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PACER REVISITED[*]

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ABSTRACT

This paper discusses a modified version of the PACER concept for power and nuclear material production. In the PACER concept, a 20-kt peaceful nuclear explosion is contained in a cavity about 200 m in diameter, filled with 200 atm of 500°C steam. Energy from the explosion is used to produce power, and the neutrons are used to produce materials such as ^{233}U. The present idea is to modify the PACER concept in three ways to improve the practicality, predictability, and safety of power production from this technology and thus improve public acceptance of this power source. These improvements are (1) line the cavity with steel; (2) replace the steam with molten salt, LiF + BeF$_2$; and (3) reduce the explosive yield to about 2 kt. PACER is the only fusion power concept where the underlying technology of the power source itself is proven and in hand today. The molten-salt shock-suppression and heat transport system and the durability of the underground cavity need demonstration.

INTRODUCTION

Power can be produced with known technology by repetitive nuclear explosions (called peaceful nuclear explosions) contained in an underground engineered cavity. In the PACER concept [1], the steam in the cavity is passed through a turbine, producing 1000 MWe for an explosion every 7 hr. The steam, which is filtered of debris and useful materials, dampens the shock wave so the pressure against the cavity wall rises from 20 MPa before the explosion to 26 MPa right after the explosion.

This paper discusses several aspects of a modified version of the PACER concept, including cavity design and fireball pressure dynamics. More details of the modified PACER concept and the thermodynamics leading to the cavity pressure after the explosion are given in Ref. 2.

The PACER concept is modified in three ways: (1) the cavity is lined with steel; (2) the steam is replaced with molten salt; and (3) the explosive yield is reduced to about 2 kt.[1] Lining the cavity with steel makes it engineerable and predictable, and prevents contamination of the working fluid. The steam working fluid is replaced with molten salt, LiF + BeF$_2$ (FLiBe) in the form of droplets, to absorb energy and suppress shocks.[2] This change results in an ambient pressure below 1 atm soon after the explosion and allows much of the its energy to go into evaporation, thus reducing the pressure in the cavity right after the explosion to about 3 MPa. Also, because tritium is insoluble in the molten salt, it can be removed almost completely, thus reducing the tritium inventory by a factor of 100,000—from $\sim 10^7$ Ci using steam to ~ 100 Ci using FLiBe. Then, when the explosive yield is reduced to 2 kt, the cavity volume is reduced by a factor of 50, which reduces the peak pressure in the cavity by a factor of 9.

In the modified PACER concept, the cavity is tall and cylindrical—rather than spherical—with a smaller radius of curvature and a hemispherical roof (Fig. 1). As such, the cavity should be much more durable.

A comprehensive test ban would exclude all peaceful nuclear explosions to test such concepts; however, a threshold test ban that limited tests to 15 kt or even 2 kt would permit testing. The low ambient pressure ($\ll 1$ atm), low tritium inventory, and low fissile inventories should all contribute toward public acceptability of the concept. The close connection with nuclear weapons technology is problematic; however, interest in a reusable underground test chamber [4] may help develop this type of power source.

CAVITY DESIGN

The three cavity shapes considered in this report are shown in Fig. 2, all with the same volume and hence the same equilibrium pressure. The spherical cavity provides the greatest distance from the explosive, which minimizes the pressure pulse over that of the equilibrium pressure. However, its large dome must be supported. The horizontal cylindrical tunnel

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[1] Nuclear explosive yield traditionally is expressed in tons (2000 pounds) of TNT equivalent, which is 4.186 × 10^9 J and in this paper is abbreviated as kt of yield energy.

[2] An alternate shock suppression system using springs and shock absorbers behind plates is discussed in Ref. 3.

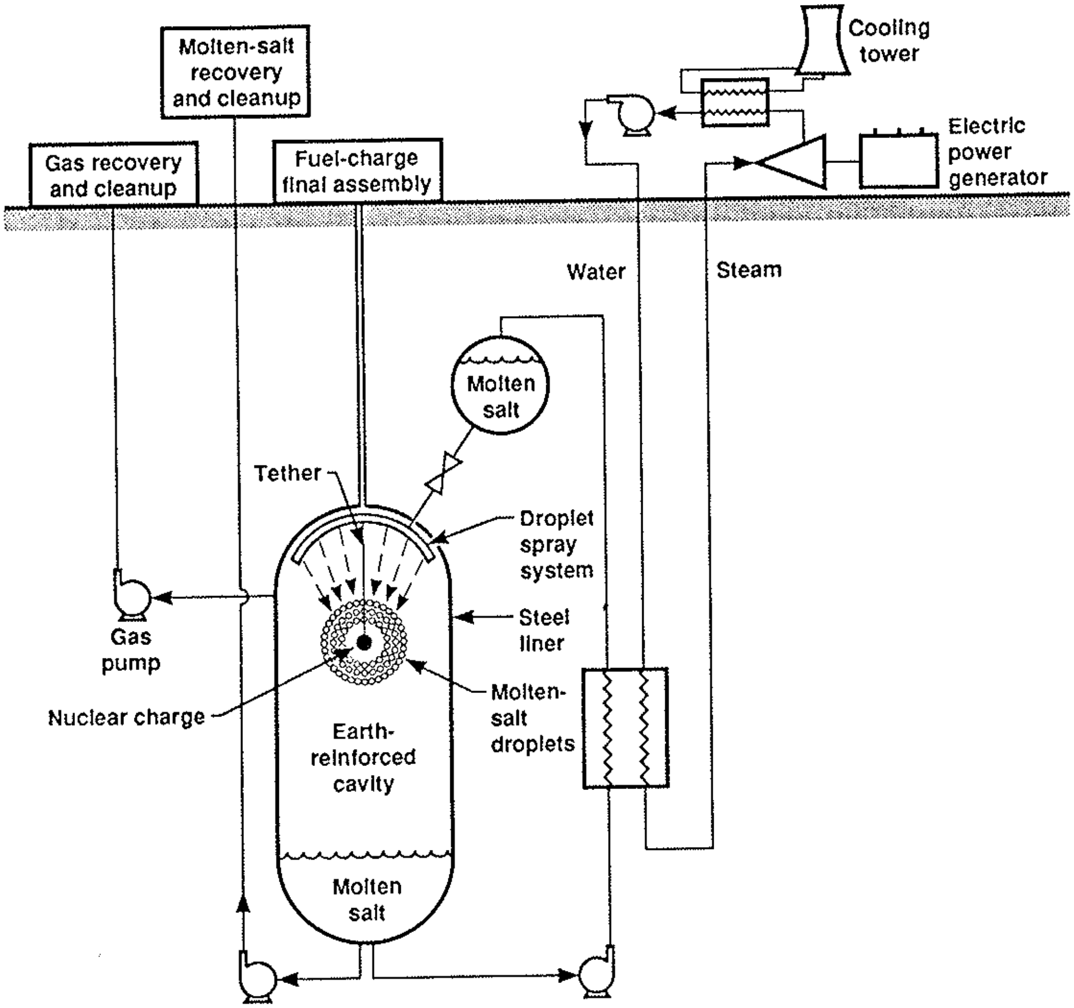

Fig. 1. Schematic of a fusion power system using peaceful nuclear explosions contained in an underground cavity. Molten salt is used to absorb the explosive energy, dampen shock waves, and remove heat.

can be as long as necessary because each end is independent. The roof is supported as a simple arch. The vertical cylinder or shaft has a dome that is more self-supporting than a simple arch; however, the vertical walls of the shaft must be supported against inward collapse. Nevertheless, with this shape the droplets will drain better.

As proposed, the cavity will be constructed underground in high-integrity rock material so the unsupported roof and sides of the cavity will not collapse under cyclic stresses. The suggested cavity shape of a tall cylinder with a hemispherical dome resembles a farmyard silo. This shape will maximize volume and minimize the radius of the domed roof.

The cavity will be lined with steel and secured to the rock with regularly spaced rock bolts or tendons. The steel skin will be convex, as shown in Fig. 3, to keep it tightly stretched against the rock. Then, when the pressure pulses arrive, the skin can transmit the pressure into the rock without a "slapping" effect and thus will prevent the rock from rebounding into the cavity, or spalling.

The static inward pressure on the skin will be up to 0.1 MPa (1 atm) if air infiltrates the rock. The region around the cavity must be pumped free of water because the hydrostatic pressure ($\gg$ 1 atm) would collapse the skin inwardly. If this region is pumped below 1 atm, the stress in the rock bolts could be reduced while still ensuring that spalled material is retained and the rock is reinforced.

The steel skin is designed to overcome an inward pressure, P, of 0.1 MPa. However, if the pressure behind the skin is $\ll$ 0.1 MPa, then no inward load between pulses is on the skin other than that made by the rock bolts. During the pulse, the only added inward load will be caused by rebound, which is minimized by the droplet shock-suppression system.

A convex skin resembling a tufted seat cushion, which was studied for another application [5], may be useful for the cavity liner design shown in Fig. 3. Design parameters for one case used the scaling relation $Pr_2/\sigma t = 0.86$ for $r_1/r_2 = 0.36$. Two examples of parameters are shown in Table 1. The stress in the skin is σ, and the skin thickness is t. The value of σ used here is 140 MPa.

Since the excavated cavity will not conform to the desired skin shape, grout will be injected to fill the gap. A grout material must be chosen carefully so that it has low

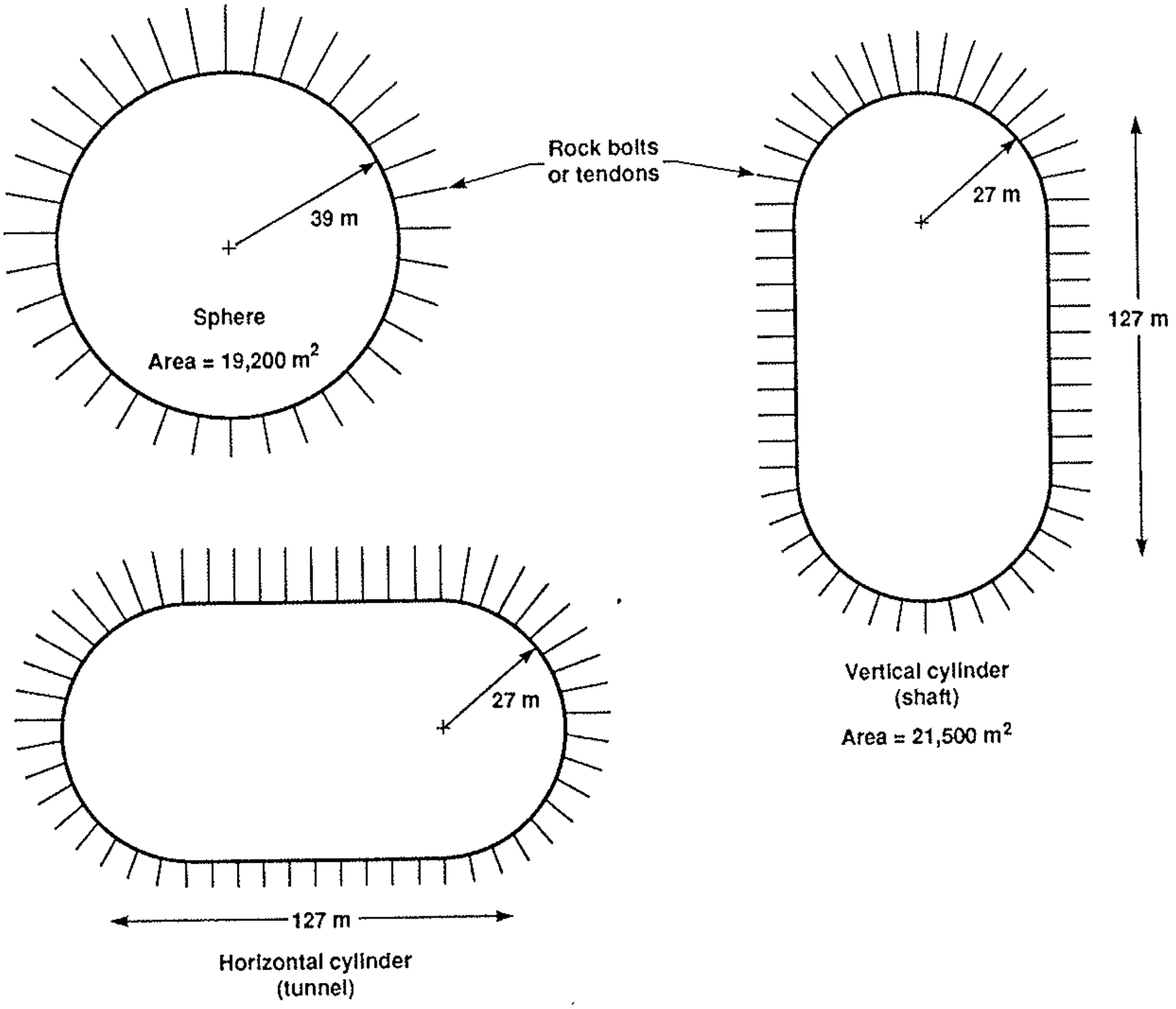

Fig. 2. Three candidate cavity shapes, each of 250,000 m^3. The vertical cylinder is the preferred choice.

vapor pressure at $\geq$ 500°C. Ideally, the vapor should be low in oxygen, nitrogen, silicon, and other materials that would contaminate the molten salt if an inward leak occurred. Such contamination would cause difficulties when the molten salt is processed to remove fissile materials.

Holes drilled for the rock bolts will form a collection system for pumping gaseous material in the region behind the skin to maintain the low gas-phase pressure ($\ll$ 1 atm). In effect, the local hydrostatic pressure would be low. A system of tubes attached to the back of the skin connects each apex and can be used to check leaks in the skin, especially around the apex fixture plates. This system also can be used to keep the pressure well below 1 atm behind the skin. However, preventing grout from plugging the collection system is a design problem that must be solved. To make the job of pumping easy, the rock formation should be fairly gas tight and have low outgassing properties at elevated temperatures. Concrete has fairly low outgassing at room temperature [6], so some cracks could be filled with high-pressure, pumped concrete grout. However, as mentioned, oxygen should be avoided—for example, in the form of H_2O.

Table 1: Example parameters of cavity liner shown in Fig. 3.

Parameter	Case 1	Case 2
r_2 (m)	1	2
r_1 (m)	0.36	0.72
t (mm)	1	2
Number of 3-cm-diam bolts to hold vacuum load at 140-MPa stress in the bolts	1	4

Maintaining a low gas pressure in the cavity makes pumping tritium gas easy.

CAVITY SKIN OR LINING DESIGN

The thermal design of the cavity skin is important. If salt is sprayed on the walls before each shot, the salt-carrying debris from the nuclear device and its surrounding material will not be frozen directly onto the wall. Instead, it will flow to the pool at the bottom of the cavity or freeze onto the existing frozen salt layer. Flowing fresh molten salt can clear

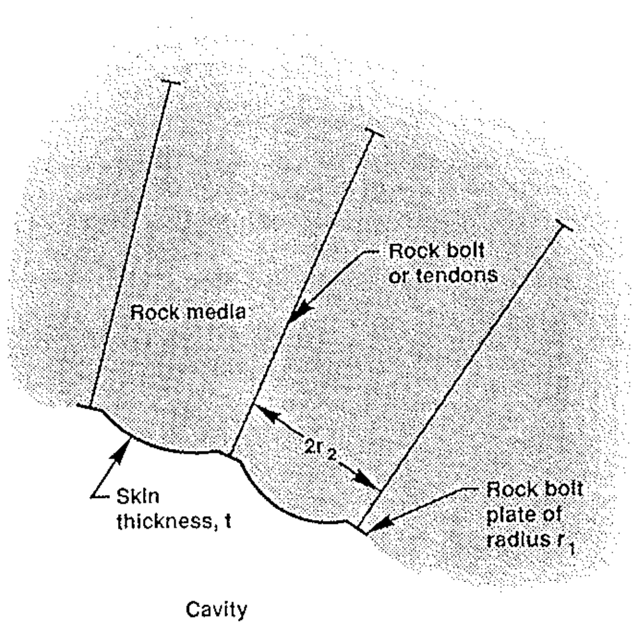

Fig. 3. The convex-shaped-skin cavity liner is attached to the rock material with rock bolts. The liner prevents contamination of the molten salt with rock material and reinforces the rock media.

or remelt this layer. Therefore, the steel skin will remain at an ambient temperature much below the melting point of the molten salt (363°C), except for a short time ($\ll$ 1 hr) between each shot (typically 1/hr). The frozen salt layer can then reduce the thermal stress on the wall.

The steel skin also must be corrosion resistant. For example, alloys high in nickel are good; Hastelloy-n would be excellent; and type 316 stainless steel may be adequate. Pipes used to carry the molten salt to the droplet spray system and to spray the walls will be made of the same material as the skin. The system of pipes to carry the molten salt from the cavity to the pumps and primary heat exchanger is conventional, except the pipes must withstand pressures to about 3 MPa at a pulse rate of about 1/hr. The cavity, its liner, and the piping system must withstand about 200,000 shots over a 30-yr period.

The walls of the lower part of the cavity will be cooled actively so that a reasonable temperature ($<$ 650°C) is maintained during the intershot time of $\sim$1 hr while the heat is removed by circulating the molten salt.

FIREBALL PRESSURE DYNAMICS

The fireball, composed predominantly of vaporized salt with very little nuclear explosive debris, is assumed to condense quickly onto the cold droplets. One limiting process is heat conduction from the surface of a droplet to its interior. The time is characteristic of the thermal diffusivity $k/\rho c$, which for FLiBe is 1.7×10^{-7} m^2/s, where k, the thermal conductivity, is 0.8 W/m K; ρ, the density, is 2050 kg/m^3; and c, the heat capacity, is 2350 J kg^{-1}K^{-1}. The thermal diffusivity time for a droplet of radius r is $\rho c r^2/k$. For spheres, substantial heat can be absorbed in one-tenth of the thermal diffusivity time. For a droplet 1 mm in diameter, this would be 140 ms. The vapor rushing past the droplets from the expanding fireball will distort and break up droplets and cause internal circulation or vortex motion. This vortex motion can enhance heat transfer by up to a factor of 2.7 [7] and oscillations by a similar factor [8]. One way to ensure that the droplets are about 1 mm in diameter is to inject them into the cavity rather than rely on break up of larger droplets. The time to extinguish the fireball appears to be limited by conduction into the droplet rather than by heat transfer within the gas or from the gas to the droplets or by condensation onto the droplets.

After the heat is distributed over 2 kt of molten salt for each kiloton of nuclear energy yield, the pressure in the cavity will drop below 1 atm, which corresponds to a temperture of about 1200°C. An additional 5 kt of molten salt will bring the temperature down to 700°C. If the energy in the fireball can be transferred to the liquid droplets in less time than the expansion time of the cavity (natural frequency of vibration), then the stress in the steel liner can be substantially reduced. By the end of this brief interval, the chemical composition of the salt is assumed to return to its former state.

Before the next shot, the tritium, helium and other noncondensable gases must be pumped out. The molten salt must be pumped through a heat exchanger to lower its temperature and recharge the upper reservoir shown in Fig. 1. The nuclear charge (fusile and fissile) is then lowered on a tether or dropped, and the droplet spray system is turned on to fill the cavity with the appropriate distribution of molten-salt droplets.

CHEMICAL PROCESSING DYNAMICS

During the explosion and shortly afterward ($\ll$ 1 s), the salt and other material will break into atoms and be ionized. The events in this short interval are left for a future paper, as are the droplet spray system and cavity overpressure.

The salt can be kept in a reduced state by continuously reacting it with metallic beryllium; then the tritium will exist as T_2 gas and can be removed by pumping. The uranium also can be removed by reacting with beryllium and by separately removing the uranium from beryllium by fluorination, or the salt can be fluorinated directly in a separate tank. The small amount of fissile material left would be very dilute in the huge amount of salt, so criticality is prevented. Fission products can be continuously removed to limit their hazard potential, as suggested for the redesigned molten-salt reactor [9,10] where safety is enhanced by removing fission products rapidly.

CONCLUSIONS

Power can be produced with known technology by repetitive peaceful nuclear explosions contained in an underground engineered cavity. This paper discusses a modified version of the PACER concept that uses molten salt as the working fluid rather than steam. The modifications discussed in this paper should improve the practicality, predictability, and safety of power production from this technology and thus should improve public acceptance of this power source.

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