BOILING LIQUID CAULDRON STATUS REPORT

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ABSTRACT

The progress made over the past year in assessing the feasibility of the high-temperature, boiling cauldron blanket concept for the tandem mirror reactor is reviewed. The status of the proposed experiments and recently revised estimates of the vapor void fraction in the boiling pool are discussed. These have strong implications on the direction of the work for FY81.

DISCLAIMER

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CONTENTS

	<u>Page</u>
1. Introduction	1
2. Review of Early Predictions	2
3. Small-Scale Experiments	5
3.1 Design of Experiment with MHD Effects	5
3.2 Water Experiments	10
3.3 Other Relevant Experiments	12
4. Conclusions	14
References	15

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1. INTRODUCTION

The liquid-pool or cauldron concepts proposed by R. Werner have as one of their main goals to minimize the amount of structural material exposed to intense neutron bombardment. The two configurations which looked the most attractive at the beginning of this study were:

- (1) The boiling-liquid pool or cauldron concept.
- (2) The heat-pipe liquid pool concept.

Almost all of the study effort has been focused on the first concept during the first year of this program, because the boiling cauldron seemed to be the simplest approach with the least amount of solid materials exposed to the energetic neutrons.

During the initial study phase, three key problem areas were identified which have an impact on the feasibility of the boiling cauldron concept. They are:

- (1) Volumetric boiling stability with highly nonuniform internal heating.
- (2) Large void fraction.
- (3) Effects of the horizontal magnetic field.

Due to the difficulty of making analytical predictions, it was proposed to run a small-scale boiling liquid metal experiment to try to resolve these questions.

Of the three questions, the most serious problem seemed to be the large void fraction predicted in the preliminary study of Ref. 1. Such a large void fraction would impose severe design and economic penalties on the boiling cauldron concept. This report summarizes our efforts to obtain an answer to the void fraction question, including the design of a meaningful experiment.

2. REVIEW OF EARLY PREDICTIONS

A rough estimate of the average pool void fraction was made in Ref. 1 based on the average internal heat generation rate, $\bar{q}''$:

$$\bar{x}_v = \frac{f_{LH} \bar{q}'' H_0}{\bar{\rho}_v \bar{u}_v h_{fg}} \quad (1)$$

where f_{LH} is the fraction of the total internal heat generation carried to the free surface by the vapor as latent heat, H_0 is the initial pool height, $\bar{\rho}_v$ is the mean vapor density, $\bar{u}_v$ is the mean vapor velocity and h_{fg} is the latent heat of vaporization.

A rough estimate for the mean vapor velocity, $\bar{u}_v$, was obtained using the bubble terminal rise velocity, U_∞ , based on classical single bubble results [2]:

$$\bar{u}_v \approx U_\infty = C_B (g_c \sigma / \rho_L)^{1/4} \quad (2)$$

where C_B is a constant of order unity, g_c is the gravitational conversion factor (equal to 1.0 for SI units), σ is the surface tension coefficient and ρ_L is the liquid density. For $C_B = 1.18$, we estimated an average bubble rise velocity for sodium at a liquid pool temperature of 1273 K (1000°C) of about 0.23 m/s, in reasonable agreement with data for both air and steam bubbles in water [2] and for mercury vapor bubbles in mercury [3]. This is a lower limit for the actual vapor velocity in a vigorously boiling pool.

As a rough estimate for the fraction of the input neutron power carried by latent heat, we used a value of $f_{LH} = 0.02$ based on an example in Tong [4] for subcooled pool boiling. The actual f_{LH} will clearly be much larger than this value for near-saturated pool boiling.

For the cauldron conditions with $\bar{q}'' \approx 1.0 \times 10^6 \text{ W/m}^2$ (for a neutron wall loading of 2.0 MW/m^2) and an initial pool height, $H_0 = 5 \text{ m}$, we estimated an average void fraction of about 0.17 without a magnetic field. (If the average bubble travels only half the pool height, the void fraction would be about half this value.)

Using data of Mori, et al., [3] on the effect of a horizontal magnetic field on the rise velocity of single bubbles, we estimated that a 2 tesla horizontal magnetic field would reduce the bubble rise velocity by roughly a factor of two for sodium bubbles with diameters around 3 to 4 mm. This, in turn, would roughly double the average void fraction, resulting in a rather high value somewhere between 0.17 and 0.34.

Because the fraction of the internal heating carried by latent heat, f_{LH} , will certainly be much larger than 2% for our near-saturated pool boiling conditions, it was our judgment that the above estimate of $\bar{f}_v$ was actually a lower bound. In particular, near the first wall $\bar{f}_v$ was expected to be much larger. This conclusion was based in part on the fact that the average sodium vapor velocity, V_s in the dome region above the pool required to transport the thermal power to the condenser, was estimated to be about 1.5 to 2 m/s. (This could possibly be reduced

by a factor of two by geometry changes.) However, the bubble velocity in the presence of a 2 tesla magnetic field was estimated to be only about 0.12 m/s. In order for the heat input to be transported to the surface, we speculated that rather large vapor voids would have to form and produce large turbulent motions of the superheated liquid as they rose to the surface; this would probably occur even in the presence of a 2 tesla magnetic field. Only in this way would there be sufficient vapor transport to the surface as well as sufficient superheated liquid transport to the surface to obtain a total average surface evaporation plus vapor flow rate equal to the required 1.5 to 2 m/s. (This is referred to as the churn-turbulent boiling regime in the literature.)

In support of these speculations, it is interesting to compare this value of 1.5 to 2 m/s to the surface vapor velocity of boiling sodium in conventional pool boiling with heating from the bottom. The peak or critical heat flux (CHF) for sodium pool boiling at 1273 K (1000° C), lies between 240 and 400 W/cm² using various CHF correlations. The corresponding surface vapor velocities lie between about 1.0 and 1.6 m/s compared to our average value of about 1.5 to 2 m/s for volumetric boiling. From this comparison we can conclude that we will indeed require very vigorous volumetric boiling with large void fractions in order to transport the neutron heating power to the liquid free surface.

At this point, it was clear to us that a small-scale experiment would be required unless by some good fortune we could find relevant experiment results for the vapor void fraction and the physical behavior of a vigorously boiling pool under conditions of nonuniform internal heating in the published literature.

3. SMALL-SCALE EXPERIMENTS

In an effort to obtain a better estimate of the boiling cauldron behavior, we pursued four approaches:

- (1) Design of a liquid metal pool boiling experiment with nonuniform internal heat generation and magnetic fields.
- (2) Preliminary qualitative pool boiling experiments with water.
- (3) Design of a quantitative water pool boiling experiment.
- (4) Extensive searches of the pool boiling literature.

The results of each of these efforts will be described in detail in the following sections.

3.1 Design of Experiment with Liquid Metal

Significant progress was made in the design of an experiment to determine the MHD (magnetohydrodynamic) effects on pool boiling with uniform volumetric heating in a horizontal magnetic field. Several issues were addressed:

- (1) Heating method.
- (2) Magnetic field effects.
- (3) Required size of the experiment and scaling parameters.
- (4) Diagnostics and instrumentation.
- (5) Behavior of the pool with vigorous boiling.

We had hoped to be able to use a transparent electrolyte in order to combine MHD tests with visualization of the pool boiling. This would have permitted the direct interpretation of the MHD effects on the boiling behavior at different heating rates. Electrolytes have been used successfully in the investigation of MHD effects on the turbulent-flow, convective heat transfer of a single-phase, electrically-conducting liquid (e.g., Ref. 5). However, it soon became apparent that use of electrolytes for boiling heat transfer experiments was not feasible due to the small electrical conductivity of electrolytes relative to liquid metals.

The electrical conductivity, σ , is a factor in Lykoudis' boiling magnetic interaction parameter, β :

$$\beta = B^2 \sigma T_{SAT} \left[\frac{1}{\rho_e C_p L T_{SAT}} \frac{1}{(\nu h_{fg})^3} \right] \quad (3)$$

This parameter, in turn, determines the MHD effects on the boiling Nusselt number for the classical case of heating from the bottom of the pool [6]:

$$\frac{Nu}{Nu_0} = \left[\frac{1}{1 + 17.5 \beta^{1.25}} \right]^{2.46} \quad (4)$$

where Nu_0 is the Nusselt number for $B = 0$ and P is the pressure in MPa.

For sodium at 1000°C, $\beta \approx 0.1$ to 1.0 for T_{SAT} from 5°C to 50°C, while for electrolytes β is on the order of 10^{-6} or less. For this low a value of β , there would be no detectable MHD effects on electrolytes.

As a result, we decided to design a boiling liquid metal experiment in which we would first run sodium and then a mixture of sodium and lithium.* In parallel with the design effort, we decided to study volumetric pool boiling of water in order to gain a better physical understanding of the boiling regimes and pool behavior at various thermal power input levels. These water experiments will be described in the next section.

A large number of methods for producing nonuniform heating of a liquid metal were examined (see Warner, Internal Tech. Rept., 1969). One of the most attractive methods (see Jones) was induction heating of the power supplies and expansion of personnel with the goal of 100% efficiency. However, a serious drawback of this method is the very small penetration depth of penetration of the RF into the liquid metal at the usual RF frequencies. Typical values are 1/2 inch penetration of a 1000-gal container filled with sodium at 10 Mc and less than 1/4 inch at 100 Mc. Frangopolis on the edge of the container and the liquid metal surface to simulate the nonuniform heating conditions existing within.

An alternative heating scheme using a large number of small heaters, as sketched in Fig. 1, offering a simple alternative of a large number of heaters to inner radius of only 1 inch, was also considered and rejected.

* To complement our approach, the group at the University of Washington proposed doing a liquid mercury experiment in a magnetic field using injection of inert gas bubbles through the bottom.

magnitude variation in the local internal heat generation in the radial direction. A final decision between the RF and dc heating methods was deferred pending the outcome of the water experiments.

The next question addressed was that of the required size of the experiment. The minimum size experiment must certainly be about an order of magnitude larger than the final vapor bubble size. As a rough measure of the bubble size, we took the bubble diameter at departure from a surface site, D_{BD} . Ivey [2] quotes a bubble departure diameter given by:

$$D_{BD} = K_{BD} \left[\frac{q_c}{g(\rho_L - \rho_v)} \right]^{1/2} \quad (4)$$

where K_{BD} is usually taken to be on the order of unity; this value of K_{BD} appears to be valid for water at about 1 atm, but it is not of general validity.

Deane and Rohsenow [7] say that the limited data for potassium bubbles fall in the range of two correlations recommended by Cole and Rohsenow [3], one for water and one mostly for organic fluids. These correlations have the same form as Eq. (4), but the effective K_{BD} for the correlations is:

$$K_{BD} = C_{BD} N_{EO}^{5/4} = C_{BD} \left[\frac{\rho_L C_p T_{SAT}}{\rho_v h_{fg}} \right]^{5/4} \quad (5)$$

where N_{EO} is the Eotvos number and $C_{BD} = 1.5 \times 10^{-4}$ for the water correlation (Deane and Rohsenow, Eq. 4), while $C_{BD} = 4.65 \times 10^{-4}$ for the correlation for other fluids, mostly organic compounds (Deane and Rohsenow, Eq. 5).

The predicted values of the bubble departure diameters for sodium using these three relations are shown in Fig. 2 as a function of the saturation pressure. The dramatic difference in the predictions for D_{BD} on the order of 1.0 compared to the Cole and Rohsenow correlations is quite apparent.

We have assumed that the correlations of Cole and Rohsenow give bubble diameters of the right order of magnitude for sodium. Using these values, we see that a rather high pressure and temperature experiment is required to keep the bubble diameters small so as to keep the apparatus small. For example, for boiling sodium at $T_{SAT} = 1155$ K ($P_{SAT} \approx 1$ atm), we see that D_{BD} could range from about 4 mm to 14 mm. This would require a small-scale experiment with a minimum dimension of at least 14 cm, since the actual vapor void sizes can be much larger than these bubble diameters on Fig. 2 in the churn-turbulent boiling regime. (It is possible to decouple the required pressure and temperature by use of an inert cover gas, and this was also considered as an attractive possibility.)

In running the experiment, it was concluded that we would have to run at about the same velocity ratio, $V_s/U_\infty \approx 6$ to 8, as the boiling cauldron. (Recall that V_s is the average velocity of the vapor at the free surface and U_∞ is the terminal bubble velocity.) This, in turn, implies that we

would have to have about the same maximum internal heat generation as in the cauldron, namely about 7 W/cm^3 near the first wall. These are very challenging experimental conditions.

The minimum diagnostics required include measurements of the surface temperature distribution, vapor pressure in the dome region, pool surface level in both the nonboiling and boiling regimes, and input power level. Some of these measurements, such as the pool surface level in the boiling regime, are very difficult to accomplish reliably in a sealed, opaque container. These complications inevitably increase the cost and complexity of the experiment.

3.2 Water Experiments

After initial design efforts on the liquid metal experiment, we estimated that the cost of even the simplest experiment would be on the order of \$50,000 or more. This prompted us to try to obtain the maximum possible information from water experiments first.

We decided to start with some preliminary, qualitative flow-visualization experiments with water. We compared the pool boiling of ordinary tap water by heating through the bottom surface of a beaker to the pool boiling by volumetric heating in a microwave oven. We found that the boiling behavior was not too different for the same level of heat input. At low heat inputs, the bubbles seemed to appear throughout the volume with microwave heating and the boiling was well behaved with no signs of bumping or instabilities. When a wire was inserted in the water, there

was additional bubble nucleation and growth on the wire. The internal heat generation in the wire by the microwave is probably higher than in the surrounding water; this is similar to the situation that wires inserted in the boiling cauldron would experience due to neutron heating. Even with the wire present, bubbles still appeared throughout the volume as well.

The smooth surface of the pyrex beaker used did not appear to provide many nucleation sites in the microwave heating. However, there were many sites activated when the beaker was heated from the bottom. Unfortunately, the home microwave oven was severely power-limited and could not produce the desired vigorous boiling with large void fractions which was easily obtained for bottom heating.

However, these initial water experiments were so encouraging that we decided to try to extend them using a more powerful microwave heater. We planned to make quantitative measurements of void fractions at various levels of internal heat generation, as well as to photograph the pool behavior. We reasoned that if the void fractions we measured without a magnetic field were unacceptably large, they would probably be even worse with a magnetic field. In this case there might be little to be gained by building and running an expensive liquid metal experiment to study the MHD effects.

3.3 Other Relevant Experiments

We have put the discussion of the literature search at the end rather than at the beginning, as is customary, because of "historical" reasons. While we began a careful search of the literature at the very beginning of the study, we did not uncover the most important and relevant work until December 1980. By good fortune, we learned that a group at Brookhaven National Laboratory had run extensive pool boiling experiments with volumetric heating to simulate loss-of-flow accidents in LMFBR's. Thanks to Dr. Owen Jones, we obtained several of the original reports and papers on the work [9, 10, 11, 12].

The principal results of these studies using ohmic heating of pools of zinc sulfate-water mixtures are shown in Fig. 3 (from Ref. 12). The top figure shows experimental results and the bottom figure shows theoretical predictions of average void fraction. The abscissa is the velocity ratio, $j_{g\infty}/U_\infty$, where $j_{g\infty} \equiv V_s$ is the velocity of the vapor off the free surface of the pool and U_∞ is the terminal velocity of single bubbles. For the boiling cauldron conditions, this becomes the ratio of about 1.5 to 2.0 m/s to 0.23 m/s (without a magnetic field), which is about 6 to 8. Assuming churn-turbulent flow, this implies that the average void fraction would be between about 0.60 and 0.70 without any magnetic field effects (Fig. 3).

A lower limit on the average vapor velocity in the boiling liquid pool (ignoring the effects of the liquid velocity) is:

$$\overline{u}_v \approx \frac{u_\infty}{1 - \overline{\alpha}_v}$$

For $\overline{\alpha}_v = 0.70$ and $u_\infty = 0.23$ m/s (without a magnetic field), this gives $\overline{u}_v = 0.77$ m/s. Putting this value in Eq. (1) yields a lower bound on the fraction of the thermal power carried by the latent heat of the vapor, f_{LH} , of about 0.28. As expected, this is much higher than the value of 0.02 used in the original estimates.

It should be noted that the local vapor void fractions near the sides and particularly above the cylindrical plasma chamber will tend to be much higher than the pool-averaged void fraction estimates of 0.60 to 0.70 quoted above. This will lead to severe neutron penetration into the dome structure unless significant modifications are made to the cauldron design.

As an example of a possible solution, it has been suggested (by J. D. Lee of LLNL) that the liquid pool could be extended to fill the entire dome region. If this upper liquid region can be maintained in a subcooled state (by the coolant flow in submerged condenser tubes), it would be possible to cause a good portion of the vapor to condense in this subcooled liquid before the vapor reached the top of the dome. Careful positioning of baffles (as suggested by Owen Jones of Brookhaven National Laboratory) could further help redistribute the vapor and reduce the void fraction above the reactor. In regions near the magnets where this approach is not possible, a "conventional" blanket design employing a

coolant flow in channels might have to be employed. The lithium or lithium compound in this portion of the blanket would probably then be in cans or modules inside a "conventional" blanket structure.

If for some reason the subcooled liquid pool above the reactor could not be used or maintained, then it is always possible to use a conventional blanket design for the entire dome region. In any event, it seems clear that each of these possible solutions to the problem of the large void fraction above the reactor involves some significant design and cost penalties. This has led us to reconsider the other liquid-pool options.

4. CONCLUSIONS

- (1) The average vapor void fraction of the boiling cauldron is now estimated to lie between 0.60 and 0.70 even without a magnetic field.
- (2) This high a void fraction would impose severe design and economic penalties on the boiling liquid cauldron concept.
- (3) As a result, it is now felt that the major attention should be focused on the heat-pipe liquid pool concept during the present year (FY81).

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TABLE 1

Typical Sodium Property Data for the
Liquid Pool Blanket Conditions

Saturation temperature, T_{SAT}	1275 K (1000°C)
Saturation pressure, P	0.273 MPa
Latent heat, h_{fg}	3.77×10^6 J/kg

Saturated liquid properties:

Density, ρ_L	726 kg/m ³
Specific heat, C_p	1280 J/kg-K
Thermal conductivity, k_L	48 W/m-k
Thermal diffusivity, α	5.21×10^{-5} m ² /s
Dynamic viscosity, μ_L	2.2×10^{-4} kg/m-s
Prandtl number, $Pr = (C_p/k)\mu_L$	0.0059
Surface tension coeff., σ	0.10 N/m
Electrical conductivity, σ_c	1.58×10^6 mho/m
Volume expansion coeff., β_L	3.0×10^{-4} °C ⁻¹
Grashof number, $Gr = \frac{g \beta_L \Delta T_c W^3}{\nu_L^2}$	2.52×10^{12}

for $T_L = 1000^\circ\text{C}$
and $W = 1\text{m}$

Saturated vapor properties

Density, ρ_v	0.68 kg/m ³
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Isometric view of cauldron blanket module.

Fig. 1 Simplified sketch of one possible arrangement to obtain a radial variation in internal heat generation in a liquid metal pool boiling experiment.

SODIUM BUBBLE DEPARTURE DIAMETER FROM A HEATED SURFACE

Fig. 2 Estimation of the departure diameters of single sodium bubbles from a heated horizontal surface.

Fig. 3 Experimental data (Fig. 3a) and analytical predictions (Fig. 3b) of the pool-average void fraction from Ref. [12]. (The references listed on Fig. [3a] are those in Ref. [12].)