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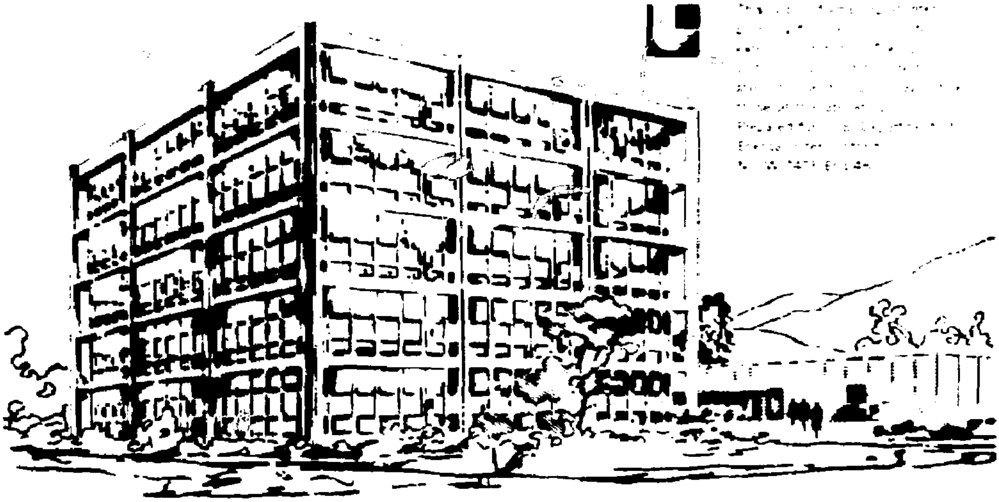

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A NOVEL SCHEME FOR MAKING CHEAP ELECTRICITY WITH NUCLEAR ENERGY

ABSTRACT

Nuclear fuels should produce cheaper electricity than coal, considering their high specific energy and low cost. To exploit these properties, the scheme proposed here replaces the expensive reactor/steam-turbine system with an engine in which the expansion of a gas heated by a nuclear explosion raises a mass of liquid, thereby producing stored hydraulic energy. This energy could be converted to electricity by hydroelectric generation with water as the working fluid or by magnetohydrodynamic (MHD) generation with molten metal. A rough cost analysis suggests the hydroelectric system could reduce the present cost of electricity by two-thirds, and the MHD system by even more. Such cheap power would make feasible large-scale electrolysis to produce hydrogen and other fuels and chemical raw materials.

INTRODUCTION

Nuclear energy is both abundant and inexpensive as raw fuel. It is being used widely to produce electrical energy at about the same cost as electrical energy from coal. However, considering the very high specific energy and the low cost of the nuclear fuels, they should be able to produce much cheaper electrical energy. What needs to be done is to find ways of converting nuclear energy to electricity that take advantage of these unique properties of nuclear fuels, so that a large cost reduction is realized.

This paper discusses one approach that takes a large step in this direction, perhaps yielding a two-thirds reduction or more in the cost of electrical energy. This in turn would allow the economical use of electrolysis for producing hydrogen and other fuels and chemical raw materials.

In a steam-turbine electrical generating plant, heat from a nuclear reactor is used to boil water, producing superheated steam. Basically, the scheme outlined here replaces the steam-producing reactor with an engine in which the expansion of a gas heated by a nuclear explosion is used to raise a mass of liquid, producing stored hydraulic energy. This opens the way to the application of hydroelectric generation of electricity, which is much cheaper than the expensive steam-turbine system. Still other systems using stored hydraulic energy are possible, such as a magnetohydrodynamic (MHD) generator driven by flowing liquid metal, which may reduce the cost even more.

WATER-PISTON ENGINE

Expansion Chamber

Suppose a large, cylindrical chamber with a hole in the bottom was partially filled with water, as shown in Fig. 1. If a nuclear explosive were detonated in the gaseous region, with a yield not so large as to break the chamber but still large enough to make a high pressure in the gas, then the water would be driven out the hole at the bottom at high speed. As the water level fell, the gas, now heated by the nuclear energy, would expand and do work on the water.

This arrangement constitutes the essence of an engine that will convert nuclear energy into kinetic energy of moving water (the high-speed jet coming out the hole at the bottom). The obvious limitation of this engine is that the water-gas interface is Taylor unstable if the water level falls at an acceleration greater than the acceleration of gravity. Taylor instability would lead to mixing of the water and the gas and the production of a lot of hot water and cool steam that will not do much work in the expansion.

[In the following calculations, h, Δh, and R are defined in Fig. 1; $\bar{E}$ is the time-averaged power in the water jet; Y is the yield of the nuclear charge; p is the pressure at the start of the expansion; g is acceleration due to gravity; γ is the specific heat ratio for the heated gas; and η is the expansion ratio $h/\Delta h$.]

Assume, then, that the flow rate out the hole is regulated so that the water falls at 1 g. This will require a time-variable hole size, i.e., small at first and getting bigger as the expansion progresses. In addition, assume that $\Delta h = R$ and that it takes the same amount of time to fill the chamber as to empty it.

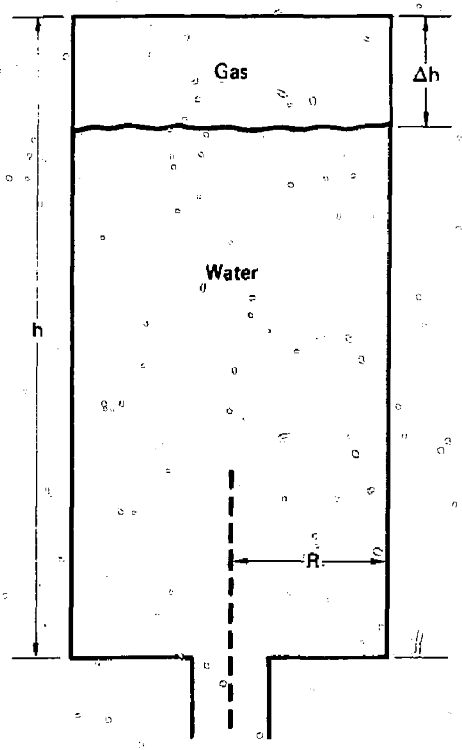

FIG. 1. Elements of the water-piston engine.

The time it takes for the water to fall the distance h − Δh in the expansion chamber is

$$t = \sqrt{\frac{2(h - \Delta h)}{g}} = \sqrt{\frac{2\Delta h(\eta - 1)}{g}} \quad . \tag{1}$$

Therefore, its cycle time will be

$$\tau = 2\sqrt{\frac{2\Delta h(\eta - 1)}{g}} \quad . \tag{2}$$

The amount of work done will be

$$W = \frac{p\pi R^2 \Delta h}{\gamma - 1}\left[1 - \left(\frac{h}{\Delta h}\right)^{-(\gamma-1)}\right] = \frac{p\pi\Delta h^3}{\gamma - 1}\left[1 - \eta^{-(\gamma-1)}\right] \quad . \tag{3}$$

Note that $\Delta h = \left[(\gamma - 1)Y/\pi p\right]^{1/3}$. The time-averaged power will then be

$$\bar{E} = \frac{W}{\tau} = \frac{\pi^{1/6} g^{1/2} p^{1/6} Y^{5/6}\left[1 - \eta^{-(\gamma-1)}\right]}{2\sqrt{2}(\gamma - 1)^{1/6}\,(\eta - 1)^{1/2}} \quad . \tag{4}$$

Using numerical values of $\gamma = 1.4$, $\eta = 6$, and $g = 1000$ cm/s^2 gives

$$\bar{E} = 3.62 p^{1/6} Y^{5/6} \text{ ergs/s,} \tag{5a}$$

with p in dynes/cm^2 and Y in ergs; or, with p in atm (10^6 dynes/cm^2) and Y in GJ (10^{16} ergs),

$$\bar{E} = 0.078 p^{1/6} Y^{5/6} \text{ GW.} \tag{5b}$$

At p = 100 atm,

$$\bar{E} = 0.168 Y^{5/6} \quad . \tag{6}$$

Notice that $\eta = 6$ and $\gamma = 1.4$ imply that the thermodynamic efficiency is 51%.

Power Smoothing and Velocity Sorting

Something needs to be added to the above described engine in order to make it really useful. The power comes in pulses, whereas the electrical power we hope to obtain should come at a steady rate. Still worse is the fact that the water doesn't all come out at the same velocity. We need to store the energy to run electrical generating equipment between pulses and to sort out the various portions of the water according to their velocities so that all the water can be used efficiently. Note that one cannot store the energy of flowing water for a very long time because, even for a very smooth pipe, the loss of kinetic energy is about 1% for a length of flow of one pipe diameter.

One scheme that will accomplish both velocity sorting and energy storage would be as follows (see Fig. 2). Suppose that the water, as it came out of the nozzle at the bottom of the expansion chamber, was directed up a large shaft that was tilted slightly off the vertical. This shaft would be long enough to allow the vertical motion of even the highest-velocity water to be slowed down and stopped by gravity. As each portion of the water neared its apex, its horizontal motion would carry it to the lower side of the shaft. Here it would be collected into storage chambers at whatever level it reached. Note that not much dynamic head would be lost in this scheme because the friction between the water jet and the air in the shaft would be much less than that between flowing water and a confining wall. Also, the air in the shaft could be moving so that the relative velocity between air and water would be less than the jet velocity.

Adding this element gives an engine that converts nuclear energy into stored hydraulic energy.

CAPITAL COST

Expansion Chamber

If an explosive is detonated in a spherical pressure vessel that is untamped--i.e., there is a vacuum outside the vessel--the maximum stress in the wall will be

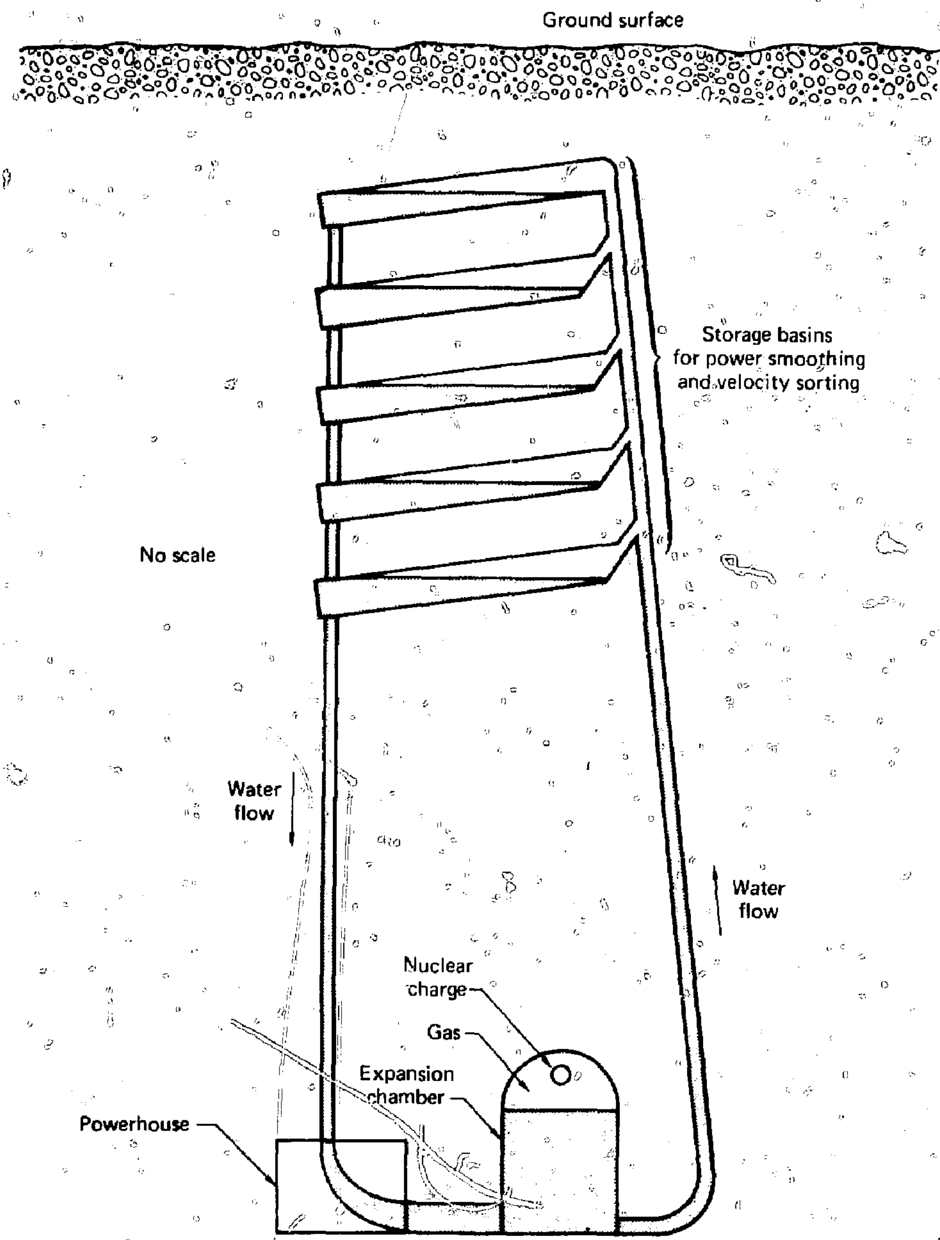

FIG. 2. Conceptual schematic of an engine for producing stored hydraulic energy, coupled with a hydroelectric plant. The path of the water is shaded.

$$\sigma_{max} = \frac{3(\gamma - 1)Y}{8\pi R^2 \delta} \left[1 + \sqrt{1 + \frac{4ME}{9(\gamma - 1)^2 Y\rho(1 - \nu)}} \right], \qquad (7)$$

where σ_{max} is the maximum tensile stress, R the radius, δ the thickness, E the elastic modulus, ρ the density, and ν Poisson's ratio of the vessel; Y is the explosive yield; and M is the mass and γ the specific heat ratio of the atmosphere plus explosive debris inside the vessel. This stress can be separated into three parts: 1) the equilibrium stress due to the steady pressure (the first 1 inside the brackets), 2) an overshoot due to the sudden appearance of the pressure (the 1 inside the radical), and 3) an overshoot due to the impulse in the expanding shock from the explosion (the other terms inside the radical). Note that if a high-specific-yield nuclear explosive is used and the surrounding atmosphere inside the vessel is a light gas such as hydrogen or helium, the ratio M/Y will be small, making the shock impulse small.

The expansion velocity of the vessel will be equal to the net applied impulse divided by the mass of the vessel:

$$v = \frac{I}{4\pi R^2 \rho_v \delta}, \qquad (8)$$

where I is the net impulse given to the vessel on the way to its static equilibrium, R is the radius and δ the thickness of the vessel, and ρ_v is the density of the vessel material.

Now let us assume that the vessel is tamped--i.e., immersed in some dense solid or liquid medium so that when the vessel expands, the surrounding medium (the tamper) expands, too. Let us also assume that the mass of tamper that moves is much greater than the mass of the vessel. In this case the expansion velocity will be equal to the applied impulse divided by the mass of the tamper that moves:

$$v_T = \frac{I}{4\pi R^2 \rho_T C_T \Delta t}, \qquad (9)$$

where ρ_T is the density and C_T the sound speed of the tamper, $\Delta t = R/C_V$ is the 1/4-cycle time of the vessel, and C_v is the sound speed of the vessel material.

Then the ratio of the expansion velocities is

$$\frac{v_T}{v} = \frac{\rho_V C_V \delta}{\rho_T C_T R} . \qquad (10)$$

The overshoot in stress will be reduced from the untamped case by the ratio v_T/v. For vessels and external materials of interest, the value of this ratio will be in the range of 0.3 to 0.1.

If one assumes good tamping and a nuclear charge with a specific yield of at least 0.1 GJ/kg, the overshoot stress will be much less than the equilibrium stress. Let us assume then that the vessel need contain only the equilibrium pressure. In this case a vessel made of HY80 steel, stressed to 60,000 psi (1/3 safety factor), would weigh 1.2×10^4 lb/GJ of explosive yield (assuming γ = 1.2*). An infinite cylinder would require 4/3 times as much steel per unit volume as a sphere. The expansion chamber is actually a cylinder with endcaps, a shape which will be between a sphere and an infinite cylinder. Let us assume, then, the upper limit of the infinite cylinder for the weight, or 1.6×10^4 lb/GJ.

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*The assumption of $\gamma = 1.2$ to calculate the containment volume is justified because immediately after the explosion much of the gas will be so hot that it will undergo molecular dissociation. However, it takes several seconds for the expansion to go to completion. During this time the hot gas can mix with cooler gas near the walls or with water droplets so as to cool down and recombine, thus increasing γ to approximately 1.4. If this happens too fast, the pressure will rise higher than that which occurred in the first few milliseconds after the explosion. On the other hand it may be possible to tune the engine by having the mixing occur at a rate such that the pressure drop due to expansion cancels the pressure rise due to increasing γ. This would make the engine expansion partly isobaric and partly adiabatic, slightly increasing the power and slightly decreasing the efficiency.

Note that even though the energy from the explosion is contained within the gaseous region, the pressure is transmitted everywhere inside the expansion chamber (but not out the hole), because of the water. Therefore, a volume η times as large as is needed to contain the energy must be built to contain the pressure produced by the energy deposited in the gas.

The cost of fabricating a pressure vessel from HY80 steel will be in the range of $5 to $15 per pound, depending on size, location, and complexity. Using $15/lb to estimate the cost of the expansion chamber gives a cost of $(2.4 \times 10^5)\eta$ \$/GJ, or \$$1.44 \times 10^6$/GJ for the case where $\eta \approx 6$ as in Eq. (5). Therefore, the cost per unit power is approximately $8Y^{1/6}$ \$/kW, using Eq. (6) for the relationship between power and yield.

Assume that the expansion chamber is to be built deep underground, to provide the tamping and secondary containment, and that the overburden pressure is greater than the peak pressure reached in the expansion chamber. This will allow the expansion chamber walls to be always in compression, giving an additional fail-safe feature. The cost of mining a large cavity deep in competent rock, grouting the walls, and lining the cavity with a gas-tight steel bladder is estimated at $180 to $380 per cubic meter.[1] The volume to contain a tamped explosion is

$$V = \frac{(\gamma - 1)Y}{p} , \tag{11}$$

or, with $\gamma = 1.2$ and $p = 100$ atm $\approx 10^{-8}$ GJ/cm^3,

$$V = 2 \times 10^7 \text{ cm}^3/\text{GJ or } 20 \text{ m}^3/\text{GJ} . \tag{12}$$

Multiplying by $\eta = 6$ gives 120 m^3/GJ for the engine having an expansion ratio of 6 calculated earlier. This would cost \$$4.56 \times 10^4$/GJ or $0.27Y^{1/6}$ \$/kW using the higher mining cost of \$380/m^3. This is negligible in comparison with the \$8/kW for the strong steel vessel that is to be put inside. This shows that there is a large potential for reducing the cost of the expansion chamber.

The cavity described above is capable of functioning as the expansion chamber by itself, even though it costs a small fraction of the cost of the strong steel vessel. What could go wrong is that the rock near the cavity walls might gradually move about and crack under the repeated stress variations caused by the explosions. If this happens, the roof might cave in because the rock is supporting the overburden pressure. What the strong steel vessel does is to guarantee the survival of the expansion chamber even if the rock gives out.

Shaft and Storage Basins

Let us assume that the cost of the shaft and the storage basins (the storage basins would be rather small) is about the same as the cost of the large water conduit between the top and bottom reservoirs of an underground pumped storage installation. Reference 2 gives this cost as \$7/kW to \$14/kW for a conventional system (updated to 1978 dollars). Because in our system the water and gas will be radioactive, an additional gas-tight steel liner will be needed; this will about double the cost, bringing it to \$28/kW if the higher base figure is used.

Total Capital Cost

Three more major components are needed to make a complete nuclear-electric power plant: a return water conduit, a hydroelectric powerhouse, and a heat exchanger to get rid of the excess energy due to various inefficiencies.

As stated above, the water conduit costs \$28/kW.

The same reference[2] estimates a powerhouse, complete with turbogenerators, at about \$55/kW.

Since the heat exchange would probably be to atmospheric air, an intermediate as well as final heat exchanger would be needed; this might cost about \$40/kW for the two stages.

With these three components, plus the shaft and storage basins, the capital costs excluding the expansion chamber thus would be \$151/kW.

Table 1 gives the minimum nuclear charge yield, the expansion chamber cost, and the total capital cost for three plant sizes.

The total capital cost is less than one-third the cost of a conventional nuclear plant. If the operating expenses can be made low enough, it will be possible to produce electricity for about one-third the present cost.

TABLE 1. Minimum nuclear charge yield, expansion chamber cost, and total capital cost for three plant sizes.

Plant size (GW)	Nuclear charge yield (GJ)	Expansion chamber cost ($/kW)	Other capital costs ($/kW)	Total capital cost ($/kW)
1	8.5	11	151	162
10	134.8	18	151	169
100	2136	29	151	180

NUCLEAR CHARGE COSTS

The main operating expense will probably be the cost of the nuclear charge. Electricity costs about $10/GJ or, if the 1/3 cost factor is applied, $3.3/GJ. It might be reasonable to apply as much as 1/4 of this cost, or $0.8/GJ, to the cost of making the nuclear charge. Thus, it is seen that for a conventional-size plant of 1 to 2 GW the nuclear charges would have to be rather inexpensive. At minimum yield, the charges could cost no more than, say, $10 to $20 each. Notice, though, that the expansion chamber costs only about 10% as much as the rest of the plant. This suggests that one might make an oversize chamber to accommodate a larger yield such that the cost could be as high as $100. Still, it is doubtful whether a nuclear charge can be made for as little as $100.

As stated earlier, the expansion chamber may be much less costly than so far calculated. The mined, gas-tight cavity to contain this expansion chamber can actually do the expansion chamber's job (at least for a few cycles), but it costs only about 1/30 as much. Perhaps a more realistic figure for the cost of the expansion chamber would be 1/10 the cost estimated earlier. This would allow still higher charge yields to be used, so that the allowed cost of the nuclear charge might be as high as $1000.

Since electricity will be so much cheaper, it will be economical to produce hydrogen and other fuels by electrolysis on a large scale. In this case, the plants could be much larger, say 10 to 100 GW. This scale will let the allowed nuclear charge cost to go to $1000 or more even if the expansion chamber cost is $8Y^{1/6}$ $/kW.

A neutron-absorbing blanket can be made an integral part of the nuclear charge. This will utilize neutrons produced in the explosion to transmute fertile material into fissile material and other useful isotopes such as tritium. To recover these isotopes the nuclear-charge debris will have to be extracted from the water and gases contained in the system. Tritium, for instance, will probably combine with the water. However, the amount of water that need be present is so small that the tritium could be recovered at present day prices after only a few days or weeks of operation. It seems likely that by this means fissile material, tritium, and many other useful isotopes would become very much less expensive.

SOME MORE NOVEL CONCEPTS

It is humbly acknowledged that the cost estimates given in this paper are crude and inadequately researched. Intuition says that they will only go up if done correctly and in detail. On the other hand, the scheme is itself incompletely exploited. With these thoughts in mind, I wish to offer a few more ideas that become possible once the basic engine concept is accepted. The hope is that reconceptualizing and integrating various parts of the system will counteract the tendency of the cost to rise and in fact may lead to further cost reductions.

Magnetohydrodynamic (MHD) Generator

First of all, note that there is rather small amount of captive, reusable working fluid (the water). This may be about 3000 tons for a 1-GW plant, increasing in direct proportion to the power. Note also that the water can attain fairly high velocities (140 m/s) on a 1000-m head. This suggests the feasibility of generating electricity by the Hall-effect MHD approach, using a conducting liquid instead of a hot gas. What needs to be done is to make the water sufficiently low in resistivity; probably a resistivity of a few hundred milliohm-centimeters is about right. This could be done by, for instance, adding NaOH to get the resistivity down to a few ohm-centimeters and then adding enough colloidally suspended graphite to short out 80 to 90% of the path length. The water would be accelerated by gravity to full velocity and then slowed at the bottom of the return conduit by the magnetic field, in the process efficiently producing electricity. This approach might prove to be much cheaper to build than a conventional hydroelectric powerhouse (which was one of the major cost items in the preceding calculation). It would also be virtually maintenance-free because the only moving part would be the water. Using molten lithium, sodium, or NaK instead of water might also be considered; liquid-metal-driven MHD generators would require much lower magnetic fields, temperatures, and fluid velocities and would, therefore, be much less expensive than gas-driven MHD generators.

The return water conduit is itself a major cost item. This is because the water must be run down the shaft at a very low velocity. Remember that the fractional loss of dynamic head is approximately 1% per pipe diameter, even for a very smooth pipe. Suppose that only the top portion (say 10%) of the conduit were made in the conventional way. Then suppose that at the bottom of this section the water were run through an annular nozzle so that a hollow cylindrical high-speed jet was formed (see Fig. 3). In addition the water would be given a slight radial velocity inward, so that as the water fell and gained speed, the radial velocity would contract the jet to compensate for the area reduction of the annular section of the jet due to the speed-up, thus keeping the jet from breaking up. The hollow region in the center of the jet is necessary because the area loss rate cannot be matched all along the jet by a single radial velocity. At the bottom the hollow region would disappear and the water would be at full velocity, ready to enter the MHD generator. It is obvious that the portion of the conduit that contained the jet need be only slightly larger than the jet, enough so that the water did not touch the wall. This diameter would be much less than if the water were moving slowly at the same volume flow rate, and thus the volume and cost of the conduit would be reduced by a large factor.

Two Expansion Chambers

Still other schemes may be practical. It may be that a better way to deal with the variable water speed can be found that does not require taking the water up a large tunnel. If a scheme can be devised to manage the variable water speed at the full depth of the expansion chamber, the pulsed nature of the power output could be handled by using two expansion chambers. In addition, if the expansion chambers become much less expensive than the $8Y^{1/6}$ \$/kW estimated earlier, one could consider increasing the expansion ratio. This would allow an increase in efficiency and a reduction in the heat rejected at the surface, giving a reduction in the heat exchanger cost.

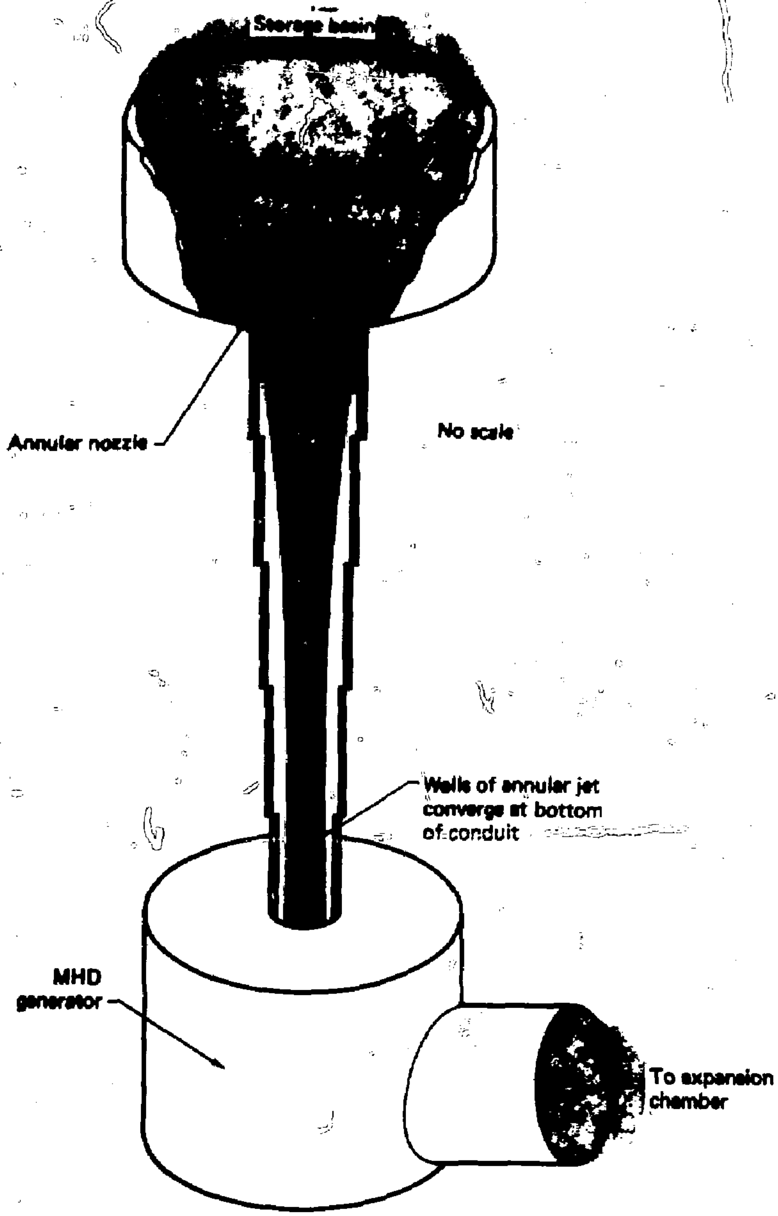

FIG. 3. Scheme for minimizing conduit diameter.

Dense Liquid Metal Working Fluid

Definite advantages are obtained by using a dense liquid metal such as molten lead, or a low-melting-point eutectic of similar density, as the working fluid. Notice that if p is held constant, the height of the two fluid conduits is inversely proportional to the density of the fluid. Therefore, if molten lead were used instead of water, the length of the conduits would be reduced by about a factor of 10. This would, presumably, reduce their cost by the same factor. Also, this would allow the full overburden pressure to be used without the tops of the conduits coming near the surface of the ground.

Helium could be used as the expansion gas if lead or some other liquid metal were used as the working fluid. This is so because the boiling points of these metals are so high that the helium gas would stay fairly pure throughout the cycle. An analysis of the expansion chamber cost calculation shows that, at the same efficiency, helium at $\gamma = 1.66$ leads to the same cost as that calculated for steam starting at $\gamma = 1.2$ and going to $\gamma = 1.4$ during the expansion. This is mainly because, to reach an efficiency of 51%, an expansion ratio of only 3 is needed with helium, vs 6 with steam. Halving the expansion ratio leads to an expansion chamber length that is only 0.61 times the length for steam and a fluid height in the chamber of only 0.5 times the height for steam. In addition, the combination of helium and lead should result in a very benign chemical environment (no corrosion, oxidation, hydriding, etc.).

An efficiency problem arises if the diminished height of the conduits becomes comparable with the height of the fluid in the expansion chamber. Having passed through the generators, the working fluid must retain enough of its kinetic energy to refill the expansion chamber to the initial height. This portion of the source energy is not available for power generation, but must be circulated around the system. When the hydraulic head is large compared with the height of the fluid in the expansion chamber, this circulating energy is a small fraction of the system energy; but if the conduits, shortened by virtue of the denser working fluid, become comparable in height with the fluid in the expansion chamber, then there is a large fraction of circulating energy, with a resultant inefficiency. This problem is partly solved by using helium as the working gas. Burying the system deeper and working at higher pressure helps greatly. The height of the conduits is proportional to p, and the height of the expansion chamber is proportional to $p^{-1/3}$. This gives the ratio of conduit height to height of fluid in the chamber as $p^{4/3}$. Thus, if the expansion chamber were put at 2000 m depth, where the overburden pressure is 400 atm, one would have a conduit height of 400 m with $\rho = 10\ g/cm^3$ liquid. If helium were used, at 51% thermodynamic efficiency, the height of the fluid in a 100-GW expansion chamber would be only 34 m, giving a height ratio of nearly 12, which is more than adequate.

Economic questions arise about using an expensive liquid metal as the circulating fluid. Therefore, let us calculate the amount of lead that might be required. Assume E = 100 GW, p = 400 atm, $\gamma = 1.67$, $\eta = 3$. We will then have Y = 922 GJ, $R = \Delta h = 17$ m, $h - \Delta h = 34$ m. The volume of lead in the expansion chamber will then be $V = \pi R^2(h - \Delta h) = 3.09 \times 10^4\ m^3$, giving a mass of about 3×10^5 metric tons. The fate of the lead during a cycle is that it falls down to the bottom of the expansion chamber, falls up to the top of the up conduit, falls down to the bottom of the down conduit and falls up to its starting point in the expansion chamber. Ignore the fact that not all the lead has to travel the whole distance (this will tend to overestimate the amount of lead present). The time it takes to complete a cycle is

$$\tau = 2\sqrt{\frac{2 \times 400}{10}} + 2\sqrt{\frac{2 \times 34}{10}} = 23.1\ s\ , \tag{13}$$

and the time it takes to fall out the bottom of the expansion chamber is

$$t = \sqrt{\frac{2 \times 34}{10}} = 2.6\ s\ . \tag{14}$$

Therefore, the amount of lead in the system will be

$$M = 3 \times 10^5 \times \frac{23.1}{2.6} \approx 2.6 \times 10^6 \text{ metric tons.} \tag{15}$$

Lead costs about \$840/metric ton, so let us assume \$1000/metric ton installed. This works out to $\$2.6 \times 10^9$ or \$26/kW. The use of lead instead of water reduces the cost of the conduits from \$56/kW to \$5.6/kW, so that the net saving is \$56 - (\$26 + \$5.6) = \$24/kW. Thus it is seen to be economical to do this. However, resource availability may be a problem, since the present U.S. yearly consumption of lead is only about 10^6 tons.

Racetrack Engine

In principle it is possible to build a system such as is shown in Fig. 4. In this scheme a fluid charge arrives at the top of the expansion chamber just as another fluid charge is driven out the bottom. Once out of the expansion chamber, the fluid flows around the rest of the racetrack, giving up most of its kinetic energy to the MHD generators. Since some of the fluid will always be going through some of the MHD generators, it should be possible to maintain a constant voltage in the external electric circuit by switching.

In order to calculate the power, let us assume that the velocity of the fluid, as it enters the expansion chamber, is $v_0 = \sqrt{p/\rho}$, where p is again the peak pressure in the chamber and ρ the density of the fluid. Assume, also, that gravity is negligible and that the nuclear charge is fired just as the leading edge of the fluid reaches the bottom of the chamber. In this case, if the variable-outlet nozzle is properly regulated, the fluid will enter and cross the chamber at constant velocity. The time to accomplish this will then be

$$\tau = \frac{(2\eta - 1)\Delta h}{v_0} , \tag{16}$$

and the energy given to the fluid will be

$$\Delta E = \left[1 - \eta^{-(\gamma-1)}\right] Y \quad . \tag{17}$$

Note again that $\Delta h = \left[\frac{(\gamma - 1)Y}{\pi p}\right]^{1/3}$.

The average power will then be

$$\bar{E} = \frac{\Delta E}{\tau} = \frac{Y^{2/3}\, p^{5/6} \left[1 - \eta^{-(\gamma-1)}\right]}{\pi^{1/3}\, \rho^{1/2}\, (\gamma - 1)^{1/3}\, (2\eta - 1)} \quad . \tag{18}$$

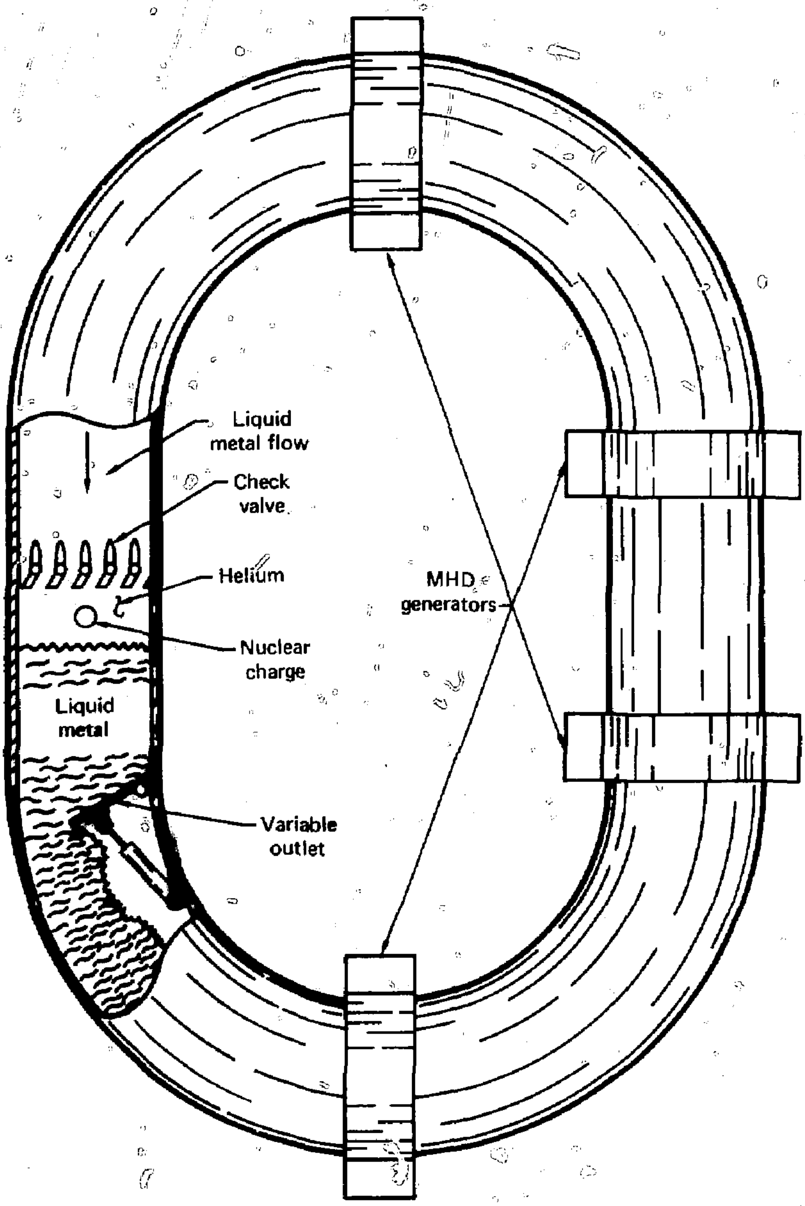

FIG. 4. Racetrack engine.

Using numerical values $\gamma = 5/3$ and $\eta = 3$ (51% efficiency) gives

$$\bar{E} = 0.053 \frac{Y^{2/3} p^{5/6}}{\rho^{1/2}} , \tag{19}$$

with $\bar{E}$ in GW, Y in GJ, p in atm, and ρ in g/cm^3. Thus it is seen that at high pressures the power will be much higher than with the engine that depends on gravity to move the fluid out of the chamber.

Figure 4 was drawn with a major radius (R) on the turns equal to 4 times the minor radius. The straight sections have a length of $(2\eta - 1)\Delta h$, with $\Delta h = R/4$. Using $\eta = 3$, the part of the mean circumference outside the straight section on the expansion chamber leg is $L = 2\pi R + (2\eta - 1)(R/4) = 7.53R$, and the maximum velocity of the fluid is

$$v_{max} = \sqrt{v_0^2 + \frac{2p}{\rho}} = \sqrt{3}\ \ v_0 \quad . \tag{20}$$

The distance this part of the fluid would go if not slowed down by the MHD generators is

$$S = v_{max}\ \tau = \sqrt{3}\ (2\eta - 1)\frac{R}{4} = 2.17R \quad . \tag{21}$$

Therefore,

$$\frac{S}{L} < 0.29 \quad . \tag{22}$$

Thus it is seen that this geometry will have more than three separate fluid charges going through the MHD generators at any given time.

The average specific kinetic energy of the fluid, $(1/2)\rho v^2$, will be about equal to U, the energy per unit volume it gained in passing through the expansion chamber. The loss in specific energy is

$$\Delta U = \frac{1}{2}(\rho v^2)\frac{\ell}{d}f \quad , \tag{23a}$$

and

$$1 - \epsilon_f = \frac{\Delta U}{U} = \frac{(1/2)\rho v^2}{U}\frac{\ell}{d}f = \frac{\ell}{d}f = 0.01\frac{\ell}{d} \quad , \tag{23b}$$

where ℓ is the length and d the diameter of the flow, f is the friction factor, and ϵ_f is the frictional efficiency factor.

The maximum possible ℓ is along the outermost circumference, i.e.,

$$\ell_{max} = 2\pi(R + \frac{R}{4}) + 2(2\eta - 1)\frac{R}{4} = 10.35R \quad , \tag{24}$$

and the minimum flow diameter will be about

$$d = 2\Delta h\sqrt{\frac{v_0}{v_{max}}} = 3^{-1/4}\left(\frac{R}{2}\right) = 0.38R \quad ; \tag{25}$$

therefore,

$$\epsilon_f > 0.73 \quad . \tag{26}$$

Thus, it is seen that the frictional losses will be acceptable.

REFERENCES

1. S. L. Ridgway and J. L. Dooley, "Underground Storage of Off-Peak Power," in Proc. 11th Intersociety Energy Conversion Engineering Conference, Stateline, Nevada, September 12-17, 1976 (American Institute of Chemical Engineers, New York, 1976), vol. 1, p. 586.
2. R. H. Resch and D. Predpall, "Pumped Storage Site Selection: Engineering and Environmental Considerations," in Pumped Storage, an Engineering Foundation Conference, Franklin Pierce College, Rindge, N.H., August 18-23, 1974 (American Society of Civil Engineers, New York, 1975), p. 39; F. C. Rogers, "Existing Hydroelectric Generation Enhanced by Underground Storage," ibid., p. 415. I assume that the curve in Fig. 6 of Resch and Predpall is for 1000 MW, not 100 as cited in the note.

GS:jm