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HIGH PRESSURE WATER AS A HEAT TRANSFER MEDIUM IN NUCLEAR POWER PLANTS

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HIGH PRESSURE WATER AS A HEAT TRANSFER MEDIUM IN NUCLEAR POWER PLANTS

By

A. M. Weinberg and F. Murray

Useful work can be extracted efficiently from a nuclear chain reaction only if the coolant operates at high temperatures. This fact leads directly to the conclusion that water at ordinary pressures is unsuitable as a power plant coolant. To avoid this difficulty inherent in water cooling, alternative heat transfer fluids such as gases or liquid metals (either of which can be raised to very high temperatures) have been proposed.

There is another coolant*, neither liquid metal nor gas, which is capable of withstanding rather high temperatures. This is water under high pressure. The critical temperature of water is 374°C, its critical pressure is about 215 atmospheres. Decomposition of water under pile radiation is a phenomenon which has been studied rather extensively; the decomposition products, H_2, O_2, and H_2O_2 can be coped with satisfactorily. Corrosion by hot water is not excessive in stainless steel systems and possibly even in aluminum systems. These facts suggest that a high pressure water power plant may be built with less development work than either the gas or liquid metal plants, and that such a plant might be very reliable.

The main objection to hot water as coolant is that nowhere in such a system is there a really high temperature; the use of superheat is therefore almost precluded. This will reduce the thermal efficiency of such a plant as compared to one in which superheat is available. But the magnitude of this loss is small since during the superheating part of a steam engine cycle the heat absorption is very far from being isothermal. This means that much less is added to the efficiency of a steam cycle by superheat than would be calculated from the simple Carnot formula.

The main reason for investigating the high pressure water system is not that such a system will necessarily compete thermodynamically with either the gas or metal system. Rather it is that hot water (either light or heavy) will probably have to be used in thermal breeders or converters. Any large scale program of breeding or converting makes little sense unless the by-product power is used. Thus, even if the hot water system is less favorable as a power plant than other systems, a point will very probably arise in the development of large scale nucleonics where power from hot water will have to be extracted as a by-product of 23 production.

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* The use of fluorocarbons or diphenyl or other low vapor pressure liquids is not considered here because the decomposition of these materials under pile conditions probably makes them very awkward to handle.

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There are other possible applications where the minor thermodynamic disadvantage of the hot water system might be offset by other considerations. For example, it is not entirely certain that a lattice of ordinary water and unenriched uranium will not chain react if the temperature of the water is raised sufficiently. In any event the enrichment needed to make such a machine operate will be small. On an economic basis such plants might compete with the highly enriched machines usually contemplated when metal or gas cooling are discussed.

2. General Characteristics of a High Pressure Water System

High pressure water can be used as a coolant alone in a solid (e.g. Be) moderated pile or it can be used as both moderator and coolant in a homogeneous or heterogeneous arrangement. In either case, general features of a high pressure water system will be the same. Water at very high pressure circulates through the pile where it picks up heat. It then circulates through an evaporator in which saturated steam at a pressure rather lower than the pile pressure is generated. The conditions in such an evaporator are in some respects similar to those existing in the condenser of a mercury turbine. We prefer an evaporator for generating steam rather than a flash chamber in which the pile water is converted into steam because, (1) If the high pressure water is a homogeneous uranium solution, it would be out of the question to flash it and send the intensely radioactive steam to a turbine. (2) Even if the pile is heterogeneous, pile water would pick up sufficient radioactivity (O^{19}, iron, etc.) to render the turbine inaccessible, at least during operation. PWR or BWR

Whether the pile water is flashed or is used to boil turbine feed water there will be a temperature loss in the steam generator. In principle this temperature loss can be the smaller in the flashing scheme provided the circulation rate could be made sufficiently high; i.e., the ratio of flashed water to unflashed water very small. On the other hand the temperature drop in the evaporator can also be reduced by forcing the circulation of the water used as working fluid. BWR w/ Recirculation

A common feature of all high pressure systems in which the water is used as moderator is the pressure tank. In order to reduce the thickness of the pressure tank it will be economical to design these piles as elongated cylinders - a shape which is also suited for efficient production of isotopes in a surrounding blanket. For example, consider a heavy water homogeneous breeder with a Laplacian of about 6×10^{-3} cm^{-2}. A critical infinitely long cylinder will have a radius of about 31 cm. With a Th^{-P-9} blanket the overall radius might be increased to about 50 cm. This is somewhat less than the radius of standard high pressure (1200 lb.) boilers.

Naturally in a pressure breeder it will be necessary to keep the Th slurry and the urnaium solution separate. This will require a thin tank inside the pressure tank. It would be preferable if this tank could be made of Be;

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however, if Be cannot stand up under the high temperatures inside the breeder it will be possible to use a thin stainless steel tank.

One end of the high pressure boiler should be removable, at least in the heterogeneous system, in order to make removal of the rods possible. For this reason we prefer to think of the pressure tank as enclosing the end shield. This construction would allow the high pressure flanges to be accessible at all times. Removal of the flanged head would expose the ends of the rods protruding through the shield.

Insertion of control rods constitute a major problem. One possible solution would be to mount a rod in the reflector through a special high pressure nickel thimble. The rod could be actuated magnetically through this thimble. Another possibility is to include the rod and its actuating mechanism inside the pressure tank. Any electrical connections to the motor would be rather easy to attach through the walls of the tank.

3. Thermal Efficiencies in High-Pressure Systems

The use of saturated rather than superheated steam does not affect the thermal efficiency of a turbine very much as the following table shows:

Overall Turbine-Generator Efficiencies $\left(\frac{\text{Heat input}}{\text{power output}}\right)^{-1}$ for Condensing (2" Hg) systems. From Newman et. al. Modern Turbines, p. 64 (Wiley)

Steam Pressure	Superheat 0°F	200°F
300 lb.	20.8	22.3
400	21.4	23.1
500	21.8	23.4
600	22.2	23.8
700	22.4	23.9

The values in the table are overall figures which take into account the change in engine efficiency of the turbine with superheat. It is seen that 100°F Fahrenheit improves the thermal efficiency by about 0.75%.

The usual objection to steam of low quality is that turbine blades do not stand up very well if they are operated with very wet steam. On the other hand it is very probable that the use of modern alloys will make wet steam turbines entirely practical. Mr. C. J. Colley of Monsanto engineering department points out that modern gas turbines are constructed which can withstand hot coal ash at temperatures much above those encountered in a steam turbine. He feels confident that with sufficient incentive for a wet steam turbine, one could easily be developed.

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For small power installations, or installations in which most of the generated heat is to be used for process work, it may be well to keep in mind reciprocating steam engines. Such steam engines often use saturated steam, and their reliability is comparable to that of good turbines.

4. The Problem of Superheat

From the efficiency table it is evident that superheat is not a matter of overwhelming concern, although it is desirable. What are the possibilities of incorporating a superheater in the high pressure water system? At present we have been able to think of the following methods of applying superheat.

(1) Separately Fired Superheaters

Such a superheater could be a Be or graphite pile cooled with steam (in which case the working fluid would become radioactive), or cooled with gas or liquid metal in which case a special heat exchanger would be needed. Another possibility is to use ordinary coal burner. For many installations this latter method might prove economical and feasible, since the energy put into superheat is only a small fraction of that put into the production of steam.

(2) Reflector Superheater

If the Th blanket in the breeder were solid (as ThO_2 or Th metal) we estimate that somewhere in the neighborhood of 10% of the pile heat would be produced in it. This heat would come from pile γ rays, Th^{232} capture γ's, Th^{233} and Pa^{233} decay and U^{233} fissions. Since Th and ThO_2 melts at very high temperatures it would be possible to use this heat as superheat - possibly by means of a liquid metal as heat transfer agent if it is undesirable to pass steam directly through the Th blanket.

(3) $D_2 + O_2$ Recombination

In the homogeneous system $D_2 + O_2$ recombination could yield about 6% of the total fission energy. This figure is based on a heat of formation of water of 3 ev/molecule, and production of $D_2 + O_2$ equal to 2 ion pairs per 100 eV of fission fragment energy. Because of the high pressure inside the machine, the bubble formation probably can be suppressed, the degassing and recombination taking place over a catalyst bed (which is the superheater) outside the pile.

5. Preliminary Design of a Th-23 High Pressure Water System

In this section we present preliminary calculations on a Th-23 light water power plant designed so that it is self-sustaining; i.e., so that as much

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23 is produced as is destroyed. In such an arrangement the essential fuel is Th which is rather plentiful. For practical power generation purposes this is an important advantage.

We consider a pile consisting of parallel plates of Th enriched with 23 and cooled by parallel sheets of water flowing between the plates. The plates will be 2 mm thick, and are coated with Al. The general idea of such a pile in which Pu was used as the enriching agent has already been discussed by Wigner. The advantage of 23 is that its use offers the possibility of sustaining the original enrichment in the Th.

We assume $\eta_{23} = 2.35$. In the arrangements we consider the fast effect ϵ is estimated at about 1.02; hence for every 23 destroyed, 2.4 neutrons are produced. This means that the ratio

$$\frac{\text{Total cross section of water, fission products, etc.}}{\text{total cross section of 23}} \leq 0.4$$

if the system is to "hold its own".

The Xe loss is 6%, the Pa^{233} loss is about 2% (assuming $\sigma_{Pa^{233}} = 170b$ and 0.75 Kg of Pa^{233} and 10 Kg of 23 in system on average), and the Al losses are about 2%. This leaves 30% available for water loss. For safety we should keep the water loss below 20%. This determines the minimum ratio of 23 to water, and, for any volume ratio of Th to water, it determines the minimum isotopic ratio of U^{233} to Th^{232}. Thus we have

$$\frac{\text{Mass of Water}}{\text{Mass of 23}} \leq \frac{18 \times 620 \times 0.2}{0.59 \times 233} = 16.2$$

$$\frac{\text{Mass of 23}}{\text{Mass of 02}} \geq \frac{1}{16.2} \frac{\text{Mass of Water}}{\text{Mass of 02}} = \frac{1}{16.2 \times 11} \frac{V_{H_2O}}{V_{02}} = .0056 \frac{V_{H_2O}}{V_{02}}$$

A volume ratio reasonable from the construction view point is $V_{H_2O}/V_{Th} = 4$. The minimum enrichment, R, for this ratio is about 2.5%. We now determine the critical size for this enrichment and volume ratio.

We calculate $K = \eta\epsilon pf$ as follows. Since $V_{H_2O}/V_{Th} = 4$, the scattering cross section per Th atom is $\sigma_{Th} + \frac{1}{18} \times \frac{232}{11} \times 4\sigma_{H_2O} = 12 + 206 = 218$ barns. The value of $\left(\int\frac{\sigma dE}{E}\right)_{eff}$ at this dilution is 32b according to CP-3093. This must be reduced in the ratio 1 + R since enrichment displaces Th atoms. Hence the resonance escape is

$$p = \exp - \frac{N_{Th}}{N_{H_2O}\sigma_{f_{H_2O}}} \left(\int\frac{\sigma dE}{E}\right)_{eff} = \exp \frac{-1}{4} \quad \frac{11 \times 18 \times 32}{232 \times 40 \times (1+R)}$$

$$= \exp - .164 = 0.848 \quad \text{For } R = .025$$

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Both η and f will depend on R, the ratio of 23 to Th. Thus

$$\eta = \frac{2.35 \times 620R}{620R + 6.1} = \frac{1450R}{620R + 6.1} = 1.59$$

where we have assumed $\sigma_{a_{Th}} = 6.1b$. The absorption cross-section of the Th + 23 is per c.c.,

$$N_0\sigma_{a_0} = \frac{11 \times 6.1 \times 6}{232(1+R)} + \frac{11R \times 620 \times .6}{233(1+R)} = \frac{(1.73 + 17R)cm^{-1}}{1+R}$$

while the absorption cross section of the H_2O per c.c. is

$$N_1\sigma_{a_1} = \frac{0.59}{18} \times .6 = .0196 \ cm^{-1}$$

The parasitic losses are taken to be about 10%. The thermal utilization is therefore

$$\frac{1}{f} = 1 + 0.1 \times \frac{17R}{1.73 + 17R} + \frac{.0196 \times 4}{(1.73 + 17R)(1+R)}$$

For R = .025, this gives

$$f = 0.94$$

and

$$K = \eta \varepsilon p f = 1.59 \times 1.02 \times .848 \times .94 = 1.29$$

Taking $\tau = 40 cm^2$ for the H_2O -Th mixture, we find

$$\Delta \cong \frac{\ln K}{\tau} = 6.35 \times 10^{-3} cm^2$$

Since the tank holding the pile is to run at high pressure, it will be desirable to make the pile radius rather small - say 35 cm. The height will then be 78 cm. The active lattice is somewhat smaller than this because of the blanket of Th, which is needed to catch leakage neutrons. We estimate the saving to be about 5 cm. in each dimension. The active pile volume will therefore be $0.192M^3$ of which $.04M^3$ is Th. The total mass of Th in the machine is 440 Kg, and the total mass of 23 is 11 Kg. If the pile is run at such high temperature that the water density is reduced, the critical amount will be somewhat higher than 11 Kg.

For heat extraction it is advantageous to make the Th plates very thin. We assume that plates 1 mm thick are possible to fabricate. Then the total heat transfer surface in the pile is 0.8×10^6 cm^2. If we assume an average heat flux of 30 $cal/cm^2/sec$ is attainable), the power output of the machine is $.8 \times 10^6 \times 30 \times 4.2 \times 10^{-3} \cong 98$ megawatts, or about 9 megawatts per Kg of 23. The enormous heat flux of $70/cal/cm^2/sec$ is not unreasonable since because of the high temperature of the water the heat transfer coefficient is very high.

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We have assumed Al coatings for the plates. Since we wish to keep the Al loss to about 2%, it will be necessary to use coatings only 1/2 mm. thick. Such coatings will be required to stand up only a relatively short time; the original 23 in the system is used up at the rate of some 100 gms. per day, and the plates will probably have to be replaced fairly frequently.

We assume the water flows through the pile at 10 M/sec. The total flow per second is $\pi \times 35^2 \times \frac{4}{5} \times 10^3 = 3000$ Li/sec, and the average temperature rise per pass is

$$\frac{98 \times .24 \times 10^6}{3 \times 10^6} = 8^\circ C$$

If the pile is operated at a pressure of 1200/lb./sq. in. the temperature of the water is about 300°C. We estimate the viscosity to be 1.1×10^{-3} poise and the thermal conductivity to be 25×10^{-4} cal/cm^2/sec °C which may be compared to 1 cal/cm^2/sec/°C at ordinary temperatures. The very high coefficient arises from the fact that at this high temperature the viscosity is lower, while the specific heat and conductivity are higher than at room temperature. ?

The pressure drop is about an atmosphere. The required pumping power turns out to be about 300 kw.

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