrial wastes, there is no reasonable process available for rendering the waste material harmless so that it might be subsequently dispersed. For a power reactor, shipment of the calcined wastes even as far as 1000 miles does not impose intolerable burdens on the economy of the electricity production. Conceivably a

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* 1 mill = one thousandth of a dollar.

problem might arise if the total quality of these extremely dangerous cargoes required to be transported nationwide, within one year, exceeded some threshold, since the likelihood of an accident would then begin to have a significant effect on the waste disposal costs. But otherwise it remains remarkable that any waste product--in itself of zero value--should be transported considerable distances within the economic framework of a single production unit.

The application of nuclear explosives for creating underground storage for harmful wastes, as an alternative to the existing methods, at present does not appear to be of proven economic value, but it could in the future prove to be a valuable addition to the Federal anti-pollution program particularly if used in conjunction with a regional water resource management scheme. There is clearly a tremendous variation by location and geology in the cost to the public of disposing of wastes, and equally clearly there is need of a battery of techniques for assaulting the problems of pollution of the water system. It should be emphasized that, in the proposed method of waste disposal by means of a contained nuclear explosion, the geology and hydrology of the site must be thoroughly known, particularly in the case of toxic wastes. In many cases, the high cost of obtaining this information may preclude use of the method; in other cases, the information may previously have been obtained, so reducing the marginal costs. This factor alone supports the argument that each individual case should be considered on its own merits, without regard to any single generalization of the "preferred" method of managing waste disposal.

5.6 SUMMARY

This chapter summarized the results arrived at in five Special Reports by MATHEMATICA on shale oil production, mining, natural gas (and oil) production stimulation, cratering, and a set of other potential processes using nuclear explosives. The four particular applications just mentioned all prove to be of major economic interest.

However, this conclusion is based on quite different economic aspects from case to case. Some applications, like shale oil production using nuclear explosives, have large uncertainties attached to them in the process-engineering field after the nuclear explosion has taken place. Other applications, e.g. natural gas stimulation, are relatively simple processes once the nuclear explosion occurred; but they do have attached to them technical uncertainties as to how far and how extensive the effect of the nuclear explosion to production will be: in the case of gas stimulation we noticed the importance of the fracture system around the chimney, its extent and duration.

Separate from this set of technical and engineering uncertainties which vary from application to application or even from one place to another, we have a set of differing expectations of the potential benefits to the economic system as a whole, that is, the overall potential added to United States recoverable resources, or the recoverable resources of any other nation.

If now, by coincidence, technical and engineering certainty, and the expected maximum resource values added by this technology would coincide for any one particular application, then the decision of where to initiate experiments and direct the available research and development funds would be solved in favor of the application where certainty and expected resource values are largest. Unfortunately, this is not the case here. From the point of resource development one would, among the completely contained applications, clearly give preference to the development of the <u>in situ</u> recovery of the large U. S. oil shale deposits. This is a particular situation which holds for the United States and may not necessarily hold in any other nation. At the same time, the technological uncertainties attached to the recovery process after the nuclear fragmenting takes place are largest in exactly this application. A completely new process has still to be developed on an experimental, a prototype, and, finally, a large-scale operational basis, with no definite guarantee that the resulting process will fulfill the many technical assumptions which at present have to be made in any economic evaluation of this production process.

On the other side, the process which in the long run may hold the least spectacular gains, i. e. natural gas stimulation by nuclear explosions, has attached to it a very primitive recovery system, basically the opening of one or several production wells after detonation, allowing for a satisfactory solution to the contamination problem, which may be assured at some cost.

Similar situations occur frequently in economics: in investment decisions, portfolio selection, budget allocation. For the firm or agency, it will then be a question of how much risk the decision maker is willing to incur: at a low or at no risk, a certain but relatively small gain will accrue while possibly larger, more spectacular breakthroughs are foregone. With the same amount of capital invested and at a high level of risk, larger gains can potentially be made if the decision maker is prepared to accept the increased probability that his whole investment into the new technological development might be lost if the more unfavorable conditions hold. By allocating his funds to both extreme cases such as to choose a suitable combination of risks, the decision maker may be able to find the risk-and-profit level he is prepared to accept.

As was shown in the discussion of the particular applications of nuclear explosives, there exists in addition to the above general investment problem also a whole range of technical and economic optimization problems. To mention only a few, we refer here to the size of the diameter, emplacement depth, the reduction of emplacement costs, and the increased cost which will occur when trying to reduce the diameter of nuclear devices. Other technical and economic problems particular to each application will be posed by the relevance of contamination problems, the distance from consumer markets versus the costs of safety, the time required for the completion of the project versus the costs incurred due to safety problems, and so on. Such problems deserve further attention in economic research and will have to be answered in later studies.

Overall, the expected benefits to single industries alone are such that enough incentive is given even to particular firms to initiate research and development efforts in the peaceful application of nuclear explosives. This is already the case in natural gas stimulation and in mining of copper ores by the in situ leach method. In oil shale, a cooperative effort of the oil industry developed to cover the more extensive risks and investments required in this field to develop a completely new technology where nuclear explosives are only a preliminary step in the still uncertain production process.

Cratering projects and earthmoving projects, where the use of nuclear explosives is called for, are still of such a scale that most of these projects within the United States or in other countries would warrant government initiative and participation. This is particularly true for projects which by themselves are collective goods, e.g. isthmian canals affecting many regions and nations, mountain cuts, water resource developments, etc. A possible exception may be strip mining operations using nuclear explosives, which, under suitable conditions, may yield substantial economies to individual enterprises.

Thus a very broad interest in the Plowshare technology has already been generated within the United States. With the demonstration of technical feasibility by several experiments in each of these fields, the remaining technical and economic uncertainties can be cleared away. In many ways the present report opens up many more questions than originally it set out to answer.

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ERRATA FOR PNE-3005

On page 155 the first footnote should read:

* Charges above 2 MT have been extrapolated from the published AEC charges (see Section 3 of this report).

On page 156 line 7 should read:

KT to 50 MT (larger than the 15 MT yield of maximum permissible ex-