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HYDRAULIC POWER PLANT

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NUCLEATION OF STEAM BUBBLES IN A PROPOSED OCEAN THERMAL GRADIENT
HYDRAULIC POWER PLANT

Technical Memorandum No. M-80-76-7

by

Earl J. Beck*

ABSTRACT

This is a study of the nucleation of steam bubbles generated by cavitation in seawater and the ways of utilizing the resultant steam in a steam-driven version of the air lift pump. A method is described wherein micronuclei consisting primarily of microscopic particles with adsorbed gas layers are activated in a cavitating venturi then grown to a useful size by evaporation in a subsequent section of the pump tube. A small laboratory demonstration is described and various conditions of flow observed are reported. A rational explanation for the activation nuclei is given. The bubble growth observed is as predicted, and is given.

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INTRODUCTION

This report discusses the problems and possible solutions to the development of two-phase flow (seawater and low pressure steam) in the pump column of a proposed steam lift pump. The steam lift pump is a major component of the Ocean Thermal Gradient (Hydraulic) Power Plant, (OTGHPP) U. S. Patent 3,967,449 of 6 July 1976. A preliminary analysis at the time of the patent disclosure indicated that success would depend upon the ability to nucleate the steam bubbles in a dynamic system in which they would then grow at a planned rate, forming the necessary low densities in the water column. The investigation of possible nucleation methods and a demonstration of the effect in a small experiment was the goal of this independent research effort.

While not a principal part of the effort, the determination of the pumping head and a preliminary examination of the pumping potential seems relevant in understanding the total problem.

The industrial paradigm for the steam lift pump is the well-known but poorly understood air lift pump. A brief description of the air lift pump and a new analysis of its pumping rate and head in terms of the important variable, quantity of air pumped per unit of water pumped, are given. By air pumping is meant the forcing of compressed air into the pump at the proper point.

Referring to Figure 1, air is introduced at the foot of the pump tube at point A. Much of the inefficiency in operation of an air lift point occurs before this point--in the compressor, lines, in the cooling of the air which has been heated during compression, and in the injection nozzles. Experience has shown that the best efficiency and pumping action is obtained by introducing the air as small bubbles--of the order of 1/8 to 1/4 inch in diameter has been found to be satisfactory, if not optimum. The buoyancy of air bubbles causes them to rise in the water column faster than the water, and is one source of inefficiency. The smaller the bubbles the greater their drag, the slower the relative velocities and the slower the slip, S . As will be seen in the discussion of the steam lift pump, small bubbles can be expected with seawater, and the slip should be minimal. Making small bubbles in the air lift pump can be done only at the cost of loss of orifice pressure, which requires power. The following partial analysis* of the air lift pump will allow a ready understanding of the source of pumping head and the distribution of energy in terms of hydraulic heads. In Figure 2(a) the quantity of air would be just sufficient to raise the air water mixture to the pumping head H , is indicated as Q_0 , and is also plotted (no particular value) on the abscissa of Figure 2. At this value, slip is 100% and no useful pumping occurs, but at a higher Q_s , the additional air produces pumping heads in the form of h_f (friction)^s and h_v (velocity).

*For a complete analysis and best estimate of the losses, it is suggested that the author be contacted directly.

The variable parameter is the ratio Q_s/Q_w , but for clarity in this initial discussion, these parameters are plotted as the abscissa and ordinate, respectively, of Figure 2. The only source of pumping action in either the air lift or steam lift pump arises from the difference in densities in the water column outside the pump's submerged pipe and the vapor-water mixture inside the pipe; in addition the partial vacuum in the steam lift pump has the effect of increasing the apparent submergence by a head, h_b .

The maximum theoretical pumping head, H_{max} and its distribution as various pumping heads is indicated on Figure 1.

Important to this discussion is the opportunity for producing cavitation bubbles at the steam lift pump's intake and controlling the static pressure along the tube's length. This will insure that an optimum ratio, Q_s/Q_w is maintained and that the bubbles neither overexpand or collapse, as cavitation bubbles are wont to do. To maintain cavitation bubbles, the author believes the water must be accelerated in a cavitating venturi at elevation 0 to 1 (Figure 1) then perhaps decelerated to a slightly higher pressure from 1 to 2, and then introduced into the pump tube proper. While the design details of every aspect are not yet well known, theory indicates a very effective pumping action at a relatively low value of Q_s/Q_w which in turn promises very economical pump designs.

Even though it is intended to present here only sufficient understanding of air and steam lift pumps to clarify the discussions of nucleation to follow, readers may appreciate Figure 2(b), taken from Stenning and Martin (1967), showing performance of their experiment, schematically shown in Figure 3. Symbols have been changed to those used by the author, and given in the list of symbols. Stenning and Martin did not show the exiting velocity head, h_{v3} separately so it was added to their schematic showing slug flow, Figure 4. Their analysis does not conflict with that shown in Equation 1 of Figure 1. However, it is believed that their dynamic analysis does not have the visual clarity of the hydraulic presentation, Equation 1. Further, their attempt at correlating friction loss with the work of Griffith and Wallis (1964) does not seem adequately to describe the losses in their experiment. The general shapes of the curves for various values of R_1 are seen in Figure 3. That curve for R_1 of 0.532 is almost exactly that for the CEL Demonstration Experiment¹ (CELDX) discussed later. They may be explained as follows:

(a) A certain minimum value of Q_s is needed to raise the water-air (steam) mixture to the top of the pump's tube, without producing pumping. There is no water velocity, so the slip, s , is 100%. Q_w might, it would seem, be reduced with smaller bubbles, as discussed earlier.

(b) With a small increase in Q_s above Q_{os} effective pumping is accomplished and increasingly so as Q_s increases--up to a point; for R_1 of about 0.5 and a flow, Q_w of 0.010 cubic feet per second (point on curve inked in solid), the flow is increasing only at the same rate as the air, Q_s . At about Q_w of 0.011, the flow peaks and decreases with

increased air flow rate. This is entirely consistent with Equation 1 of Figure 1, and this is due to the diversion of the increased pumping head, H_{\max} , with increased air flow to friction and velocity head losses.

(c) At some greater value of Q_s (not shown in Figure 3) the velocity would be so high that the flow would be "choked" as understood in compressible flow. In a sense, the flow is choked here, as a maximum in mass flow is achieved at a relatively low air (steam) flow rate.

What is not obvious from Figure 3 is that the net effective pumping head, H , does not reach a maximum with Q_w . For an air pump, clearly it would not be wise to operate at too high an air rate, because of pumping costs. But in the case of the steam lift pump, and the OTGHPP, we will be looking toward maximum power production with least condensing water costs and minimizing other factors such as capital equipment cost. It is highly probably that the optimum point of operation will be slightly to the right of the peak, Figure 3.

Before proceeding to nucleation as it relates to the work at hand, we should compare the physical aspects of the air lift pump and the steam lift pump, as presently understood and shown in Figure 5. The commonality of shape is purely accidental. The reasoning for the shape of the air lift pump will not be discussed here but the steam lift pump's features will be discussed. First, the length, L , of both is not measured from the nozzle entry, but from the venturi nozzle's throat, at elevation 0. Water is accelerated into both pumps by the static heads appropriate to each and the throat pressure, p_0 (not shown), according to the well-known hydraulic relationship:

$$v_0 = (2g p)^{1/2} \quad (3)$$

where p is given in terms of hydraulic head in feet of water. We will assume a throat pressure of 0 absolute in the case of the steam lift pump, our principal focus. In that case,

$$v_0 = (2g S_b)^{1/2} \quad (4)$$

In other words, the entire static head of the submergence and the atmospheric pressure would be used up in accelerating the water through the converging nozzle. In fact, there is considerable experimental work indicating that it may be desirable to operate at a pressure in the water stream below absolute zero pressure in the nozzle throat, section 0. This can be done with proper velocity pressure recovery in a diffuser, and appears rather simple with a system exhausting to a partial vacuum, as is the case with the OTGHPP.

The next section discusses the requirements for nucleation in the steam lift pump of the OTGHPP.

NUCLEATION--THE GENERAL PROBLEM

The creation of a second phase in a single phase material probably requires the presence of the second phase in trace amounts. This is believed to be true no matter what the phase change, whether from solid to liquid, liquid to solid, or liquid to gas, or gas to liquid. Neither the change from gas to solid nor solid to gas seems to challenge the above thesis, nor does deliquescence. With one exception, all the known cases of phase change can be explained in terms of heterogeneous nucleation, while most of the interesting theories involve homogeneous nucleation. The condensation of energy to matter following a cosmic "big bang" is the one exception. There appears to be no requirement or explanation for a preexisting solid phase. Homogeneous nucleation theory has been especially interesting to metallurgists, but their recent achievements in growing single crystal solids from ultra-pure liquids would appear to contradict most of their claims for homogenous nucleation.

A great deal of understanding of the formation of a gaseous phase from the liquid--evaporation or boiling--results from numerous investigations of the tensile strength of water. It has been estimated that perfectly pure water, if it were obtainable and could be contained in a perfect container without surface imperfections, would have a tensile strength of some 300 atmospheres. Experience has shown that to avoid nucleation in "tap water," it frequently is necessary to reduce the static overpressure to something less than the vapor pressure of steam at the water's temperature; no case was cited in the literature reviewed of successful avoidance of nucleation in cavitating venturi operating at or slightly below zero absolute pressure. Rouse (1938) cites Reynold's work probably the earliest recorded evidence of planned laboratory cavitation (Appendix I). Rouse's work appears to solve the problem of nucleation as required for the development of an OTGHPP. A literature survey of alternative methods of nucleation was made for this study to determine possibly advantageous methods and for completeness. The only experimental work done here, a small demonstration experiment, utilized a cavitating venturi.

There are a great number of theories on the nature of micronuclei in hydraulic machinery and systems that cause cavitation, and these are reviewed in a later section. However, the author's concept of the cavitating process (except for the probably rare case of small air bubbles evolving from aquatic plants during photosynthesis or as flotation bubbles, illustrations of which are given later) is somewhat different from most of these. Figure 6 was first developed as a discussion aid, and was at first considered only analogous to the method of micronuclei's activation. It is now considered that it may present an excellent picture of what happens in a cavitating situation. In the upper part of the sketch, a bar of a solid (for example, ductile mild steel, copper, lead, clay, etc.) is

shown with an internal flaw, as frequently is found in poor grade castings. When the bar of original length L is stretched by an amount ΔL , there might be a slight local reduction in diameter, but almost certainly an almond-shaped cavity would be formed. This would be a "true vacuum" to the extent that there are no dissolved or interstitial gases in the solid. The discontinuity or weakness in the structure has allowed the formation of an internal cavity--which if in a fluid would almost certainly immediately be filled with the fluid's vapor and diffused dissolved gas, if present. Except for small air bubbles, probably rare in nature, the important micronuclei are probably microscopic particles of solids with adsorbed gases on their surface. It is also probably true (and certainly helps the discussion) to consider that particle size is an important factor in determining the depression in pressure necessary for their activation. By activation is meant growing of micronuclei to a bubble size sufficient for their continued growth as is observed in cavitation. As now perceived, cavitation may be a two-step process, although continuous in a real-life situation. As visualized, initial "stretching" of the water in the very low pressure area of a cavitating stream produces small bubbles (spherical because of surface tension), as described above and shown schematically in Figure 6. The contents of the bubble are very low pressure steam and dissolved gases, migrating from the surrounding water according to Fick's law of diffusion. The size of the bubble will be determined by temperature, overpressure, and the amount of dissolved gases and the volume of water each microbubble has to draw on. Since diffusion is time-dependent, the length of residence in the low-pressure area may be of importance in determining its final size, important in the next step. If in this successive step, pressure is increased, the vapor will condense, but only if the local vapor pressure of the water is exceeded*. Even if this vapor pressure is exceeded by deceleration of the water stream, according to Bernoulli's theorem, the noncondensable gases will not immediately dissolve into the surrounding water. But the effective size of the bubble will have been reduced, and its growth when needed may not be possible. The permanence of the microbubble with increased pressure can be seen in Appendix I. The above observations have more than passing interest in the practical aspects of the development of an OTGHP.

The nature of bubble growth from this point is well understood. It is the subject of many papers, but for the reader not widely read in the cavitation literature, it is best presented in a brief paper by R. Scoria (1951), reproduced here as Appendix II. This is a particularly appealing discussion, because the conditions and Scoria's observations can readily be duplicated in the kitchen with no equipment except a source heat, a pan and a simple thermometer.

* We assume here that the case of interest is seawater evaporating at about 80°F, for a vapor pressure of about 1/2 psia.

Some observations of my extension of Scoria's work to very low pressures and temperatures may be helpful in understanding the entire cavitation problem, especially since we intend to exploit the phenomena. It is also the basis for my contention that the activation of a micronuclei involves actual rupture of the water structure, and not the growth of a micronuclei as discussed by Scoria and many others. It is also the basis for my thinking of cavitation as a two-step process.

Figure 7 is a plot of vapor pressure of water versus temperature, from a temperature of -170°C to 10°C , and below -15°C is pure extrapolation. Handbook values of water's vapor pressure over ice to as low as -50°C can be found. Whether the concept of water's vapor pressure is valid over water at these very low temperatures (pressures) is debatable, but the figure is instructive for discussion. Extrapolating Scoria's work to these very low saturation temperatures and pressures would require a very large initial bubble to grow a sizeable bubble (activate a micronucleus to usable size). This requirement derives from the very low vapor pressure and high surface tension, which in our case is seawater at about 80°F . Clearly, we can not "grow" bubbles from micronuclei at these pressures; a process similar to that described, beginning with Figure 6 as a visual model, is necessary.

SEAWATER AS AN OTGHP WORKING FLUID

With the above as an introduction, we can begin to formalize our problems, and evaluate ocean water at about 80°F as a potential fluid. First, it must be "dirty" in the microscopic sense, and it must contain dissolved air. In addition, it is also necessary that the solid contaminants have an adsorbed layer of noncondensable gases to be effective micronuclei. This is borne out by experiments designed to increase water's apparent tensile strength. Micronuclei have been effectively removed (to a very small size, at least) by microporous filters. In other experiments, the gaseous adsorbents have been described and dissolved in the surrounding fluid by subjecting it to very high pressures for a few days. In either case, the available nuclei were deactivated for the purposes of subsequent test. Whether or not this discussion considers all aspects of the nature of the nuclei is largely irrelevant, but the discussion is instructive. Seawater is very dirty material; in terms of nuclei, it has copious quantities. But it also has another very important property: the tendency for gas bubbles formed in it to coalesce.

One of the most commonly reported phenomena in two-phase flow is the formation of "slugs" of gas by coalescence. Whether it is the cause of the instability in flow ("chugging") or whether it results from instability from other causes, it is almost certain at this point of understanding that we must avoid such instabilities. One probable way to do this will be to attempt to develop a "stable froth" of optimum sized bubbles, closely packed. The vapor/water volume ratios are critical to

efficient utilization of condensing water and minimization of friction loss, discussed briefly elsewhere. For our purposes, seawater appears to be nature's best material; it has copious micronuclei lots of dissolved air gases, and is capable of maintaining a semistable froth. One paper found in the literature discussed the probability of coalescence of two adjacent gas bubbles and reported an experiment that showed that bubbles in distilled water are 10 times more likely than those in seawater to coalesce (Lessard, R. R. and Zieminski, S. A., 1971).

The effect of temperature on coalescence is plotted from that paper (Figure 8) and shows that coalescence is facilitated by increased temperature. While temperature is not a variable under our control--we plan to use warm ocean water in the pump. It is instructive to note the trend in later discussions of a small experiment (CELDX) in which water at about 210°F (both fresh and salt) was boiled.

While it is beyond the scope of this report to discuss the systems analysis details of a complete OTGHP in detail, it is interesting to note that in preliminary calculations by the author, (1) the probable ratio of volume of steam to volume of water is low enough that bubbles will be approximately spherical, (2) the septa between them will probably be fairly thick (compared with wall thickness in soap bubbles), and coalescence may be a minimum problem.

NUCLEATION AND BUBBLE GROWTH

From a design standpoint, the central problem in inducing bubble growth and therefore cavities which will allow useful pumping is not only the activation of nuclei, but growing the bubbles to a useful diameter in a preplanned environment. The probable growth rate during evaporation, or collapse rate during condensation is so high that the thermodynamicist is almost indifferent to the available temperature difference. Which is equivalent to saying that the Δt in the equation

$$Q = h A \Delta t$$

is largely irrelevant, because the heat transfer coefficient is so large. This is true at relatively high pressures and temperature, e.g., at about 1 atmosphere and 212°F. But it is even more so at very low pressures and saturation temperatures, e.g. 80°F. This can be seen by comparing the ratios of the specific volume to latent heats of evaporation at those temperatures:

$$212^{\circ}\text{F}: \frac{v_g}{h_{fg}} = \frac{26.80}{970.3} = 0.0276 \text{ cu ft/Btu} \quad (5)$$

$$78^{\circ}\text{F}: \frac{v_g}{h_{fg}} = \frac{673.6}{1049.8} = 0.6416 \text{ cu ft/Btu} \quad (6)$$

The ratio of the first quotient divided by the second is 23.2, which is to say that the economy of cavity formation is some 23 times better

at about 80°F than at 212°F, considered only from the standpoint of heat supplied and transferred. This is a favorable observation for the potential of developing a steam lift pump by means of boiling warm ocean water.

The literature on cavitation is replete with theories and experimental data for the growth rate of bubbles, usually at about 1 atmosphere pressure because of the ease of working at that level. Figure 8, from Plesset and Zwick (1954) is particularly interesting in that it includes Rayleigh's predictions for growth rate. Rayleigh's predictions did not include the effects of heat removal from the water around the growing bubble, which requires that heat diffuse (transfer) through a cool boundary layer except at the inception of bubble growth. More important for this study than the growth rates, which are very high in any case, are the implications of the effect of operating at pressures less than about 1 atmosphere, which would be the case for OTGHPP. Figure 9 predicts growth of a small nucleus from a diameter of perhaps 0.1 mm to 1 mm in about 7 or 8 ms, with a liquid superheat of 3.1°C, or 5.6°F.

The saturation pressure within a bubble is:

$$P_t = P_a + \frac{2\sigma}{r} \quad (7)$$

where P_t is the total internal pressure, P_a is the local static pressure, and ρ is the surface tension. Using the approximation that the temperature of saturation at 1 atmosphere, 212°F, and the liquid superheat is that required by the second term, $\frac{2\rho}{r}$ is about 5.6°F for a 1 mm diameter bubble, and assuming for discussion that the change in surface tension is small and that all else is similar, we can obtain a rough approximation of the time for bubble growth to 1 mm as:

$$\text{time, } d = 0 \text{ to } d = 1 \text{ mm} = \frac{(7.5)(5.6)}{(23.2)(80-35)} = 0.04 \text{ ms} \quad (8)$$

for a cavitating venturi with a reduced static pressure of about 0.1 psi. The term (80-35) in the denominator of Equation 8 is the difference between the water temperature and the saturation temperature at the reduced pressure in the venturi throat, and represents the thermal driving temperature for evaporation into the low-pressure bubble. The accuracy of the above estimate is largely irrelevant, as bubble growth would obviously be much more rapid than needed for engineering purposes in any case. For instance, for a water velocity of 52 feet per second as might be expected with a submergence of about 10 feet, in a cavitating venturi, the entire $\frac{1}{5}$ bubble growth would be accomplished in a distance of about $52 \times 4 \times 10^{-5} = 2 \times 10^{-3}$ feet, a very small distance in a large machine. This and other similar calculations tell us nothing of how to grow a micronucleus to a size where its growth can be predicted as above, the phase I part of nucleation and bubble growth.

Equation 7 predicts that in a cavitating venturi, where P_a may be zero absolute or even lower (the water in tension), the saturation temperature and pressure in the bubble are a function of surface tension and

radius (diameter) only, and that for a micronuclei the internal pressure would be very high, as would its internal saturation temperature. It seems unlikely that bubble growth from steam production and heat transfer is possible under these conditions.

Returning to the concept of "rupture" of water placed in tension, with the micronuclei as weakening agents for water in tension, a plausible explanation, not found in the literature, for early microbubble growth is as follows. First, it seems very improbable that nucleation can be accomplished at cavities in micronuclei. This is the usual explanation for nucleation at solid surfaces by Beck (1968) and many other sources. The particles are simply too small, and the concept requires certain geometric aspects not available on such a small structure. A more plausible explanation is at hand. Figure 10 shows a microparticle with adsorbed gas molecules and no particular shape. It might be a particle of a skeleton from plankton or a particle of volcanic dust settling through the water column. The surrounding water is at least partially saturated with atmospheric gasses. At atmospheric pressure or slightly above while still near the surface, the adsorbed layer is at or near equilibrium, i.e., there is no significant detachment or attachment of adsorbed gases to strip or add to the layer. Of course, there may be continuous interchange maintaining equilibrium.

When such a particle is placed in a very low pressure stream as in a cavitating venturi, the water around the particle is placed in tension and the nucleating layer of adsorbed gases, normally many or at least a few layers thick, appears to be a rarefied or low-pressure layer of noncondensable gases. According to Fick's law of diffusion, the surrounding water is super-saturated in noncondensable gases with respect to this rarefied layer. Since all the gases are well above their critical temperatures, there is no requirement for nucleation, change of phase or heat transfer, nor are there particular requirements for critical radii, particle size, etc. However, there well may be a size relationship requiring different tensions for different particle diameters. It is believed that this theory is adequate for explaining all of the observed facets of practical heterogeneous nucleation, and will stand the test of time and close inspection. Several other pet theories have been discarded by the author in favor of this most general of all conceived. Two other plausible explanations for early microbubble growth are found in Appendix III.

This explanation of micronuclei would not deny the utility of small undissolved gas bubbles, from whatever source. Two possible sources are shown in Figures 11 and 12 from the sources indicated. Such bubbles should function as activated nuclei as found, but the author believes they are too scarce to be of much utility in an ocean power system. However, the initial CELDX^a experiments discussed later indicated there were sufficient gas bubbles in the seawater from near shore at Port Hueneme, California, to serve as micronuclei

^aCivil Engineering Laboratory Demonstration Experiment

Before leaving the theory of micronuclei activation based on adsorbed gas layers as discussed above, some thoughts on the practical aspects of these nuclei are in order. First, it would seem that for any ocean situation, a limited knowledge based on the simplest of laboratory scale experiments (numerous references attest to a lack of scale effects in cavitation) should allow rational design of a steam lift pump's cavitating venturi section, where nuclei activation occurs. If there is a particle size effect, and there are essentially limitless "weaknesses" or micronuclei, then there are arguments against the occurrence of over-activation. For instance, let us assume that an optimum bubble size in the pump column is 2 mm and that for the particular design, the desired ratio of steam to water by volume is 9; that is, the steam bubbles occupy 1/10th of the volume, and the average density of the steam-water mixture is $64/10 = 6.4$ pounds per cubic foot, or 0.1 kg per liter. This may or may not be a good choice, but has the virtue of simplicity in illustration. This steam/water ratio is about 2-1/2 times that for close-packed spheres, so the bubbles would not be spherical. Assuming them to be approximately cubical (also not true), complete nucleation for engineering purposes would require $\frac{1,000}{(0.2)^3} = 1.25 \times 10^6$ nuclei per litre of seawater. We can make further estimates of interest if not proven utility. Typical seawater has about 25 ml of dissolved gasses per litre of seawater, and if half this is successfully diffused to the micronucleus's surface during its activation, the volume of the activated micronuclei (neglecting a small amount of water vapor at the very low vapor pressure and the volume of the micronuclei and adsorbed gas) following activation would be:

$$\frac{25}{(2) (1.25 \times 10^6)} = 10^{-5} \text{ ml/bubble} \quad (9)$$

Each bubble will have a diameter of about 3×10^{-2} mm at 1 atmosphere, and a much larger diameter at the low pressures in the venturi. Whether this is adequate for OTGHPP remains for later experiments to determine. Some insight will be gained in the discussion of the Civil Engineering Laboratory Demonstration Experiment, (CELDX), below.

While cavitation nucleation in a venturi gave early promise of a preferred method for the OTGHPP's steam lift pump, the original assignment was more general and other methods of activating nuclei were investigated. No matter which method of developing nuclei might be adopted, it appeared that because of other requirements of flow and bubble growth, a low-pressure area, if not a truly cavitating venturi, would be required. Therefore, there appeared to be every advantage to the venturi's use, if it could be done so successfully. It has no moving parts and while there are pressure losses (power losses to the system from friction), these seemed to be of the same order or less than alternative systems and no

specific additional equipment such as transducers, acoustic oscillators or nuclear decay sources will be required. The patent anticipates the use of alternative devices to secure optimum performance and efficiency, and the apparent utility of the cavitating venturi does not rule out other devices with further developments. The simplicity of the venturi and the excellent state of methods for designing venturis recommend this approach, so it was used in the first exploratory experiments, the CELDX.

ALTERNATIVE PATHS TO NUCLEATION

While the alternative nucleation (activation) devices will not be discussed in detail, the bibliography lists at least one example of each, discussed in detail. As a rule, the practical aspects and power requirements of each are not given, as most of the experimental work reviewed is scientific, and not designed for engineering purposes.

Alternative methods of nucleation, with comments on each are:

(a) Acoustic. There is an extensive history of cavitation damage to underwater acoustic equipment, and the effects of the air bubbles produced on underwater sound. There is no question but that by using state-of-the art machinery, nucleation can be induced in a moving water stream. The active surfaces will require renewal and the equipment and its power requirements are far from trivial.

(b) Mechanical, e.g. magnetostriction. The effects and the problems are similar to the acoustic devices, which they resemble except in mechanical details and power requirements.

(c) Energy deposition from nuclear decay or fission may produce micronuclei, and is the basis for both cloud and bubble chambers. This source of nuclei has commanded some attention in physiological studies because it seems to be implicated in divers' bends. Walder (1975) concludes that the energy from alpha and beta particles from radioactive decay is neither large enough nor deposited in a short enough track to provide the occasional nucleus for the formation of a bubble in the 2.2 percent or so cases where decompression does not prevent its formation. This in spite of the long-time success of bubble chambers. He concludes that once every 21 days in an average man there is a spontaneous fission of a Uranium 238 atom, and that this is most likely to occur in the bones, where the uranium normally is found in the body. He makes no distinction between gas and steam, which I should like to explore briefly before leaving this subject and discussing a possible approach.

My earlier explanation of nucleation requiring an adsorbed gas layer on a particle of solid provided the required gaseous phase not as steam but as gasses above their critical temperatures, while early bubble growth would then be from gas diffusing to a low concentration area. Part of the growth would be from evaporating water, but because of the very low partial pressure, the water contribution would be minimal, in spite of the high superheat of the surrounding (80°F) water with respect to the

bubble's low saturation temperature. In a diver, the tissue at the point of bubble growth would be supersaturated with respect to the normal concentration of gases at that pressure, but there would be no available superheating for vapor transmission and evaporation. Then the high energy particle would create temporarily a fairly large bubble of superheated steam; the supersaturated gas in the surrounding fluids would "see" this as a low concentration area, and gas would move by diffusion. Because of the probably large bubble size and the superheat of the gas, the bubble would not collapse rapidly. If diffusion proceeded rapidly, the bubble would survive the cooling process. If not, the very high heat transfer rates during the subsequent condensation would collapse the bubble. From this argument, we can conclude that if in the steam lift pump, production of nuclei by nuclear reactions is necessary, the requirement would be for their production in an area where bubble growth would be immediate. This would not be in the extremely low-pressure section of a cavitating venturi, but probably where the static overpressure would be just slightly below the saturation temperature of the liquid. The nuclei would activate largely steam bubbles produced essentially instantaneously; the gas molecules involved in this initial bubble would be mostly from the small volume of water evaporated.

In summary, alternatives to activation of micronuclei in a cavitating venturi will probably not be necessary; but there are some alternative paths to bubble formation if they are needed. If the energy from radioactive decay or fission should be used, beta particles of relatively long range would seem to be very desirable in a large system, in that fewer emitting sources would be required. The experiments necessary to investigate this further appear to be relatively simple and inexpensive, but they would involve the handling of relatively large amounts of radio-active materials. A full-scale system moving millions of gallons of water an hour past a radioactive source would present formidable health-physics problems, and if fission were necessary, a potential for contamination of the ocean.

THE CIVIL ENGINEERING LABORATORY DEMONSTRATION EXPERIMENT (CELDX)

From the initial literature survey, it was considered almost certain that effective steam production in a cavitating venturi emptying into a vertical pipe could be accomplished, if the pressure were appropriately controlled. Only one reference, Gosselin, A. and S.C. Kranc (1971) was found reporting work on expansion of gas bubbles in a liquid to a low pressure area, and this was for a nozzle emptying into a very low gas pressure, not water. It seemed to say nothing of what would happen in the case of a rising water-steam column traveling at velocities relatively low compared with the velocity of sound, and with a slightly expanding section to achieve some velocity head recovery. A small experiment was contrived, which not meeting all the design requirements as then understood for a full-scale power plant, would show activation of micronuclei

in one section, then rapid steam bubble growth (stage two) in a subsequent section. A system boiling seawater at about 80°F would have a pressure below $1/2$ psia at the pump exit, and the required barometric head would be over 32 feet-- a very large system for exploratory work. To keep the scale of the experiment manageable, the water was heated to about 210°F and in so doing, boiling was active on the electrical heating elements used, Figure 13. This had the potential disadvantage of at least partially deaerating the seawater during heating, as well as possibly deactivating the micronuclei as they came in contact with the heating elements' hot surfaces, by degassing. In spite of these drawbacks, the experiment always performed well, but in a variable manner. It was a successful demonstration of the principle and also produced some technical information of use in later analyses.

The main components of the CELDX (Figures 13 and 14) consisted of a tank of salt water (some runs with fresh water were also made) recently removed from the ocean at Port Hueneme, California, in which the water was heated to nearly boiling by electrical immersion heaters. A demonstration run consisted of partially evacuating the steam chest using a laboratory vacuum pump taking its suction from the remote end of a small surface condenser, with a trap to remove the condensate between the condenser and pump. In most test runs, the overall height was about 12 feet, although some runs were made with 4 feet less glass tubing; not data were taken for the latter runs. The vacuum was maintained at a constant value by bleeding air into the vacuum line with a small hissing valve, which could be adjusted easily with weights. For some runs, this did not seem to be necessary; it was later realized that there was a variation of at least 2 degrees from run to run in the water's temperature, which could account for this. The barometric height, h_b , was set to provide not only good visual demonstration, but a reasonably impressive head, H ; in a real system, the downcomer would be filled with water and H could not be easily seen. The turbine would throttle the water to a constant height as shown in the patent drawings. It was also found that without the hissing valve controlling the vacuum, on some runs the barometric head, h_b , would suddenly increase and the pumping action would be stopped if cold water ran across from the downcomer to the pump tube.

Starting proved to be a problem, and it was only the most fortunate of circumstances that it started the first time it was tried--it would not start the next day, no matter how coaxed. The obvious way to start it up was to pull a vacuum with the vacuum pump, eventually causing boiling in the pump tube, in this case made of straight 1 inch diameter glass laboratory tubing, spliced from 4-foot lengths. The vacuum pump was of limited capacity and with cool weather in an unheated building in the winter, the glass tubing was cold, and would cool the upper layer of hot water in the pump tube as it rose. The first day was a little warmer than the second, and even with a short experimental length (4 feet) pumping started immediately. On the second day, boiling in the pump tube could not be accomplished for any combinations of inlet temperatures and condensing temperatures. It was finally decided that cooling of the upper

layer of incoming heated water was the problem, and from then on the normal method of starting was to exclude the hot water with a rubber laboratory stopper at the lower end of the tube until the moment of starting, and with the vacuum conditions established. Under this method, the pump always started and, once started, continued until the lower end of the intake was exposed to air, when the water had been pumped.

Several conditions of boiling were noticed at various times, and the two principal ones are shown schematically in Figure 15. At 15 (a), the expected and hoped for condition, the incoming water was well-nucleated, and the column was filled its entire length with an off-white froth, with bubbles of apparently about 1/16 inch in diameter. Under this condition of boiling, with an adequate supply of activated nuclei, pumping of the control volume always took 4 minutes, plus or minus perhaps 10 seconds. A second condition, as illustrated at 15 (b) occurred perhaps two-thirds of the time, and always if the pump were stopped and restarted during a run by either cutting off the condensing water or letting in air; in either case, the vacuum was broken. For this condition, pumping time was about 4 minutes, plus 15 to 20 seconds. The lower end of the pump tube, which was white in appearance over its entire visible length, is shown in Figure 16. This is in contrast with the conditions in Figure 16, as shown schematically in Figure 15, (b), where bubbles could be seen in the pump tube's central section, and coalescence and the slug flow shown schematically in Figure 4.

When the remarkable consistency in pumping rate was realized after a number of runs, it was assumed that the condenser, known to be marginal in capacity, was controlling the rate. However when much later calculations were made based on the equations at the bottom of Figure 1, it became apparent that what was being observed were minor variations in flow rate, under considerable difference in effective boiling height. That is, when boiling did not begin over the tube's full diameter until about 2 feet above the inlet, the effective height, h_b was reduced and probably the actual inlet velocity. However, because even a small change in steam production increased the average velocity in the tube greatly, and this in turn increased the head loss from friction considerably because this varies as the velocity squared, approximately. So while a change in point of general boiling would change h_b and H_{max} , as well as h_f , the net effect was a very small change in v_1 , the water velocity determining the length of a run. It is estimated from some approximate calculations that the maximum change in heads would displace the point of operation, A, Figure 2, by less than 1/4 inch.

Only one other set of operating conditions is worth discussion in detail. The steam chest, Figure 13, was originally equipped with adapters so that a pump tube of either 1-inch ID or 3-inch ID could be used, and a few runs were made with the larger tubing. While the condenser as operated had sufficient capacity for the small pump tube, it did not for the 3-inch tube. But the system worked well. It could be readily started by pumping slowly with a vacuum pump, with the condenser also in operation. When boiling started, it was general over the full length of the tube,

and the action was very violent--violent enough to shake the little experiment. But it would only run for about 1 minute, then the boiling would stop and water in both columns would stand at a height, h_b , until the condenser caught up. Then the action would repeat. Normally, total pump time was still about 4 minutes, but at least one-third of this time the condenser was swamped with uncondensed steam. The condenser's capacity was clearly limiting the pump's flow rate.

The single attempt was made to augment the surface condenser by making a crude contact condenser, shown protruding into the downcomer in Figure 17 but not in use in this run. When tap water was used, the compact condenser seemed to increase the rate (visually observed) with the large pump tube for a few seconds. But the tap water contained so much air that the system was overwhelmed. The vacuum pump could not keep up and its use was abandoned.

EFFICIENCY OF THE SYSTEM

One component included in the above system did so little that it is not discussed in connection with the experiments. There was very little condensate accumulated, even for many runs. The system makes little steam at near atmospheric pressure; the weight of condensate would be even less when boiling occurs at 80°F . In terms of Carnot efficiency, this was a poor system--but Carnot efficiency does not really apply, as there is no compression part of the cycle--only expansion. After a year and a half of thermodynamic calculations based on varied assumptions, it became apparent that while the steam lift pump is a thermodynamic device, turning a small amount of heat into work, it could be better understood as a hydraulic device. We must look on the warm water as a mass to be elevated, in preparation for producing power in a hydraulic turbine. Since the heat is free (if it were not, the scheme would be preposterous), we really aren't concerned with efficiency except as it affects (a) machine size and cost and (b) condensing pumping power, which must be subtracted from the power produced by the turbine.

CONCLUSIONS

1. Of the various known methods of producing nucleation in warm seawater that may be useful to the steam lift pump of the OTGHPP, the use of a cavitating venturi seems to be the simplest and probably most useful.
2. The concept of a steam lift pump has been successfully demonstrated experimentally.
3. Little is known from these studies and the demonstration experiment of what may be expected in a large system operating on warm ocean water at a higher vacuum.

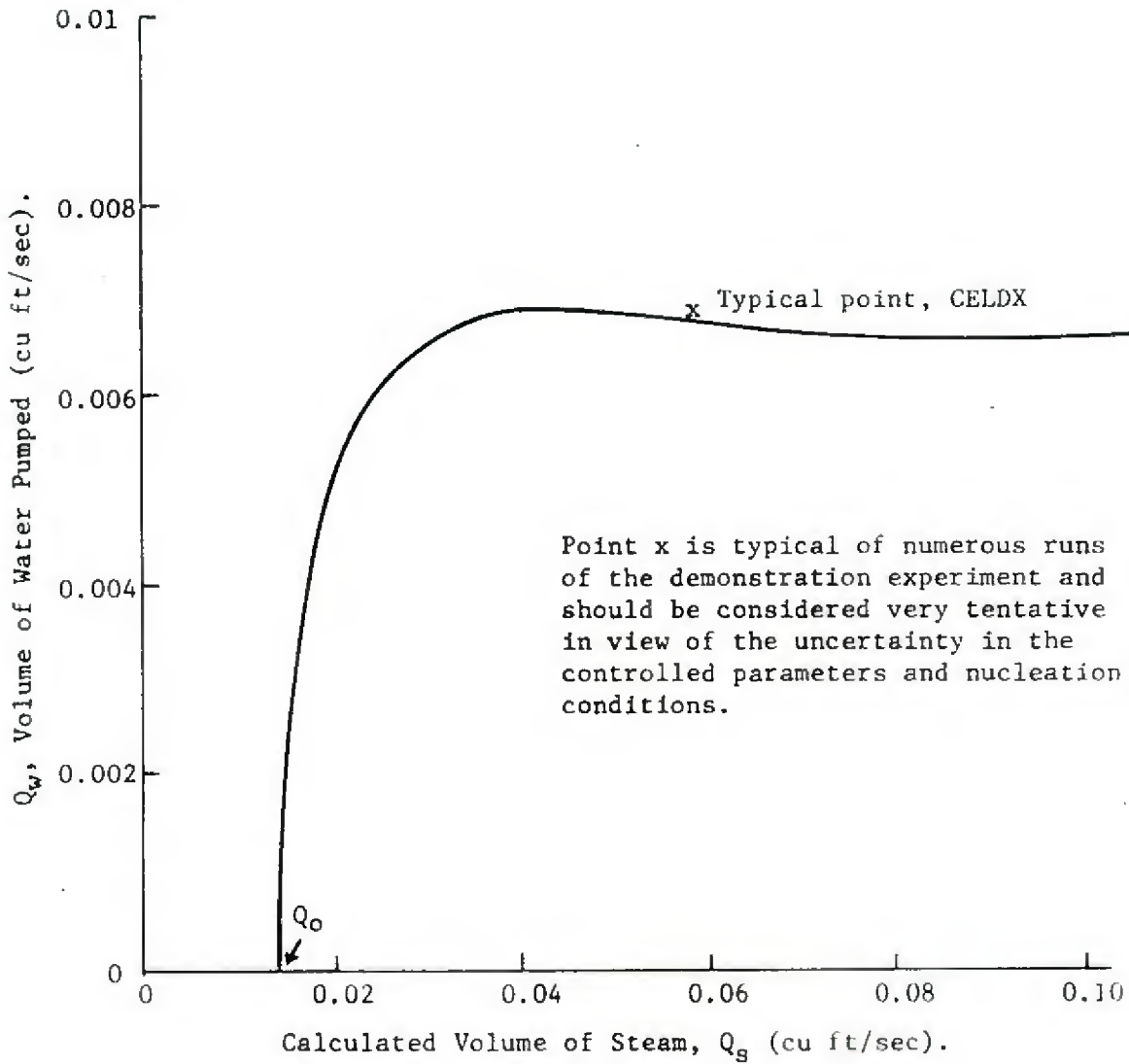


Figure 2(a). Constructed curve of flow characteristics for the CELDX steam lift pump, showing typical value for a single point, x.

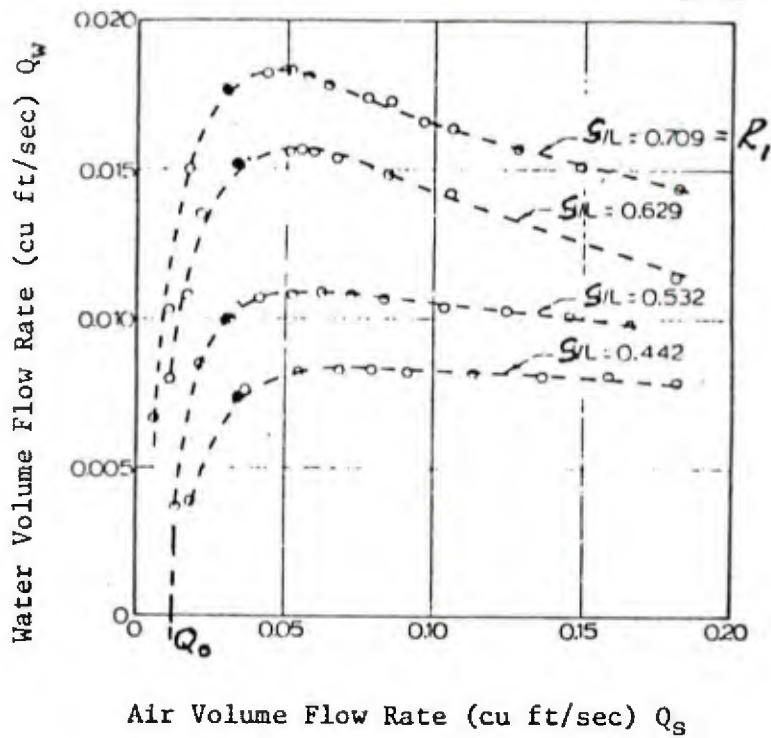


Figure 2(b). Air lift pump model performance data, Stenning and Martin (1967). Symbols changed to agree with notations in this study.

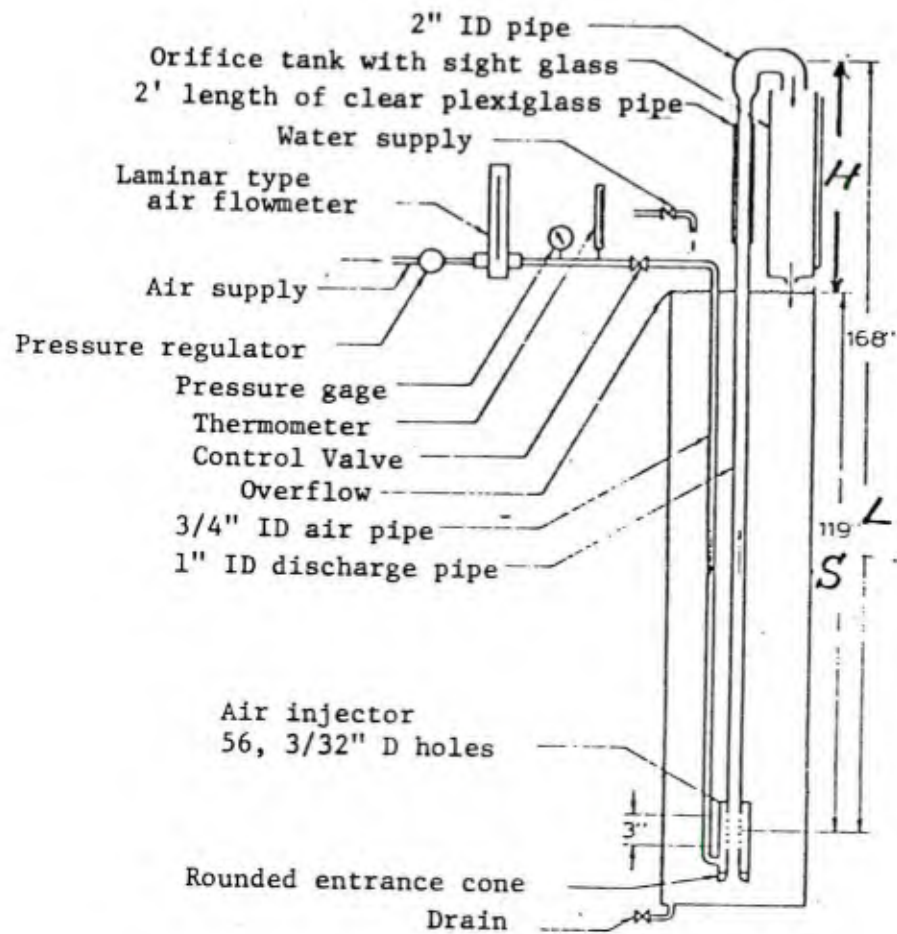


Figure 3. Details of Stenning and Martin (1967) experiment (compare with Figure 15 of this study).

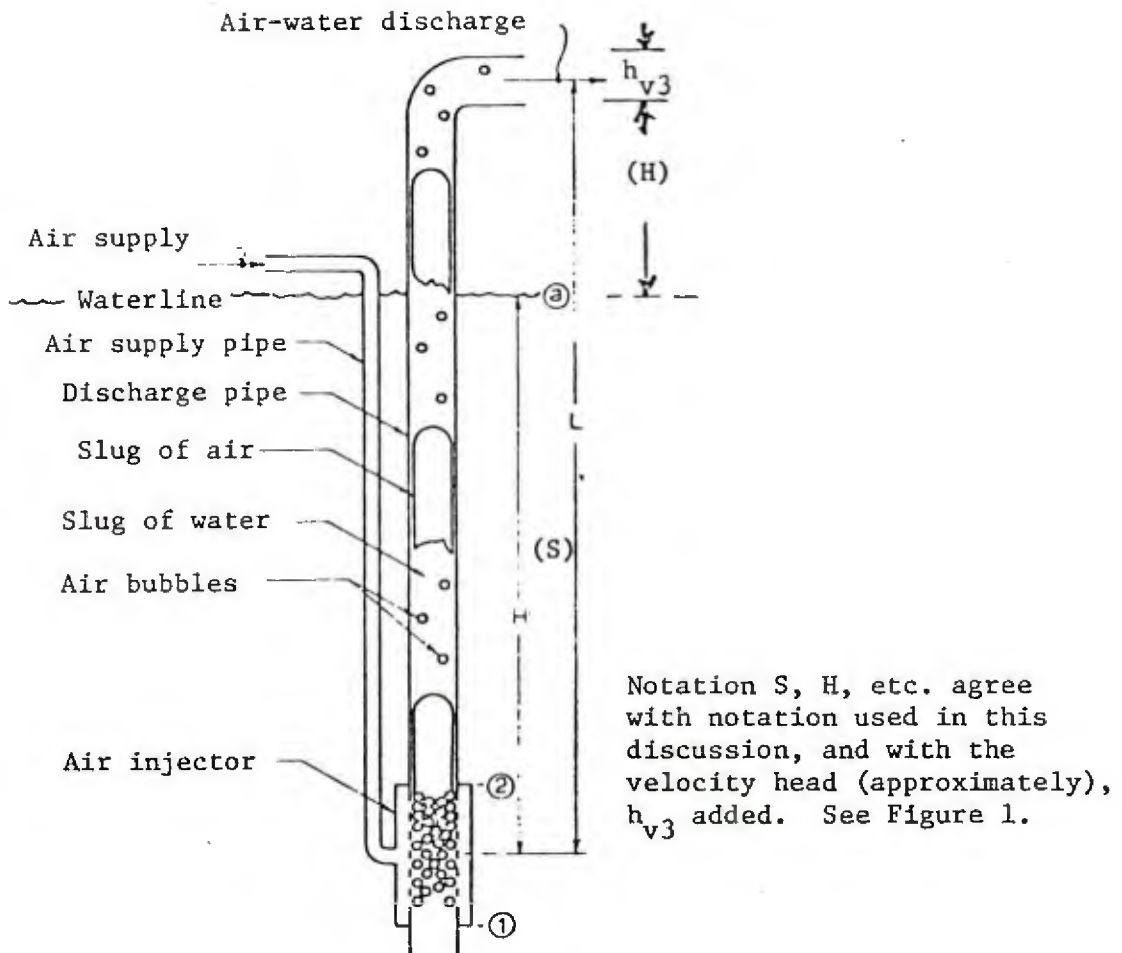
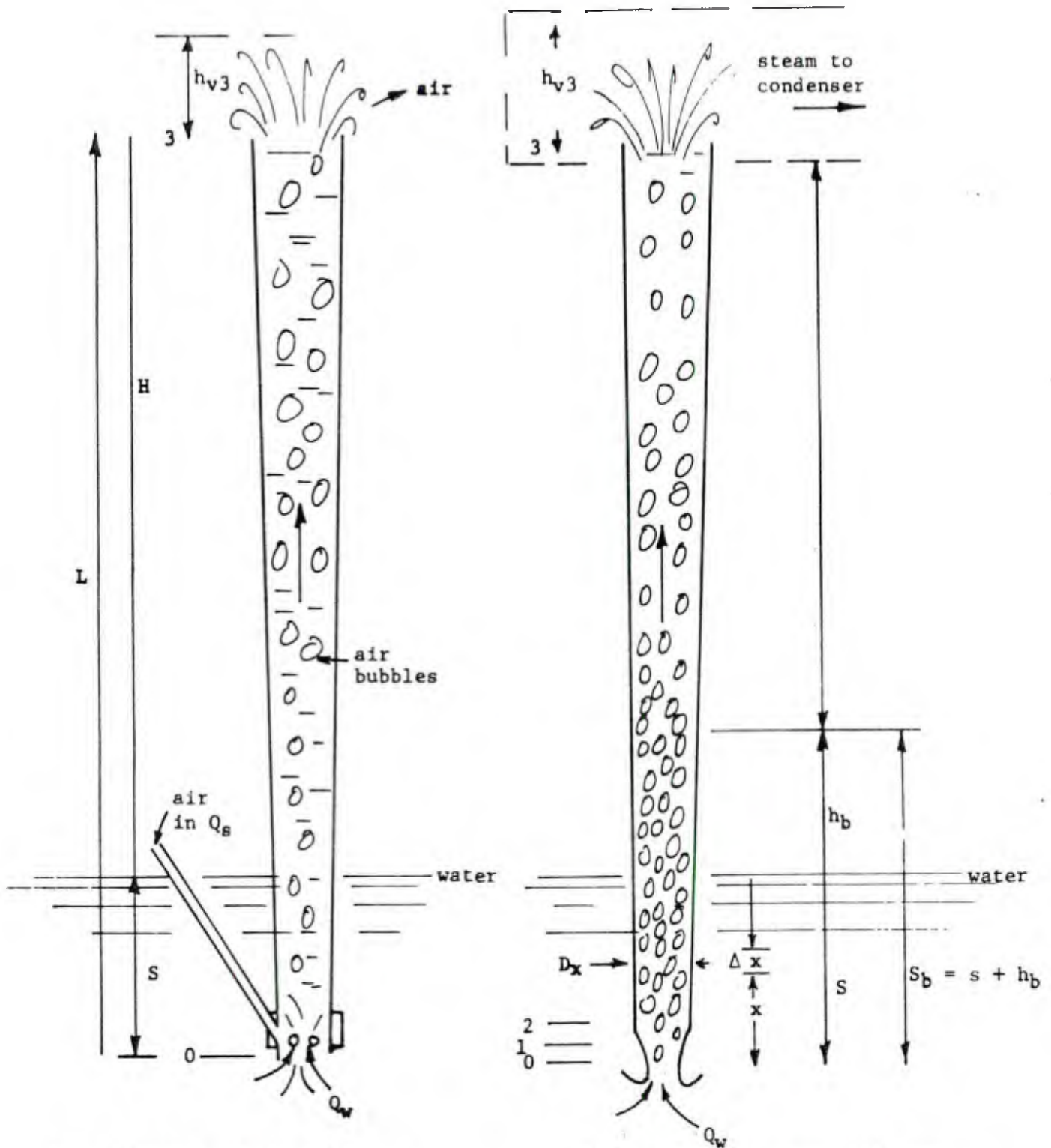


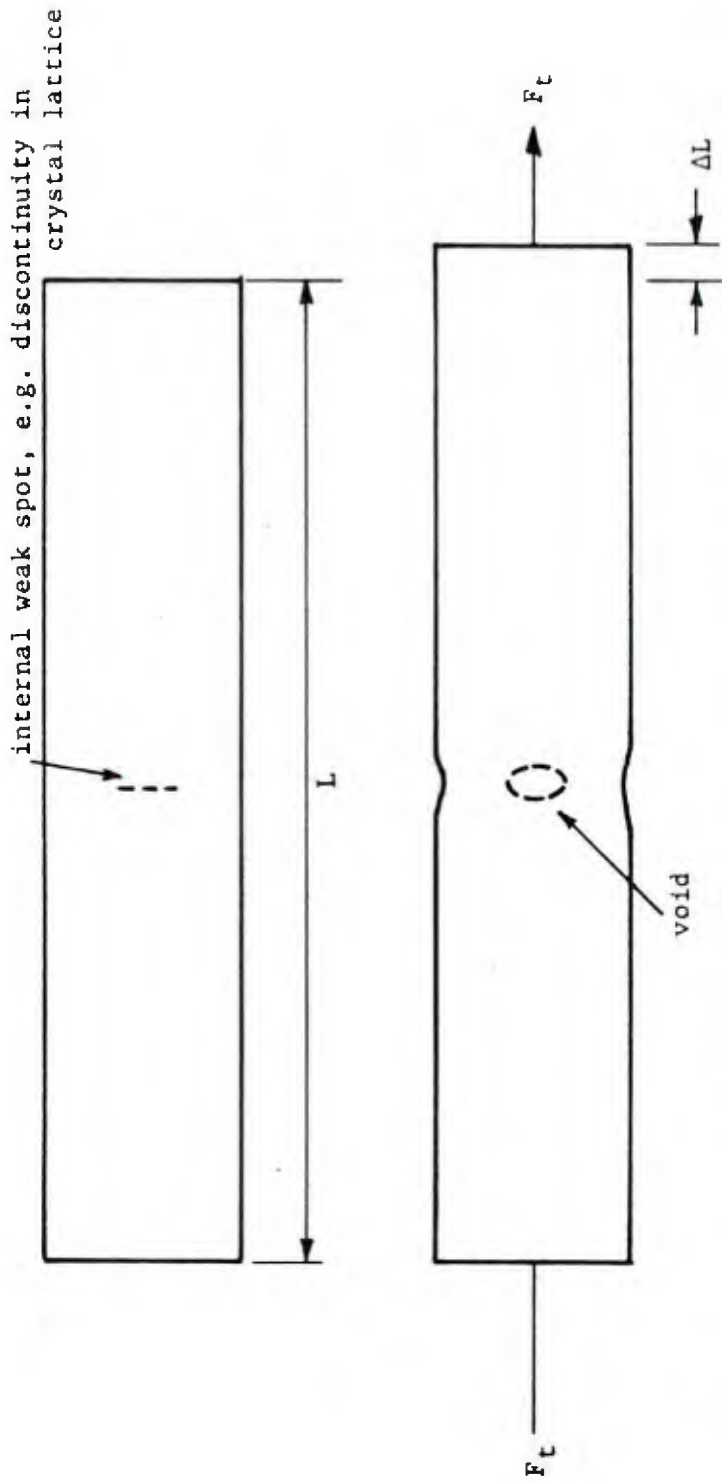
Figure 4. Schematic of model air lift pump used by Stenning and Martin (1967).



(a) Schematic of air lift pump.

(b) Schematic of steam lift pump.

Figure 5. Schematic of air and steam lift pumps, showing commonality and differences. The air lift pump requires a source of compressed air, the steam lift pump does not. On the other hand, a source of cooling water (not shown this figure) to condense the steam produced in the steam lift pump is a requirement of that device.



NOTE: Tension in material of bar resulting in void is analogous to tension in water in a cavitating venturi, which leads to formation of a cavity. The latter cavity is filled with water vapor by diffusion and evaporation.

Figure 6. Hypothetical activation of a "bubble" in a metal bar with an internal crystal lattice defect analogous to formation of bubble in a cavitating venturi.

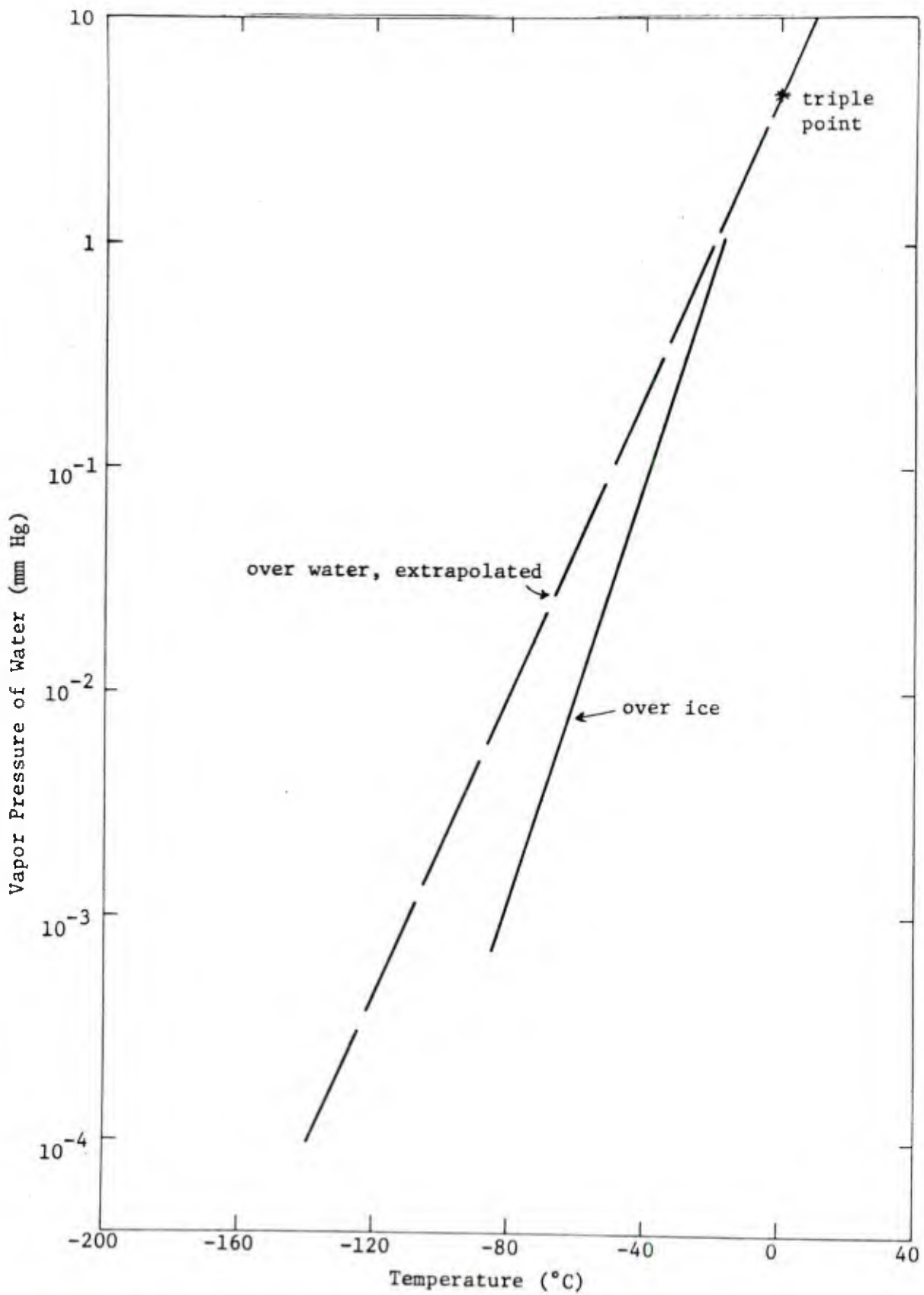
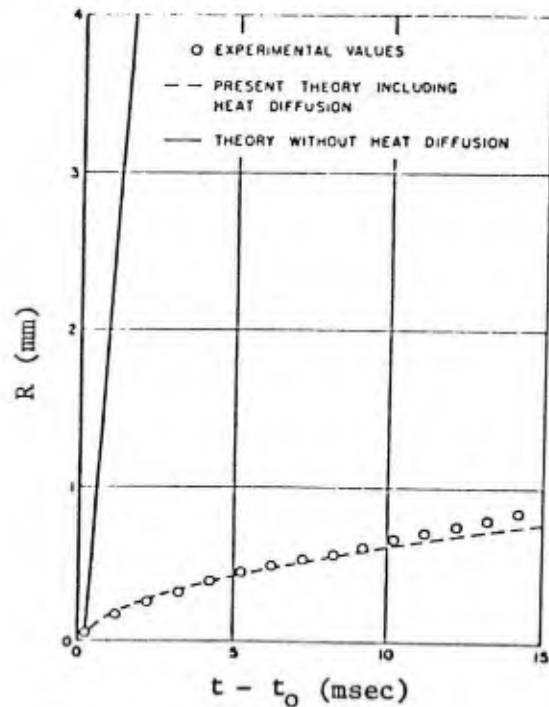


Figure 7. Plot of water vapor pressure a function of temperature extrapolated to very low temperatures. At very low temperatures, the available vapor pressure in a bubble is too low to prevent its collapse against surface tension.



Note: The solid curve is the Rayleigh growth curve neglecting the cooling effect; the dashed curve includes this effect by the method indicated in the text. (Plesset and Zwick, 1954)

Figure 8. Comparison of theoretical bubble radius-time values with experimental values in water at 1 atmosphere with superheat temperature of 103.1°C.

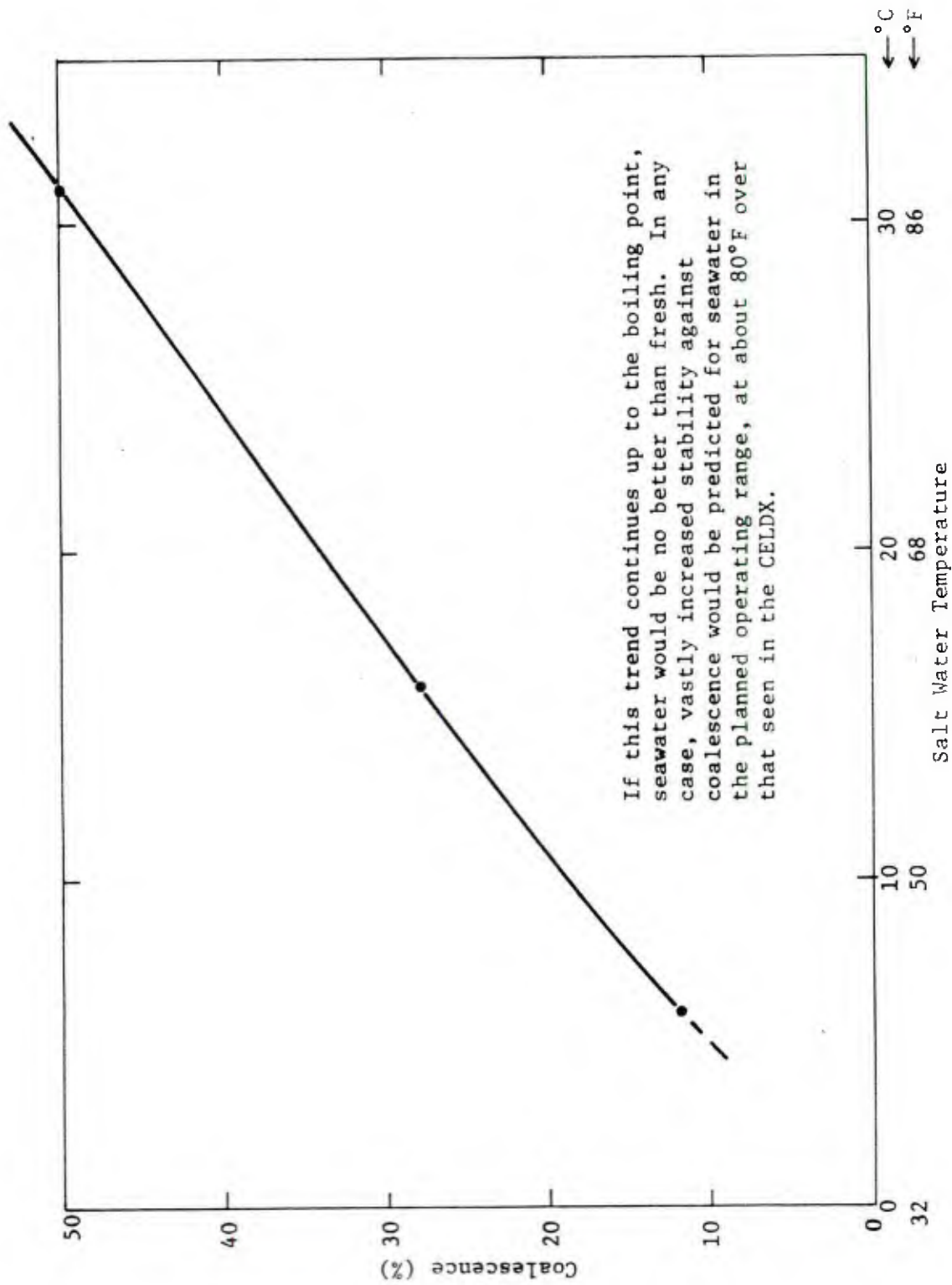
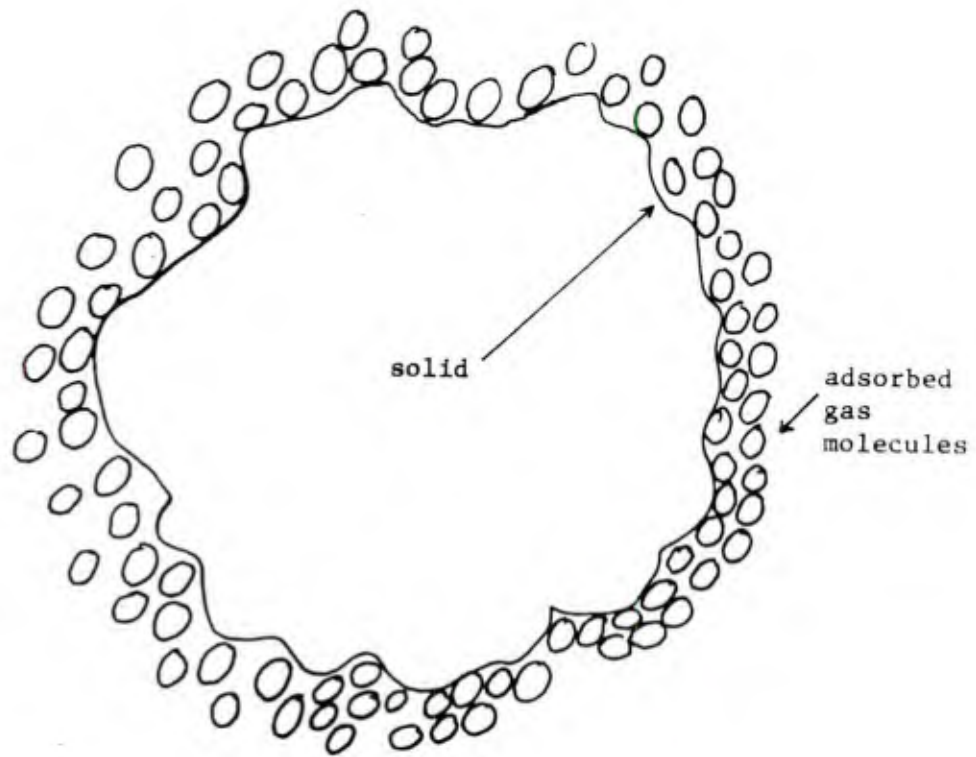


Figure 9. Coalescence data for seawater plotted from Lessard and Zieminski (1971).



NOTE: See Appendix II for probable ways a micronucleus can provide the basis for bubble growth.

Figure 10. Schematic representation of a solid particle (volcanic ash, exoskeleton, etc.) with adsorbed gas.

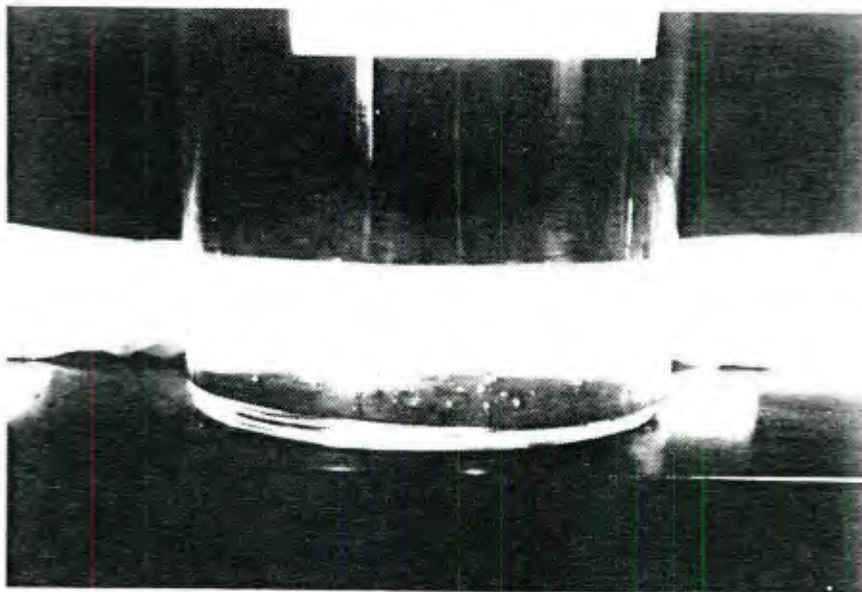


Figure 11. Oxygen bubbles evolved during photosynthesis, as in this instance from algae, would provide ideal nuclei for bubble activation.



"Hastigerina Pelagica," Allan W. H. Be,
Science, Cover, Vol. 192, 28 May 1976.
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Figure 12. Flotation bubble in a planctonic foraminifer, with a diameter of 2 millimeters. Such bubbles would be ideal nuclei for steam bubble growth and would not require activation in a cavitating venturi, just as those formed as in Figure 11 would not.

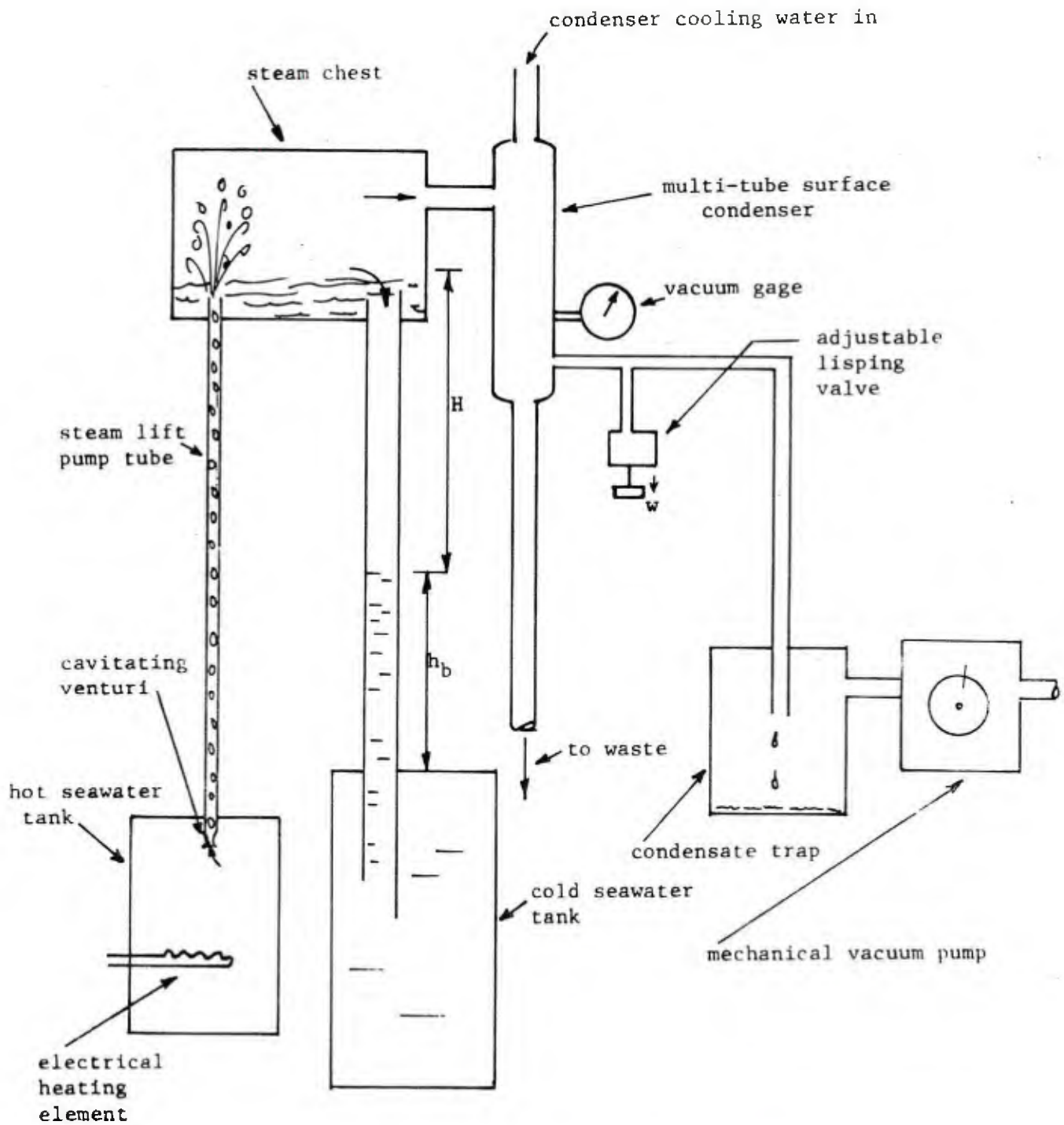


Figure 13. Schematic of Civil Engineering Laboratory Demonstration Experiment (CELDX) shown photographically in Figure 16. This is a model steam lift pump, similar to Stenning and Martin's (1967) air lift pump.

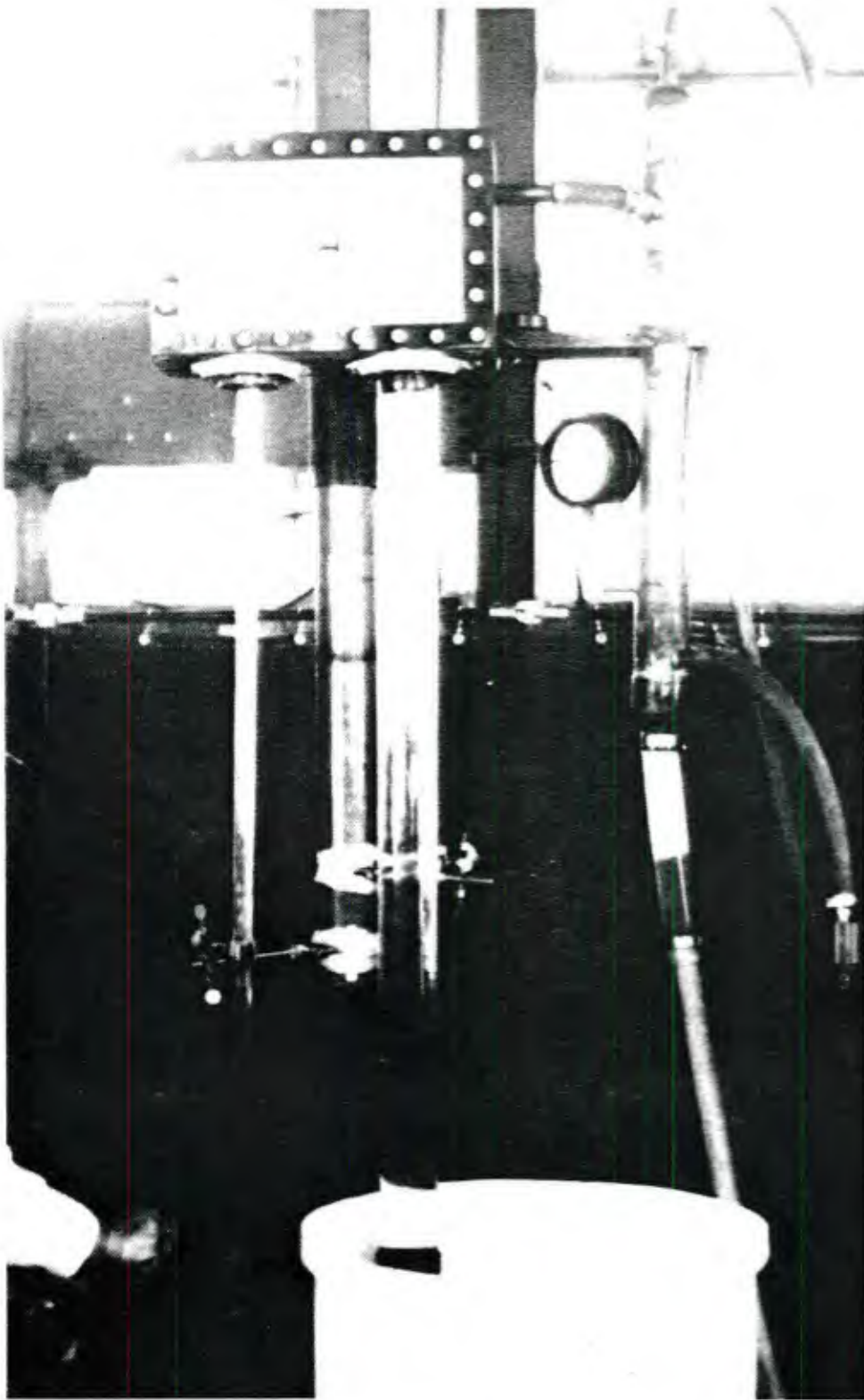


Figure 14. The Civil Engineering Laboratory Demonstration Experiment of the steam lift pump.

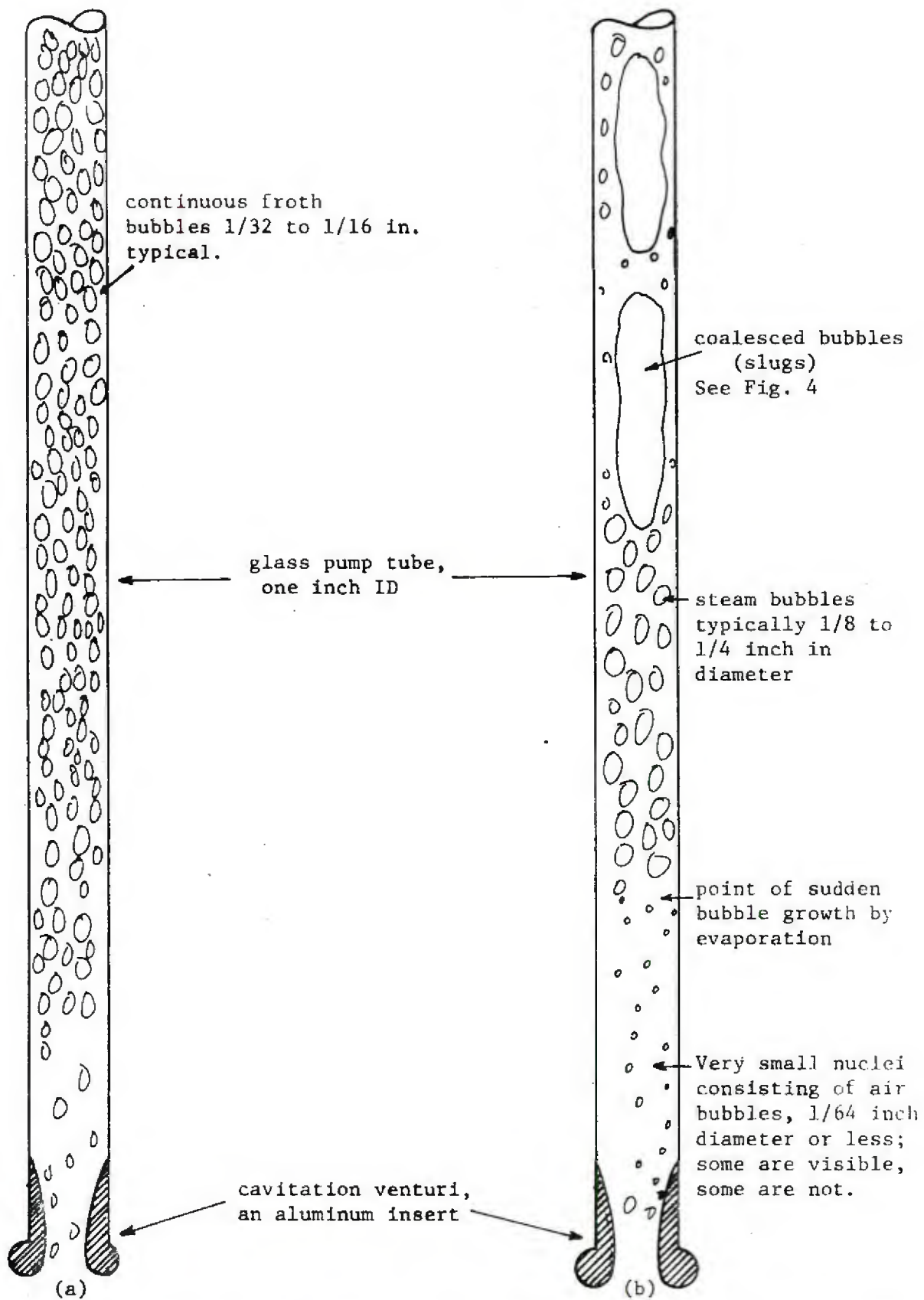


Figure 15. Schematic of pump tube in operation, showing continuous froth at (a) and intermittent bubbles at (b), where usually visible but widely spaced nuclei bubbles were seen in water, then boiling became general higher up, and coalescence above that.

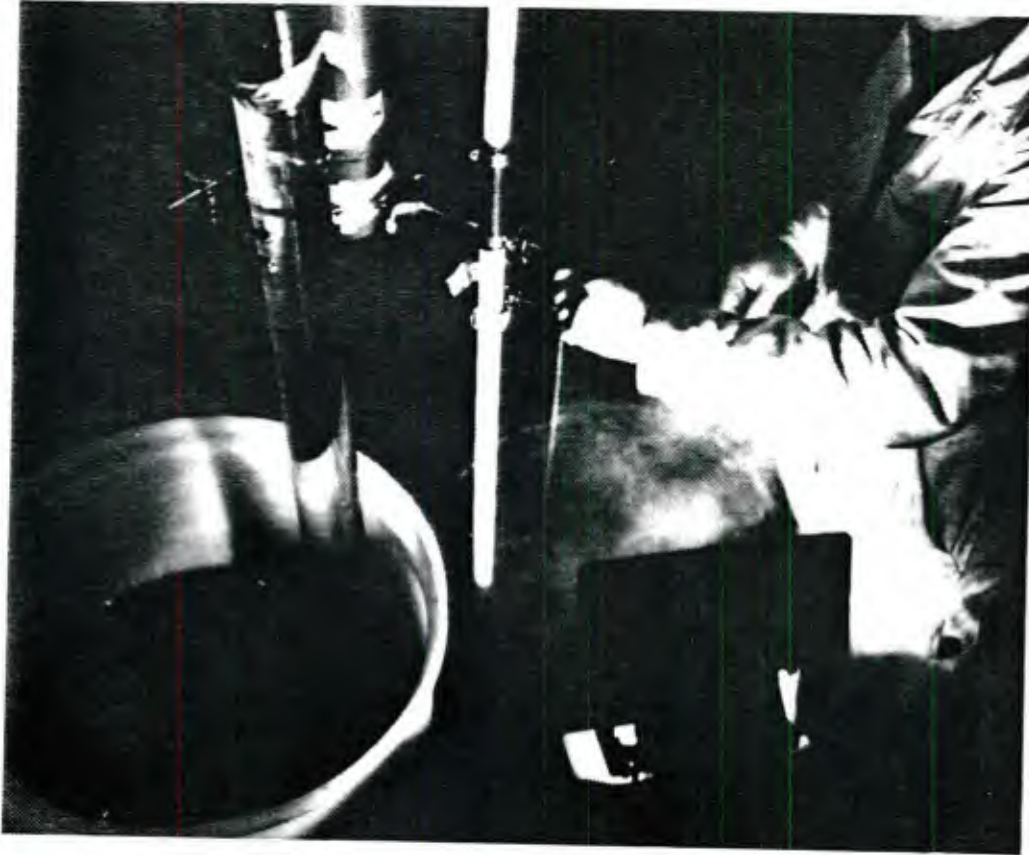


Figure 16. CELDX with ample nucleation from the bottom of tube as shown in Figure 15 (b) and no apparent coalescence. Contrasts with Figure 15 (a).

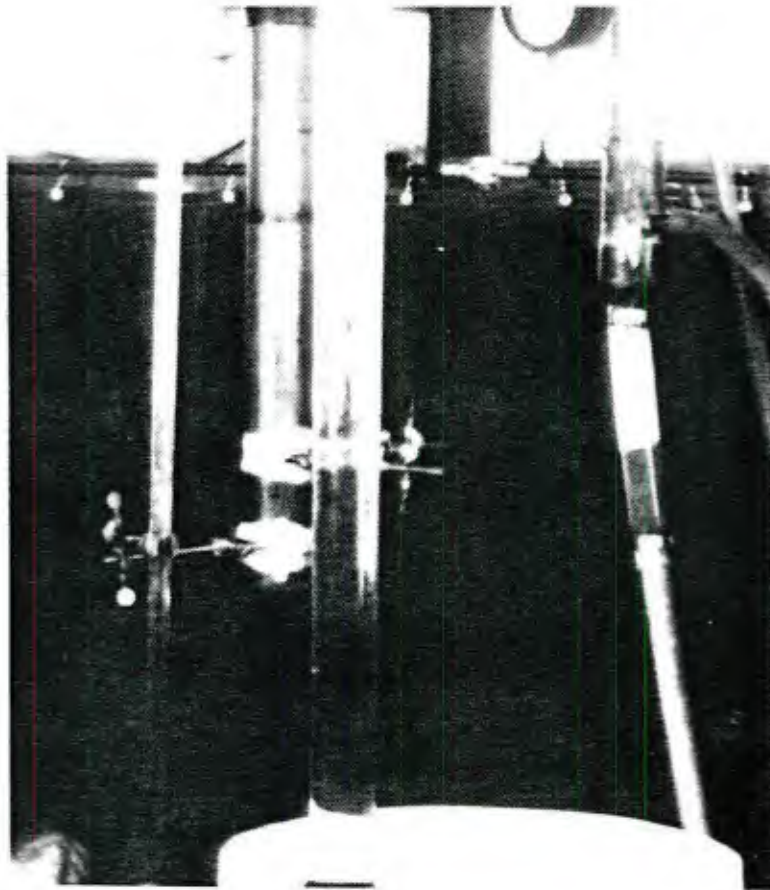


Figure 17. Central portion of pump tube in CELDX, showing slug flow in the pump tube from bubble coalescence.

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APPENDIX I
APPLICABILITY OF CAVITATION EQUATIONS

Sec. 32] *APPLICABILITY OF THE EQUATIONS* 129

by H. Rouse

For instance, in the case of air under normal atmospheric conditions, a change in velocity from 50 to 250 feet per second will result in an error in pressure change of only 1.2 per cent if computed on the basis of constant density. As a matter of fact, the influence of variable density upon the dynamic pattern must be taken into account only under relatively high velocity changes—such as are encountered, for instance, in the free efflux of gas from a high-pressure container, or in the motion of airplane propellers and projectiles.

32. Cavitation. A liquid, unlike a gas, may be considered truly incompressible so far as those types of flow usually encountered in hydraulic engineering are concerned. Nevertheless, while compressive stresses will thus have no further bearing upon the applicability of the flow net in cases of liquid motion, it must be recalled that liquids may not ordinarily be expected to withstand tension to any appreciable degree. In the laboratory, to be sure, it has been shown that water has a tensile strength of at least 34 atmospheres; but it is essential that the water so stressed be extremely clean and free from dissolved air. Under average conditions a liquid will seldom fail to boil once the pressure of vaporization is reached—close to absolute zero at normal temperature.

It is evident that for given boundary conditions either the velocity of flow or the hydrostatic load on a closed system may so be varied that a pressure intensity of absolute zero will be approached at some point on the boundary; that is,

$$p_{\text{obs}} = E_s - \rho \frac{v^2}{2} - \gamma h \rightarrow 0$$

In the case of the two-dimensional bend of Fig. 11a, the point of minimum pressure intensity will occur along the inner wall near the midpoint of the bend. If now the pressure intensity at this point is reduced to the vapor pressure of the liquid, either by increasing the discharge or by reducing the pressure load, it is evident that the liquid passing this point will just begin to vaporize. If the discharge is further increased, the region of vaporization will grow in size, a cavity forming immediately beyond the midpoint of the bend and appearing to ease the curvature of the innermost filaments. Continued increase

in discharge will cause further growth of this vapor pocket, until finally the flow as a whole becomes unstable.

A simple laboratory demonstration of this phenomenon—cavitation—was devised long ago by Osborne Reynolds,¹ and may easily be repeated by the reader. A small glass tube is heated over a flame and drawn out in the form of a Venturi meter

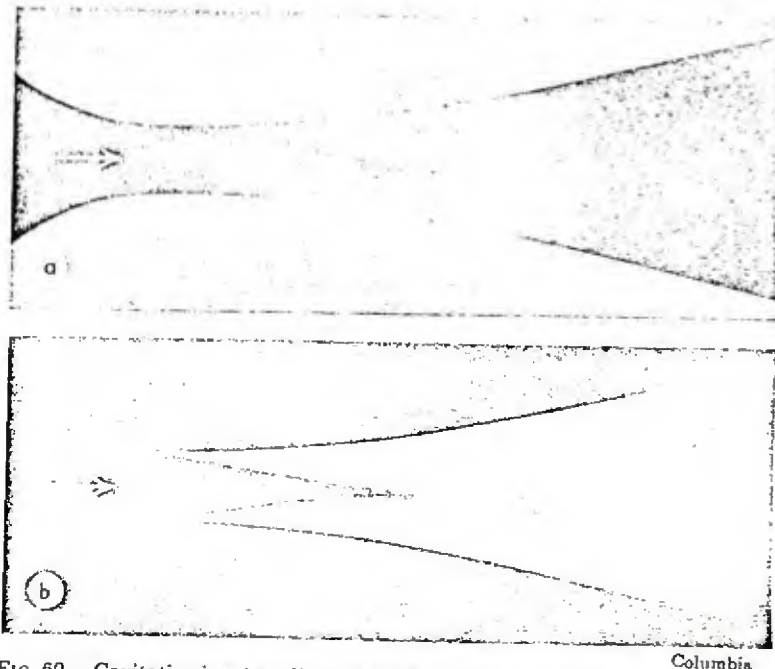


FIG. 60.—Cavitation in a two-dimensional Venturi throat; (a) front illumination, (b) rear illumination, under identical conditions of flow.

with a fairly great contraction. If this is connected with a water faucet by means of rubber tubing, at even relatively low rates of flow a white cloud of vapor may be observed just beyond the throat. As the discharge is increased, the zone of cavitation will lengthen, the intensity of the formation and subsequent collapse of the vapor bubbles making itself apparent through a distinct-hissing sound and perceptible vibration of the tube. Photographs of a two-dimensional contraction of this nature may be seen in Fig. 60, front illumination emphasizing the region

¹ REYNOLDS, OSBORNE, "Papers on Mechanical and Physical Subjects," vol. 2, p. 578, 1901.

of actual cavitation and illumination from the rear showing the appreciable quantity of air which is brought out of solution by the extreme reduction of pressure and not redissolved. It is quite evident from the photographs that the effect does not extend entirely across the flow section, but is limited to the region of maximum curvature—and hence maximum velocity and minimum pressure—at the boundary.

The occurrence of cavitation in hydraulic machinery is obviously a disadvantage, if only because of the resulting loss in efficiency. There is, however, a far more serious aspect of the problem, the importance of which has led to extensive research on cavitation in this country and abroad. High-speed motion pictures of this process indicate that conditions in the cavitation zone are far from steady—in fact, the vapor cloud seen with the naked eye is merely an average impression, for the successive stages of vaporization, movement downstream, and condensation repeat themselves so many times a second (the number of cycles varying directly with the velocity) that the eye is quite incapable of following. The formation of the vapor pockets is in itself of little consequence—but the abrupt collapse of these cavities as they are carried into regions of higher pressure is accompanied by sudden compressive stresses of exceedingly high magnitude. If the point of collapse is close to a solid boundary, the boundary surface is then subjected to countless intermittent shocks, and will sooner or later fail through fatigue. It was formerly thought that the corrosion—pitting—of metal parts of hydraulic machinery was due to a chemical action intensified by the low pressure. But laboratory tests indicate that such chemically inert (though brittle) substances as glass will fail quite readily, the zone of failure even lying somewhat below the exposed surface. Moreover, in every case the pitting has not been found to occur at the point where the pressure drops, but where the pressure abruptly rises, this marking the region of collapse of the vapor pockets.

Measurements of the pressure distribution along a Venturi throat during cavitation provide an excellent picture of the mean dynamic pattern.¹ In Fig. 61a may be seen a typical series of pressure distribution curves, taken under conditions of constant

¹ACKERET, J., Kavitation, "Handbuch der Experimentalphysik," vol. IV-1, Akademische Verlagsgesellschaft, Leipzig, 1931.

THEORY OF THE ADIABATIC BUBBLE

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Experiment

The film coefficient of heat transfer from a hot metal surface to a boiling liquid was estimated by Farber and Scorah¹ from experiments with an electrically heated wire submerged in the liquid. The heat-flow rate was given by the consumption of electric power. The temperature drop through the film was taken as the difference between the surface temperature of the wire and the mean temperature of the liquid. The surface temperature of the wire was estimated by a small thermocouple. The graph of film coefficient as a function of temperature drop through the film is called the boiling curve. The data plotted in Fig. 1 were obtained from 6 different test wires made of Chromel C alloy, 0.040 inches in diameter by 6 inches long, operated in a horizontal position under atmospheric pressure plus 20 inches of water.

Visual Observations

From visual observations of the boiling process, it was possible to identify at least six different variations corresponding to different regions along the boiling curve. The transition from one type into another, though gradual, is represented by lines in Fig. 2. The different types of boiling are described as follows:

- I. For ΔT values from 0 up to about 4°F , steam was produced by evaporation at the liquid-vapor interface. The heat transfer from the metal surface to the liquid took place by conduction and single-phase convection, which maintained an upward flow of superheated liquid.
- II. Ebullition began at a ΔT value of about 4°F . For values of ΔT from 4 to about 11°F , many small spheroidal bubbles would leave the metal surface, combine to form larger bubbles, which condensed in superheated liquid before reaching the liquid-vapor interface. The boiling was nucleate in the sense that the bubbles originated at favored spots on the metal surface.

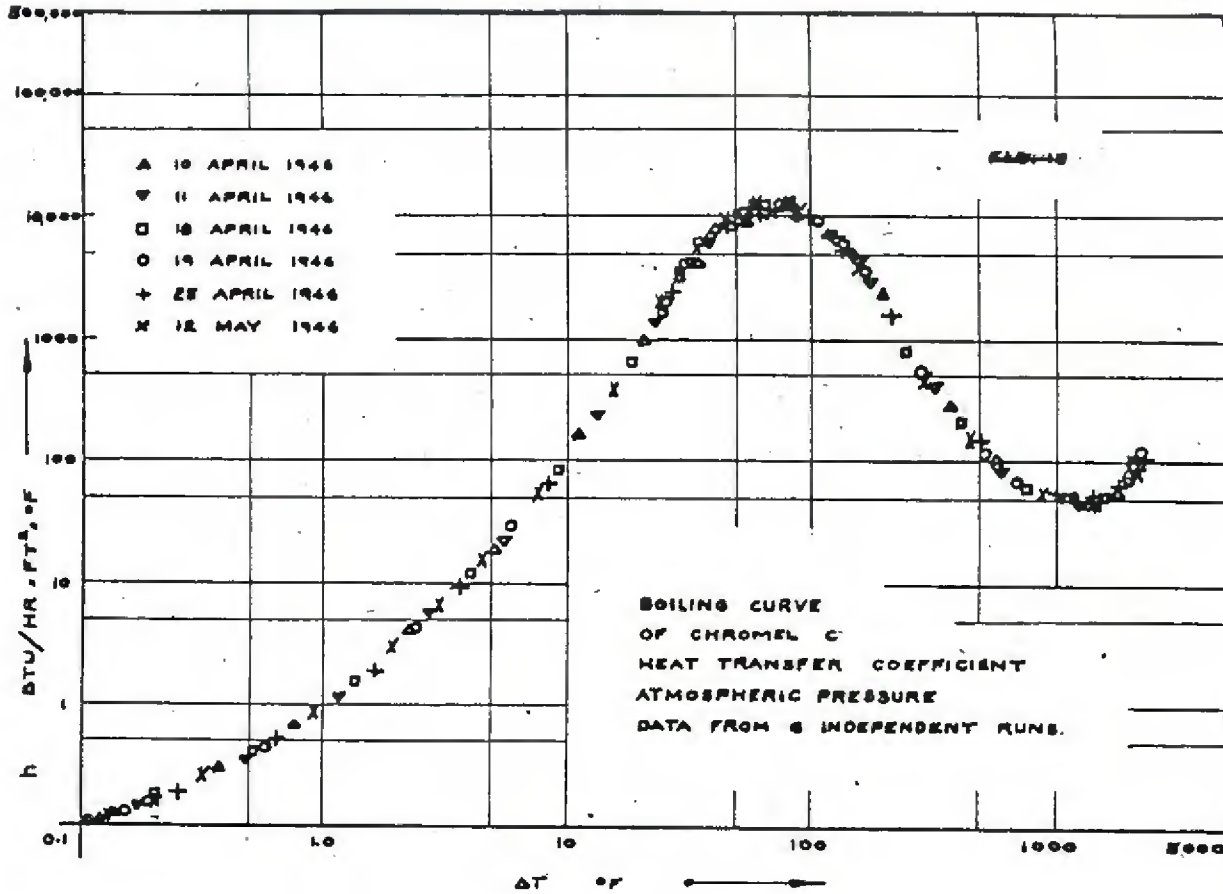


Fig. 1

III. For values of ΔT from 11 to about 65°F, nucleate boiling was observed. Larger and more numerous bubbles were generated, and they were able to transport steam to the liquid-vapor interface. Whether these bubbles increased or decreased in size could not be observed since several bubbles would almost invariably combine before reaching the interface.

IV. For values of ΔT from 65 to 400°F, an unstable steam film formed around the wire, and large bubbles originated at the outer surface of this film. This steam film was not mechanically stable, and under the action of the circulation currents the film appeared to collapse and reform rapidly. The presence of this steam film provided additional resistance to heat transfer, and reduced the value of the heat-transfer coefficient.

V. For values of ΔT from 400 to 1000°F, the steam film around the wire was stable in the sense that it did not collapse and reform repeatedly. The shape of the outer surface of the steam film varied continuously under the action of the circulation currents and the rapid discharge of steam bubbles.

VI. For values of ΔT above 1000°F, the influence of radiation became pronounced. In this region, the wire was observed to radiate visible light. The steam film was very stable mechanically, and the orderly discharge of bubbles suggested (1) that the frequency and location of bubble origination was controlled by factors operating at the outer surface of the steam film, and (2) that "favored spots" along the wire were without effect.

The sketches in Fig. 3 represent the phenomena observed in the different regions along the boiling curve. Photographic observations were tried with disappointing results.

Condensation of Zone - II Bubbles

The observed behavior of zone-II bubbles may be explained by considering the effect of size on their thermal stability. Neglecting the second-order effects due to gravitation, the action of surface tension is to increase the pressure of the steam within the bubble above that of the surrounding liquid, in accordance with the following equation:

$$P_v = P_1 + \frac{4\sigma}{d}$$

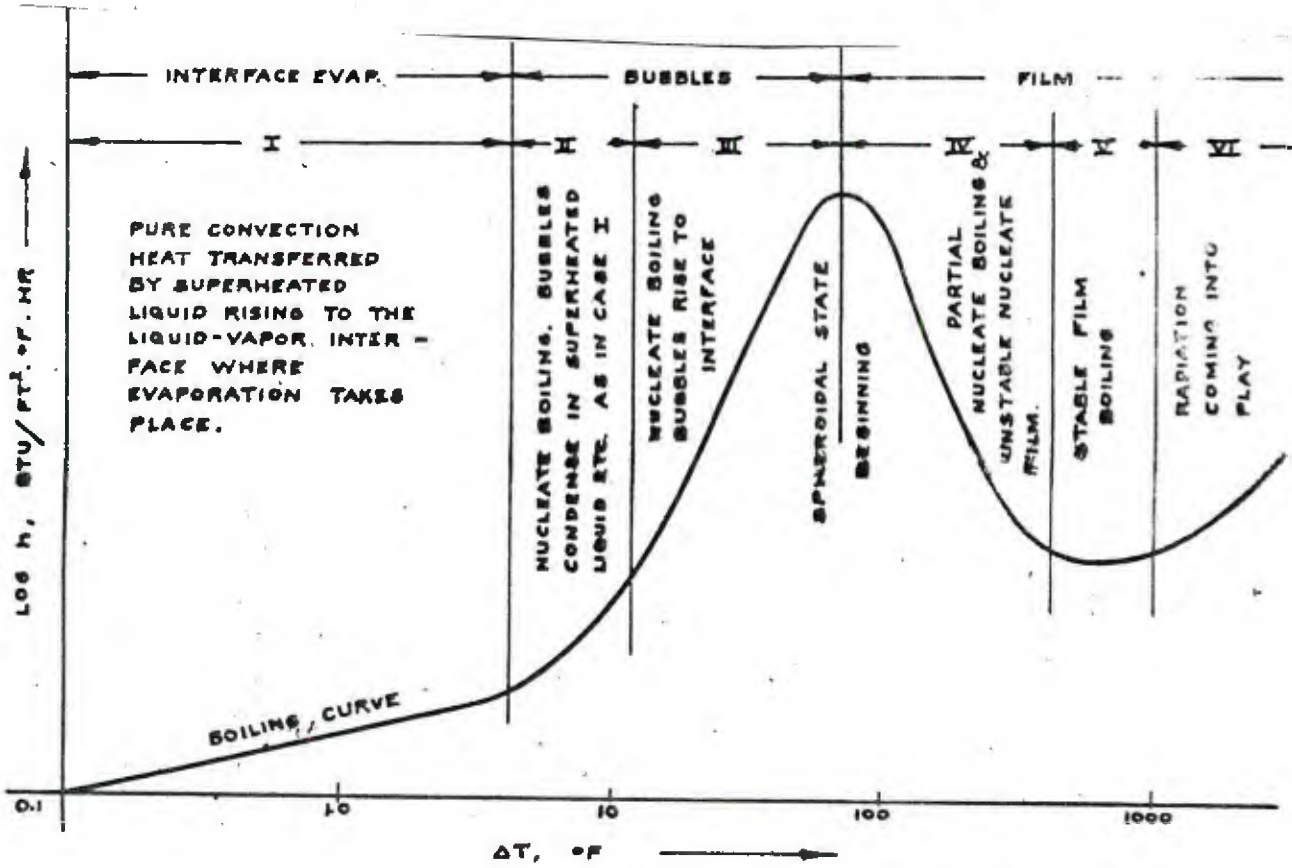


Fig. 2

where P_v = pressure of the vapor within the bubble, psiab

P_1 = pressure of the surrounding liquid, psiab

σ = surface tension of the liquid-vapor interface, psi

d = diameter of the bubble, inches.

The diameter of the bubble is, then

$$d = \frac{4\sigma}{P_v - P_1}$$

and the surface tension is estimated from the following relation:

$$\sigma = 0.470 \times 10^{-3} - 0.634 \times 10^{-6} t,$$

where t is the temperature of the water in °F.

Now consider zone-II operation with the liquid on the heating surface under a pressure of 1 atmosphere and a superheat of 4°F. Vapor is formed at favored spots on the heating surface, swept-up into a bubble, and launched into the surrounding superheated liquid. Due to the action of surface tension, the steam within the bubble is compressed to some pressure above 1 atmosphere. To simplify the argument, consider the bubble filled with saturated steam at a temperature corresponding to the pressure within the bubble. For a given bubble temperature, the pressure can be interpolated from the steam tables, and the diameter of the bubble computed. For the above conditions, the following results apply:

Bubble Temperature °F	Bubble Diameter Inches
220	.000535
218	.000725
216	.001106
214	.002250
212	∞

These data are shown graphically in Fig. 4.

With 4°F of liquid superheat, the water surrounding the bubble operates at 216°F. Bubbles smaller than 0.001106 inches in diameter have temperatures above 216°F, and consequently, transfer heat to the colder, surrounding liquid. As a consequence of this heat loss, condensation takes place at the vapor-liquid interface of the bubble, and the bubble volume and diameter decrease accordingly. With

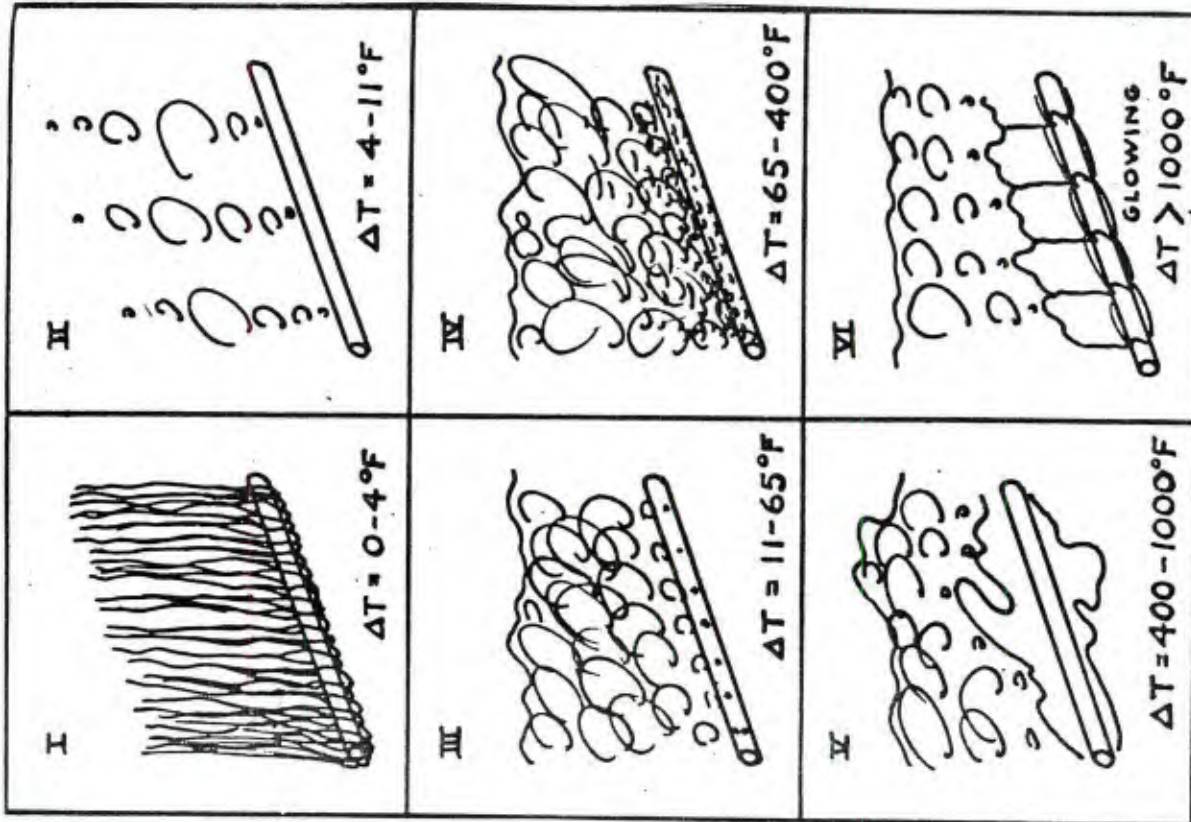


Fig. 3. Typical Boiling for the Different Sections

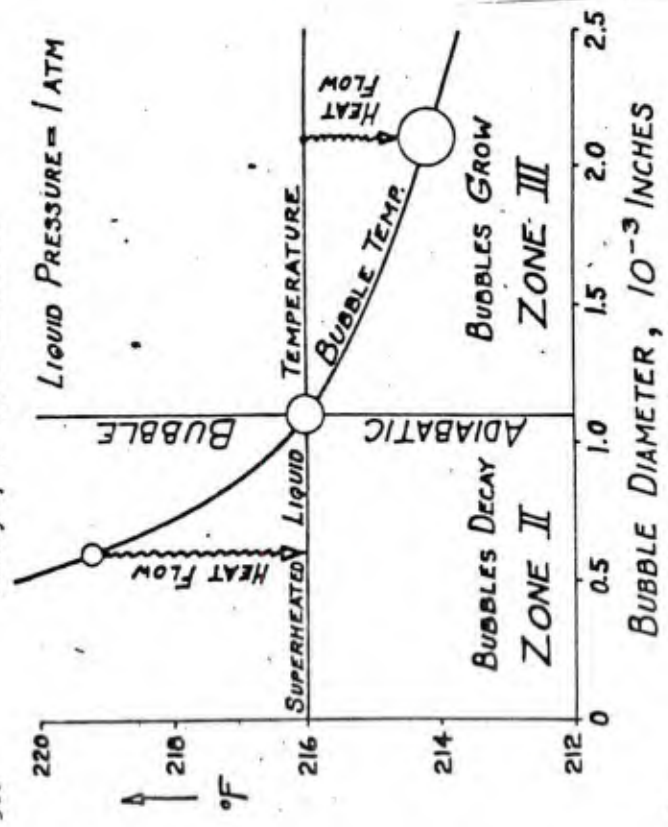


Fig. 4

diminishing bubble diameters, both the saturation pressure and temperature increase within the bubble. The result is a greater temperature difference between the remaining bubble vapor and the surrounding liquid, and a correspondingly greater rate of heat loss. This condensation process continues until the bubble vanishes, as observed in zone II.

Growth of Zone - III Bubbles

On the other hand, bubbles larger than 0.001106 inches in diameter have temperatures below 216°F, and the flow of heat is from the warmer liquid to the colder bubbles. This transfer of heat to the bubble causes evaporation at the liquid-vapor interface, and the bubble volume and diameter increase. This evaporation process at the bubble interface continues so long as there is sufficient liquid superheat to maintain the liquid temperature above the vapor temperature of the bubble, as observed in zone III.

The Adiabatic Bubble

A bubble 0.001106 inches in diameter floating in water at 216°F and 1 atmosphere pressure has the same temperature as the surrounding water. There is no heat transfer, and in this sense, the bubble exists in an adiabatic state. The adiabatic bubble acquires an interesting significance for it marks the boundary between zone II and zone III on the boiling curve. The effect of liquid pressure and superheat on the size of the adiabatic bubble is shown in Fig. 5.

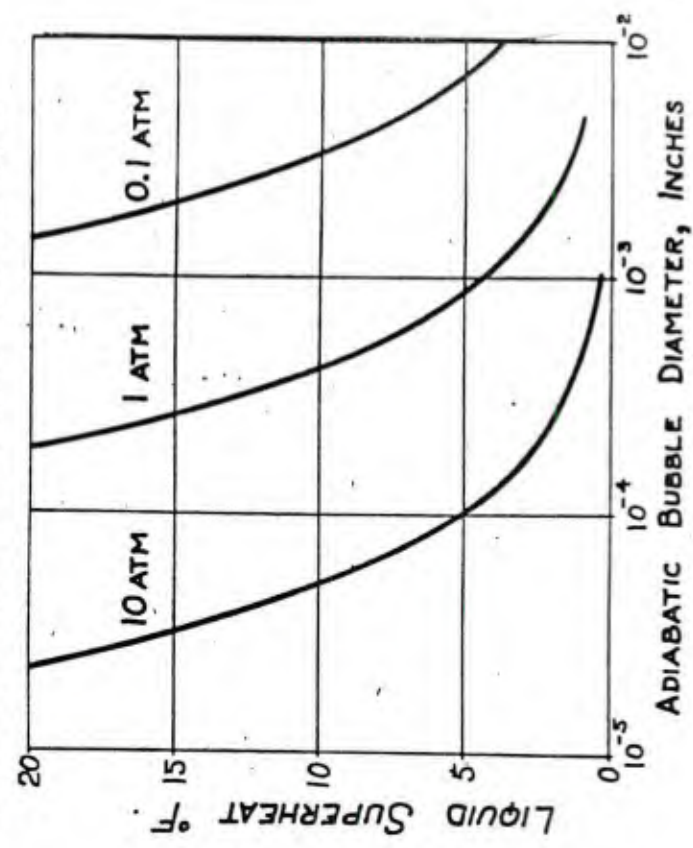


Fig. 5

REFERENCE

1. A.S.M.E. Trans. 70, 369 (1948).

APPENDIX III
SPECULATIVE DISCUSSION OF CAVITATION VENTURI
NUCLEATION AND BUBBLE GROWTH

Because the following explanation is pure speculation, it is presented as a separated section of the report.

Based on the literature survey and the limited experiments, it seems probable that nucleation and bubble growth have a two-stage sequence, and this fact will have important implications on the design of the relevant sections of a steam lift pump in the development of the OTGHPP.

Referring to Figure 12, which represents a very small but discrete particle with adsorbed gas, there seem to be at least two possible explanations for how such a small particle with a radius so small as to prevent application of Equation (7) can function as a nucleus. First, if the particle is, because of its adsorbed gas layer, hydrophobic, then the analogy shown in Figure 6 may be entirely correct. If placed in sufficient tension, the nonwetted particle could conceivably allow rupture of the water's structure, and the resulting cavity would then be filled with gas by diffusion from the surrounding water (according to Fick's law, which requires only a concentration gradient) and by evaporation of a very small amount of water vapor. Diffusion requires much more time--relative to evaporation, so the time the nucleus is in the activation zone of low pressure, phase 1, should determine its final size. Then it can be manipulated by flow into a slightly higher pressure area, where the bubble can grow, as detailed in Appendix II.

The above concept demands rupture, the following one does not. If the adsorbed layer of gas molecules is fairly "thick," i.e., several layers of molecules, and held sufficiently strongly by suitable forces (e.g., VanDerWalls forces), then when the overpressure on the particle is released in the venturi, and perhaps placed into tension, the radius of the particle plus its gas will expand. Initially in equilibrium with the dissolved gas in the surrounding seawater, this expanded volume would be "seen" by dissolved gas in the seawater as a low-pressure, low concentration area. There is no requirement that the particle be hydrophobic. Rather, if hydrophilic, the gas layer can be placed in tension along with water. The dissolved gas in the water would diffuse to the expanded layer of gas affixed to the particle and the nucleus would now soon become a gas bubble. Growth could then occur by heat transfer when the bubble's internal pressure became sufficient and its radius large enough to support itself against collapse.

Both explanations are plausible, and certainly both are useful; both require similar environments for activation of a nucleus in stage 1 --by diffusion of gas, primarily and then growth in stage 2, by evaporation and lesser diffusion. The second explanation has the advantage of not requiring rupture of the water structure and is at the moment in favor with the author.

LIST OF SYMBOLS AND FORMULAS

H	Useful pump head, feet
L	Pump tube length, feet, measured from venturi throat in steam lift pump
S	Submergence, feet
Q_w	Water pumped rate, cubic feet per second
Q_a	Air or steam flow rate, cubic feet per second, average in pump volume
h_v	Velocity head, feet of fluid flowing = $v^2/2g$
h_f	Friction head, feet of fluid flowing
x	Vertical distance from venturi throat, feet
D_x	Inside diameter of pump tube at height x, feet (pump tube is normally round in section at all positions).
h_b	Barometric height, feet of fluid, the water column supported by the partial pressure difference between 1 atmosphere and the vacuum pressure in the steam chest.
S_b	Equivalent barometric submergence = $S + h_b$ in feet. The head producing flow into the pump's inlet, if the venturi is operating at 0 psia throat pressure.
H_{max}	Theoretical maximum head in a frictionless system, feet of fluid flowing = $S(R_2 + 1)$ in an air lift pump, = $S_b(R_2 + 1)$ in a steam lift pump.
R_1	Dimensionless ratio, S/L for air lift pump, S_b/L , steam lift pump.
R_2	Dimensionless ratio, Q_s/Q_w .
Q_o	(See Figure 2(b)), the intercept value of air flow, Q_s for which the water-gas mixture rises to the height L, but no flow of water is accomplished. At this condition, bubble slip is 100%.