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A REFLUX CAPSULE STEAM GENERATOR FOR SODIUM COOLED REACTORS

by

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ABSTRACT

Pressurized water reactor plants at numerous sites have sustained significant leakage through their steam generators. The consequent shutdowns for repairs and replacements have damaged their economics. This experience suggests that if steam generators for liquid metal fast breeder reactor's (LMFBR's) continue to be built as presently designed some of them will have similar problems. Because of their larger capital investment, the consequent damage to the economics of LMFBR's could be more serious.

Reflux capsules provide a way to separate sodium from water and to reduce thermal stresses in steam generators for sodium cooled reactors. Their use would also eliminate the need for a primary heat exchanger and a secondary sodium loop pump.

INTRODUCTION

References 1 through 10 discuss leakage in steam generators. This leakage is especially crucial in sodium cooled reactors because of the exothermic chemical reaction between sodium and water with the concomitant release of hydrogen. As noted in Reference 11, present designs include systems to handle this leakage. However, the above referenced experience indicates that this is going to be a persistent problem.

There are two basic causes of steam generator leakage. One is corrosion, which is hard to control because of varying impurities in feedwaters. The other is stress and motion due to thermal transients. If thermal stresses could be reduced, it may be possible to control corrosion. In any event it is desirable to separate sodium from water and steam. Reflux capsules have the potential for providing both the separation and reduced thermal stresses.

REFLUX CAPSULES

Reflux capsules have been used for many years for testing materials for resistance to corrosion of liquid metals and for vacuum pumping. Their operation is based on two fundamentals of physics. One is that a gas, which in this case would be a vapor, will fill all of the available space. The other is Earth's gravity.

The operation of a reflux capsule consists of boiling a liquid in the lower portion of a vertically-oriented, evacuated, sealed capsule to generate vapor and then condensing it in the upper portion. The condensed liquid is returned to the lower portion by gravity. Thus the heat of vaporization of this working fluid is transferred from a high temperature source, which in this case would be sodium flowing along the bottom portion of the capsule (i.e., the evaporator section) to a coolant, which in this case would be water or steam flowing along the upper portion of the capsule (i.e., the condensing section).

The heat flow up a reflux capsule is equal to the product of the mass flow rate of vapor and the heat of vaporization. This mass flow rate of vapor is the triple product of the density and velocity of vapor and the cross sectional area of the vapor surface. The density is determined by the temperature. The velocity is determined by the pressure drop up the capsule. When a reflux capsule is operating below its full capacity all vapor is condensed out before it gets to the end of the capsule. Thus, since the capsule is evacuated at room temperature, there is a low pressure region at the end which provides the pressure drop. If this pressure drop is greater than that needed for the critical pressure ratio, as defined in Reference 12, the vapor will go up the capsule at the velocity of sound. This is the maximum possible velocity in a capsule with a constant cross sectional flow area.

If a reflux capsule were to operate at its acoustic velocity, as shown in Appendix A, the heat flow rate up the capsule would be a direct function of both the pressure and density of the vapor. Thus it is necessary to choose a fluid which has usable values of vapor pressure and density over the desired temperature range. For this case, as shown in Figures 1 and 2, which were plotted from data in Reference 13, the fluid is mercury.

As shown in References 14 and 15 and described in Appendix B, there are materials with sufficiently low solubilities in mercury to provide a long capsule life at the temperatures under consideration for the Liquid Metal Fast Breeder Reactor. Iron is one of these. As noted in Reference 16, if the capsule is made of certain materials like iron a small amount of magnesium and titanium has to be added to make it wet the surface of the evaporator. Since the mercury is essentially distilled in the evaporator and magnesium and titanium have much lower vapor pressures than mercury, the magnesium and titanium should stay in the evaporator section.

For mercury, as shown in Appendix C, if the vapor pressure at the liquid surface is more than twice the pressure in the top end of the capsule, the vapor will go up the capsule at the acoustic velocity. At this velocity, as shown in Appendix D and plotted in Figure 3, the heat transfer capability of mercury reflux capsules would go from about 450 Mw per square meter of liquid surface at 400 degrees C to about 1660 Mw/m^2 at 500 degrees C.

However, the achievement of this high heat transfer

Fig.1 VAPOR PRESSURE of MERCURY vs TEMPERATURE

(From Handbook of Chemistry & Physics, 31st Ed., 1949)

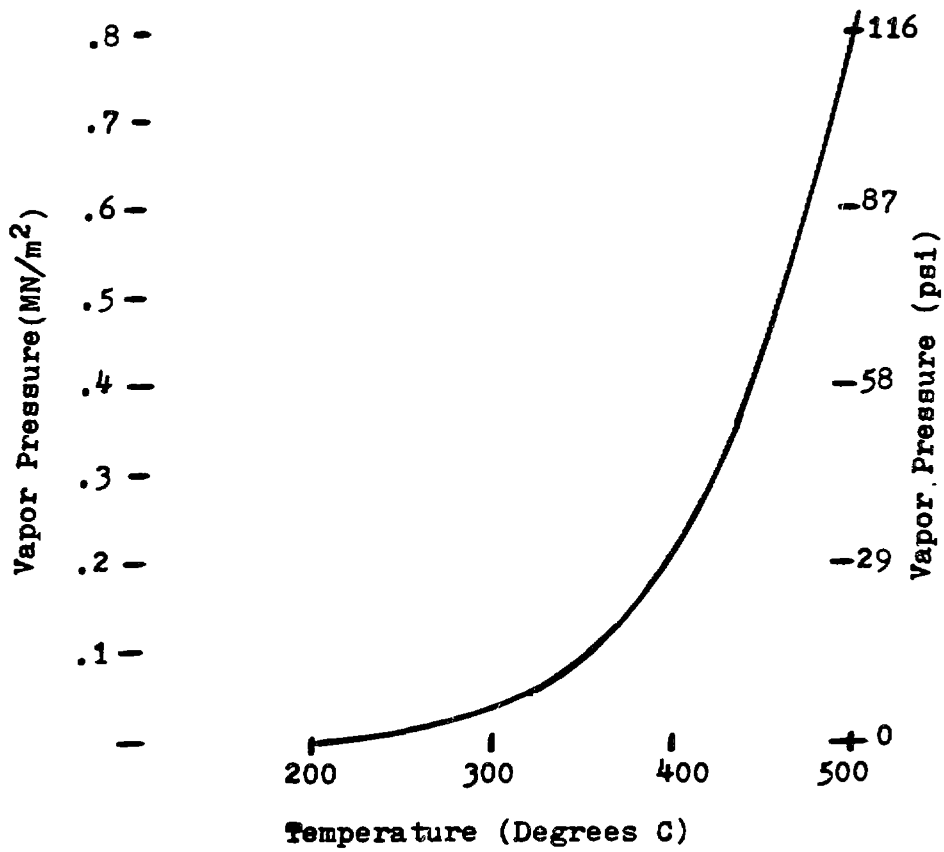
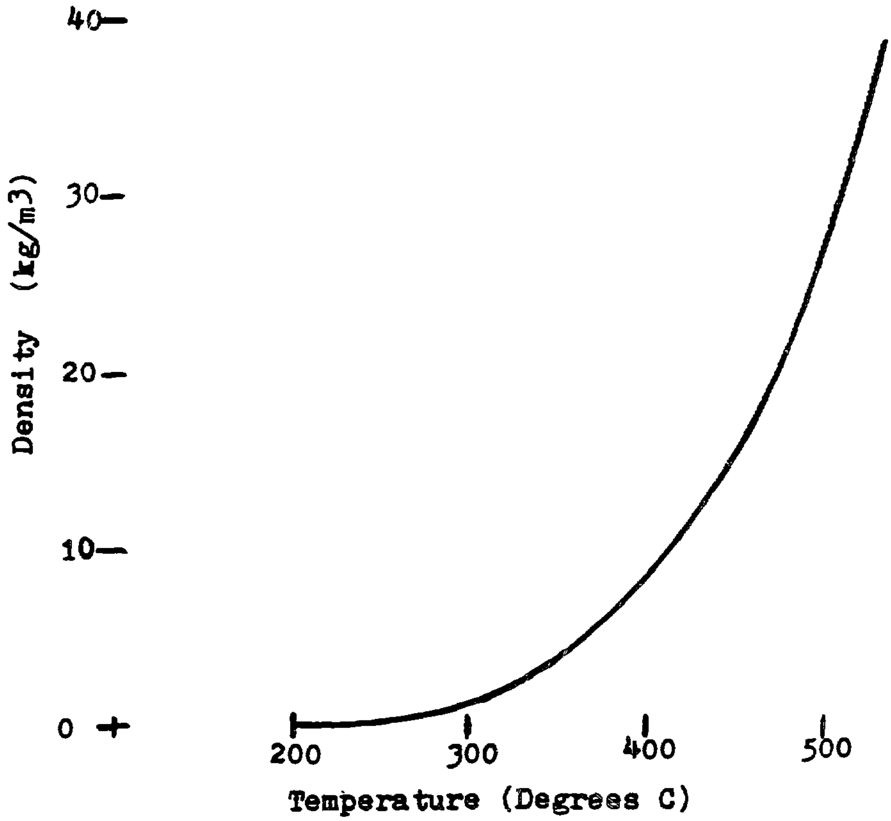


Fig. 2 DENSITY of SATURATED MERCURY VAPOR vs TEMPERATURE

(From Handbook of Chemistry & Physics, 31st Ed., 1949)



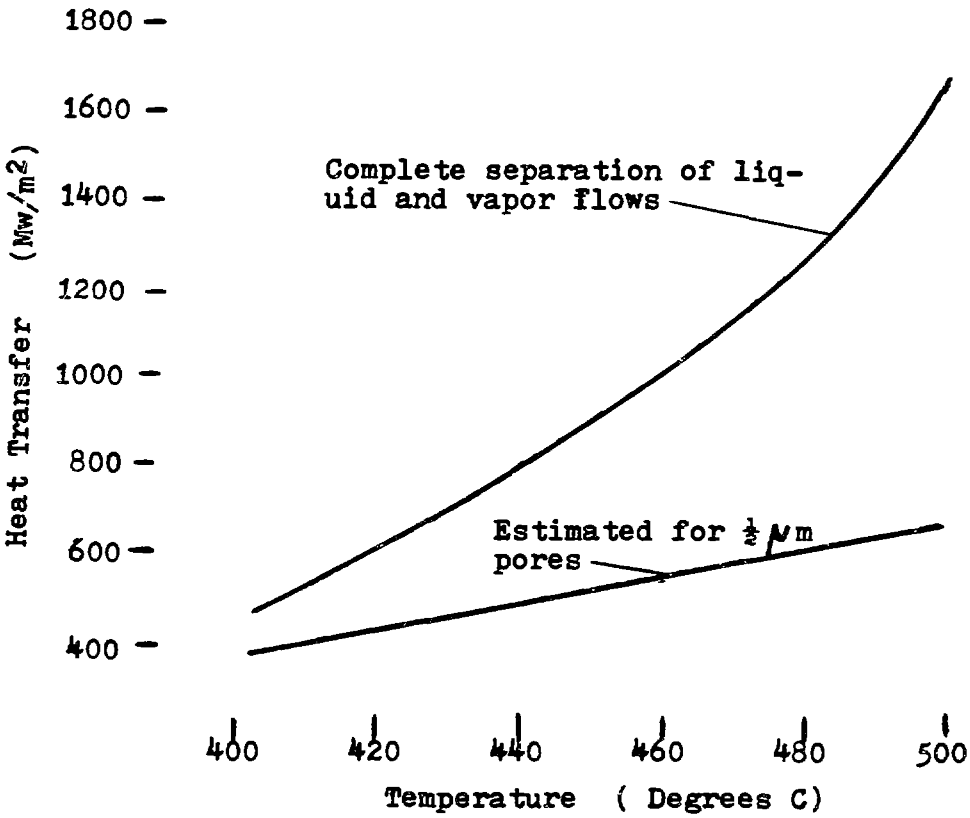


Fig. 3 Heat Transfer Capabilities of Mercury Reflux Capsules

rate under steady state conditions requires almost complete separation of the upflowing vapor from the downflowing liquid; so the high velocity vapor does not pick up and entrain the liquid before it gets back to the evaporator. This tendency for entrainment makes it necessary to have a flow separator as shown in Fig. 4a. As shown in Fig. 4b the separator in the condensing section has to be permeable; so the vapor can get to the capsule wall to be condensed. The flow separator in the adiabatic section need not be permeable. There should be no interchange between the vapor and liquid flows in this section. However, a permeable separator will also be needed in the evaporator section to ensure that drops of liquid do not get carried up with the vapor. As shown in Fig. 4b, this will probably have a conical shape and it may not extend all the way to the bottom. Its purpose will be to provide enough heat capacity to ensure that during steady state operation all mercury passing through it goes out in the vapor state.

As shown in Reference 17, the holes in the separator have to be as small as possible so the surface tension force of the liquid can prevent entrainment. In Appendix E the approximate criterion developed in this reference was used to calculate the heat flow rates for mercury with a permeable flow separator which has an effective pore diameter of one half micron. The results are plotted as the lower curve in Fig. 3. It should be noted that, as can be determined from Reference 18, a one half micron diameter hole

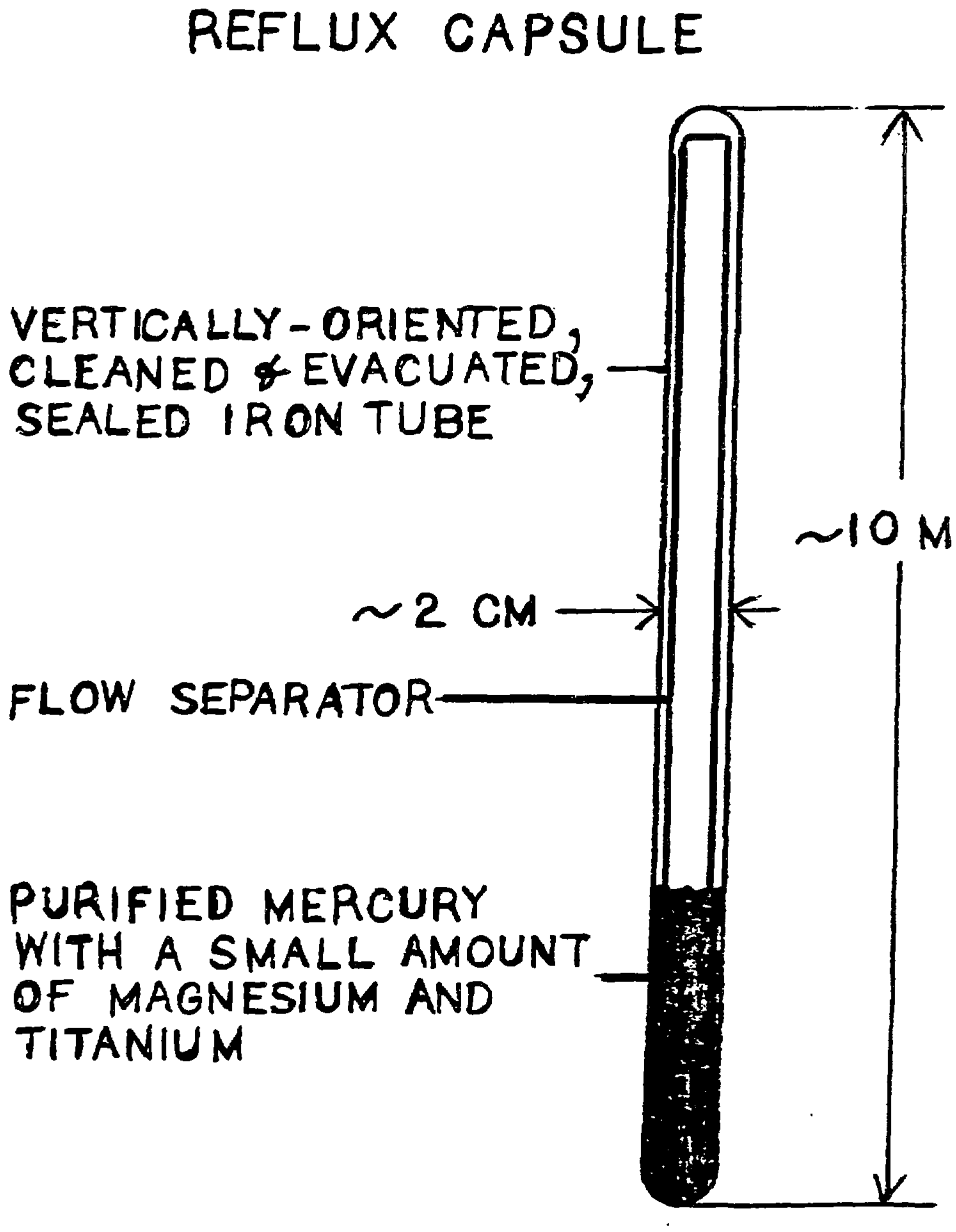


Fig 4a Inoperative Reflux Capsule

OPERATING REFLUX CAPSULE

Patent Pending

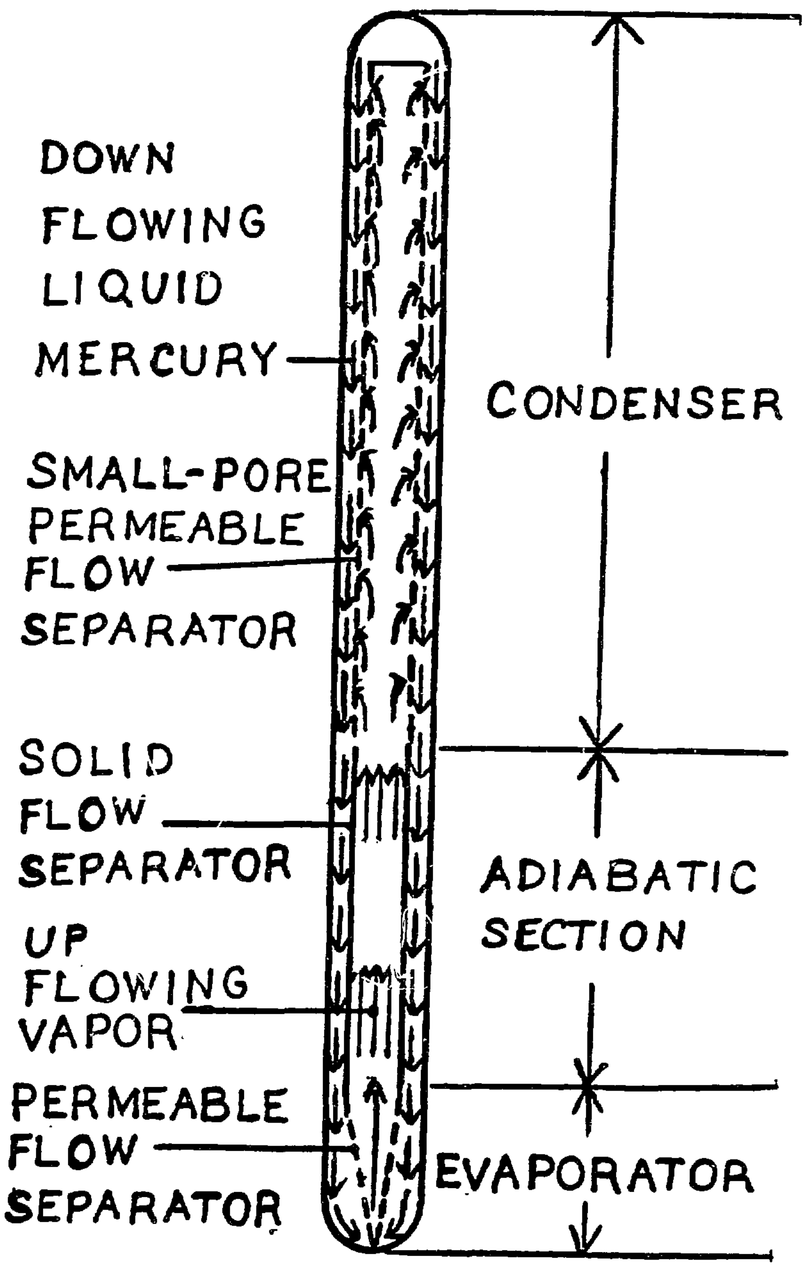


Fig. 4b Operating Reflux Capsule

is about 2000 times larger than the diameter of a mercury molecule; so there is ample room for improving the performance of the separator by reducing the effective pore diameter. Also, if the flow separator is made of iron, which mercury does not wet, there will be an additional repulsive force at the surface which will tend to enhance the separation of flows. Thus by using a well designed flow separator it should be possible to get better performance than shown by the lower curve.

In steady state operation the mass flow rate of the liquid down must equal the mass flow rate of the vapor up. As shown in Appendix F, the flow area required for the liquid mercury flowing down under the force of gravity is very small because the density of liquid mercury at these temperatures is over six hundred times greater than the density of the vapor.

REFLUX CAPSULE ASSEMBLIES

Since these reflux capsules will be long and spindly, like reactor fuel elements, they will not be self supporting and will be hard to handle; so about 91 of them will be put together into an assembly. The bottom, evaporator sections of the reflux capsules will be put into thimbles that will go into the liquid sodium which is coming out of the reactor. The top, condensing sections will be put into thimbles that will go into the H_2O in the steam generator. The open ends of these thimbles will have external threads, which will be screwed into circular headers. These threads will be cut so that when the capsules are taken up to operating temperature, their expansion will make positive seals in the headers. The bottom thimbles will be screwed into a sodium header, which will have external "O" rings. The top thimbles will be screwed into an H_2O header, which will have external threads. These will be cut to make a positive seal in the floor of the steam generator when it is at operating temperature. To separate the sodium from the H_2O, the middle portion of the reflux capsule, between the two headers, will be an adiabatic section in a vacuum chamber. Thus there will be a vacuum between the sodium and the H_2O.

Since the sodium will be the heat source, the bottom thimble will always be hotter than the inserted reflux capsule. On going up to operating temperature the thimble will tend to expand away from the reflux capsule leaving an undesirable gap. To prevent this, the bottom portion of the reflux capsule will be put into compression at room temperature by cooling it and simultaneously heating the thimble prior to inserting the reflux capsule into the thimble. After the capsules are inserted all of these thimbles can be screwed into the sodium header as indicated in Fig. 5a.

Since the upper, condensing end of a reflux capsule will always be hotter than its thimble, this can be a sliding fit at room temperature. Thus the upper thimbles can be screwed into the H_2O header as indicated in Fig. 5b, and then all of them together slid onto the reflux capsules in the sodium header to form the reflux capsule assembly.

Since the sodium is essentially unpressurized, the external force on the evaporator end of the reflux capsules will be essentially that due to the mercury vapor pressure shown in Fig. 1. But the upper thimbles in the steam generator will have up to about 3000 psi of external steam pressure applied. Thus the upper thimbles, reflux capsules, and internal structures must have a combined compressive strength that will withstand this force. In addition, as noted in Reference 19, free hydrogen in the steam generator will tend to diffuse through the thimbles. Although the open ends of these thimbles will be connected to a vacuum pump, there may be regions that are sealed off from it. To prevent hydrogen from going into the reflux capsules there should be a hydrogen barrier material between these upper thimbles and the reflux capsules. This might be a thin coating of tantalum which could be put on by a fused salt bath process.

Since there will be large differences between the sodium, and hence the reflux capsule, temperatures and the water temperatures, it will be necessary to have composite, multifoil insulation on the floor of the steam generator to protect it from thermal transients. This is depicted in Fig. 6 along with the cylindrical shrouds that will be needed to ensure vertical flow along the thimbles. These will be part of the reflux capsule assemblies. Thermal sleeves in the inlet feedwater pipes will also be necessary. The flow blocking grids, which the shrouds will fit into , are shown in Fig. 7.

BOTTOM HALF
REFLUX CAPSULE ASSEMBLY
(Patent Pending)

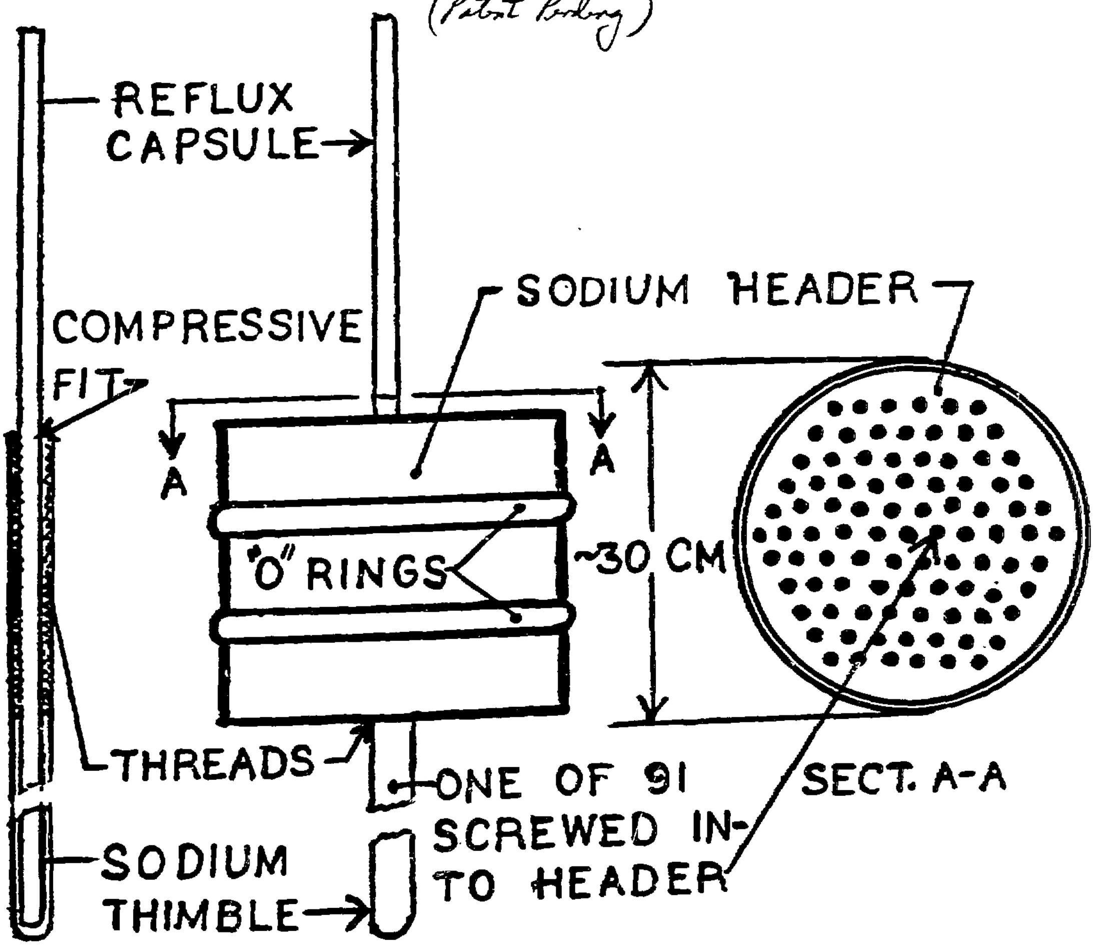


Fig. 5a Sodium Portion of Reflux Capsule Assembly

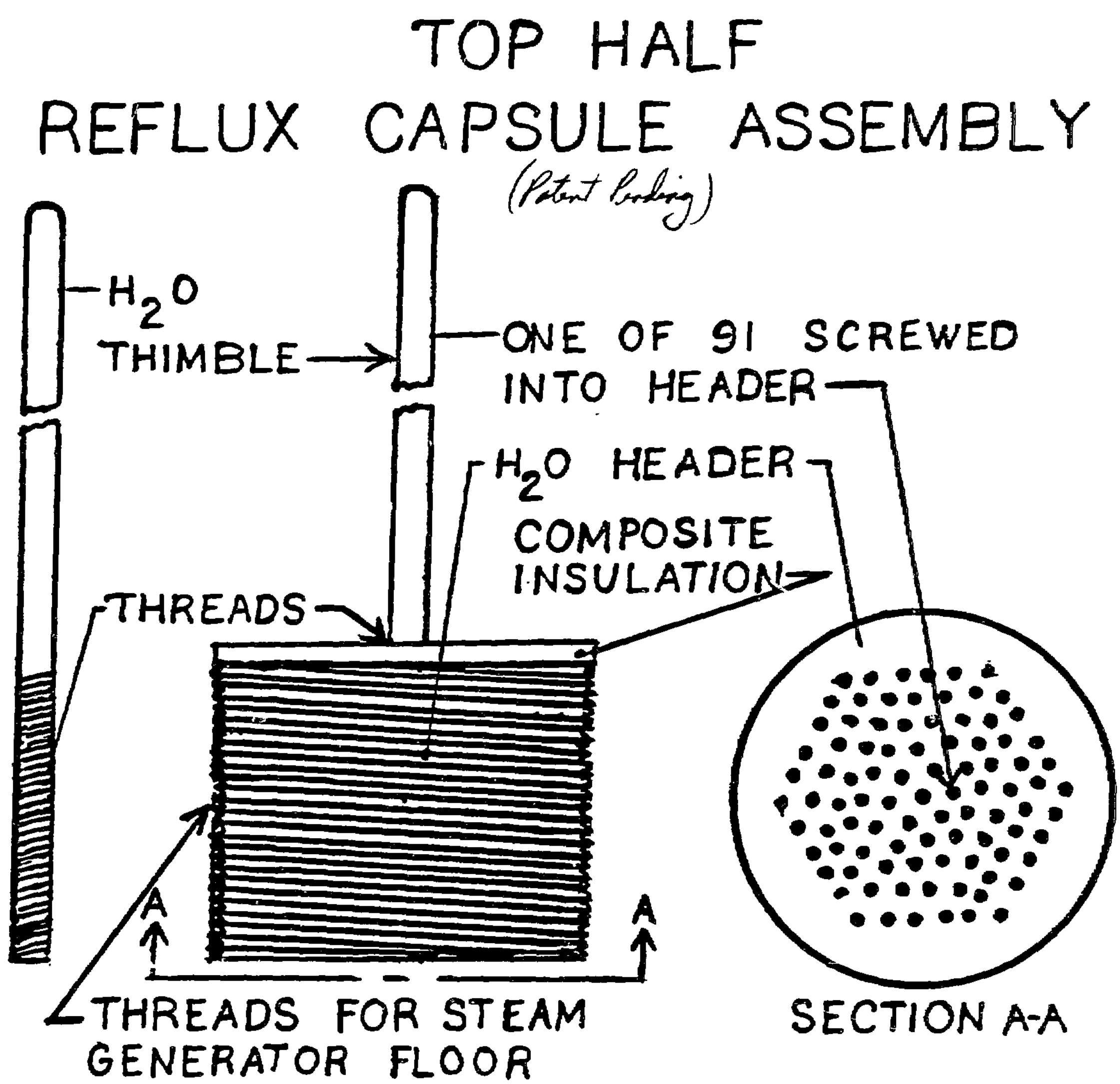


Fig. 5b H_2O Portion of Reflux Capsule Assembly

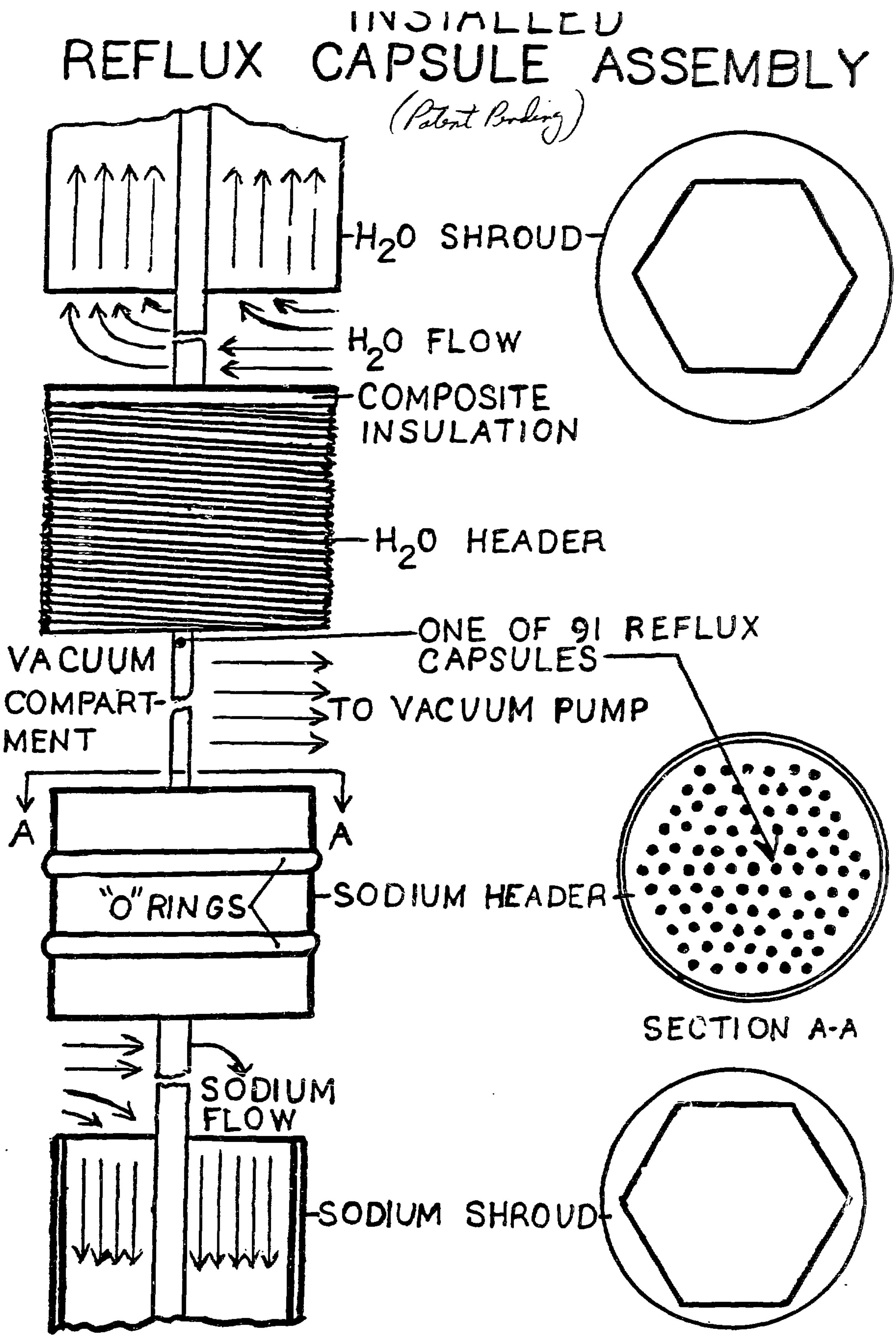
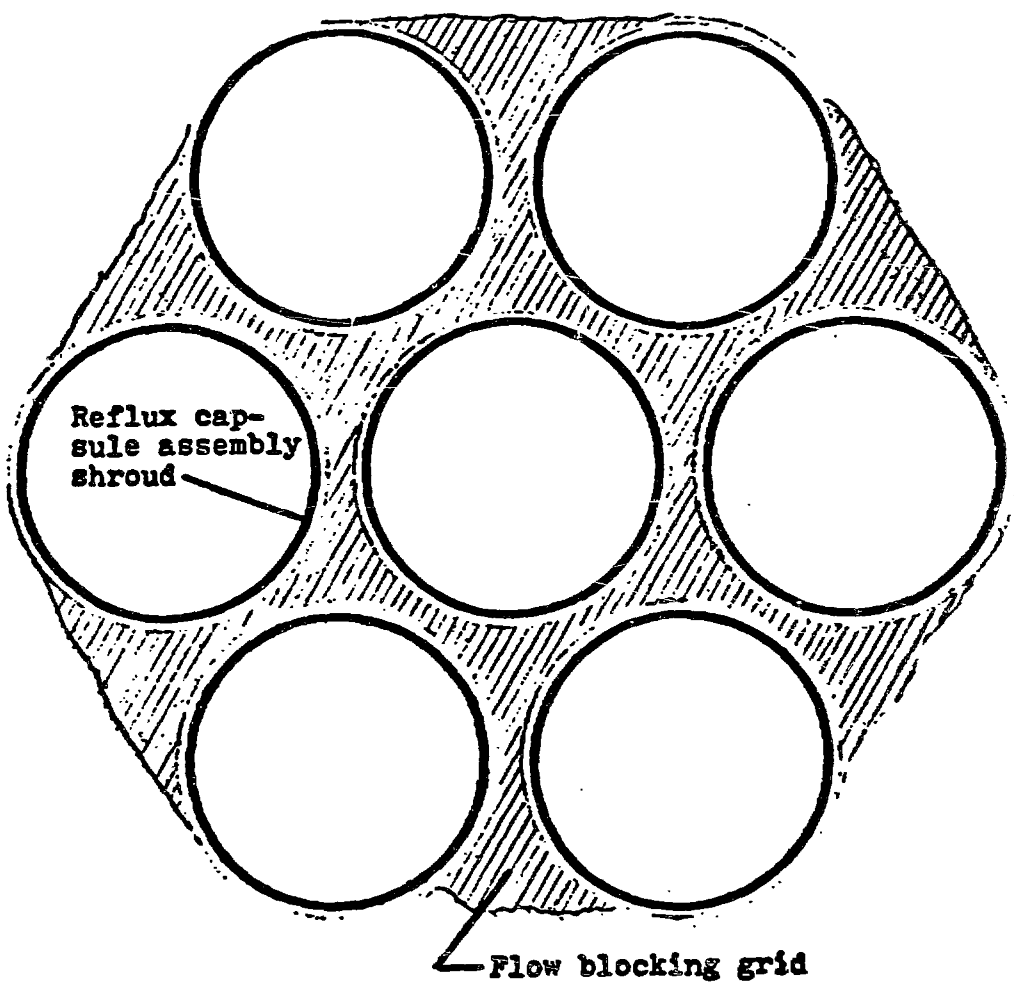


Fig. 6 Composite of Installed Reflux Capsule Assembly

Fig. 7 FLOW BLOCKING GRIDS FOR SHROUD REGIONS



The axial position of these assemblies will be fixed at only one place, i.e., where the fuel assemblies are screwed into the steam generator floor. Both ends of the assemblies will be free to expand, and the "O" ring seals on the sodium header will allow the adiabatic section to lengthen without creating excessive thermal stress when it is taken up to operating temperature. If necessary the "O" rings could have just enough inert gas in them to make them seal at the operating temperature. As stated before, the radial expansion will be used to positively seal the threads. This can be done without creating excessive thermal stress. To prevent water from going into the threads, the reflux capsules would always be heated to operating temperature before water is put into the steam generator.

STEAM GENERATOR

The operating temperature of reflux capsules will be nearly that of the sodium at the cool end of the evaporator section. In order to get maximum steam temperature it will be necessary to have the sodium flow through several groups of reflux capsules in series, as shown in Fig.8 In this schematic the sodium flows upwards along the first group of reflux capsules, as in a counterflow heat exchanger, to produce maximum steam temperature. The sodium would also flow upwards along the third group of reflux capsules so that it would also operate at the maximum temperature. This would minimize the cross sectional mercury vapor area

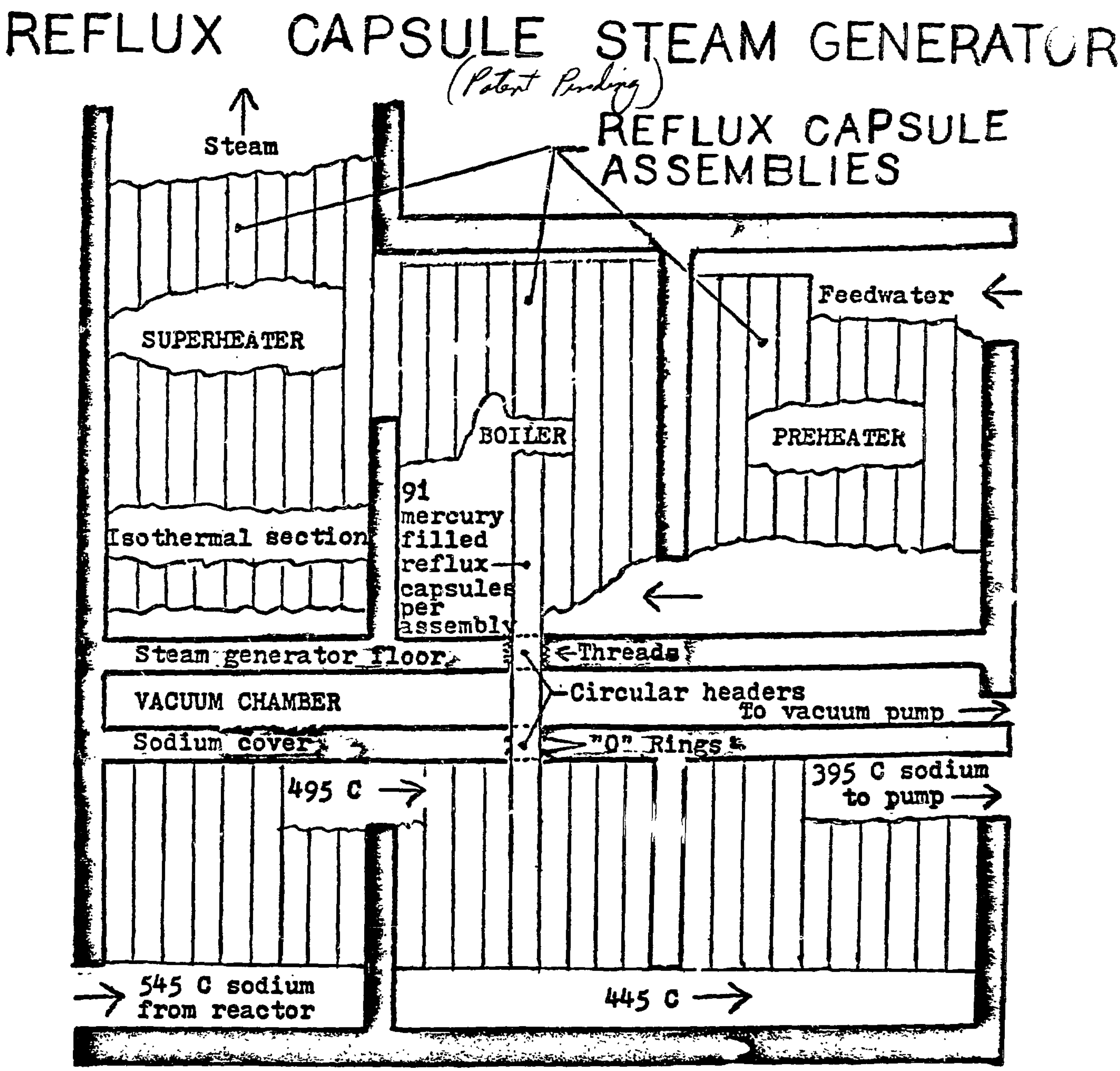


Fig. 8 Flow Schematic for Maximum Steam Temperature

required for this preheater group.

Another possible flow schematic is shown in Figure 9. This would maximise the natural circulation flow and hence minimise the required pumping power at the expense of a reduced steam temperature.

Reflux capsules are ideal for transferring heat between two different fluids because the heat transfer lengths need not be the same. Thus reflux capsules can operate as heat flow transformers. In this case if the same sodium flow area and velocity as in the reactor is assumed, the flow lengths in the sodium in each of the three compartments would be about one meter. If one meter is assumed for the vacuum chamber height and another meter is assumed for the thickness of the steam generator floor and the sodium cover, this would leave seven meters or more for heat exchange to the H_2O.

To reduce the neutron activation and transmutation in the steam generator to a minimum value, the wall between it and the nuclear reactor would be a neutron shield. This could be made up of alternating thicknesses of iron and boron-ten-carbide with steel plates outside for corrosion protection. In order to take away the neutron and gamma heating in this shield it would be designed to operate at a temperature somewhat above the temperature of the sodium which comes from the reactor.

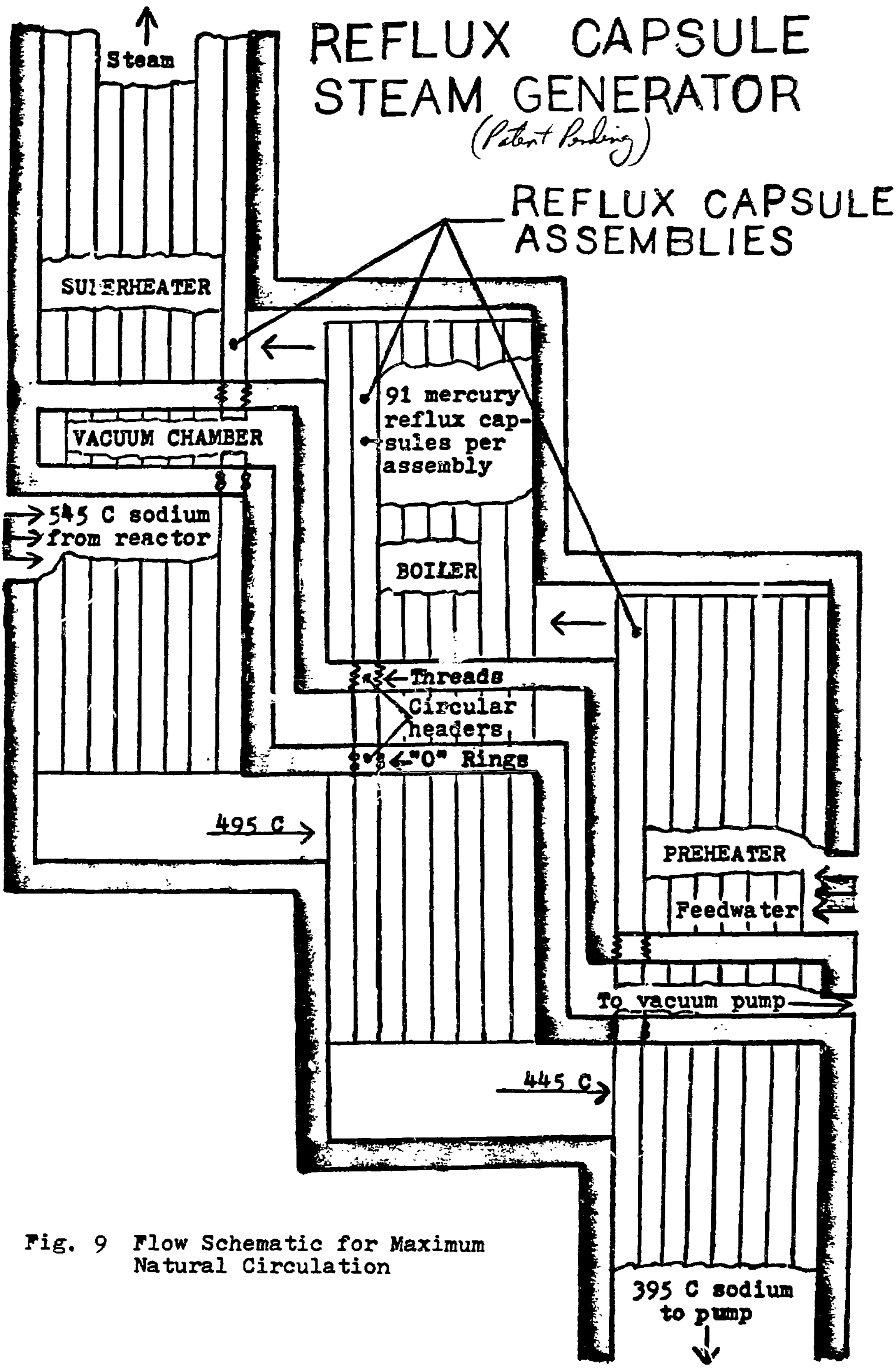


Fig. 9 Flow Schematic for Maximum Natural Circulation

VACUUM CHAMBER

At operating temperatures any water leaking into the vacuum would immediately flash to steam and would be pumped off as a vapor. The amount coming off could be instrumented; so the plant could be shut down if there was an excessive amount coming out.

Any sodium vapor leaking into the vacuum chamber would condense out on the first cool surface; so by design this would be a sodium vapor condenser with a return pipe which would take this sodium to the purification system and hence back to the primary coolant.

If both water and sodium vapor leak into the vacuum chamber at the same time, the sodium will react with the water to form sodium hydroxide and hydrogen. The hydrogen would be pumped off by the vacuum pump. The sodium hydroxide, which has a melting temperature of about 320 degrees C, would tend to condense out. As long as the floor of the vacuum chamber is kept above 350 degrees C this sodium hydroxide would be in a fluid state. Thus the floor of the vacuum chamber would be designed so that any significant quantity of sodium hydroxide would flow under gravity to a heated sump from which it could be pumped out for repurification.

The vacuum system would also be instrumented to detect mercury vapor so the plant could be shut down if a leak developed in any of the reflux capsules.

CONCLUSIONS

If it is assumed that the average mercury reflux capsule operates at 470 degrees C and that a flow separator in the condensing section has an effective pore diameter of one half micron, about 570 Mw of heat can be transferred up the capsules per square meter of cross sectional mercury vapor area. This is nearly the amount that would be needed for each loop of a four loop, 1000 MWe LMFBR.

The use of mercury reflux capsules in a sodium-H_2O steam generator will make the following possible:

1. The separation of the sodium from the H_2O by a vacuum region.
2. The elimination of excessive thermal stresses that cause yielding, fatigue, and stress corrosion.
3. The matching of the different heat transfer characteristics of the sodium and the H_2O by having different heat transfer areas in the two fluids. Thus there will be more heat transfer area in the H_2O than in the sodium.

This reflux capsule steam generator, with its intermediate mercury loops, will eliminate the need for a primary heat exchanger and a secondary, sodium-loop pump in a sodium-cooled nuclear reactor plant.

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Appendix A

Heat Transfer Capability of a Reflux Capsule Operating at Sonic Velocity

1. The heat transfer rate, $Q = \dot{M} \cdot \Delta h$

   where $\dot{M}$ = mas flow rate of vapor (kg/sec)

   and Δh = heat of vaporization (joules/kg)

2. $$\dot{M} = \rho \cdot A \cdot v_s$$

   where ρ = density of vapor (kg/m3)

   A = cross sectional area of vapor (m^2)

   v_s = sonic velocity (m/sec)

3. $$v_s = \left(\frac{\gamma p}{\rho}\right)^{\frac{1}{2}} \quad \text{(m/sec)}$$

   where γ = ratio of specific heats of the vapor

   p = pressure (N/m^2)

   (From Hausmann, E. & Slack, E.P.; Physics; p 531)

4. From 1.,2., and 3.:

   $$Q/A = \rho \left(\frac{\gamma p}{\rho}\right)^{\frac{1}{2}} \cdot \Delta h$$

   or, $$Q/A = \sqrt{\gamma} \cdot (\rho p)^{\frac{1}{2}} \cdot \Delta h \quad \text{(watts/ } m^2\text{)}$$

Appendix B

Material for Mercury Reflux Capsules

As noted in Reference 1 post-test, electron-beam microprobe analyses have shown that the corrosive attack on mercury container materials is, "approximately related to the solubility of the elements in mercury and to the total amount of soluble elements present in the alloy". Thus for long life capsules all of the elements in the capsule material should have low solubilities in mercury.

Table 1, which was derived from data in References 1,2, and 3, lists materials in the approximate order of increasing solubility in mercury at 500 degrees C. Iron with a value of 0.2 ppm is a satisfactory material, but nickel with a value of 75. ppm is probably not. Since iron is the cheapest of the low solubility materials it will probably be used for the base with one or more of the others with lower solubility added to increase compressive strength.

Because of its high surface tension mercury does not wet the surfaces of some of these materials. Iron is one of these. As noted in Reference 4 if iron is used, small amounts of magnesium and titanium must be added to the mercury in the evaporator section to make it wet the surface and thus provide good heat transfer to the mercury. Since titanium has an affinity for hydrogen, and readily hydrides, it will be important to not have hydrogen or

Table 1: SOLUBILITIES IN MERCURY

Material	Solubility in Mercury at 500 degrees C (parts per million)
Tungsten	
Tantalum	.002
Molybdenum	
Columbium	.03
Vanadium	
Cobalt	
Iron	.20
Chromium	
Nickel	75.
Manganese	

hydrocarbon contamination in the capsule. These could cause dewetting problems like those described in Reference 5.

As also noted in Reference 5, a columbium surface grossly dewetted on exposure to air at operating temperature. Since most of these refractory metals readily oxidize, it will be important to have clean metallic surfaces and to not have oxygen in the capsules.

There is another factor which must be considered before choosing alloying elements for iron. This is that as noted in Reference 6, free hydrogen in high pressure steam tends to diffuse through the container walls. Thus there may be some hydrogen going into the capsules even if a barrier is put between the thimbles and the reflux capsules. Thus elements like tantalum that hydride should not be used as alloys in the iron. However, one of these materials, used in a fused-salt bath process, may provide the hydrogen barrier and a protective coating for the outside of the capsule. Fortunately, tungsten and molybdenum are not affected by hydrogen; so they can be used as alloying agents in the iron.

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Appendix C

Critical Pressure Ratio for Mercury Vapor

In Reference 1 the critical pressure ratio for a gas in a constant flow area nozzle is given as:

$$\text{Critical pressure ratio} = \frac{\text{p in nozzle}}{\text{Driving p}} = \left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma}{\gamma - 1}\right)}$$

where γ = ratio of specific heats. In Reference 2 mercury vapor is listed as a monatomic gas. In Reference 3 the value for γ for monatomic gases is given as 1.66. Thus:

$$\text{Critical pressure ratio for mercury vapor} = \left(\frac{2}{2.66}\right)^{2.52} = 0.5$$

Thus if the mercury vapor pressure leaving the evaporator is more than 2.0 times the pressure just above it, the flow will be choked at the velcity of sound.

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Appendix D

Heat Transfer Capability of Mercury Vapor at Sonic Velocity

As given in Appendix A, this heat flow rate is:

$$Q/A = \sqrt{\gamma}\,(\rho\, p)^{\frac{1}{2}}\,\Delta h = \sqrt{1.66}\,(\rho\, p)^{\frac{1}{2}}\,\Delta h \quad (\text{watts/m}^2)$$

Temperature (Degrees C)	ρ[a] (Kg/m³)	p (#/in²)[a]	p (N/m²)[b]	Δh (BTU/#)[a]	Δh (joules/kg)[c]
374.4	5.37	20.0	13.8x10⁴	121.5	2.82x10⁵
399.4	7.80	30.0	20.7	120.5	2.80
426.1	11.32	45.0	31.0	119.4	2.77
446.7	14.74	60.0	41.4	118.6	2.75
477.8	21.37	90.0	62.1	117.4	2.72
501.1	27.78	120.0	82.8	116.4	2.70
537.8	40.14	180.0	124.2	115.0	2.67

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a From Hodgman, C.D., Editor in Chief; Handbook of Chemistry & Physics; Thirty first edition, 1949; Chemical Rubber Publishing Co.; Cleveland, Ohio; pages 1926 & 1927.

b $p = \frac{20.0\ \#}{\text{in}^2} \times \frac{4.45\ \text{N}}{1\ \#} \times \frac{1^2\ \text{in}^2}{2.54^2\ \text{cm}^2} \times \frac{10^4\ \text{cm}^2}{1\ \text{m}^2} = 20.\ (.69 \times 10^4\ \text{N/m}^2)$

c $\Delta h = \frac{121.5\ \text{Btu}}{1\#} \times \frac{2.2\#}{1\ \text{kg}} \times \frac{1055\ \text{joules}}{1\ \text{Btu}} = 121.5 \times (2321)\ \frac{\text{joul}}{\text{kg}}$

Temperature (Degrees C)	$(\rho p)^{\frac{1}{2}}$ $\frac{\text{kg}}{\text{m}^2\ \text{sec}}$	Δh $\frac{\text{joules}}{\text{kg}}$	Q/A $\frac{\text{watts}}{\text{m}^2}$
374.4	860.8	2.82 x 10⁵	242.7 x 10⁶
399.4	1270.7	2.80	458.4
426.1	1873.2	2.77	668.5
446.7	2470.3	2.75	875.3
477.8	3642.9	2.72	1276.6
501.1	4796.0	2.70	1668.4
537.8	7060.7	2.67	2428.9

Appendix E

Estimated Heat Fow Rate in Reflux Capsules at Entrainment Limit

An expression for the heat flow rate up a reflux capsule at the entrainment limit, which is based on the upward vapor flow drag force being equal to the surface tension force in the condensed liquid going through a flow separator, is given in Reference a. This is:

Heat Flow Rate Up the Capsule, $Q/A = \left(\frac{\sigma \rho}{C_D D_p}\right)^{1/2} \cdot \Delta h$

where,

σ = Surface tension in the condensed liquid (N/m)

ρ = Density of vapor (kg/m3)

C_D = Drag coefficient = 3.33

D_p = Effective pore diameter in flow separator (m)

Δh = Heat of vaporization (joules/kg)

If a permeable flow separator in the condensing section has an effective pore diameter of one-half micron, this equation becomes:

$$Q/A = \frac{\Delta h}{(3.33 \times 0.5 \times 10^{-6})^{\frac{1}{2}}} \times (\sigma p)^{\frac{1}{2}}$$

This gives the following values for Q/A:

Temperature (Degrees C)	Δh^c (joules/kg)	σ^b (N/m)	ρ^c (kg/m^3)	Q/A (Mw/m^2)
399.4	2.80 x 10^5	.390	7.80	379
426.1	2.77	.383	11.32	447
446.7	2.75	.377	14.74	503
477.8	2.72	.370	21.37	592
501.1	2.70	.360	27.78	661

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a Equation 17 on page 17 of A Study of Heat Pipe Applications in Nuclear Aircraft by C. C. Silverstein; National Aeronautics & Space Administration, NASA-CR-72610-SL-104, 1969.

b Extrapolated from data on page 1747 of the *Handbook of Chemistry & Physics*, Thirty first edition, 1949

c See table in Appendix D.

Appendix F

Liquid Condensate Flow Area in a Mercury Reflux Capsule

In a reflux capsule operating in a steady state condition the mass flow rate of the liquid condensate down has to equal the mass flow rate of the vapor up. The mass flow rate of vapor up the capsule is given by:

$$\dot{M}_v = \rho_v \cdot A_v \cdot \bar{v}_v = \pi r_v^2 \rho_v \bar{v}_v$$

where r_v is the radius of the vapor, ρ_v is the density, and $\bar{v}_v$ is the average upward velocity. The radius of the vapor will be essentially the same as the inner radius of the flow separator. The mass flow rate of the condensed liquid down the capsule is given by:

$$\dot{M}_c = \rho_c \cdot A_c \cdot v_c = \pi (r_c^2 - r_s^2) \rho_c v_c$$

where r_c is the inner radius of the capsule, r_s is the outer radius of the flow separator, ρ_c is the density of the liquid condensate, and $\bar{v}_c$ is the average downward velocity. Thus for equal mass flow rates:

$$\frac{\text{Vapor area}}{\text{Condensate area}} = \frac{r_v^2}{r_c^2 - r_s^2} = \left(\frac{\rho_c}{\rho_v}\right)\left(\frac{v_c}{v_v}\right)$$

Since the most condensate area will be required for the highest vapor velocity, this is the sonic velocity. The velocity of the liquid condensate flowing down under the force of Earth's gravity is:

$$v_c = \sqrt{2 g l} = 4.427 \sqrt{l} \quad \text{(m/sec)}$$

where g is 9.8 m/sec^2 and l is the height of the condensation point above the bottom of the evaporator. The minimum condensate velocity will be obtained in the drops which are condensed in the lower part of the condenser, i.e., just above the adiabatic section. Thus:

$$(v_c)_{min} = 4.427 \sqrt{l_e + l_a}$$

where l_e and l_a are the heights in meters of the evaporator and adiabatic sections of the reflux capsule. The maximum condensate velocity will be obtained in the drops which are condensed at the top of the condenser. Thus:

$$(v_c)_{max} = 4.427 \sqrt{l_e + l_a + l_c}$$

where l_c is the height in meters of the condenser section. The average condensate velocity down will be:

$$\bar{v}_c = \frac{4.427}{2} \left[\sqrt{l_e + l_a} + \sqrt{l_e + l_a \ l_c} \right] \text{(m/sec)}$$

Assuming a reflux capsule where

$$l_e = 1 \text{ m}, \ l_a = 2 \text{ m}, \text{ and } l_c = 6 \text{ m}$$

$$\bar{v}_c = 10.5 \text{ m/sec}$$

If we assume the capsule is operating at 468 degrees C at sonic velocity, as can be determined from Appendices A and D,

$$\bar{v}_v = 219 \text{ m/sec}$$

so,

$$\bar{v}_c / \bar{v}_v = \frac{10.5}{219} = .048$$

According to Reference 1 the density of liquid mercury is given by:

$$\rho_c = .073554 \left[1 + 10^{-6} \left\{ \begin{matrix} 181.456t + .009205t^2 + .000006608t^3 \\ .6732 \times 10^{-7} t^4 \end{matrix} \right\} \right]$$

where t is the temperature in degrees C. For 468 degrees C this gives a value of 12,463 kg/m^3. From Appendix A it can be determined that the density of mercury vapor at this temperature is 19.2 kg/ m^3. Thus the ratio of these densities is:

$$\rho_c/\rho_v = \frac{12,463}{19.2} = 649$$

Thus the ratio of the flow areas is = .048 x 649 = 31. Or the required flow area for the condensate in this example is less than 1/30th of the vapor flow area.

Reference

1. Washburn, E.W., Editor-in-chief; International Critical Tables of Numerical Data, Physics, Chemistry & Technology; Volume 2; McGraw Hill Book Company, N.Y., N.Y.; pages 457 and 458.