and King (1972) as modified by Rodrigo and Seader (1975) and specified in Table 2.

With no forbidden splits, step 1 of the strategy generates the flow sheet in Figure 2*a*, where heuristic 2 has been applied throughout; thus, the large value of $\alpha_{AB} = 3.5$ dictates that split ($A/BCDEF$) be made first in the sequence. Then, $\alpha_{EF} = 3.0$, the next largest adjacent relative volatility, dictates that split ($BCDE/F$) be made next. Similarly, the last necessary decision is to perform split (BC/DE) followed by splits (B/C) and (D/E). The resulting initial flow sheet has a cost of $\$1.234 \times 10^6$/yr.

We note that α_{AB}, α_{CD}, and α_{EF} are reasonably close in magnitude, which suggests that we consider interchanging the ($\cdot\cdot C/D\cdot\cdot$) and ($\cdots E/F$) subproblems giving a slightly decreased cost of $\$1.213 \times 10^6$/yr, and consider interchanging the ($A/B\cdots$) and ($\cdots E/F$) subproblems, which, however, leads to a slightly increased cost of $\$1.219 \times 10^6$/yr. The improved sequence is shown in Figure 2*b*.

A further improvement can be made to the sequence in Figure 2*b* by interchanging splits ($A/B\cdots$) and ($\cdot C/D\cdot\cdot$), which have reasonably close adjacent relative volatilities. This leads to the sequence shown in Figure 2*c* which has a decreased cost of $\$1.153 \times 10^6$/yr. No further interchanges are suggested by the heuristics.

Unfortunately, the final sequence shown in Figure 2*c* is not the optimal solution, which has a cost of $\$1.084 \times 10^6$/yr and is achieved by a further interchange between subproblems ($\cdot E/F$) and (D/E). The failure to produce the optimal solution is due to the small, but important, effect of *n*-pentane on the relative volatility for 1-butene/*n*-butane. In Table 2, α_{DE} is taken as 1.21. However, as discussed by Gomez and Seader (1976), $\alpha_{DE} = 1.197$ when only D and E are present, but $\alpha_{DE} = 1.226$ in the presence of *n*-pentane. The result is that the cost of split (D/EF) is 15% less than the cost of split (D/E), and the total sequence cost is reduced by making split (D/EF) before split ($\cdot E/F$). Nevertheless, we discovered a near optimal flow sheet by examining only four of forty-two flow sheets and eleven of thirty-five distinctly different separators.

Not included in the strategy discussed above is the consideration of energy integration. Especially when the lowest cost sequences are close in cost, energy integration may be the deciding factor among various alternative sequences. A method for synthesizing optimal distillation sequences, where condensers and reboilers are integrated, has been presented by Rathore, Van Wormer, and Powers (1974).

NOTATION

K_i = vapor-liquid phase equilibrium ratio for component i
P = pressure
T = temperature
α_{ij} = relative volatility of component i relative to component j

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Nucleate Boiling in Thin Liquid Films

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Nucleate boiling in thin liquid films requires low temperature differences for the same rate of heat transfer than is usual for nucleate boiling; this is supported by the research of Fletcher et al. (1974), Rychkov and Pospelov (1959), Parizhskiy et al. (1972), and Mesler (1976). Detergents in the film reduce the temperature differences even more (Nishikawa et al., 1967). These facts are rather surprising since they were not predicted. One

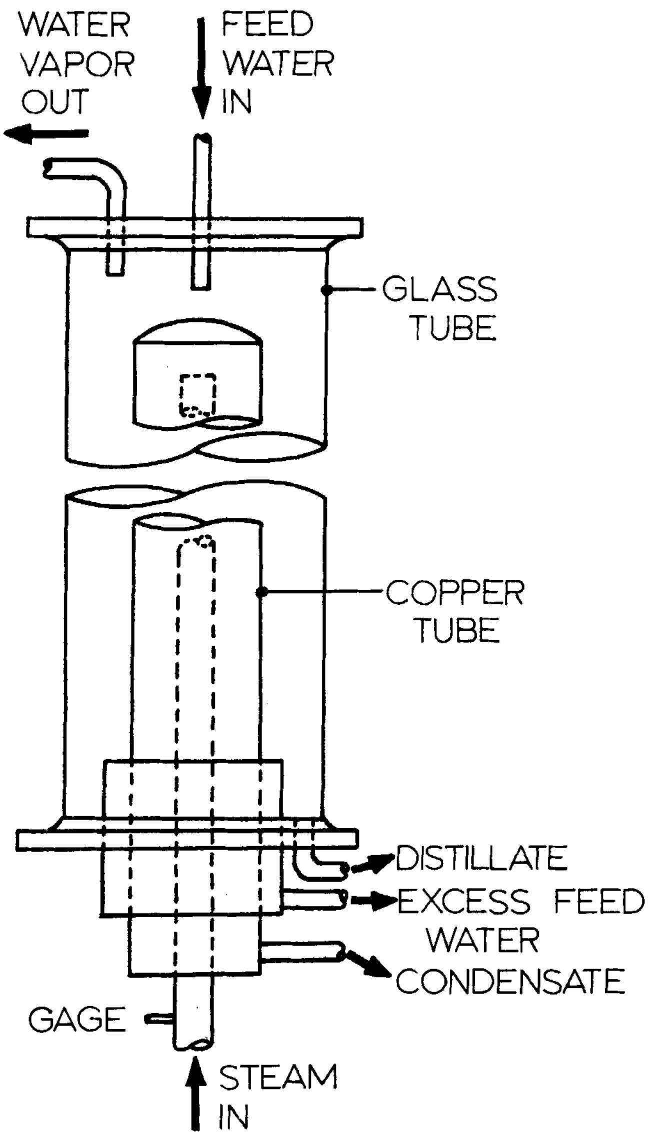

Fig. 1. A sketch of the apparatus.

obvious possibility is that here ebullition is in some way enhanced.

Reports of the lower temperature differences when boiling from thin liquid films have slowly been accumulating from a variety of sources. The effect may be limited to the low heat fluxes but is still important in many applications, such as in desalination and refrigeration, where smaller temperature differences provide powerful economic incentives.

Nucleate boiling is a very effective process for heat transfer which owes its effectiveness to the collective action of many bubbles on the heater. Bubbles originate from nucleation sites on the wall. These sites are usually surface imperfections, such as pits or scratches, which are able to retain vapor when a preceding bubble detaches. The retained vapor is a seed or nucleus from which the next bubble can grow. Bubbles are also known to originate spontaneously in the liquid owing to chance accumulation of greater energy by a group of molecules, but this is not an important source of bubbles in nucleate boiling.

Ebullition in a thin film is different because the vapor vents from the liquid very close to the heater. Liquid away from the heater during nucleate boiling is only slightly superheated, but near the heater there is a steep temperature gradient with some temperatures well above saturation. Small bubbles shrink rather than grow at just a short distance from the heater because they lack the higher superheats necessary for smaller bubbles to grow. With the venting process so close to the heater, however, smaller bubbles created during vapor venting may gain access to conditions that would cause them to grow.

Nowhere in the boiling literature has there been found any suggestion that the venting of a vapor bubble might generate new bubble nuclei. Still, this hypothesis cannot be easily dismissed when one reviews the literature on bubbles breaking through a vapor-liquid interface.

The venting of a bubble at an interface is a complicated phenomenon (Newitt et al., 1954). Prior to venting, the bubble is partially submerged. Venting starts with rupture of the top surface of the bubble. The submerged bubble wall converges on the center and causes a jet to be ejected up from the center. The jet breaks up, and only the bottom portion snaps back. Drops are created both from the rupture of the top surface of the bubble and from the breakup of the jet. When a bubble in a thin liquid film vents, it does not have the underlying liquid to form the jet; otherwise, its venting is similar.

Liquid jets and drops are known to entrain gas when they flow through a gas and into a liquid. A common example is a stream from a tap falling into a vessel. The entry of a laminar jet carries a film of gas surrounding it as it plunges beneath the surface if it has a certain minimum velocity (Lin and Donnelly, 1966). The film breaks up into bubbles a short distance below the surface. A turbulent jet has a rough surface before entry and entrains a greater quantity of gas depending on the roughness (Henderson et al., 1970). Blanchard and Woodcock (1957) report that they observed a jet formed by drop impact entrain tiny bubbles when the jet snapped back.

MacIntyre (1972) reports that under some conditions the rupture of a large bubble will generate numerous small bubbles with diameters less than 0.1 mm at the periphery of the top film. These tiny bubbles are frequently entrained by the downward jet and carried a centimeter or two below the surface.

A test of the hypothesis that bubble venting during nucleate boiling in a liquid film generates additional nuclei was certainly indicated on the basis of this information. A simple experiment was devised. A film of water was allowed to flow down the outside of a copper tube internally heated with steam. Close-up, high-speed motion pictures were taken of the boiling. Bubbles travel down the tube with the water flow and away from their own nucleation sites. Thus, nucleation following their venting cannot be attributed to the initial site.

A sketch of the apparatus is shown in Figure 1. The tube was 0.6 m long and 29 mm O.D. It was enclosed in a glass tube of 50 mm I.D. so a clear view of the entire tube was possible. A stream of water was directed onto a spherical cap at the top of the tube to produce a uniform flow around the tube. Tap water at 20°C containing a small amount of detergent was used. The flow rate was about 200 ml/min, and the steam pressure was 140 kPa abs. A Fastax camera took pictures at 5 000 frames/s halfway down the tube.

Examination of these pictures provided ample support for the hypothesis. New bubbles do grow from the disturbances in the liquid film where venting has occurred.

Figure 2 is a sequence of photographs selected to show a bubble venting and the subsequent appearance of new bubbles. The new bubbles grow in the liquid film where

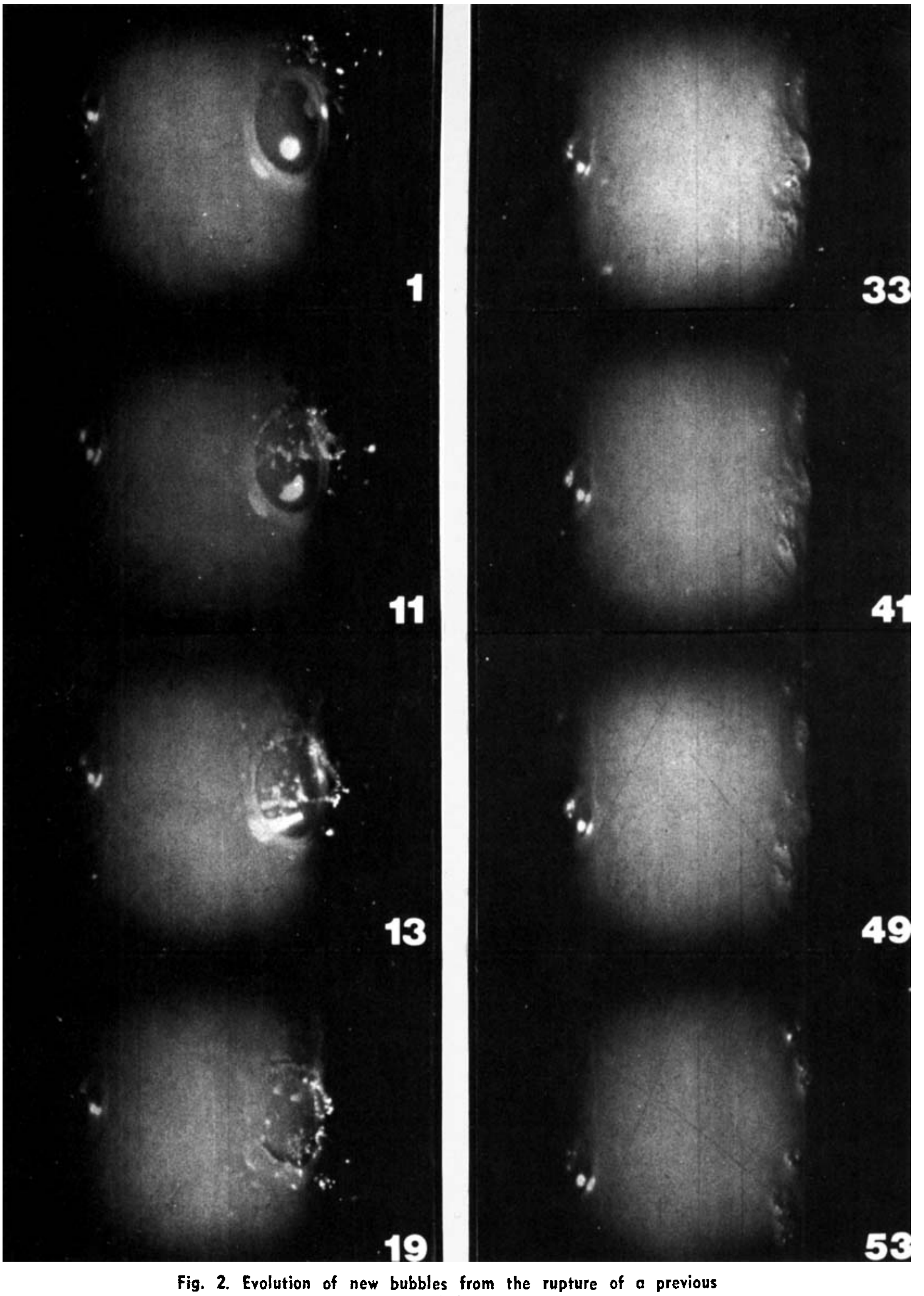

Fig. 2. Evolution of new bubbles from the rupture of a previous bubble.

the burst bubble previously existed. Figure 3 is a sketch of just the bursting bubble tracing developments until the new bubbles are seen.

Film flow down the tube carries the bubble and its remains with it. The bursting bubble is first seen in the upper half of the frame, and the new bubbles are last seen in the lower half. The bubble on the left and new bubbles on the upper right late in the sequence are not pertinent and are thus not shown in the sketch.

When the bubble ruptures, its top film collects along an edge. The edge seen in frames 11 and 13 travels across, the bubble consuming the film and producing drops. Rupture of the film began in frame 8, which is not shown here. Drops from the venting of a neighboring bubble (seen in frame 1) initiated rupture.

Before venting, liquid is welled up in a ring at the base of the bubble. During rupture, the ring collects some of the film that retracts into it and begins to level out. Remains of the ring are still recognizable when new bubbles are seen to grow among them.

The photographs demonstrate that there is nucleation associated with bubble venting when boiling in thin liquid films. This has previously gone unrecognized. This nucleation is in addition to that from the usual sites on the surface. This additional nucleation can be expected to enhance the heat transfer. How much the lower temperature

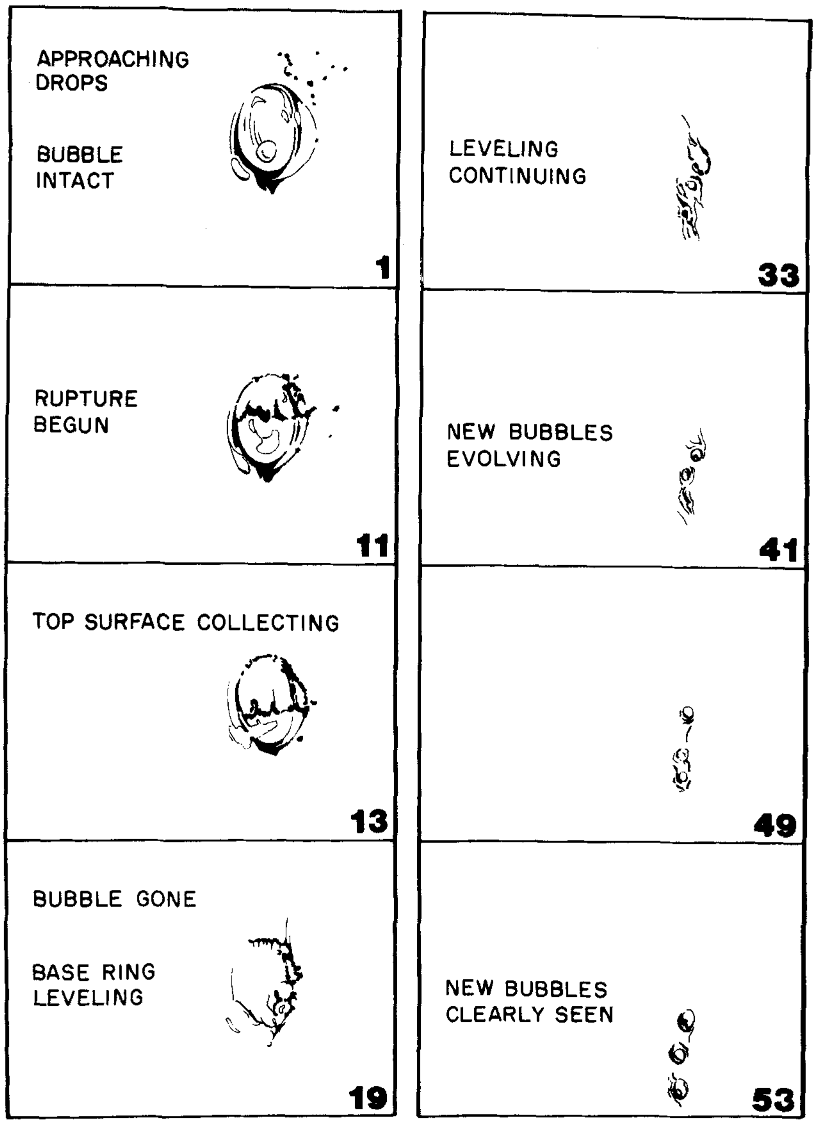

Fig. 3. A sketch of identifying important stages in the evolution of new bubbles.

differences during nucleate boiling in thin liquid films depends on nucleation from this newly recognized source remains to be determined.

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EDITORIAL NOTE

After reviewing this manuscript, V. A. Sernas examined some high-speed movies taken during their investigation (Fletcher et al., 1974) and observed support for the hypothesis.

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