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THE GENERATION OF USEFUL POWER BY THERMONUCLEAR EXPLOSIONS (u)

R

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PREFACE.

The following note summarizes the present state of thoughts about generation of useful power by T.N. explosions as evolved in discussions among W. Brobeck, H. Brown, M. Mills, R. Goranson, D. Griggs, E. Teller, and others. Many of the ideas contained herein have been previously discussed in LAMS-1859 by F. Reines of LASL. An earlier progress report by W. Brobeck has appeared as COMB-17. This is a further report containing results of subsequent discussions.

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THE GENERATION OF USEFUL POWER BY THERMONUCLEAR EXPLOSIONS

1. INTRODUCTION.

This note is a partial summary of work carried out so far on the topic of thermonuclear power generation by explosion of thermonuclear bombs. The long-range purposes of such an arrangement would be comparable with those of Project Sherwood, namely an enormous augmentation of the world's fuel supply, to the point where the world-wide fuel shortage now envisaged in fossil fuels, and conceivably even in fission fuels in some hundreds of years, would no longer be a concern. The Sherwood method of extracting thermonuclear energy depends on confining a plasma at high temperature but very low density so that the reaction time is long - a fraction of a second - and the energy is generated non-explosively. Making the reaction sustain itself under such conditions is an as yet unsolved problem.

An alternative method is to use a thermonuclear bomb, in which the high density and high temperature of the reactants make the reaction go very rapidly (a few times 10^{-8} seconds) producing an explosion. The problem of making the reaction go in a bomb almost all of whose energy is thermonuclear has thus already been solved, but the problem of making use of this energy to generate, for example, electric power has not.

The enormous pressures and temperatures associated with the bomb must somehow, since they cannot be withstood by a material container, be mitigated or absorbed. Explosions can be converted to useful power, as the internal combustion engine shows. The very large energy per explosion produced from a thermonuclear requires that a very large quantity of some material be interposed between it and the walls of any container in which we hope to confine the explosion. Because shocks are transmitted with much less reduction in peak pressure as a function of radius in solids and liquids, a gas filled container of large radius is indicated; one opaque to visible radiation will prevent too much radiant energy from the fireball from reaching the container walls and overheating them. The mass of gas should be several times the equivalent mass of high explosive which makes the same amount of energy as the bomb, so that the gas comes only to a fraction of the temperature to which gaseous products of an HE explosion rise.

Though the present schemes involve the use of a small amount of fission fuel, it generates a very small fraction of the total energy (perhaps a few per cent). Further more, this fraction can probably be reduced by bomb design, perhaps ultimately almost to zero. In addition, the same container which contains the explosion may conceivably be used to breed plutonium (or U^{233}) with what amounts to an enormous breeding ratio, so that the economic supply of fission fuel might be greatly extended. These two ameliorations of the requirement for fission fuel, however, are even more speculative than the rest of the scheme, and therefore will be omitted in the fuel cost calculations which follow. It should be noted that power costs of 6-7 mils are typical for steam plants in the U.S. In Europe 12-15 mil power is considered competitive; elsewhere costs are even higher.

II. FUEL COSTS.

In general, fuel costs will be smaller (per KWH) the larger the yield of the bombs which can be used, since most of the cost lies in the fissile material which does not increase in amount very rapidly with the desired total yield. The ratio of total to fission yield will be lower for the smaller yield bombs, a situation which we wish to avoid in order to conserve fissile materials. Let us consider three yields, 200 KT, 1 MT, and 5 MT.

Present thermonuclear designs are aimed at minimum weight and/or dimensions for a given yield. Though cost minimization is already a factor, minimum use of materials in short supply, which is not quite the same thing, is considered more important. One would therefore expect designs of bombs for power to be quite different, since total cost is the item to be minimized, and size and weight matter hardly at all. Since the use of [redacted]

b(3)

b(3)

Present fuel costs are 3-4 mils for typical fossil fuel plants in the U.S., running up to double that or higher even in some foreign industrialized areas. This comparison proves nothing about the workability of the bomb generation of power, since Sherwood and reactors also have, in principle, very low fuel costs. The low fuel cost indicates that the real economic questions will arise in the capital investment involved in the construction required to make the scheme work. The technical question is to find such an economic scheme. The fuel cost at 200 KT is high enough to be a little discouraging for fear that amortization of investment costs will be high enough to put the total beyond economic utility. For the higher yields the fuel can be considered essentially free, so that considerably higher investment costs than those of steam plants can still be economic.

III. PLANT SIZE.

As in most power plants, an economic advantage is gained by having a large output, since some costs are independent of power output, so that their per KWH cost is inversely proportional to the used capacity of the plant. In the case of the bomb generation of useful power, such costs are perhaps the largest unknown cost, since they comprise whatever the container may be for the working fluid. If the container lasts a time independent of the total number of explosions in it, its cost is likely to be roughly proportional to the size of the bombs regularly exploded in it. One would then explode bombs with a frequency proportional to the used power, and inversely proportional to the bomb yield and the efficiency of energy conversion.

Plant size is likely to be limited by the power consumption in an area within a reasonable distance from the plant. Transmission costs generally run about 1 mil per KWH per hundred miles, so about two or three hundred miles is generally considered the maximum allowable transmission distance; this in turn has led to steam plant sizes up to 10^9 watts, with hydroelectric plants up to 2.5×10^9 watts. The latter is likely to be a better comparison for bomb-produced power, but a more conservative 10^9 watt plant size will be used in the examples provided here. Sites are likely to be limited in number, since they must be some distance from heavily populated areas and may also require particular geologic conditions.

For orientation, it may be calculated that using 1 MT bombs at 25% conversion efficiency in a 1,000,000 kilowatt plant requires an explosion every 10 days.

IV. OPERATION OF THE PLANT.

Some thought has been given to the choice of storage and working fluids and the cycle to be used. Rock itself is a possible storage material, but its poor conductivity requires that it be in pebbles no more than an inch

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in diameter to get the energy out in a few days, and there is some likelihood that the bomb energy will melt the rock which will then agglomerate into a mass of large dimensions from which energy extraction is very slow. The cycle of putting the energy into steam and having the steam move water has quite a low efficiency (10%) so that the use of steam itself both as storage and working fluid seems attractive.

The steam must absorb almost all of the bomb's energy, so that quite a bit of it will be required. Let us imagine the use of a large hole deep underground to contain the steam and the explosion, returning in a later section to the important and difficult problem of constructing such a hole at a reasonable cost, or indeed at all, and with strong enough walls to withstand the forces to which they will be subjected. For the moment let us say that the hole has strong rock walls. Let us also say that the hole has a radius of 750 feet, and is at a depth of 3000 feet. The hole will contain superheated steam at high density, temperature, and pressure. Before the explosion, for which we will use a 1 MT bomb, the temperature is 600°F, the pressure 2000#/in^2, the density about 3.6#/ft^3 and the energy content 2 MT HE equivalent of energy. Adding 1 MT of energy will raise the temperature to 1650°F and the pressure to 5000#/in^2. By adding water to bring the density up to 4.7#/ft^3 ambient p becomes about 4000 psi and T about 1000°F. The water should be added before the explosion to avoid bringing the temperature to 1650°F at any time.

The 1 MT bomb makes a fireball, then sends a shock out through the steam, which is enough more opaque than air so that not more than a tenth percent or so of the energy will reach the walls as radiation. This amounts to 160 cal/cm^2, which should produce little effect on the walls, since they are in good enough thermal contact with the steam to prevent melting. Using the Taylor similarity solution for the overpressure, good only so long as it is much greater than the ambient pressure, and saying $\gamma = 1.4$ for steam, one has a shock overpressure when it reaches the walls of $.133\ E_{tot}\ f/R^3$, with $f = 1.167$ for $\gamma = 1.4$, giving $.6\ E_{tot}/V = \frac{.6 \times 4 \times 10^{22}}{4.2 \times 11.5 \times 10^{12}} = 5 \times 10^8\ \frac{\text{dynes}}{\text{cm}^2}$, that is 500 atmospheres or 7300 psi.

On reflection, this pressure of course increases, with the ratio ξ of the reflected to the incident pressure on a rigid wall being given in terms of and the ratio ξ_o of the incident to the ambient pressure by:

$$\xi = 1 + \frac{(\xi_o - 1)^2}{2\xi_o\left(1 + \xi_o \frac{\gamma - 1}{\gamma + 1}\right)} + \sqrt{\frac{(\xi_o - 1)^4}{4\xi_o^2\left(1 + \xi_o \frac{\gamma - 1}{\gamma + 1}\right)^2} + \frac{2\gamma(\xi_o - 1)}{\xi_o\left[(\gamma + 1) + \xi_o(\ -1)\right]}}$$

Ambient Pressure p_o	Incident Pressure $p_o = 7300 + p$	ξ_o	ξ	Reflected Pressure
2000 psi	9300 psi	4.7	3.5	33000 psi
3000	10300	3.4	2.8	28500
4000	11300	2.8	2.4	27000

Thus the reflected pressure is slightly lower for a higher ambient pressure.

As the shock reflects and rebounds from the center, the kinetic energy is transformed into heat, until finally all except that which is transmitted out through the walls as seismic waves is converted into heat content of the steam, raising its temperature and pressure. If a temperature adjustment is desired, water can be pumped down into the hole, helped by the static head, which would be 1300 psi for 3000 feet.

If no tension is allowed in the walls, even during shock conditions, a larger hole will be required. The hydrostatic pressure of the overburden then serves a necessary purpose, since the tangential stress in the walls is approximately given by $\frac{3}{2} P_H - \frac{1}{2} P_I$ (a positive sum means compression, negative tension, with P_H hydrostatic and P_I internal pressure).

One would also want to go to a deeper hole, say 5000 feet, which might make P_H at the top of a 1000 foot radius hole 3000 psi. An initial pressure of 2500 psi is used at 800°F and 4#/ft^3. The overpressure of 7300 psi is reduced by a factor of 2.5 (the increase in volume in going to a 1000 foot from a 750 foot radius) to 2800 psi, or a 5300 psi incident pressure, with $\xi_o \simeq 2$. This gives $\xi = 1.8$, so that the reflected shock will be about 9000 psi. Under these circumstances there will be no tension in the wall, even when the shock reflects, and the compressive stress in the wall after the reflections can be computed by noting that the 6 MT energy content increases by 1 MT, and the steam table indicate that this increase in energy raises the temperature to 1160°F and pressure to 3500 psi, so that there is 4500-1750 $\approx$ 2800 psi compressive stress in the walls.

If one does not worry about tension during shock conditions, but only under static conditions, the 750 foot radius hole at 3000 foot depth will serve. Since internal pressure, 5000 psi after explosion, is less than three times the 2000 psi static external pressure, there is no tension in the cavity walls, under static conditions.

One would of course be able to use a smaller hole if the individual explosions were smaller (and more frequent if the power output is to be the same). The necessary hole volume is proportional to the bomb yield. This would reduce investment costs if the hole digging is very expensive (as it may well be). The savings so made must be balanced off against the increased fuel costs which accompany lower yield bombs.

V. MISCELLANEOUS CONSIDERATIONS.

a) The energy is to be transferred by moving the steam up through a hole bored into the rock down from the surface to the underground chamber. The hole could be 4-8 feet in diameter, and lined toward the bottom with steel. To generate 10^9 watts at 25% efficiency means 4×10^9 watts of heat = 4×10^9 joules/sec = 10^9 cal/sec = 4×10^6 BTU/sec. The steam energy content is of the order of 1000 BTU/# so that 4000 lbs/sec must be transferred. At 5#/ft^3 this means 800 ft^3/sec, and a 50 ft^2 cross section (8 ft. diameter) requires 16 ft/sec velocity, which involves very little pressure loss.

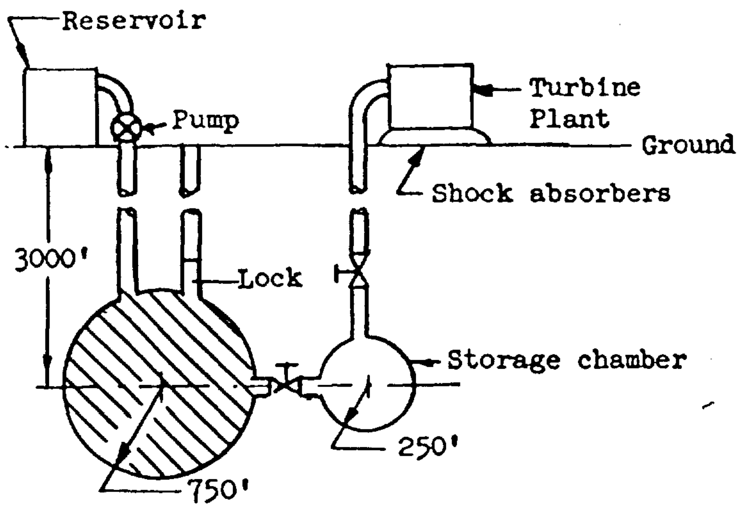
b) The integrity of the wall is important at the top, since the erosion of material from the top and consequent build up of the floor will cause the hole gradually to climb up toward the surface. If the installation must last for 20 years with explosions at 10-day intervals, and the hole must not climb more than 250 feet, the erosion per explosion cannot be more than $\frac{250 \times 12}{20 \times 36.5} = 4$ inches per explosion. It may be advisable to explode the bombs somewhat below the center of the hole, to reduce pressure on the upper surface. Erosion of the floor is less serious.

c) The establishment of the steam filling after the hole is dug would presumably involve the explosion of a smaller bomb (100 KT, say) in water at the bottom of the hole to fill it with low-temperature and pressure steam. Subsequent larger bomb explosions will heat the steam to higher temperatures, and pumping more water in cools it down again. In fact, after every explosion during the steady state more water is pumped in to lower the temperature. To keep the pressure driving the turbines constant while energy is drained from the hole (and the pressure in it drops), a valve will be inserted in the steam pipe.

d) Following the valve the utilization of the steam will be in a relatively conventional steam turbine plant, such as already exists at the Lardarello steam wells in Italy where electricity is generated from underground steam. 25% efficiency should not be difficult to attain with the steam temperatures available, by condensing the steam and reheating inlet water.

e) Additional bombs are inserted through a lock in a separate hole leading down to the combustion chamber. Since weight is no object, it should be possible to insulate the bomb from the high temperature of the steam.

f) The activity of the water will be kept down by keeping the [redacted] Since a shot is exploded every 10 days, the "average" activity, that is the activity well after a shot, will be the same [redacted] The steam volume in the 750 foot radius hole is 1.75×10^9 cubic feet, or about 10^{10} gallons, so that the activity is 50 millicuries/gal of steam. When condensed the volume is reduced by 10, so that the activity is 500 mc/gal of water. These are reasonable numbers (easily shielded), but immediately after a shot the activity will be very much higher (15 times higher 1 hour after explosion). It may therefore be advisable to have a separate chamber, sealed off from the main combustion chamber, from which steam can be drawn while the activity in the main chamber decays b(3) (a day or so). The installation would then look schematically as shown below.



It may be cheaper to avoid the extra chamber and invest the amount necessary in shielding to withstand the higher activity. Of course the activity is a problem only if it does not settle out. It seems unlikely that it will, since the bomb fragments will be very small, and such fission products as condense will condense on them. The small particle size make the settling time very long. For 1 micron radius, steel particles using η of steam at 500°C as 3.5×10^{-4} poise (which it is for air, CO_2, etc.) one gets a settling velocity $U = \frac{2}{9}\frac{a^2 \rho g}{\eta} = .04$ cm/sec or 40 meters in 10 days. Neutrons emitted from the bomb will be captured in the hydrogen of the water, since at .1 of liquid density the hole has a thickness of water of 2 kg/cm^2 (equivalent to 75 feet of water).

g) The leakage of heat out through the rock is easily calculated to be in the steady state $4\pi R^2 K \frac{T}{R}$ where K is the conductivity of the rock. If T = 1000°F, $K = .0040 \frac{\text{cal}}{{}^\circ\text{C cm sec}}$, and R = 750 feet, the heat loss is about $12 \times 30 \times 750 \times .004 \times \frac{5}{9} \times 1000 = 5.4 \times 10^5$ cal/sec = 2 megawatts. Since the heat generation = $\frac{\text{Power}}{\text{Efficiency}}$ is 4 Billion watts, this is only .05%. Of course the loss rate will be quite a bit higher as the rather long-period transient heat flow occurs, but we can afford to have it even a hundred times higher, and such factors as the film drop between steam and rock will serve to reduce it.

h) The seismic shock produced by the explosion must be more thoroughly investigated. However, the heat capacity of the steam in the hole appears to do quite a good job of cushioning the shock of a 1 MT explosion from the rock, which feels a shock of about 30000 psi for a time governed by the sound speed in the steam. The spike of pressure extends over about 1/5 of the radius, so that the pressure drops by some factor like 4 after a time equal to $\frac{R}{5c_{sound}}$. It drops more when the rarefaction arrives from the center at $\frac{R}{c_{sound}}$. Since c_{sound} is about 2000 ft/sec, these times are (for R = 750 feet) about 0.1 and 0.4 seconds. If the energy transmitted into the rock is $p\Delta V$, then a radial motion of 1 foot under the maximum pressure is 2000 x 10^6 dynes x 12 x 5 x 10^8 cm^2 x 30 cm = 3.6×10^{20} ergs, which is 1% of the bomb energy. If it is strong enough, or if the larger (1000 foot) hole and consequent smaller pressure is used, the wall should not move this far. 1% of the bomb energy, however, should produce no spalling at the surface, especially since the rarefactions may catch up with any strong shocks before they reach the surface. It may well be advisable, however, to shock mount the turbines and other surface machinery, and perhaps to locate them some distance from the surface point over the explosion chamber, piping the steam some distance if necessary.

The cushioning effect of the steam in the hole may be better understood by calculating its mass, which, for a 750 foot radius and .1 liquid density, is 5.5 megatons of steam. Since five grams of steam can absorb the energy of a gram of TNT without being raised to an inordinately high pressure, the cushioning effect of the steam combined with its poor mechanical coupling to the high density rock walls, may well keep the rock from undergoing too high a pressure. The propagation of seismic effects of course depends on the nature of the rock surrounding the hole.

VI. DIGGING THE HOLE.

It is apparent that the largest problem of the entire proposal is "digging" a hole for the combustion chamber (and the steam storage chamber, if it is separate). This is true not only because it is so large and so deep, but because of the large static and even larger dynamic forces exerted on the walls in steady state and during explosions.

There is some question whether so large a hole can be dug at all at these depths by conventional means (smashing the rock with explosives, and lifting it out). This is because of the local stress concentrations produced in blasting operations, in view of which the walls of so large a hole may not be able to take, unsupported, the pressure of the overburden, which may amount to 2000-3000 psi. Much less could the walls then support a high shock pressure from the bomb without spalling.

Steel support of the upper half of the hole might be possible, but would be very expensive (~$100,000,000 or more). If the hole could be dug by conventional means, at a cost of $1 to $10 per cubic yard, its cost would be 60 to 600 million dollars. Anything like the latter cost would add enough to the capital investment (whose total should not exceed three to five hundred millions) to sink the project.

One must therefore look for some non-conventional means of excavation, and such immediately suggests itself in the use of high-yield bombs for this purpose. In fact there appears to be a method, of which one can say nothing more hopeful at the moment than that it is not obviously impossible. This method, if successful, may not only dig the hole but provide it with rock walls of unusually high strength and free from stress concentrations.

The idea is to find a region of porous rock of fairly low density which can be compressed (without being melted) by some regime of overpressure, and then explode bombs of increasing yield in what begins as a small underground chamber. This would presumably increase the density of the rock in some region around the explosion (it will also melt some rock), thus leaving a central hole produced by the increase in density away from the center. The high-density rock so produced would, hopefully, be of high strength and relatively free from stress concentrations. Subsequent higher yield explosions in the process of digging the hole should pass through the high-density rock without melting it, because ΔV is low though p is high, except at grain boundaries where melting and resolidifying should allow outward motion if regions outside become compressed. The high pressures passing through the high density region may then compress lower density regions farther out, increasing the hole size.

There exists below the Nevada proving ground a porous rock called tuff, whose actual density is as low as 1.6 gm/cm^3, with a crystal density of 2.5 gm/cm3. Data are available connecting the density to which this rock comes as a function of the pressure exerted on it, as shown in Figure 1. It indicates that compression begins to occur at a pressure of 100 atmospheres (1500 psi), though very little compression occurs until p reaches 1000 atmospheres. After this the density rises roughly logarithmically with pressure. At a pressure of about 10^5 atmospheres, enough $p\Delta V$ work is put into the tuff in compressing it - about 250 calories per gram - to melt it. Of course higher pressure will compress the tuff still more, but as it is applied adiabatically the rock will be molten after the pressure is removed and will revert to the density of molten rock (of the order of 90 to 95% of crystal density).

The densities shown on the graph at the lower pressures are for static experiments, at higher densities they are dynamic (using high explosive shocks) faired into the Fermi-Thomas theoretical equation of state. It is not at all clear that shock pressures of 100 to 100,000 atmospheres will produce compressions as indicated, since they are of short duration. The shock overpressures produced by high-yield bombs (10 KT - 10 MT) do last quite a long time compared with high explosive shocks, so that it may turn out that the use of the ρ-p curve shown is justified.

One can get a rough estimate of the hole size generated in an explosion in tuff by saying that when the shock front is at radius r, the pressure is given approximately by $\frac{2}{3} E/\frac{4}{3}\pi r^3 = \frac{E}{2\pi r^3}$. The change in relative volume dv/v is 1- ρ_o/ρ, so that the volume change is

$$\Delta V = \int_{p\ \text{melting}}^{p\ \text{minimum}} \left(1 - \frac{\rho_o}{\rho}\right) 4\pi r^2 dr,$$ where the limits are those at which no compression at all occurs and that at which melting occurs. To this should be added the volume excess of uncompressed over molten tuff in the region of still higher pressure.

An analytical approximation can be made by saying

$\rho = \rho_o \quad 0 \le p \le p_o \quad p_o = 10^3$ atmospheres

$\rho = \rho_o(1 + \alpha \ln \frac{p}{p_o}) \quad p \ge p_o$ with $\alpha = 0.15$ and p melting $\sim 10^5$ atmospheres $= 100\ p_o$

The results are $\Delta V = \frac{2}{3} \alpha \frac{E}{p_o} = .1\ E/p_o$, which is about 15 times the volume in which melting takes place, $\frac{4}{3}\pi \frac{E}{2\pi(100 p_o)}$. For a 1 megaton bomb this amounts to $\Delta V \sim \frac{2}{3} \times 0.15 \times \frac{4 \times 10^{22}}{10^9} \sim 4 \times 10^{12}$ cm^3, or a radius of 100 meters. This implies that fifteen one megaton bombs or one 15 MT bomb may suffice to dig the hole reguired for the combustion chamber.

The compressed rock, which may be of high strength, occupies a thickness of the order of 1/4 of the radius. To sustain the overburden pressure p_{ob}, it must have a compressive strength σ such that $\pi r^2 p_{ob} \sim 2\pi r \sigma t$, and if $t \sim r/4$, $\sigma \sim 2p_{ob}$. σ for granite is at least 15000 psi, probably much more if extreme local stress concentrations do not exist, so that the 2000-3000 psi overburden pressure should be easily sustained.

The ability of the container to stand the pressure, static and dynamic, of the steam inside, is more difficult to estimate insofar as it depends on the tensile strength of the artificial wall constructed by bomb explosions. The static overpressure will be two or three times the overburden, so that the net outward static pressure will not exceed, say 4000 psi, which would require no tensile strength in the high density rock shell if the overburden pressure is 1333 psi (see p. 6). Of course the shock pressure during explosions tends to produce more tension in the rock shell.

It may be possible to do laboratory experiments, with pressures produced by high explosives, in order to determine the effect on rock of a shock pressure which, if static, would produce a tension in rock walls of a cavity under pressure p_1 with an external pressure p_o. In fact the investigation of stress waves in such configuration may well be carried on in scaled down models in laboratory tests, since the overpressures which we are interested in at the walls, of the order of a thousand atmospheres, do not even require high explosives for their production.

Scaled down underground nuclear explosions of the order of a few kilotons or tens of kilotons underground can, as mentioned before, give information concerning the excavation of the underground cavity. By filling such holes with steam and detonating additional bombs of smaller yield in them, one can perhaps learn something about the effects of power-producing thermonuclear bombs in larger steam-filled holes. Shock times are different, however, than for large bombs.

It should be noted in conclusion that many uncertainties still exist in the detailed conception of how such a plant should operate. For example, the conditions necessary to avoid radial cracking during the time that the shock runs through the walls have not been examined. If the overburden pressure is 3 times the internal pressure there appears to be no tension even in static conditions; under shock conditions it appears reasonable that greater internal pressures can be withstood but a detailed analysis is necessary.

The statements concerning the digging of the hole are very speculative, particularly as regards the formation of a strong high density shell. Experiments currently planned for a deep underground shot in Nevada, though only 2 KT, may cast more light on this subject.

Thus the statements about the costs in a practical plant are extremely tentative, with further study and particularly experimental work being needed to reduce these uncertainties. Only the operation of a pilot plant can give information on costs which is accurate to much better than a factor of two.

APPENDIX A

The following table presents the excavation costs per kilowatt of electrical capacity assuming that the volume of the hole is proportional to the size of the bomb exploded. A 10^9 watt capacity is assumed; the cost per KW is of course inversely proportional to the generating capacity.

Two pairs of assumptions are treated:

a) 1 MT bombs require a 750 foot radius hole
b) 1 MT bombs require a 1000 foot radius hole

A) The hole costs $0.5 per cubic yard.
B) The hole costs $5 per cubic yard.

(a) and (b) correspond to ~~no static tension and~~ no tension during the period of shock in the walls as outlined in part IV.

(A) represents a guess at the excavation cost if bomb excavation can be used, and (B) represents a guess at what excavation costs might be by conventional methods.

Table I

Cost (in $ per KW electrical capacity) of digging the hole

	A	B	A	B	A	B
a	6.6	66	33	330	165	1650
b	16	157	78	785	392	3925
Bomb Yield	200 KT		1 MT		5 MT	

To these costs must be added the land costs, the costs of turbines and generators, the steam pipes and control system, the pumps and water reservoirs, for which a reasonable estimate might be $100/KW.

Operating costs are estimated as 1 mil/KWH, which is high for conventional plants, on the basis that unconventional plants cost more. To this must be added the fuel costs, which were derived in mils/KWH in section II as

Table II

Fuel costs

Bomb Yield	200 KT	1 MT	5 MT
Fuel cost (mils/KWH)	2.0	0.6	0.2

If one takes the interest and amortizations cost as 10% per year of the capital investment (replacement over a 20 year period, 5% interest), and assumes a load factor of 0.7, the per KWH cost of the capital investment is 1.6×10^{-5} of the investment cost/KW. Adding fuel, operating, and amortization costs, the cost per KWH of power from a 1,000,000 KW plant is given in Table III.

Table III

Cost in mils per KWH of power from 10^9 watt plant

	A	B	A	B	A	B
a	4.7	5.6	3.7	8.5	5.4	29.2
b	4.8	7.1	4.4	15.8	9.1	65
Bomb Yield	200 KT		1 MT		5 MT	

Cost is 1 mil + F + 1.6×10^{-5} (100 + E)
where F is fuel cost in mils and E is excavation cost in $/KW

The above table indicates how important the questions posed by the alternatives a or b, A or B are. This emphasizes the need for further study and experiments. The very large ($ per KW) costs associated with excavations for 5 MT bombs result in very high power costs, but larger power output (5000 MW, for example) would bring the per KW cost of excavation for 5 MT bombs down to what they are for 1 MT bombs at 1000 MW. For 1000 MW, bombs of yields from 200 KT to 1 MT appear to give interesting power costs.

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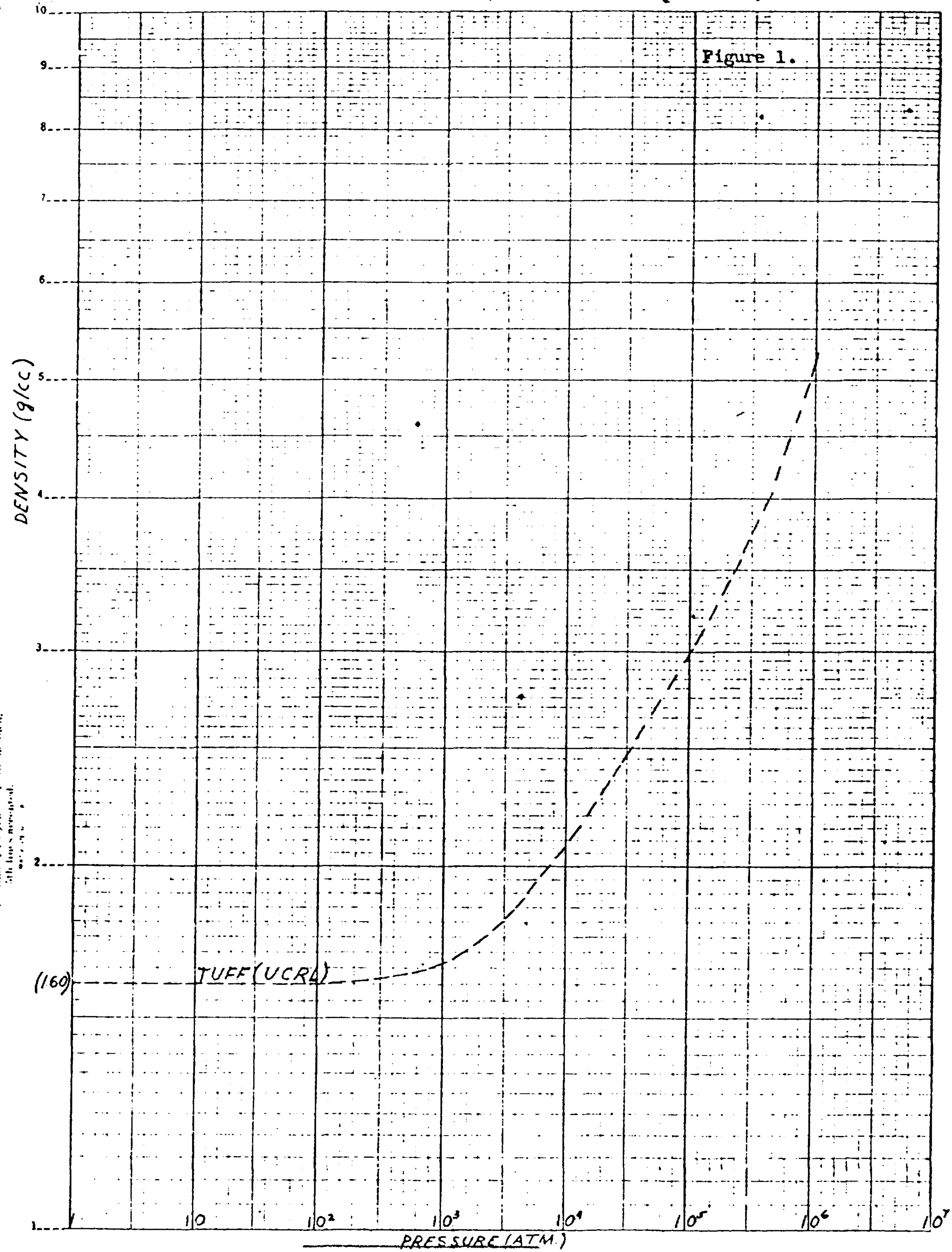

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