Talk presented at
Dartmouth, July, 1965 -
Two week course on
2 φ Ht & Mass Trsfr

Covered only part up thru
outline in order collected here.

As a preface to the next topic, I would like to read a few sentences from a modern book on heat transfer: [illegible] discuss the stability of the heat transfer process,

~~Turning now to the subject of stability~~, It seems reasonable to give the stability of the heat transfer process the generic term "thermal stability". With regard to two phase heat and mass transfer, thermal instability manifests itself in several ways. Pherhaps the most widely known form of thermal instability is the phenomenon called "burnout" which can result from operating two phase heat transfer equipment near and beyond the maximum in the pool boiling curve. The practical importance of this type of thermal instability has been recognized since 1934 when Nukiyama first observed the maximum in the pool

GRAPH

boiling curve. ✓ Since that time, the theory of thermal stability has centered about the graphical demonstration that a discontinuous ΔT will result from a monotonically increasing heat flux such as would occur in a so-called constant heat flux device. This graphical theory also demonstrates that no discontinuity will result in equipment in which the temperature of the heat source is controlled--for example in a boiler in which the heat source were a condensing fluid. This latter conclusion results from the demonstration that, as a vertical line is passed from the left to the right across the pool boiling curve, a single solution on the curve is always obtained.

The difficulty with this graphical theory of thermal stability is that it does not rigorously apply to real systems. It therefore leads to a number of erroneous conclusions regarding the design and performance of two phase heat and mass transfer equipment. Among these erroneous conclusions are:

1. In ~~so-called "fixed heat input"~~ systems ~~such as those~~ utilizing nuclear or electrical heating, burnout--in other words a temperature discontinuity--occurs when the equipment is made to pass through the maximum in the pool boiling curve. Since this is a necessary consequence of passing through the maximum in this type of equipment, it is not possible to design this type of equipment so that no discontinuity will result from passing through the maximum.
2. In equipment in which the temperature of the heat source is controlled, the equipment is necessarily stable at all points of the pool boiling curve and there is no phenomenon similar to burnout. As a result, the designer need take no special pains to avoid any temperature discontinuity since such a discontinuity cannot occur in this type of equipment.
3. Although thermal instability can lead to temperature discontinuities, it does not lead to oscillatory behavior. As a result, it is generally assumed that oscillatory types of instability in two phase systems are the result of instabilities in the mass transfer process. Indeed, it is quite common to assume that the mass transfer process is the cause of all forms of instability in two phase systems and even that the phenomenon of burnout is caused by the mass transfer process.

The May '64 issue of Nucleonics presented the quantitative theory of thermal stability which is intended to replace the old graphical theory. In that article, I derived a general criterion for thermal stability based on a somewhat idealized system. While this derived criterion is not completely rigorous in the sense that it is based on certain simplifying assumptions, ~~when applied to~~ it does apply with engineering accuracy to most real systems and it is therefore a useful tool for both design and analysis. This general criterion for thermal stability is simply

$$\frac{dQ_{in}}{dT_w} <_s \frac{dQ_{out}}{dT_w} \qquad \boxed{\text{BOARD}}$$

Rather than go through the derivation of this general criterion, let us simply start with it and in this way try to determine what is wrong with the graphical theory.

The general criterion states simply that a given piece of equipment will be thermally stable provided that these two simple derivatives bear the indicated relationship to each other. The criterion results from idealizing a generalized system and uncoupling it at the boiling interface. The uncoupled pieces are then analyzed to determine whether they would fit together in a stable manner. The derivative on the left hand side refers to the heat source side of the boiling interface. It answers the question "How is the heat flow <u>into</u> the boiling interface affected by the temperature of the interface?" The right hand side refers to the heat sink side of the interface and answers the question "How is the heat flow <u>out</u> of the boiling interface affected by the temperature of the interface?" Thus, to appraise the thermal

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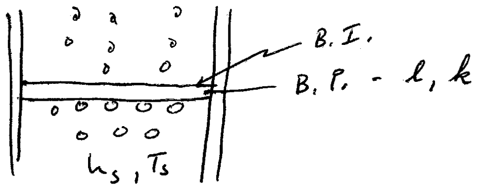
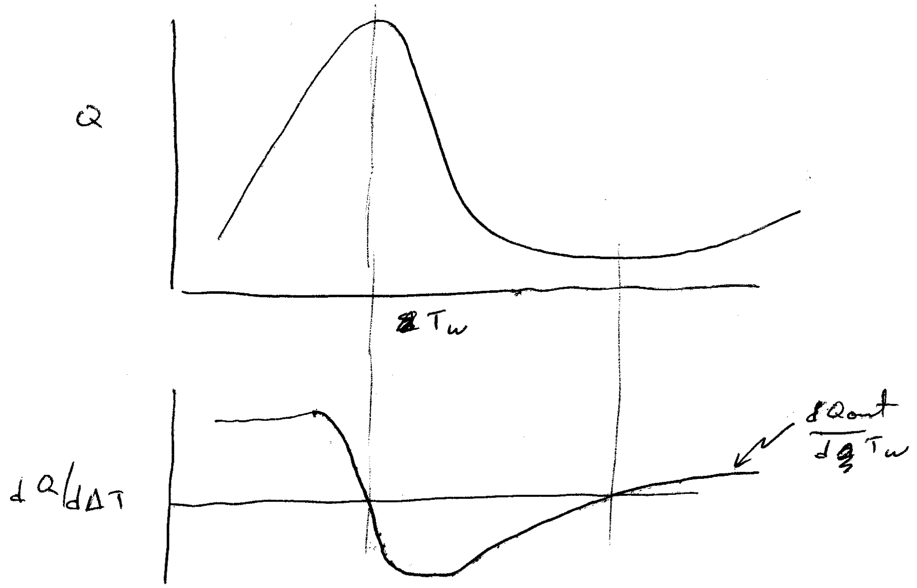
stability of a given system, we have simply to determine these two derivatives and then compare their magnitude. To perform this analysis graphically, we ~~have simply to~~ determine the two functions Qin and Qout in order to appraise the stability of the equipment over a wide spectrum of Tw. Rather than continue the discussion in the abstract, let us consider a specific boiler--namely, a so-called constant temperature type boiler in which the heat source is a condensing fluid.



For this boiler, we want to determine the two functions Qin and Qout. Now Qout is simply the pool boiling curve which applies to our particular ~~and~~ system and which we will suppose is given by



From this graph, it can be seen that dQout/dTw is negative only in the region generally called the transition region. To determine dQin/dTw, we have only to note that, for a constant condensing temperature, Qin is given by

plot $\frac{dQ}{dT_w}$

$$Q_{in} = UA(T_s - T_w) = \left(\frac{A}{1/h_s + l/k}\right)(T_s - T_w)$$

so that $$\frac{dQ_{in}}{dT_w} = -\frac{A}{1/h_s + l/k} = \text{constant} < 0$$

Adding this result to our stability graph, we see that the equipment may or may not be everywhere stable, depending on the absolute value of dQin/dTw. Analytically, we can rewrite the general criterion in the particular form

$$-\frac{A}{1/h_s + l/k} <s \frac{dQ_{out}}{dT_w}$$

As a result of our analysis, we have concluded that the general criterion for thermal stability contradicts the graphical theory in that it concludes that even so-called constant temperature systems can be thermally unstable. Returning to the graph of Q vs ΔT and recalling that dQin/dTw is finite, it can be seen that the graphical theory was incorrect primarily because it assumed that dQin/dTw $= -\infty$ -- in other words it was based on the erroneous assumption that the performance of this type of boiler could be described by a vertical line, whereas no real boiler can exhibit this type of behavior. While it is true that the derivative in this type of boiler is always less than zero, it is equally true that it is never infinite. For this reason the graphical theory was incorrect in concluding that this type of boiler is stable at all points of the pool boiling curve. If we place several lines of finite slope on our graph of Q vs

ΔT, we can quickly see that, as we move the system to the right, there will be a discontinuity in the ΔT which of course is very similar to burnout.

An experiment performed by Berenson several years ago at MIT provided the experimental evidence that the new theory is correct. In his experiment on transition boiling, Berenson constructed just such a boiler as we have discussed in which the ~~temperature~~ heat source was a condensing fluid. In a summary of this thesis published in the International Journal of Heat and Mass Transfer, Berenson reported the results of 20 experiments performed with the intention of covering the complete spectrum of the pool boiling curve. If you will plot up some of this data on linear graph paper, you will find that, in 17 of the 20 experiments, virtually no data was obtained in the transition region, in agreement with the new theory of thermal stability.

Perhaps the most important aspect of this new understanding of the stability of constant temperature equipment is the realization that the designer cannot take the stability of this type of equipment as a foregone conclusion. Moreover, from the particular stability criterion we obtained for the boiler, it can be seen that the designer can exert a very strong influence on ~~the stability~~ the thermal stability of the boiler in any of the following simple ways:

Refer to board

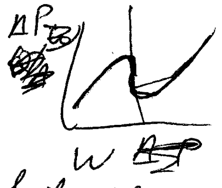
1. Minimize the thickness of the boiler plate
2. Maximize the thermal conductivity of the boiler plate
3. Maximize the heat transfer coefficient of the fluid condensing on the heat source side of the boiler plate.

1. Burnout in constant heat flux systems
   ⓐ Old way hopeless - nothing for designer to do
   ⓑ New way much can be done - quantitative
   ⓒ For instance - $\frac{dQ_{in}}{dT_w} = -\epsilon Q$
   ⓓ How about nuclear reactors?

2. Oscillatory behavior
   ⓐ Not result from old way
   ⓑ Show new way
   ⓒ So what - when system oscillates, must consider both heat + mass transfer - otherwise risk getting wrong answer

3. Dry wall phenomenon
   ⓐ Case in point where assume mass transfer problem when actually ht trsfr
   ⓑ Postulate + try to prove all sorts of things - flow regime, etc. etc
   ⓒ Have never quite gotten to the answer - as a result, keep looking deeper + deeper + will never find answer

4. Hydraulic stability - what is it? who knows. Always start with Ledinegg

   Graph 

5. Words in general about criteria - two sides - equipment + phenomenon