

A Novel Fusion Power Concept Based on Molten-Salt Technology: PACER Revisited

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Abstract—Modifications to an old concept for using peaceful nuclear explosions to achieve practical fusion power are discussed. With this concept, useful energy and materials are obtained by repetitively setting off nuclear explosions in an underground cavity. This proposal, which is based on molten-salt technology, involves two modifications:

1. Line the cavity with steel to make it engineerable and predictable rather than relying on an unsupported earthen cavity such as a cavity excavated in a salt dome.

2. Use molten salt rather than steam. More than 70% of the energy released is then absorbed by liquid-salt evaporation, and the pressure to be contained for a given yield can be reduced by a factor of 3 or more.

These modifications result in several improvements in the safety and feasibility of the contained fusion concept:

1. The tritium produced, being insoluble in the molten salt, can easily be pumped away and purified when all the vaporized salt condenses, rather than being mixed with steam.

2. The tritium inventory is substantially reduced, effectively reducing the large hazard in case of accidental venting to the atmosphere.

3. Reducing the yield used in the older studies could reduce the cost of the cavity considerably.

These improvements may make the concept practical today, and a reexamination of the concept appears in order.

INTRODUCTION

The concept of contained fusion reactions has been around for some time. Energy releases from peaceful nuclear explosions can be contained in large cavities or tanks. In a closed container, the energy is captured in a working fluid and converted to electricity via steam cycles. This system can simultaneously be used as a materials factory to produce valuable isotopes such as uranium (^{233}U), cobalt (^{60}Co), and tritium.

PAST STUDIES

Since 1959, discussion of test-ban treaties has generated concern for the possibility of concealed nuclear

tests. As a result, the principles of containment have been studied, and the ideas have been applied to energy and material production. Hammond et al. discussed the results of much of this work and its applications to commercial power production and fissile fuel production.¹

The containment vessels proposed in early studies [Project PACER (Ref. 2), for example] are large ($\approx 100\text{-m}$ radius) underground cavities excavated out of salt fields and pressurized with steam. The fuel charge, which contains deuterium, is ignited by a small fission charge. High-pressure steam is heated by absorbing the energy released and is then used to generate electricity. Thorium placed around the fuel charge is converted to ^{233}U , which is disbursed as debris in the steam. The

^{233}U is separated from the steam and used for the new fission charges; excess ^{233}U can be sold for use in fission power plants.

The concept of contained nuclear reactions is attractive because the science and technologies needed for the reactor are either proven or understood. The nuclear explosive is well tested, the energy absorption mechanism in steam is known, and the production of electricity from steam is routine. Using an underground salt cavity as a containment chamber appears feasible, based on data from previous nuclear tests in salt cavities [e.g., the Sterling field test in Mississippi in 1965 (see Ref. 3)].

Three major technical problems have kept this salt cavity reactor from receiving more consideration. First, it is unknown how well salt walls can withstand the repeated stress of nuclear explosions without plastic deformation and without risk of permanent fracture or failure by other mechanisms. Second, vast quantities of steam become contaminated and radioactive, requiring difficult and expensive processing to recover the valuable material. Third, the large inventory of tritium in the steam poses a serious environmental hazard if vented to the atmosphere. There are inherent political problems as well.

MOLTEN-SALT MODIFICATION

In this work, the PACER concept is modified by substituting molten salt for the steam working fluid and lining the cavity with steel.⁴ These changes substantially reduce the three technical problems mentioned above.

To absorb the explosive energy release, large quantities of molten salts stream down from the top of the vessel in an annular array. This array significantly reduces the overpressure on the walls that is caused by shock waves and reduces the equilibrium pressure in the tank by absorbing much of the energy through evaporation and heating of the liquid salt. The salt is then processed. The reduced pressure per unit yield will reduce the size of the cavity for a given yield and cavity pressure. Using a steel liner also reduces the lifetime uncertainty of the earth-supported cavity and prevents impurities in the earth from contaminating the molten salt.

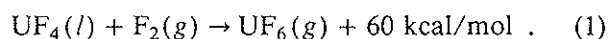
In PACER, electricity is generated by passing the heated steam from the cavity directly through a turbine that drives the generator. In the modified case, the heated molten-salt working fluid is passed through a heat exchanger, which generates steam in a separate fluid loop. This steam drives a turbine, which drives a generator to produce electricity.

The molten salt will contain lithium fluoride (LiF), beryllium fluoride (BeF_2), and thorium fluoride (ThF_4) if desired. Mixtures of BeF_2 and LiF are often referred to as Flibe. Eutectic Flibe is 67.1 wt% or 53

mol% BeF_2 (32.9 wt% and 47 mol% LiF) and has a melting point of 363°C. There are 37.13 g of Flibe per g-mole. A small percentage of ThF_4 may be added to the eutectic Flibe.

The fuel charge is surrounded with beryllium, thorium (or thorium fluoride), and a layer of Flibe, and all parts are vaporized by the energy released. Beryllium placed around the fuel charge can be a good neutron multiplier in metal form, but as a fluoride most of the fast neutrons are slowed down by inelastic collisions with fluorine rather than undergoing neutron multiplying reactions. Uranium-233 is bred from the thorium, and tritium can be generated from thermal neutron capture by ^6Li present in the Flibe. If the salt is maintained in a reducing state (fluorine deficient), then tritium exists as T_2 rather than TF, and the salt is not very corrosive. Then UF_4 and T_2 (gas) become part of the reaction mixture, with the fuel-charge products. The high explosive used in the fuel charge must be chosen carefully to minimize corrosion without complicating the separation processes, and all materials should be soluble in the molten salt.

The reaction product mixture is almost entirely molten salts (LiF, BeF_2 , ThF_4 , and UF_4). The valuable products of the reaction are relatively easy to separate from the reaction mixture. Gaseous tritium, which is insoluble in the molten salts, is pumped from the cavity as soon as the cavity is sufficiently cooled to condense the vaporized salts. After passing through the steam generation heat exchangers, the mixture is treated to remove the ^{233}U . Uranium can be separated from the molten salt by a fluorination process (alternative processes are available) described by the following chemical reaction⁵:



Uranium hexafluoride is gaseous and insoluble in the molten salt. Beryllium can be extracted from the molten-salt mixture by electrolysis or by a chemical reduction reaction. Then salt constituents are added to recondition the mixture, bringing it back to its original composition. Using molten salts as a heat transfer medium may reduce the product separation costs⁶ from those for an aqueous-based system, and processing the molten salt can limit the inventory of fission product contaminants.

REACTOR SYSTEM DESIGN

The fuel-charge energy yield fixes the size of the containment cavity. Yields being considered range from 1 GJ, which is typical of inertial confinement fusion (ICF) reactor goals, to 120 TJ [1 t equivalent trinitrotoluene (TNT) yield equals 4.184 GJ, and 1 kt equivalent TNT equals 4 TJ or 4×10^{12} J]. Except for the lower energy end of the range, the yield is partly fission and partly fusion energy.

Both cylindrical and spherical containment vessels are of potential interest. Vessel diameters range from 10 to 200 m. For large systems, cylindrical vessels may be more cost-effective because the dome on a cylindrical cavity has a smaller radius (and is thus less costly) than the dome on a spherical cavity of the same volume. Therefore, the cylindrical vessel requires less reinforcement, which reduces the cost. When cylindrical vessels are considered, the height is assumed arbitrarily to be 4.67 times the radius in the examples shown; however, other height-to-radius ratios could be considered. (The volume of a cylinder is then three times larger than that of an equal radius sphere, and the surface area is 3.3 times larger.)

The energy released is absorbed by vaporization and heating of the fuel charge and the surrounding layers of beryllium, thorium, and Flibe. The design should be such that all layers are vaporized, and a significant portion of the energy release is absorbed by the vaporization process. The fuel charge is surrounded by a vertical array of jet streams of molten Flibe (Fig. 1). The streams are ~2 mm in diameter. Theoretical modeling of blast attenuation through annular arrays of jet streams has been previously developed for cylindrical systems.⁷ The results indicate these jet systems effectively eliminate large pressure pulses at the wall over the equilibrium pressure. The use of jets to attenuate the blast in an ICF reactor design was first suggested by Burke et al.,⁸ using liquid lithium, and by Seifritz and Naegele,⁹ using Flibe. The liquid-lithium version evolved over the years to the design called HYLIFE (Ref. 10).

EQUILIBRIUM PRESSURE

The equilibrium pressure at some time after an explosion is the result of gas-phase energy density. Assuming an ideal gas phase, the equilibrium pressure can be calculated from an energy balance and the ideal gas law:

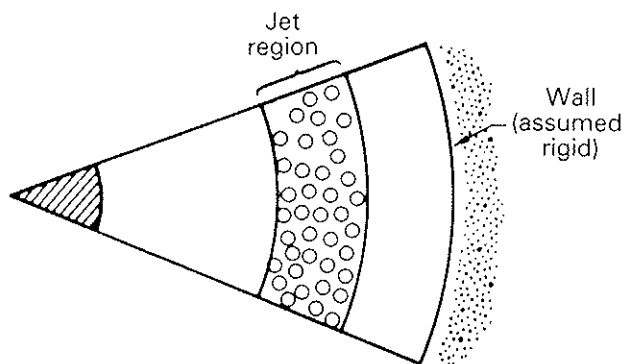


Fig. 1. Horizontal cross section of containment vessel (adapted from Ref. 7).

$$P_{eq} = \frac{(\gamma - 1)[Y - mC_p(T_v - T_{in}) - m\Delta H_v + mRT_v]}{V} + P^{sat}$$

$$= \frac{(\gamma - 1)E}{V} + P^{sat}, \quad (2)$$

where

γ = heat capacity ratio ($\gamma = C_p/C_v$)

$C_p = 2.35 \text{ J/g}\cdot\text{K}$

V = cavity volume

m = mass of Flibe vaporized

ΔH_v = latent heat of vaporization of Flibe (205 800 J/g·mol)

Y = fuel-charge yield

E = portion of yield contributing to gas-phase energy density [$E = Y - mC_p(T_v - T_{in}) - m\Delta H_v + mRT_v$]

T_{in} = temperature of Flibe before explosion

T_v = temperature of saturated vapor ($P_{eq} = P^{sat}$ at T_v when $E = 0$)

P^{sat} = pressure of vaporized gas at the vaporization temperature T_v , $P^{sat} = 133(10^{9.407 - 10054/T_v})$ (from Ref. 11 in units of pascals).

Equation (2) is derived in the Appendix. The quantity E is the portion of the yield that contributes to the superheat responsible for wall pressure above the saturation pressure. With small jet diameters (large surface area/mass ratio), a significant portion of the jet mass is vaporized, resulting in lower equilibrium pressures.

The equilibrium pressure has been calculated as a function of reactor size and explosive yield (Fig. 2, with more results in the Appendix). Both spherical and cylindrical vessels are considered. One important point must be stressed. By an appropriate choice of the thickness and radial position of the Flibe, a large portion, possibly >70%, of the total energy released could be absorbed by the vaporization process. Thereby, the gas-phase energy density and, hence, equilibrium pressure will be significantly reduced. For example, in a cylindrical cavity with a 20-m radius, a 4-TJ fuel charge is exploded. With no evaporation the equilibrium pressure is 10.4 MPa. If 90% of the energy is absorbed by vaporization ($E/Y = 0.1$), $P_{eq} = 2.9 \text{ MPa}$. If 100% is absorbed by vaporization, $P_{eq} = 2.2 \text{ MPa}$, which represents a factor of 5 pressure reduction. Hence, an important feature of the reactor will be to design the jets to allow maximum Flibe vaporization. Analysis and experiments will be necessary to determine the fraction of energy absorbed in the evaporation process.

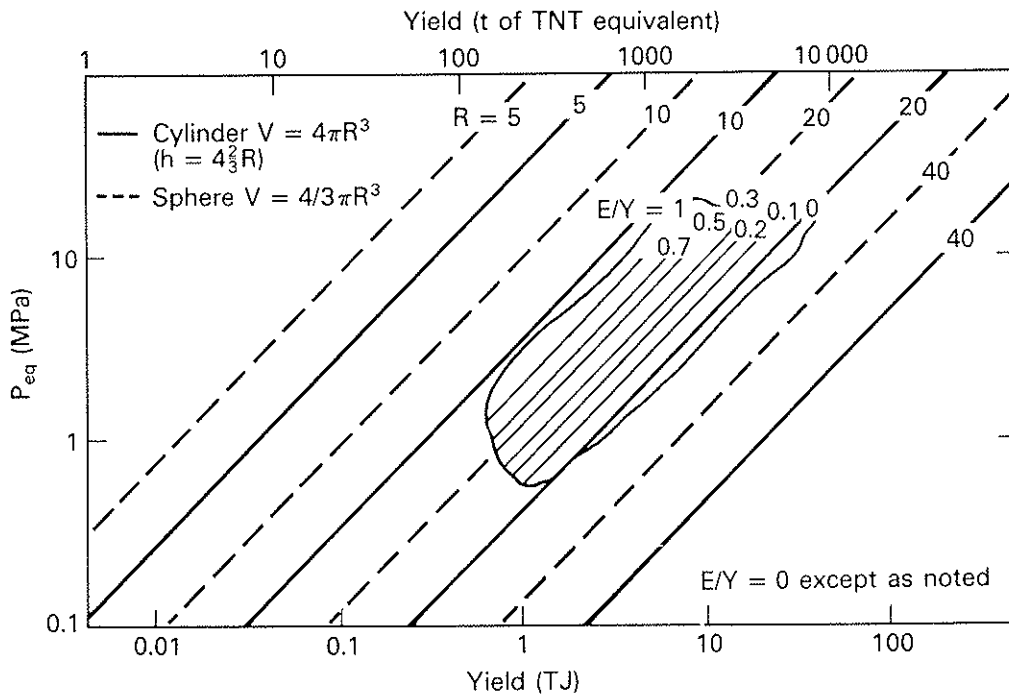


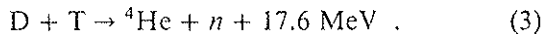
Fig. 2. Equilibrium pressure as a function of yield for various size cavities ($TJ = 10^{12}$ J).

FUEL CHARGE

The fuel charge will be based on design principles used for past underground tests in the Plowshare Program,^{12,13} which were designed to minimize the energy contribution from fission reactions. Although a deuterium-deuterium (D-D) fuel charge is discussed in Ref. 1 and later in this paper, we assume tritium is used in the fuel charge up to a 50:50 deuterium-tritium (D-T) mixture. The high explosive will be carefully selected and well tested. Explosives that complicate tritium removal and purification or that inhibit uranium fluorination are unattractive. Interactions between explosive reaction products, molten salts containing UF_4 , and hydrogen (tritium) can be studied with existing nonnuclear high-explosive testing facilities.

NUCLEAR REACTIONS

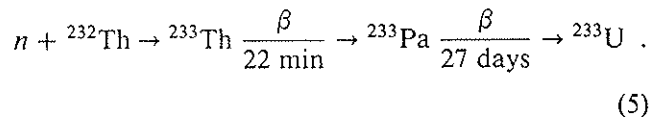
Besides electricity, the two desired end products from the nuclear explosives are tritium and the fissile isotope of uranium, ^{233}U . The reactions are initiated by the D-T reaction:



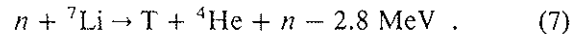
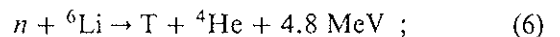
The D-T fuel is surrounded by a solid beryllium layer up to 20 cm thick. This layer absorbs and multiplies the high-energy neutrons produced by the D-T reactions as follows:



The two neutrons produced after slowing down are captured by thorium (or lithium) to breed fissile ^{233}U (or tritium):



Two reactions can be used to breed tritium from lithium:

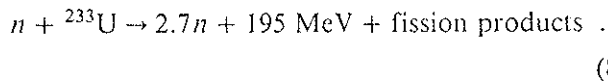


Equation (7) requires a fast neutron and produces a slow neutron useful for breeding tritium or ^{233}U . The first reaction breeds tritium using a slow neutron. Naturally occurring lithium has only 7.5 wt% 6Li , with the remainder being 7Li . Because 6Li has a very large cross section for slow neutrons, natural lithium is suitable for both reactions, and costly isotope separation should not be necessary.

The breeding configuration under consideration is based on the fission-suppressed concept. By suppressing fissioning, we maximize the number of neutrons per unit energy, thus maximizing fuel production per unit power. A Be-Li layer that encloses the fuel charge will stop most of the high-energy fusion neutrons, thereby multiplying the neutrons and breeding tritium. A layer of thorium (and more lithium if desired) encases the Be-Li layer to capture any slow neutrons.

The tritium breeding ratio T (number of tritons bred per 14-MeV fusion neutron) can be adjusted by varying the percentage of lithium in both layers. The number of fissile atoms bred per fusion neutron F also depends on the percentage of lithium. Calculations¹⁴ indicate that the sum $T + F$ is ~ 1.8 in fusion breeder reactor designs. Therefore, if one triton is needed to manufacture the next charge, 0.8 net useful atoms are bred for each fusion neutron. The energy release M (in mega-electron-volts) per fusion neutron divided by 14 MeV is between 1.6 and 2.1 and depends on T and F and how much fission occurs. If we add the alpha-particle energy of 3.5 MeV, the energy per reaction is 26 to 33 MeV. The ratio of the net useful atoms produced to the energy released is between 0.024 and 0.031 atom/MeV.

Uranium fission yields 2.7 n/fission reaction:



The net neutron production is ~ 0.5 (subtract 1.0 for propagation of the chain reaction, 1.0 for loss of one fissile atom to make the next charge, and 0.2 for capture losses). Because fission has a large energy release, it does not produce nearly as many useful neutrons per mega-electron-volt of energy as does fusion. The net number of useful atoms per unit of fission energy is 0.0026 atom/MeV. Fusion reactions produce ten times as many useful neutrons per unit of energy as fission reactions.

The fraction of the yield due to each process, fusion and fission, can be varied. If ϵ is the fraction of the yield due to fission, and $T + F$ is the net number of bred atoms per energy release, then

$$\left(\frac{T+F}{E}\right)_{\text{tot}} = \epsilon \left(\frac{T+F}{E}\right)_{\text{fission}} + (1-\epsilon) \left(\frac{T+F}{E}\right)_{\text{fusion}} \quad (9)$$

Equation (9), which is plotted in Fig. 3, shows that by having most of the yield derived from the fusion reaction, we obtain a maximum amount of breeding for a given energy release.

If we do not want to breed much excess material, the beryllium layer used for neutron multiplication is not needed. Furthermore, if D-D reactions are used in the fusion charge, as discussed in Ref. 1, the beryllium layer is not necessary. Deuterium-deuterium reactions create even more excess neutrons per unit energy than D-T reactions using beryllium. For D-D reactions, one neutron results for each 21.6 MeV or $(T + F)/E = 0.046$ atom/MeV (Ref. 1). For D-T reactions with no beryllium layer, $T + F$ is 1.27 less 1.0 to breed the tritium for the next charge. If E is 22.4, the net $(T + F)/E = 0.012$. Beryllium metal is not soluble in Flibe. Providing twice the number of fluorine atoms as beryllium atoms permits the beryllium to be converted into

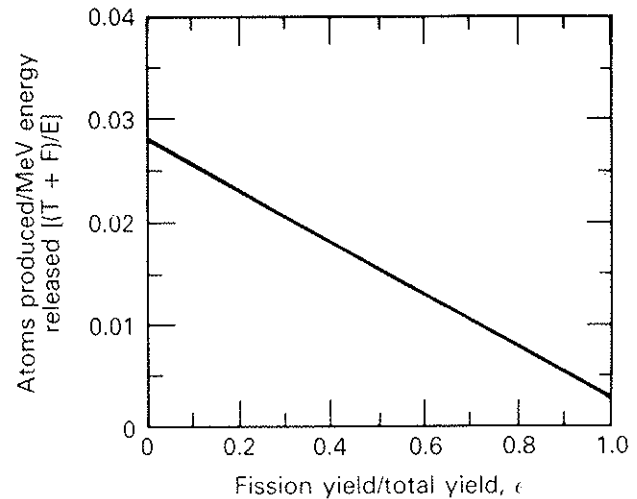


Fig. 3. Dependence of net product yield on fraction of fission yield.

BeF_2 . Having no beryllium layer reduces the necessity to convert this beryllium to BeF_2 to make it soluble in Flibe.

SAFETY CONSIDERATIONS

The containment vessel probably would be constructed underground; hence, it would be less vulnerable to terrorist attack and the earth could provide support. The tritium inventory of this system would be extremely low compared to previous steam-filled cavity concepts. Tritium has quite low solubility in Flibe. Therefore, it can be pumped out with a cryopump size of a few square metres after each explosion of a nominal 10-TJ yield and cooling period to a tritium inventory of order 100 Ci (10^4 Ci of tritium equals 1 g). This 100 Ci corresponds to the amount of tritium in a cavity of 10^5 m^3 at a partial pressure of tritium of $1.3 \times 10^{-4} \text{ Pa}$ (10^{-6} mm Hg), which is limited by the vapor pressure of condensing tritium on cryogenic pumps and not by the size of the cryopumps. Due to the low solubility of tritium in Flibe, the inventory in the chamber will be even less. The tritium inventory in the chamber walls and steel piping will be in addition to the 100 Ci. The vapor pressure of Flibe is $< 1.3 \text{ Pa}$ (10^{-2} mm Hg) at 600°C . Steam-filled cavities would have tritium inventories ranging from 10 to 100 MCi or $\sim 0.2 \text{ Ci/l}$ of water, and they would need difficult isotope separation. HTO must be separated from the steam at a high cost (10 Ci/l is a practical concentration for removal). On the basis of tritium inventory, the modified concept has a considerable safety advantage over the PACER version using steam. The safety aspects from the hazards of fission products accumulating in the salt have not been considered.

ECONOMICS

The construction cost of the containment cavity is beyond the scope of this paper. However, we would take full advantage of the considerable work on steel-lined, engineered rock cavities reinforced with rock bolts. If the liner is placed against rock, the hoop stress can be reduced by an order of magnitude.¹⁵

Flibe costs will be a small but significant part of the total. For example, 500 t of Flibe are vaporized to absorb 4 TJ of yield energy at 2MPa. At \$37/kg (Ref. 16), Flibe will cost \$19 million and scale proportional to yield. The amount of Flibe needed to absorb 4 TJ without evaporation for a temperature rise from 400 to 1300°C with 1-atm vapor pressure is 2000 t. We prefer to have at least 2000 t of salt so the pressure in the cavity will drop below 1 atm as soon as the yield energy can be spread over this much mass for the 4-TJ case.

A fuel-charge assembly plant would be constructed near the containment vessel to provide the nuclear charges. Materials fabrication would be handled remotely with robotics. A chemical treating facility also would be needed for uranium fluorination, beryllium extraction, Flibe purification, and tritium processing. This facility would be operated remotely with computer control. The total direct costs of the entire project must not exceed about \$2 billion. A sketch of the plant is shown in Fig. 4.

The revenue from the operation would come from three sources. Net electricity can be sold to electrical consumers. The uranium produced can be sold to operators of fission reactors as fuel. Excess tritium could be sold to fusion energy research facilities or for other uses.

The value of the nuclear products can be calculated on a unit energy yield basis, as follows. Assume the

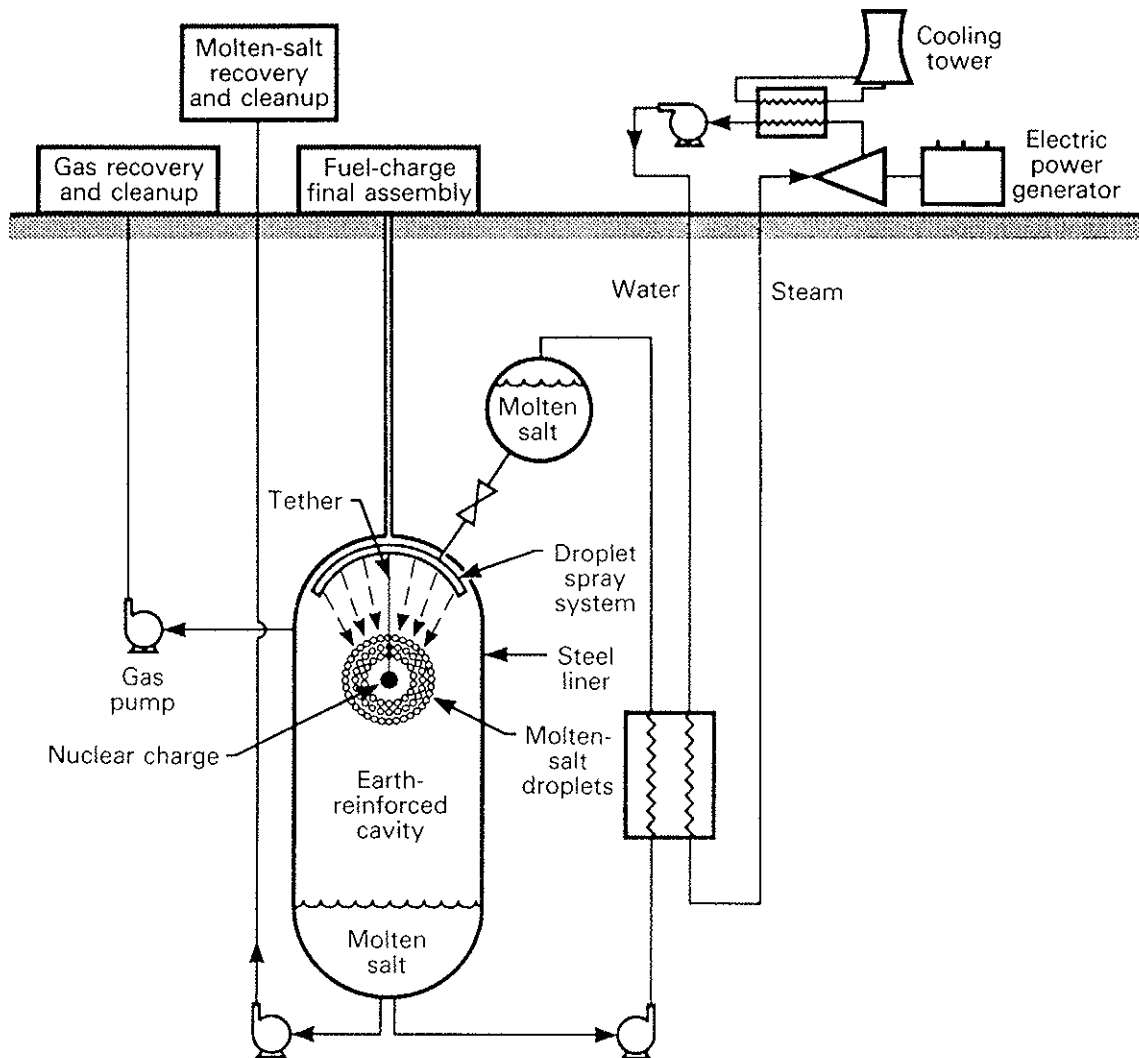


Fig. 4. Schematic of the contained fusion system.

fuel charge is 20% fission yield (Fig. 3, $\epsilon = 0.2$), and tritium is \$10 000/g. Also assume that for each triton produced, alternatively one ^{233}U atom could be produced. Uranium-233 is then worth \$130/g (e.g., the mass ratio 3/233). With this estimate, the products (either tritium or ^{233}U) are worth \$7800/TJ of yield. The total annual revenue would be greater than \$500 million from the nuclear products alone. If a plant is designed to produce 240 TJ of yield per day (perhaps a 40-TJ charge every 4 h or 4 TJ every 24 min) and to have a thermal-to-electrical conversion efficiency of 34.5%, it will produce 1000 MW (electric) of power, worth \$280 million annually (40 mill/kW·h and 80% capacity). The electricity from this plant is then worth \$3800/TJ of yield. The market value would determine which is produced, tritium or ^{233}U .

Today, the market value of ^{233}U is less than \$130/g. Assuming a market value of \$100/lb U_3O_8 ore and using the equivalent cost method, ^{233}U is worth \$60/g (Ref. 14). At \$60/g the material sales are \$3600/TJ of yield. As ore reserves are exhausted, today's depressed prices of below \$30/lb will go up considerably, perhaps exceeding the price achieved in the 1970s of \$45/lb (1970 dollars) and possibly exceeding \$100/lb early in the 21st century. The total revenues might be expected to range from \$7400 to \$11 600/TJ of yield. The cost to fabricate each charge and recover the materials must be a small fraction of this cost to achieve good economics. An economic analysis requires construction and operating cost estimates, which are beyond the scope of this work.

COMPARISON OF CONTAINED FUSION CONCEPT BASED ON MOLTEN-SALT TECHNOLOGY TO PACER CONCEPT

Table I summarizes the comparison of our contained fusion concept using molten-salt technology to the PACER concept. The qualitative differences are the large reduction in tritium inventory, ambient pressure,

and amount of working fluid. The cavity is smaller and the yield reduced substantially.

The radius of the dome of the cavity, which is the difficult part to support, is up to five times smaller than in PACER. The pressure in the cavity will be below 1 atm (0.1 MPa) except for the brief time (well under 1 min) following the explosion. This will greatly reduce the possibility of venting radioactive material to the atmosphere and thereby increase public acceptance of the concept. Containment is also made easier by reducing the peak pressure in the cavity from 26 to 3 MPa. The great reduction in tritium inventory means that radioactive materials other than tritium will be the primary safety concern in venting working fluid to the atmosphere.

SUMMARY AND REMARKS

The old idea of obtaining power from contained nuclear explosions is reexamined. A reactor could supply large amounts of electricity while producing valuable isotopes and is based on a technology essentially in-hand today, that is, peaceful nuclear explosions.

Our concept, using molten-salt technology, has several advantages over previous proposals using steam-filled cavities. Valuable products can be separated in a straightforward manner from the molten-salt mixture based on molten-salt reactor technology. Because a significant amount of the total energy released is absorbed by heating and vaporizing liquid salt, cavity pressures can be dramatically lower than pressures needed in steam-filled cavities. Also, using a steel liner in an underground cavity makes the properties and lifetime of the cavity predictable. The tritium inventory can be kept quite low, thus enhancing reactor safety and making public acceptance more likely. Possible future test-ban treaties may include provisions for peaceful nuclear explosives or testing small yields, thus permitting this concept. The molten-salt version of this concept appears sufficiently promising that a more detailed study is warranted.

TABLE I

Comparison of Contained Fusion Concept Based on Molten-Salt Technology to PACER Concept

	PACER	Salt Modification
Chamber size	Unlined salt cavity, spherical shape, 100-m radius	Steel-lined cavity, cylindrical shape, 20- to 50-m radius, 60- to 150-m height
Yield	80 TJ (20-kt TNT)	4 to 40 TJ (1- to 10-kt TNT)
Ambient pressure	20 MPa (200 atm)	0.1 Pa
Equilibrium pressure after explosion	26 MPa	3 MPa
Tritium inventory in cavity	$>10^7$ Ci	~ 100 Ci
Fluid inventory	330 000 t of steam	1000 to 10 000 t of salt (Flibe)

APPENDIX

DERIVATION OF EQUATION FOR EQUILIBRIUM PRESSURE

For the present thermodynamic analysis, we assume that a large quantity of heat is instantaneously added to an initial charge of liquid salt. The mass of salt is constrained such that the final state will be superheated vapor. The objective of this analysis is to derive an approximate expression for the final pressure in a cavity of fixed volume.

In the actual process, more salt is injected into the cavity than that which is vaporized. Before heat is added, salt injectors spray salt droplets into the chamber. Each droplet is heated and partly vaporized, as shown in Fig. A.1. Adding heat to the droplet surface is faster than diffusing heat to the droplet interior. Thus, the bulk temperature of the droplet interior rises more slowly than the surface temperature. We assume that heat absorbed by the droplet interior is small and can be neglected in the thermodynamic analysis. (This assumption precludes detailed transient modeling and results in a more conservative estimate of the final pressure.)

An idealized process is considered in which all of the liquid salt in the cavity is vaporized by the heat addition. We assume that the ideal gas law applies in the vapor phase and that the liquid specific volume is much less than the vapor specific volume ($v_l/v_g \ll 1$). With these assumptions, the Clausius-Clapeyron equation is valid for the phase change.

We can write a macroscopic first-law energy balance. The vessel and salt are considered a closed isolated system containing an internal heat source and a mass m of molten Flibe that is to be vaporized. The balance is applicable during the brief time period in which heat is added and dispersed:

$$Q = \Delta U + W \quad (A.1)$$

Since the system is a constant volume, no work is done. The heat addition, i.e., the fusion plus fission

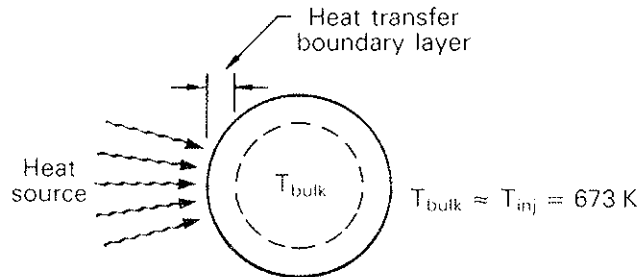


Fig. A.1. Droplet vaporization. The relatively cool droplet interior is heated only slightly above its injection temperature.

yield energy, is balanced by the change in the internal energy of the salt. Since the internal energy is a state variable, we are free to choose any thermodynamic path between the initial and final states. We chose the following path, assuming an ideal gas phase:

1. Compress the liquid to P^{sat} .
2. Heat the liquid at constant pressure to its boiling point or vaporization temperature T_v .
3. Vaporize the liquid at P^{sat} .
4. Add superheat to the vapor at constant volume and calculate P_f .

The objective is to estimate the net change in internal energy resulting from these state changes. Since the work required to compress a liquid from low pressure to P^{sat} is relatively small, it is neglected (step 1). The vaporization temperature T_v and the saturation pressure P^{sat} can be found for Flibe by

$$P^{sat} = 133(10^{9.407 - 10.054/T_v}) \text{ (Ref. 11 in pascals)} \quad (A.2)$$

and

$$P^{sat} = \frac{mRT_v}{V} \quad (A.3)$$

where V is the cavity volume.

The heat of vaporization is known at atmospheric pressure:

$$\begin{aligned} \Delta H_v &= 205\,800 \text{ J/g-mol} \quad , \\ T_v &= 1540 \text{ K} \quad , \end{aligned}$$

and

$$P^{sat} = 1 \text{ atm} \quad .$$

The heat of vaporization is assumed constant over the temperature range considered here, as indicated by Eq. (A.2) and the Clausius-Clapeyron equation:

$$\Delta H_v = -R \frac{d(\ln P^{sat})}{d(1/T_v)} \quad (A.4)$$

The internal energy change of vaporization is given by

$$\begin{aligned} \Delta u_v &= \Delta H_v - P^{sat}(v_g - v_l) \\ &\cong \Delta H_v - P^{sat}v_g \cong \Delta H_v - RT_v \quad . \end{aligned} \quad (A.5)$$

The internal energy of the vapor phase prior to the heat addition is negligible since the pressure and thus density are very low for vapor in equilibrium with Flibe at the inlet temperature.

Following the aforementioned path, the energy balance [Eq. (A.1)] becomes

$$\begin{aligned} Q = Y = \Delta U &= mC_{p,l}(T_v - T_{in}) + m\Delta U_v(T_v) \\ &+ mC_{v,v}(T_f - T_v) \quad . \end{aligned}$$

Then,

$$T_f = \frac{Y - (m\Delta H_v - mRT_v) - mC_{p,l}(T_v - T_{in}) + mC_{v,v}T_v}{mC_{v,v}} \quad (\text{A.6})$$

Conceptually, the final temperature and pressure are influenced strongly by the amount of mass vaporized and the fraction of the yield energy contributing to superheat. If we define E as the energy contributing to superheat, Eq. (A.6) can be rewritten as

$$T_f = \frac{E}{mC_{v,v}} + T_v, \quad (\text{A.7})$$

where

$$E = Y - (m\Delta H_v - mRT_v) - mC_{p,l}(T_v - T_{in}) \quad (\text{A.8})$$

and

$$P_f = \frac{mRT_f}{V} = \frac{R}{C_{v,v}} \frac{E}{V} + \frac{mRT_v}{V}. \quad (\text{A.9})$$

Finally, using the ideal gas relationship, $R/C_{v,v} = \gamma - 1$ and $P^{sat} = mRT_v/V$, we get

$$P_f = (\gamma - 1) \frac{E}{V} + P^{sat}. \quad (\text{A.10})$$

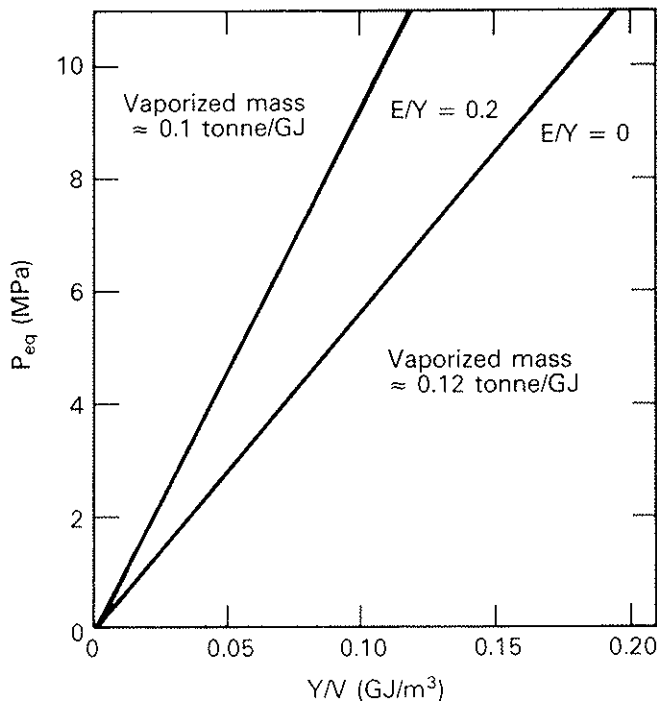


Fig. A.2. Equilibrium pressure versus yield per unit volume.

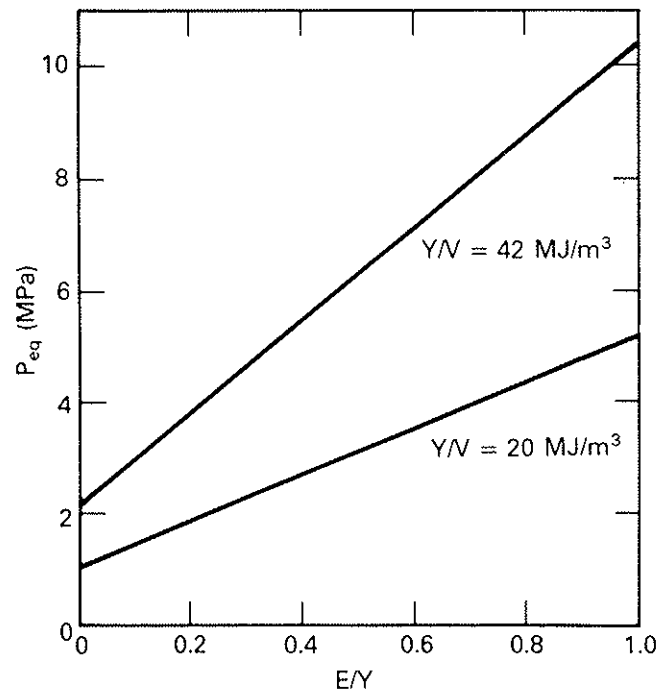


Fig. A.3. Equilibrium pressure versus fraction of energy going into superheated vapor.

The energy E represents that portion of the yield resulting in superheat.

If we assume values for T_{in} and Y , as well as the energy fraction contributing to superheat (E/Y), the mass of salt vaporized is determined. Then T_v and P^{sat} can be calculated. For the salt vapor mixture, $\gamma = 1.25$ has been estimated. Few data on mixtures of vaporized salts are available. In general, as the molecules in the vapor become more complex, γ decreases.¹⁷ For example, $\gamma = 1.67$ for monatomic gases, 1.4 for diatomic gases, and 1.3 for water. The pressure from Eq. (A.10) is plotted in Figs. A.2 and A.3 at an inlet temperature for T_{in} of 400°C.

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