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AN OVERVIEW OF VAPOR EXPLOSION PHYSICS IN THERMAL INKJET (TIJ) PRINTHEADS

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ABSTRACT

A thermal inkjet (TIJ) printhead puts individual dots on paper on demand by using microscale superheat vapor explosions to kick droplets of liquid ink out of tiny nozzles. This boiling mode- on-demand, discrete vapor explosions- furnishes the physical basis for the entire field of thermal inkjet printing (a business worth tens of billions of dollars a year worldwide). The working fluid in the “TIJ boiler” is the ink itself. A TIJ printhead of modern manufacture contains as many as 3900 such boilers, one for every nozzle in the printhead array. The boiling regime required for this application (extremely high superheat, heterogeneous nucleation of local boiling at atmospheric pressure) is unique in the field of boiling heat transfer as is the microscopic scale lengths and sub-microsecond time scales that characterize it.

INTRODUCTION

The explosive boiling that powers a thermal ink jet (TIJ) printhead is a completely transient phenomenon which never achieves steady-state conditions of heat transfer and remains completely within the inertially-limited regime of bubble growth in that the heat source that drives the vapor explosions is shut down as soon as possible after each individual nucleation event goes to completion. Because of this, the “TIJ boiler” experiences a full thermal cycle from ambient to peak operating temperature and back down to ambient again each time it shoots an ink droplet- which occurs 20 to 30 thousand times per second for each nozzle in the array.

The engine that extracts mechanical work from the explosion is the vapor bubble itself; as such, the “TIJ boiler” and “TIJ engine” are actually combined into the same device, with a portion of the unboiled working fluid representing the load. Because the boiler returns to atmospheric pressure at the end of each explosion in the course of propelling a droplet of ink out of the “TIJ boiler”, it can be thought of as experiencing a full blowdown event upon completion of every thermal cycle- that is, every droplet firing- with the blowdown itself representing the net work output of the device.

Despite these amazing circumstances, most of the normal language and physics of boiling heat transfer and boiler operation still applies to this field, although the extremely small size, high speed, and discrete nature of the explosions all pose unique engineering challenges for observing and controlling them.

In this paper, I will avoid an academic treatment of these topics in favor of giving you what I hope will be interesting and perhaps even entertaining comparisons between your “big” world of boiling heat transfer and mine- which is the world of *submicroscopic vapor explosions.*

Heartfelt thanks go to Brian G. Risch for preparing most of the wonderful scanning electron microscope pictures I have included here, Chorng-Ing Sow for his boiler scale photos, and Robert N. K. Browning for the photos he took of nucleation misfires.

No equations this time- just fun!

WHAT IS TIJ?

I’ll be using the term “TIJ” over and over again in this presentation; this stands for *Thermal Ink Jet*- the microboiler technology that is at the heart of HP’s printing technology. Very briefly: If you broke open an HP personal printer of current manufacture that looks like this one:

Figure (1): an HP TIJ printer with 3900 boilers inside you would find in it a printhead assembly small enough to fit in the palm of your hand, which delivers 6 different colors of liquid ink to a silicon boiler array chip in it, that looks like this (sorry for the false colors):

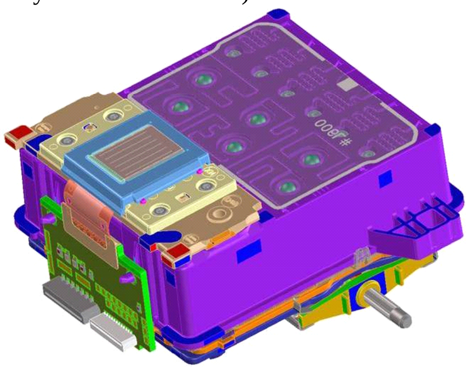

Figure (2): a TIJ printhead assembly

The boiler chip (encircled in light blue in the figure above) is about the size of a postage stamp and contains 3900 tiny boilers, each with its own ink nozzle 14 microns in diameter right next to it. This thing shoots ink droplets which fly through the air to form text and full-color images on a variety of paper types.

Here is a drawing that shows an inside cutaway view of a single TIJ nozzle and boiler unit.

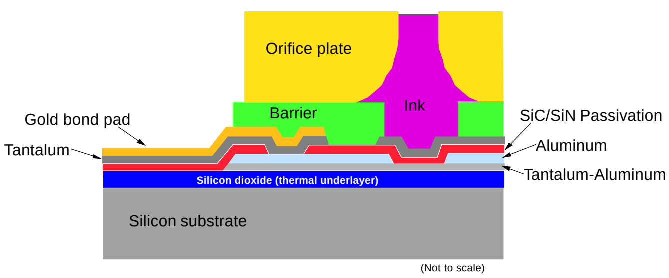

Figure (3): schematic cross-section of a TIJ boiler

The series of diagrams in Figure (4) below shows the process by which one of these devices turns a short pulse of electricity into a flying droplet of ink. Basically, we send a pulse of electricity through the tantalum-aluminum resistor, which gets really hot. Some of this heat diffuses through the SiC/SiN passivation and the Ta topcoat and gets into the ink. A little bit of the ink explodes into a vapor bubble that fills up the boiling chamber above the resistor. The bubble acts as a piston to eject a droplet of ink from the nozzle.

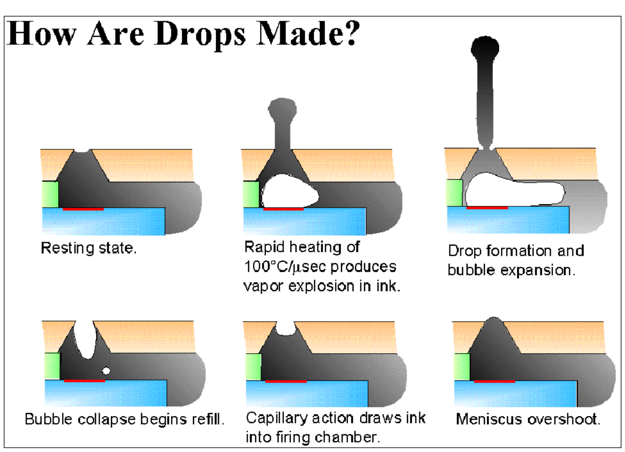

Figure (4): how a TIJ boiler generates ink droplets

The next figure shows what a small portion of the boiler array chip in a TIJ printhead looks like, seen from above. In this case, the nozzle plate is a thin film of transparent plastic so we can see right through it. The nozzles are full of ink and are pointing at you in this view. At the top of the image are some of the transistorized drive electronics that convert firing instructions from the motherboard in the printer into precisely-timed power pulses that are routed to the heater resistors under each nozzle. In the lower left quadrant, 26 little square TIJ boilers- each full of red ink- are visible. The nozzle above each is barely visible in the center of each boiler. Within each vertical column, the boilers are 43uM apart. The “extra” boilers without heaters in them are to bleed air bubbles out while we fill the assembly with ink. The two tiny white dots in each ink feed inlet are there to strain particles out of the ink (you can call it “feed water” if you like) so they won’t clog the nozzles from the inside. The dark stripe between the two columns of boilers is an ink feed passage cut through the silicon chip. To the right are the field effect transistors that drive the heaters.

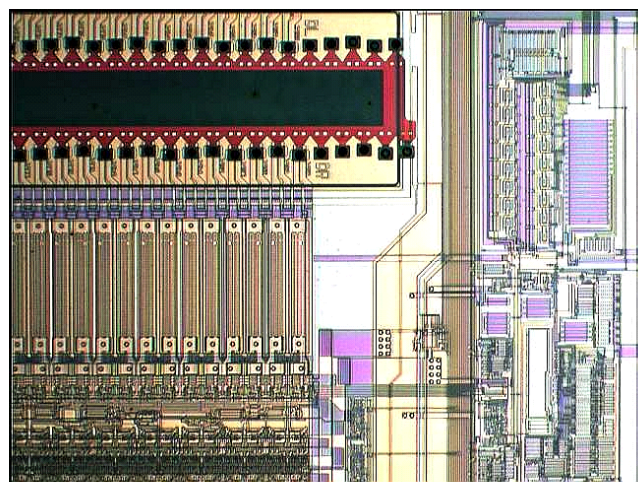

Figure (5): partial view of a TIJ boiler chip

This image is a partial view of the boiler array chip from our most recently-introduced HP printer for home and office use in the pictures on page two. The whole chip contains 3900 of these microscopic nozzle-and-boiler units, grouped into six arrays that shoot six different colors of ink. Each individual boiler and nozzle can generate about 20,000 vapor explosions per second. This device hence can throw 3900 X 20,000 = **78 million droplets of ink per second,** each of which is propelled by its own individual vapor explosion under the control of the printer’s imaging electronics and firmware.

It is a marvel of microtechnology, and allows you to print full-color photo images and high-quality black text at home.

TIJ THERMODYNAMICS, STEP-BY-STEP

Here is a series of stop-action flash photos showing what one single vapor explosion looks like. The earliest image in the sequence is in the upper left and the last in the sequence is in the lower right. You are looking straight down on a silicon chip with a TIJ heater resistor (the gray square area in the center of each image; this one is 60 microns on a side) on its surface. It is bathed in clear liquid so we can see the boiling happen. The nozzle plate has been removed but the greenish barrier material that surrounds the heater is in place.

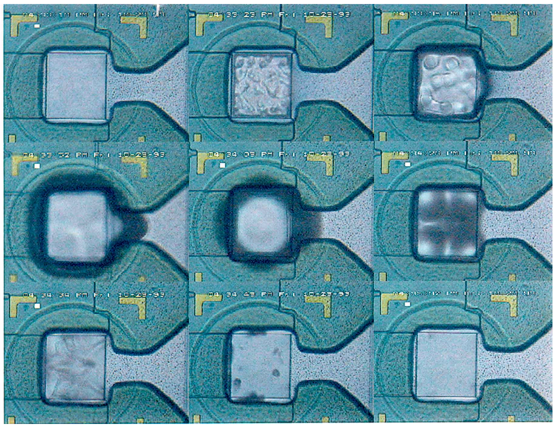

Figure (6): the boiling sequence on a TIJ heater surface

In the first image, the resistor is turned on and we are dumping heat into the liquid. Three microseconds later (second image) the hot wall has reached ~260C and the boundary layer in contact with it has vaporized and formed a blanket of steam stuck to the wall. In the images that follow, the steam bubble expands ballistically, cools off, reverses direction, and collapses. The piston-like action of the bubble is what pumps a droplet of ink out the nozzle. (In fact, if there were a nozzle plate in place, the ink droplet shot from it would hit you square in the eye right about now.) The entire process requires about 15 microseconds. Now let's examine each step in this process in more detail.

Phase (1): heat transfer

The first step in this process is the storage of superheat enthalpy in the boundary layer of ink that is in contact with the heat source. It will be this stored energy that will fuel the growth of the expanding steam bubble. In our current product line, the "hot wall" is a very small (about 400 square microns in area) electrical heater formed of a very thin metal layer (a few hundred atoms thick) through which a very short pulse of electricity (a few microseconds long) is sent whenever a single droplet of ink is desired. The heat source is separated from the working fluid to be boiled by a ~0.6uM thick protective wall. The working fluid is the ink itself, which is mostly water with cosolvent and colorant additives. The hot wall forms one surface of a boiling chamber with an internal volume of roughly 10,000 cubic microns. Let's compare this with a boiler sized for industrial power generation, as follows.

An industrial boiler will have its working fluid separated from the heat source by a wall with a thickness on the order of a centimeter. The wall thickness in a TIJ boiler is thinner than this by a factor of about 1/10,000. A boiler in a power generating plant might have a heat transfer area on the order of a hundred square meters while a single TIJ boiler has a heat transfer area on the order of a hundred square microns- smaller by a factor of ~1/1,000,000,000,000. Furthermore, while an industrial boiler would have an internal volume on the order of tens of cubic meters, a single TIJ boiler has an internal volume smaller than this by a factor of ~1/1,000,000,000,000,000. This is why 3900 of them can fit into the HP printer on your desktop..

Because the TIJ heaters are so small (a few hundred square microns in area) and the delivered electrical energy is relatively large in comparison (~1 microjoule per firing pulse), each power pulse produces instantaneous heat transfer power densities at the wall surface of ~**3.5 billion watts/square meter** (compare with that of the Sun at ~65.8 million watts/square meter). In most of our TIJ products, the wall surface in direct contact with the liquid consists of tantalum metal, which responds to this enormous heat flux with a temperature rise rate exceeding ***two hundred million degrees C per second*** in printheads of current manufacture.

The superheated boundary layer thus produced is much less than one ten-millionth of a meter thick by the time the superheat limit for heterogeneous nucleation is hit on the Ta surface, no more than a couple of microseconds after the power pulse begins- and the bulk fluid several microns outside the thermal boundary layer remains within tens of degrees C of ambient during the whole process. Detailed heat transfer modeling combined with flash photography of actual nucleation events at the tantalum surface yield estimates of resistor surface temperatures at nucleation of 260 to 280 C, compared to the thermodynamic limit of superheat for (pure) water of about 340 C.

So, whereas ordinary boiling heat transfer devices operate within tens of degrees C of the saturation temperature at steady state, and require hours to come to full operating temperature, **TIJ devices operate within ~tens of degrees C of the *thermodynamic limit of superheat*- and come fully "on line" within a few *millionths of a second.*** Because of the extremely brief duration of enormous heating rate, the bulk fluid a micron or two away from the hot wall stays within a few tens of degrees C of ambient at all times.

Phase (2): the vapor explosion

The inks used in these devices consist mostly of water and wet the (tantalum) heat transfer wall quite well, with contact angles typically no greater than 60 degrees and as low as 20 to 30 degrees with some inks in current use. The depression of the superheat limit to the levels inferred above and the observation that boiling always occurs on the wall and not within the bulk of the fluid implies the presence and activation of air nuclei in the hot wall surface of a size range (tens of nanometers) corresponding to the typical size range of grain boundary junctions and intergranular crevices in the wall itself.

Below are high-speed flash photos of a single TIJ heater immersed in water, in which I have captured eight different vapor explosions right at the instant of nucleation. In this example, the heater resistor is 100uM square. In photos like this, you can identify which regions on the resistor surface contain nucleation sites and count how many of the sites are active on any firing as a function of time, heat deposition rate, and fluid type.

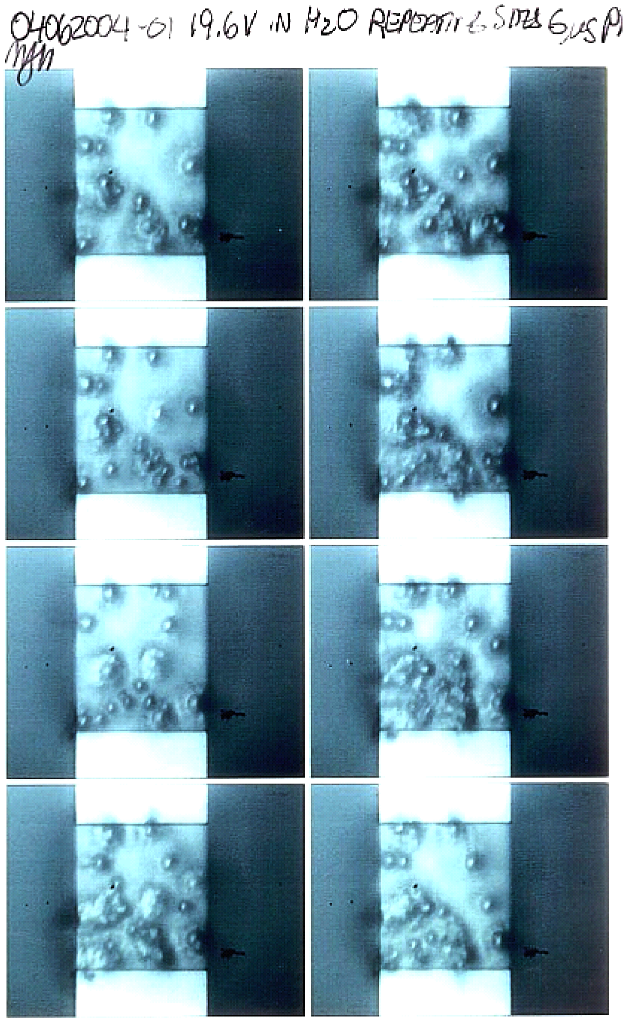

Figure (7): eight individual vapor explosions

In ordinary boiling heat transfer devices, sudden vapor explosions are not desired. Steep thermal gradients are to be avoided, effective mixing of the boundary layer with the bulk liquid is desired, and prompt nucleation at low superheats is guaranteed by deliberately designing air and vapor traps into the hot wall.

But exactly the opposite is required to ensure the consistent creation of the vapor explosions which make thermal ink jet devices work: steep thermal gradients, no mixing between the boundary layer and the bulk, and nucleation delayed to the last possible instant (i.e., the highest possible superheat). This last requirement is met by striving for fully-wetted heater surfaces which are completely free of pits, crevices, or pores bigger than grain junctions in the wall that can be activated as low-temperature nucleation sites by trapped air or vapor.

Phase (3): Vapor Bubble Growth

The individual vaporization nuclei merge shoulder-to-shoulder into a single thin film of vapor within a tenth to a quarter of a microsecond after the appearance of the first active sites. This is the amount of time required for a beam of light to travel ~75 meters- a fast process, considering that in one second, that beam of light will travel a distance equal to seven and a half times the Earth's circumference.

This vapor layer uniformly covers the resistor and propels the remainder of the hot boundary layer off the hot wall surface at an average speed (over the lifetime of the bubble's expansion) of about five meters per second. Heat transfer into the liquid is shut down by the vapor layer at this instant, and any heat delivered to the wall by the heater after this is wasted and diffuses into the silicon substrate on which the heaters reside. For this reason***, the heater resistors are shut off as soon as practicable after each nucleation is complete.*** Steady-state heat transfer as such NEVER OCCURS in these devices.

Evaporation of the thin superheated boundary layer at the advancing bubble front consumes the superheat enthalpy and furnishes the pressure which lifts the bulk ink away from the hot wall and pushes some of it out the nozzle. Detailed computer modeling of this process yields an estimate of ~50 atmospheres for the (very brief!) initial positive pressure inside the exploding nuclei. Initial accelerations of the fluid next to the exploding nuclei are correspondingly large. Evaporation continues until the superheated boundary layer (which is thinning because of heat conduction into the bulk, evaporation into the bubble, and fluid flow continuity) has been consumed- a process requiring much less than a microsecond.

Since heat cannot easily be conducted into the working fluid after bubble growth begins, ***bubble expansion in a TIJ device is entirely within the inertially-controlled regime.*** TIJ vapor explosions are ***ballistic*** in the sense that the trajectory of the vapor front is determined by conditions at "launch" and the system as a whole is in fact "coasting" thereafter. Coupled fluid flow and thermodynamic simulations of bubble growth indicate that the pressure inside the expanding vapor bubble goes subatmospheric long before the expanding vapor bubble achieves its maximum size- that is, the TIJ vapor explosion is overexpanded by the inertia of the departing fluid that surrounds it.

The expanding vapor bubble performs work directly on the unboiled ink in its vicinity, which remains within tens of degrees C of room temperature ambient during this whole process. The printhead's plumbing layout apportions this between useful work (ink pushed out the "blowdown" nozzle above the heater) and wasted work (as blow-back into the "feedwater makeup" supply plenum). As noted earlier, the vapor bubble expands into a tiny piston that fills up the "TIJ boiler" as it advances into the bulk at an average speed of about 5 meters/second, thereby displacing ink out the nozzle. Since the exit nozzle has a smaller cross-sectional area than the advancing vapor piston, the droplets emerge from the nozzle with velocities in the range of 10 to 15 meters per second.

How much working fluid actually explodes into vapor on each firing? We can get a crude estimate as follows. A typical TIJ vapor bubble expands to a maximum thickness of about 25uM off the hot wall. Ignoring ballistic overshoot for the moment, we can divide this bubble thickness by the vapor-to-liquid expansion ratio for water (about 1700:1) for any little one-micron-square patch of area on the surface of the heater and conclude that the thickness of the layer of water that actually boiled in a single explosion is on the order of ~25/1700 or *~15 nanometers.* This is smaller than the typical grain size (~30nM) of the tantalum topcoat that forms the hot wall surface.

(Note here that both the "blowdown port" and the "feedwater makeup inlet" of a TIJ boiler are completely open to atmospheric pressure at all times during operation, in stark contrast to power plant boilers. The only way that a TIJ boiler can deliver useful work to a load is by generating extremely steep, transient pressure gradients for extremely short periods of time, so as to generate extremely sharp drive impulses.)

Unlike a boiler, in which the blowdown process occurs at widely-spaced intervals and represents wasted heat and work, ***the blowdown process in a TIJ printhead in fact represents the entire useful mechanical work output of the device.*** The overall thermomechanical efficiency of a TIJ printhead as a heat engine is extremely low (less than 1%) but adequate for the purpose of throwing ink onto paper inexpensively.

Phase (4): condensation and bubble collapse

By about 10 microseconds after nucleation, the droplet of ink expelled by the vapor explosion is on its way out the nozzle and the ballistic expansion of the vapor bubble has been halted by the subatmospheric pressure inside it. A separate condenser is not required to return the vapor to liquid because the whole apparatus remains within a few tens of degrees C of ambient during normal operation. This allows the vapor to be condensed right inside the boiler itself.

As the vapor remaining inside the overexpanded bubble finishes condensing back to liquid, the bubble meniscus collapses back onto the wall. Because the heater was shut off several microseconds earlier, the heated wall is now within a few tens of degrees C of ambient itself, and the vapor bubble meniscus meets a cool wall. Any gases driven out of solution by the vapor explosion cannot redissolve as fast as the vapor can recondense, and are hence left behind as tiny bubbles (a few microns or so across) in the fluid remaining in the "TIJ boiler". These bubbles eventually redissolve on a time scale of tens to hundreds of microseconds; they are plainly visible in the 8th photo in the series I showed you earlier.

Phase (5): droplet departure and refill

While the vapor bubble is recondensing inside the boiler, the droplet ejected by the explosion has left the nozzle and is on its way through the air.

As improbable as this sequence of events may appear, TIJ printheads really do work. Figure (8) below is a flash photo of a portion of a TIJ printhead, in which 13 nozzles are in operation. Their firing cycles have been staggered so you can see how each jet of ink breaks up into one main droplet, and several smaller ones, after the jets emerge from the nozzles (which are the row of black circles running across the top of the image). In this printhead, the nozzles are spaced 43 microns apart, and the droplets of ink are traveling at about 15 meters per second.

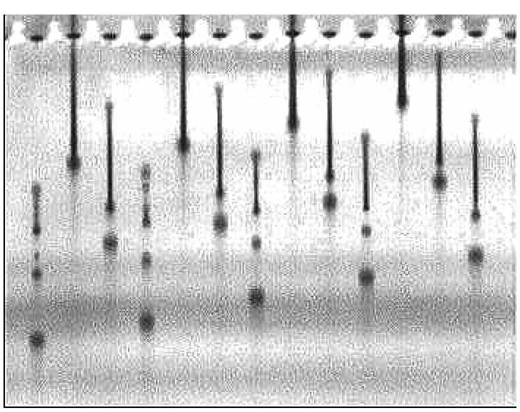

Figure (8): ink drops propelled by vapor explosions

As the droplets of ink go flying off to strike the paper nearby, the capillary force of the remaining ink in the boiler causes a fresh charge of make-up ink to be drawn into the empty boiler and nozzle from the refill port (which remains open during the whole process). The refill supply plumbing is always maintained at a slight negative backpressure, to prevent the working fluid (ink) from running right through the boiler and out the blowdown port (nozzle) which remains open to the atmosphere at all times. The capillary draw is great enough that no "feedwater pump" is necessary to overcome the negative static pressure in the supply. The refill/recharge process requires tens of microseconds to complete and as such is the slowest phase of the boiler's operation.

PROBLEMS TIJ HAS IN COMMON WITH YOU

Since the operation of a TIJ boiler is governed by the same laws of physics that apply to large-scale boilers, the micro TIJ world contains many of the same problems that the macro world of boiling heat transfer does. For example:

(Micro) boiler scale formation and sludge bake-on

The photo below shows a single TIJ heater about 20 microns x 35 microns in size. It has experienced 72 MILLION full thermal startup and shutdown cycles (a fraction of its rated lifetime!) but it has begun to fail because of **scale buildup** on its surface.

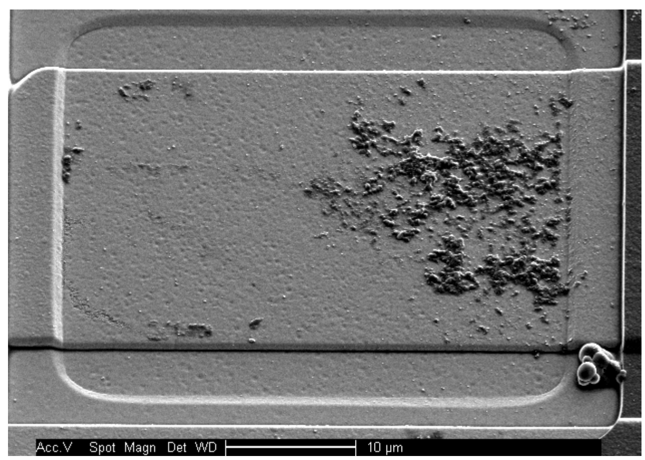

Figure (9): boiler scale buildup on a TIJ heater surface

Just like in boiler practice, scale buildup occurs in TIJ when dissolved solids in the ink (the "feed water") are boiled out of solution on the hot wall. Where do the solids come from? Each of our inks contains colorants (either soluble dyes or suspended pigment particles) and other chemicals with their own solubility limits, which may be exceeded at the wall as the ink boils to dryness there. If the resulting scale resists redissolution, it will build up irreversibly on the hot wall to the point where it interferes with heat transfer. Since the hot wall is only 6000 angstroms (0.6 micron) thick, a scale buildup with a thickness of a significant fraction of this (as is present in the example given here) will significantly impede heat flow out of the wall and must be avoided.

In the “big” world of boiler operation, 2.5 centimeters of scale buildup on a 2.5 centimeter thick boiler wall would mean heat transfer disaster, and so it does in the microworld of TIJ too. But in TIJ, we cannot drain the boiler, open a manhole, and send in a person with a 5 kilogram hammer to chisel off the scale, nor can we temporarily acidify the feedwater and eat the scale off. Remember too that this boiler is an integral, nonseparable part of a “power plant” (printhead array) consisting of no less than 3899 other boilers, ALL of which have to be operating at exactly the same full rated power level (droplet weight) for the entire 5+ year lifetime of the array, and NONE of which can be individually taken off-line for repair or replacement. We must “**condition the feedwater”** (that is, design the ink) so that it will neither form scale nor chemically consume the boiler wall during its multi-million cycle life.

Here is a high-speed flash photo of the vapor explosion occurring on a TIJ resistor fouled with scale, compared with an SEM image of the **same** resistor that shows exactly where the scale is thickest. This is a special type of heater consisting of two resistors in series, squeezed into the same boiler. Heat transfer is so impaired in the fouled zones that they cannot participate in the explosion, and the “stroke” of the resulting “steam piston” will be too short. This means the droplet of ink that this boiler will push out its blowdown port (nozzle) will be too small, and the print quality the customer sees will suffer.

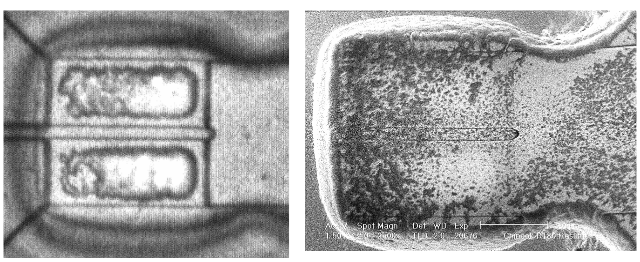

Figure (10): influence of scale buildup on heat transfer

Now**, this is a brand-new boiler with almost zero cycles on it!** Where did the scale come from? In this case the fouling is not boiler scale- it is instead a *residue left behind during the manufacturing process.*

Just as you would be displeased if your boiler vessel contractor had left 2.5cm of slag all over the 2.5cm thick heat transfer walls of the boiler you bought, so are we, if faced with **less than 0.6uM** of “slag” on the surfaces of our TIJ boilers. In the TIJ business, we are forced to manage surface cleanliness on *sub-micrometer* thickness scales.

Feedwater conditioning

In the “big” world of boiling heat transfer, the working fluid (water) is conditioned with a variety of additives intended to inhibit adhesion of scale to the hot wall, to hold finely-divided solids in suspension so they do not bake onto it, and to inhibit corrosive attack. In the micro-boiling world of TIJ, the ink chemist’s job is greatly complicated by the fact that whatever additives he or she might wish to use to accomplish the same, they may not compromise the quality of print that the TIJ printhead furnishes to the customer, who purchases the printhead not because it is a 3900-boiler intermittent vapor explosion engine operating in blowdown mode, but because the droplets of ink it shoots onto the paper allow full-color, full-page, photographic-quality images (like the ones I am handing out to you right now) to be printed in a minute or two at home or at work by a device costing about $150.

As an aside, it is possible to undercut the scale formation by spiking the working fluid with chemicals that mildly etch the wall surface on purpose. While this naturally prevents scale buildup, it also shortens the lifetime of the TIJ boiler by progressively thinning its walls away, just as it would in normal boiler management practice.

Thermal fatigue cycling

After the vapor explosion is initiated, the heater resistor is quickly turned off and the surface temperature of the hot wall begins to fall about fast as it initially rose- at several hundred million degrees C per second. The wall temperature returns to ambient several microseconds before the vapor bubble is done expanding; hence the remaining bulk fluid that was not ejected from the nozzle (which as noted is itself within a few tens of degrees C of ambient) collapses onto a similarly cool wall. This cycle of heating to ~300C and cooling to ~20C within a span of a few microseconds occurs **every time** a nozzle in the array is called on to dispense a droplet of ink, which in a TIJ printhead of modern manufacture occurs between twenty and thirty thousand times per second. Each of the thousands of individual heaters in a TIJ printhead is required to withstand billions of these thermal cycles without fatigue failure.

Typically, thermal cycle fatigue failures in TIJ occur at places where the peak transient temperatures happen to coincide with places where the protective topcoat covers discontinuous steps, ledges and corners in the film layers underneath it. This combination of transient thermal stress and stress concentrators can cause cracking of the film stack along the discontinuity, and destruction of the heater resistor when fluid seeps into the crack and flashes into steam, thereby blowing the thin films right off the silicon substrate as in this picture:

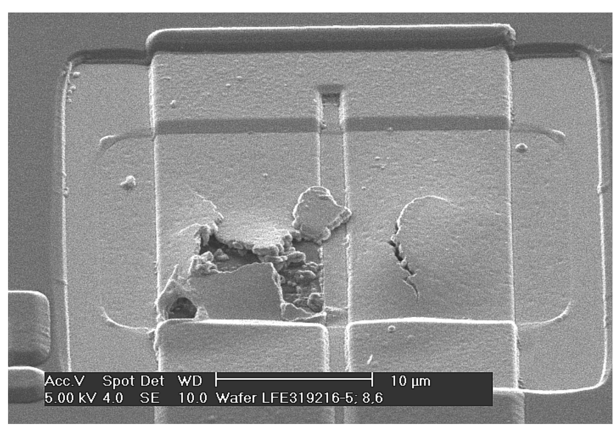

Figure (11): boiler failure due to thermal fatigue

This is another one of our “two-leg” heaters. Here you can see that the explosion that ruined one leg of the resistor propagated under the film stack and blew up the other resistor leg as well.

Firing a dry boiler

Applying heat to an industrial boiler in the absence of working fluid would cause a catastrophic failure of the heat exchange components due to extreme overtemperatures. The same is true in the world of TIJ. The photo below illustrates what happens to the heater resistor in a TIJ boiler when the drive power is left on too long in the absence of ink. The protective tantalum topcoat has been converted to oxide, which has blown free of the heater.

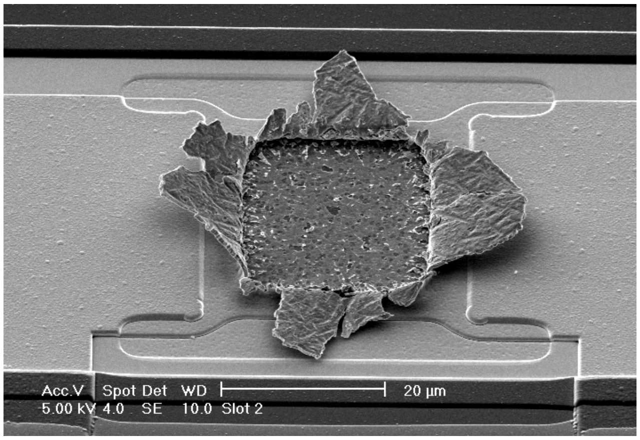

Figure (12): boiler failure due to dry-firing

Cavitation corrosion

With its blowdown port (nozzle) and its feedwater makeup supply (ink reservoir) open to the atmosphere, it is assured that a TIJ boiler will always feed on working fluid (ink) that is oxygen-saturated. The hot wall must therefore be protected with something that is as corrosion-resistant as possible, which is why we use tantalum as a protective topcoat. Tantalum is one of the most corrosion-resistant metals known because it is **self-passivating**- that is, it forms its own coating of passive oxide a few tens of Angstroms thick which is extremely robust and free of pores. However, the collision of the collapsing bubble with the wall is sometimes vigorous enough to disrupt the passivation, briefly exposing the tantalum metal to warm, oxygen-saturated ink. It promptly re-oxidizes and hence repairs the passive layer, but repeated cavitation in the same spot will eventually dig pits in the tantalum deep enough to admit ink into the electric insulating layers underneath, which destroys the printhead by short-circuiting the heater resistor.

This **cavitation corrosion** mechanism, which is familiar to the rest of you, is hence a problem we in the micro world of TIJ must deal with too. It shows a tendency to preferentially attack the grain boundaries in the tantalum topcoat, as shown in the scanning electron microscope photo below. Note the length bar; the individual cavitation corrosion pits here are about **one tenth of a micron** across.

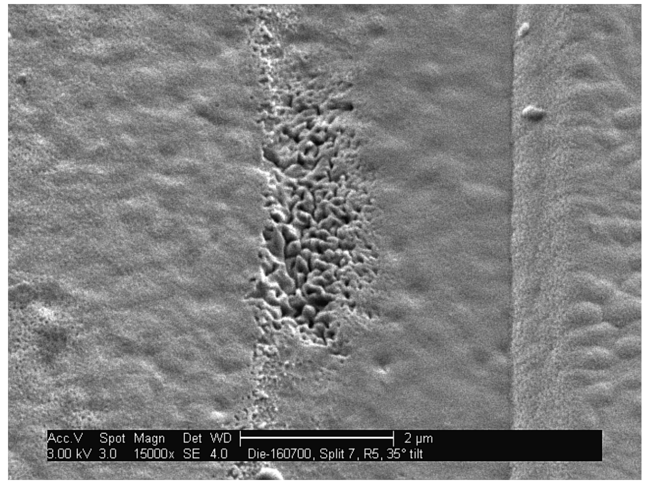

Figure (13): cavitation corrosion on the surface of a TIJ boiler

Note that the tantalum grains being attacked are both extremely small (~100 atoms across) and columnar (~1000 atoms thick, spanning the entire thickness of the Ta layer), so the resulting pits are tiny, deep, and very closely spaced. Despite the thinness of the tantalum layer, in the absence of cavitation corrosion the Ta topcoat will often last for billions of firing/thermal cycles without failure.

Cavitation corrosion in boiler practice occurs where the fluid circulation pattern inside the boiler creates local flow separation from the hot wall in regions of fast flow and high heat flux. This is also true in TIJ, where the cavitation corrosion damage occurs when the flow pattern of incoming feedwater (ink) urges the steam bubble to collapse into similarly stagnant points in the fluid flow field. Since the flow field is fairly consistent from one explosion-and-refill cycle to the next, this tends to concentrate most of the bubble collapse damage into certain well-defined zones of the heater surface, as in the above example.

AT LEAST ONE PROBLEM YOU GUYS DO NOT HAVE

In our exploration of thermal ink jet heat transfer and vapor explosion physics over the 25 years we have been in this business, we have observed “accidental” boiling modes which can take place on the surfaces of our heaters, severely impairing their operation. I’ll show you what I consider the most interesting one and explain what we know about its physics.

As you have seen, our ability to produce microscopic vapor explosions of the correct size on demand is the key to the whole technology. Since there is essentially no time ***during*** the explosion for heat transfer to occur, all the enthalpy required to support the phase change has to be stored in the boundary layer as superheat ***before*** the explosion occurs. Anything that triggers early bubble nucleation will decouple the fluid from the hot wall too soon, cutting off the enthalpy storage prematurely. This gives rise to a drive bubble that is too small, which in turn will eject an ink droplet during “blowdown” which is abnormally small and slow-moving. The too-small droplet lands in the wrong place on the paper, and bad print quality results. The customer sees it and is unhappy.

Imagine that we turn the heat on, and there just happens to be a point on the surface of the hot wall at which early bubble nucleation happens. Right at that point, the superheated fluid flashes into steam and pushes a tiny hemispherical bubble into the surrounding liquid. Because there is not much enthalpy stored in the boundary layer to support its growth, this little bubble expands only a short distance away from the hot wall and then encounters cool liquid. Its growth stops.

But there still exists stored superheat in the boundary layer covering the rest of the heater area, right in the vicinity of this isolated nucleation site. Heat transfer there is still occurring. And right around the circle where the bubble meniscus contacts the hot wall, the superheated fluid “sees” the vapor inside the bubble and nucleates into vapor too. The vapor thus produced blows back into the existing bubble, preventing its collapse, while a vaporization front races away from the original early nucleation site, following the surface and tunneling ***under*** the cool bulk fluid. As it does, it consumes the superheated boundary layer, wedges the bulk liquid a few microns out of contact with the still-hot wall, and props up the original bubble. We get a radially-propagating, circular “wedge” of vapor that performs little or no useful work against the load, but “locks out” all the resistor area it covers from participating in the vapor explosion we wanted.

TIJ misfire photos

In the first photo in Figure (14) below, the flash has captured an early site (actually a tiny air bubble stuck to the surface) that has nucleated at about ~240C (instead of ~280C, where the whole surface is supposed to explode into vapor). It grows into a little hemisphere, pokes up into the cool fluid above, and stops growing up.

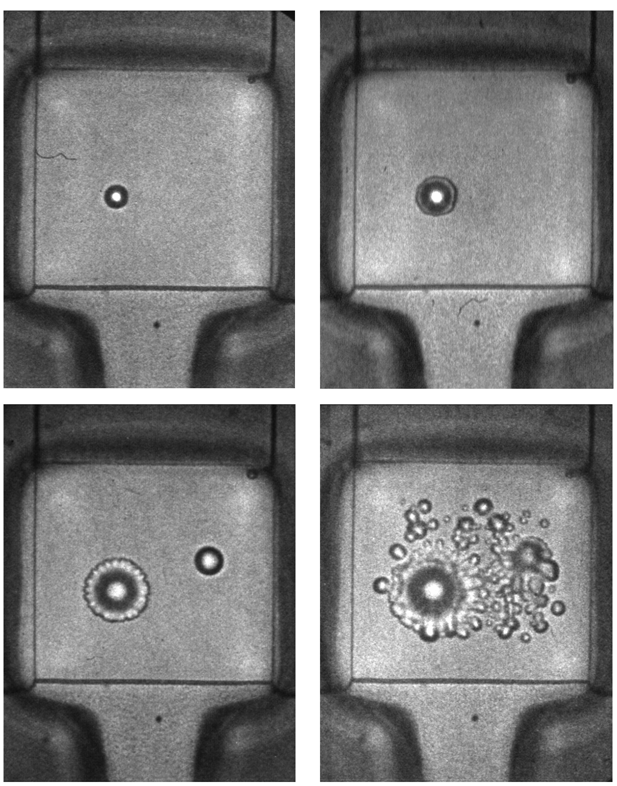

Figure (14): vapor explosion misfire sequence

In the second and third photos, taken fractions of a microsecond later, we see the hemisphere “freeze” while the steam wedge shoots out across the hot surface, eating up the stored superheat in the boundary layer. It evolves into the shape of a little fried egg, with the original nucleus as the “yolk” and the spreading wedge the “white” surrounding it. Note the *fingering instability* right at the tip of the wedge. In the last photo, the rest of the surface has hit 280C and many individual nucleation sites have suddenly become activated. Their expansion raises the local pressure in the fluid for a brief instant, which halts the spread of the wedge and hammers it flat.

Nonetheless, the damage is done. The heater now produces a vapor bubble smaller than desired, just as if the heater’s physical area were reduced by an amount equal to the area covered by the fried egg at the moment it is crushed. In my perusal of the boiling literature as it pertains to macroscopic boiling heat transfer, I have found nothing like this mentioned. I’m sure you have problems in the “big boiling” world that we do not have in TIJ, but you should be thankful that this TIJ misfire mode is not one of them!

IN SUMMARY

I had a wonderful time translating the world of TIJ, where I have worked for 26 years, into “big boiler talk” for you here. There is no way I could go into all the interesting ins and outs of this unique business in the time and space I have here. But I hope you have found this view into the “little boiler“ world worthwhile, and that you will remember some of this next time you watch your HP photo-imaging printer produce pictures of your families and friends.