observable limb shock, consistent with the fact that deflections are not clearly associated with this region (*6*).

AARON BARNES
PATRICK CASSEN
J. D. MIHALOV
Space Science Division,
National Aeronautics and Space
Administration, Ames Research Center,
Moffett Field, California 94035
AHARON EVIATAR
Department of Environmental
Sciences, Tel-Aviv University,
Ramat-Aviv, Israel

References and Notes

1. E. F. Lyon, H. S. Bridge, J. H. Binsack, *J. Geophys. Res.* **72**, 6113 (1967); D. S. Colburn, R. G. Currie, J. D. Mihalov, C. P. Sonett, *Science* **158**, 1040 (1967); N. F. Ness, K. W. Behannon, C. S. Scearce, S. C. Cantanaro, *J. Geophys. Res.* **72**, 5769 (1967); N. F. Ness, *NASA Prepr. X-692-70-141* (Goddard Space Flight Center, Greenbelt, Md., 1970); D. S. Colburn, J. D. Mihalov, C. P. Sonett, *J. Geophys. Res.*, in press; K. W. Behannon, *ibid.* **73**, 7257 (1968); C. P. Sonett, D. S. Colburn, R. G. Currie, *ibid.* **72**, 5503 (1967).
2. D. S. Colburn, J. D. Mihalov, C. P. Sonett, *ibid.*, in press; N. F. Ness, K. W. Behannon, H. E. Taylor, Y. C. Whang, *ibid.* **73**, 3421 (1968).
3. G. L. Siscoe, E. F. Lyon, J. H. Binsack, H. S. Bridge, *ibid.* **74**, 59 (1969); Y. C. Whang, *NASA Prepr. X-692-70-61* (Goddard Space Flight Center, Greenbelt, Md., 1970); J. R. Spreiter, M. C. Marsh, A. L. Summers, *Cosmic Electrodyn.* **1**, 5 (1970).
4. K. Schwartz, C. P. Sonett, D. S. Colburn, *Moon* **1**, 7 (1969).
5. J. V. Hollweg, *J. Geophys. Res.* **75**, 1209 (1970).
6. J. D. Mihalov, C. P. Sonett, J. H. Binsack, M. D. Moutsoulas, *Science* **171**, 893 (1971).
7. P. Dyal, C. W. Parkin, C. P. Sonett, *ibid.* **169**, 762 (1970); C. W. Parkin, P. Dyal, C. P. Sonett, D. S. Colburn, *Trans. Amer. Geophys. Union* **51**, 773 (1970).
8. A. C. Clarke, *2001: A Space Odyssey* (World, Cleveland, Ohio, 1968).
9. C. L. Longmire, *Elementary Plasma Physics* (Interscience, New York, 1963), p. 94.
10. R. Z. Sagdeev, in *Reviews of Plasma Physics*, M. A. Leontovich, Ed. (Consultants Bureau, New York, 1966), vol. 4, p. 23; D. A. Tidman, *J. Geophys. Res.* **72**, 1799 (1967); *Phys. Fluids* **10**, 547 (1967).
11. R. W. Fredricks and P. J. Coleman, Jr., *Publ. 717* (Institute of Geophysics and Planetary Physics, Univ. of California, Los Angeles, 1969); M. D. Montgomery, J. R. Asbridge, S. J. Bame, *J. Geophys. Res.* **75**, 1217 (1970).
12. P. Dyal, personal communication.
13. G. B. Whitham, *Commun. Pure Appl. Math.* **5**, 301 (1952).
14. We thank C. P. Sonett, P. Dyal, and S. S. Davis for valuable discussions.

25 January 1971

■

Modified Superheating of Purified Water

Abstract. *Purified water, intensively redistilled and allowed to overflow so as to shed residual adsorbate from the container, acquires a limiting thermal sensitivity to additions of long-chain fatty acids and alcohols. Thus two to three molecules of* cis-*13-docosenoic acid supplied for each 1000 molecules of exposed surface of water held quietly at the normal boiling point increases the superheat,* Δt_s, *by 10 percent.*

A clean water surface can play host to very dilute monolayers (*1*) of insoluble substances (*2*) which may then assume a planar gaseous mode (*3*). The lateral pressure between the contaminated surface and a truly clean surface has been estimated by means of the two-dimensional analog of the ideal gas equation:

$$\pi A = kT \qquad (1)$$

where π is the surface pressure, A is the surface area per molecule, k is Boltzmann's constant, and T is the absolute temperature. According to Eq. 1, there would exist a pressure of ~ 1 dyne/cm when one molecule of adsorbate occupies 412 Å^2 of water area at 25°C and a pressure of 0.1 dyne/cm where ~ 4000 Å^2 of water area are available (*4*). The small changes in surface tension associated with a dilute monolayer are known to dampen surface ripples; Garrett and Bullman (*5*) have traced the relation between damping and surface pressure for many insoluble adsorbates down to a fraction of a dyne per centimeter. Jarvis *et al.* (*6*, pp. 41–58 and figure 1, p. 43) have measured the increase in subsurface temperature (relative to that of water with a clean interface) when a dilute monolayer has been applied to shallow pools evaporating into a stream of nitrogen under ambient conditions. Working with shallow layers in the open air at room temperature has natural advantages, hence the century of distinguished researches in this area which continue today (*7*, *8*).

The observations we report here concern thermal responses to very small concentrations of surface-active compounds adsorbed from the gas phase onto deep pools of hot water, for example, at the boiling point, with the complete exclusion of foreign gas. This model, which invites attention as compellingly as the shallow pool model, embraces the vessels of domestic experience, the flasks and kettles of the laboratory and chemical plant, and, less directly, the pond and ocean. In a deep vessel of symmetrical proportions the laterally repetitive phenomena of the shallow layer are overridden by

Table 1. Relative thermal responses to additives.

Number of molecules added* (× 10^{-10})	Area of water surface per molecule of additive† (Å^2)	Increase in superheat‡ (%)
	Myristic acid	
1100	12	7
2200	6	16
	Palmitic acid	
98	140	8
490	28	18
	Stearic acid	
18	760	10
88	155	22
	Oleic acid	
18	760	11
89	155	19
	Elaidic acid	
18	760	11
89	155	21
	12-Hydroxystearic acid	
170	80	15
250	54	24
	Methyl ester of 12-hydroxystearic acid	
3.2	4300	12
160	85	40
	Methyl ester of 9, 10-dihydroxystearic acid	
3.0	4500	12
	Behenic acid	
2.9	4600	9
15	930	24
	Erucic acid	
3.0	4600	11
15	920	28
30	460	35
44	310	42
74	180	46
150	92	41
220	62	42
300	46	42
740	18	44
	Brassidic acid	
2.9	4600	11
	Lignoceric acid	
2.7	5000	12
27	500	47
	Nervonic acid	
2.7	5000	13
14	1000	35
	Behenyl alcohol	
31	440	7
150	91	12
	Erucyl alcohol	
150	91	17
	Lignoceryl alcohol	
28	490	9
140	98	21
560	24	35
	Nervonyl alcohol	
28	409	11
140	98	25
	Di-2-ethylhexyl phthalate	
26	530	17
720	19	43
	Antarox 430§	
130	105	22
630	22	41

* Error, ± 5 percent. † On the assumption that all of the adsorbate is uniformly distributed over the 82-cm^2 water surface. ‡ Percent increase in superheat above 0.39° ± 0.02°C. The values in this column are accurate to approximately 10 percent. § Nonylphenoxytri(ethyleneoxy)ethanol.

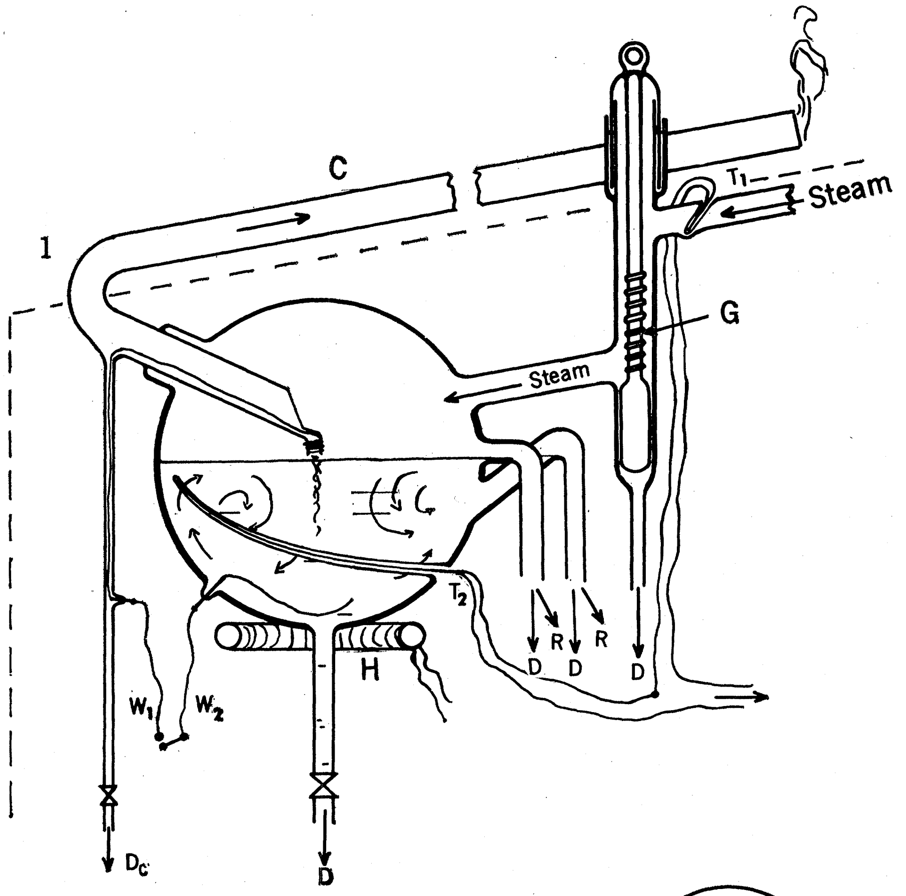
a single liquid cell in convective rotation, and it is fortuitous (sheer good luck) that the resultant temperature signals are reproducible, informative, and amenable to interpretation on the basis of what is known of the shallow layer.

In our laboratory we are presently concerned with the preparation and study of water at the atmospheric boiling point, demonstrably freed from surface contamination. Under conditions of quiet evaporation into its saturated vapor the water beneath the clean surface will reach a steady degree of superheat, Δt_s, which is dependent on the geometry of the container and the input of energy. Adsorbable reagents added to the system, even in quantity far less than that needed to form a compact monolayer on the hot water, have been found to produce an increase in the bulk temperature of the water. The change in Δt_s is readily measurable, is repeatable, and should be quantitative once the destination of the additive has been established and the fraction reaching that destination determined. The actual sensitivity of water to selected contaminants is probably greater than could be inferred from the quantities we mention here.

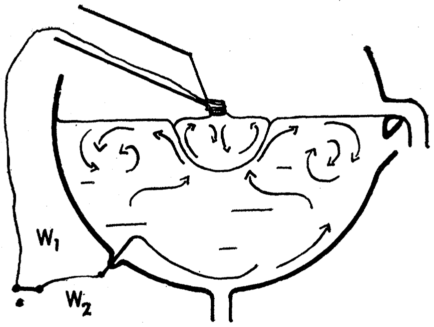
For example, the long-chain fatty acid erucic acid [*cis*-13-docosenoic acid, $CH_3(CH_2)_7CH = CH(CH_2)_{11}COOH$] (or equally, its *trans*-isomer, brassidic acid), when added in the proportion of one molecule for each 4600-Å^2 area of water raises the bulk water temperature from $\sim 100^\circ + 0.390^\circ C$ to $\sim 100^\circ + 0.430^\circ C$, where the two decimal values above $\sim 100^\circ C$ record the values of Δt_s in the two cases; Δt_s is the superheat required to drive the evaporative process. Increasing the quantity of additive to ten times the above value, although insufficient to form a compact monolayer, increases Δt_s by 35 percent. The phenomenon has been reported orally (*9*) and the methodology has been outlined (*10*, pp. 24–42). We now summarize the technique supported with better data.

The ½-liter Pyrex observation flask diagramed in Figs. 1 and 2 is held in a cabinet at 98° to 100°C and is further insulated by a steam jacket, not shown. "Pure" steam from a steady-rate boiler (*11*) enters the flask at one side and leaves by an air-cooled reflux condenser which rejects a small bleed of vapor. Condensate returns to the center of the flask, and the convectively mixed contents are allowed to overflow or underflow (*12*) from the halfway level through a switching weir, to be rejected or cyclically redistilled, at will. Quiet evaporation of the contents is maintained by a ring heater which is divided into separately energized sections, the combined input being monitored by a sensitive wattmeter. Platinum wires can be used to connect the distillate and distilland; on open circuit the drops merge in the usual manner with the distilland, whereas on closed circuit they form the floating boules (*13*) of Fig. 2. Four thermocouples are threaded into thin glass capillaries previously fused into the body of the flask; the positions of the tips are indicated in Fig. 3. The reference junctions have been positioned in the path of the feed steam and recently moved to a sep-

1



2



3

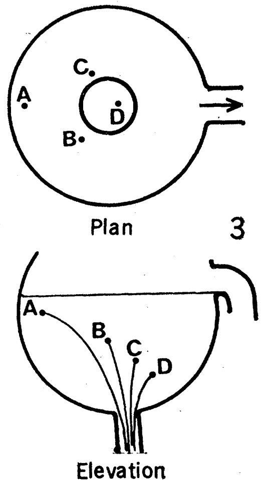


Fig. 1 (top). Schematic elevation of the reaction vessel with minimum amount of detail; for complete details see (*8*). *C*, condenser; *D*, discard; D_c, discard condensate; W_1, wire in boule; W_2, wire in substrate; *H*, ring heater; *G*, glass spiral; T_1, working thermocouple; T_2, reference thermocouple; *R*, return. Fig. 2 (lower left). Reversal of convective circulation when boules are being formed. Fig. 3 (lower right). Relative positions of temperature sensors. Thermocouple A is situated 5 mm from the wall and 5 mm from the surface of the water.

arate reference boiler. The signals represent departures from the equilibrium boiling point + Δt_s and, after preamplification, provide the potentiometric traces of Fig. 4 and, in modified form, the curves of Fig. 5. One might ask, after glancing at Fig. 4, whether the frequency and high amplitude of the temperature fluctuations are due to apparatus noise or true signal. That the fluctuations were not chiefly artifacts was demonstrated by operating the system once with $\Delta t_s \simeq 0$ and a second time by supplying a small constant electromotive force to the preamplifier. The irregularities remaining in the upper pen trace from the three submerged thermocouples were then 15 percent of the usual working trace; the irregularities in the lower trace from the single thermocouple were somewhat greater than 15 percent of the working signal.

Steady circulation within the distilland is driven by changes in buoyancy and surface tension which, when the drops are merging and the heater segments are equally energized, cause an involuting doughnut vortex (Fig. 1). With a boule present, the buoyancy streams are overridden by centrifugal surface currents (*14*) which drive a smaller vortex more rapidly in the opposite sense, as in Fig. 2. In the absence of boules and with one side or the other of the heater segments deenergized, the vortex can be replaced by vertical cartwheeling of the contents to thrust the surface toward or away from the overflow weir. The surface can thus be imprisoned by underflow or freed by overflow, and the rate of scavenging can be modified by the pattern of circulation. The boule can be used as a test probe (*15*) or reserved to reclean the surface for the next determination of Δt_s, which has routinely been performed in the absence of boules. In this report only the simplest arrangement is treated, with all heaters equally energized. Two temperature traces are taken, one for the top thermocouple A and one for the submerged thermocouples B, C, and D linked in series to furnish an approximate average temperature of the bulk water.

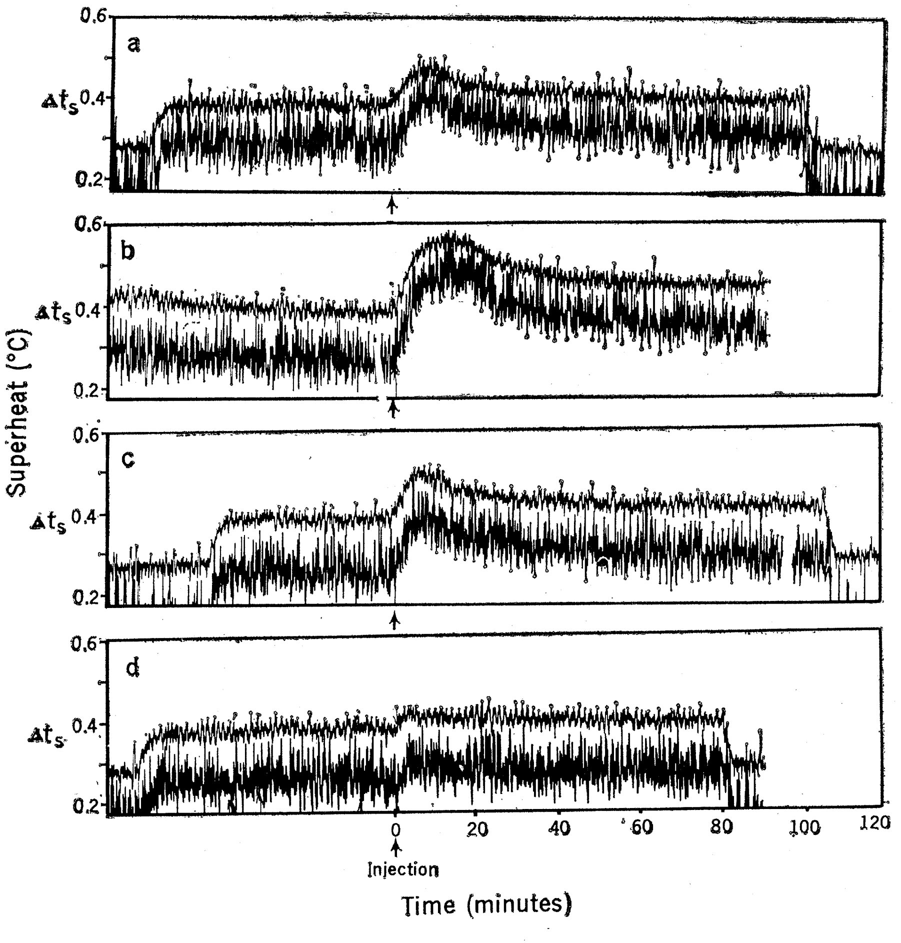


Fig. 4. Photograph of potentiometric traces of superheat temperatures: (a) behenic acid, 0.5 μg; (b) erucic acid, 2.5 μg; (c) erucic acid, 0.5 μg; (d) erucic acid, 0.1 μg. The upper traces in each pair record the average values of the three submerged thermocouples, properly related to the scale of Δt_s on the left. The lower traces in each pair are for the top thermocouple A, with the ordinate scale lowered to clarify the details. The average Δt_s for the lower trace should properly be located at 0.1°C above that of the upper trace. Zero on the time scale (see arrow) marks the moment at which the glass spiral with the additive is returned to the reaction vessel. The depressed readings on the far left were produced during the precleaning with boules.

Boules will form and superheat can be measured soon after the apparatus has been fabricated and filled, the water degassed by boiling, and nonebulliative evaporation established; but the sensitivity to additives is low and variable. A few weeks' recycling with hundreds of redistillations leaches the glassware of readily soluble material, frees the water surface from silicate-aluminate patches (*15*), and allows the sensitivity to reach a steady maximum. Indispensable precautions for cleanliness and for the exclusion of foreign material have been described elsewhere (*6*, pp. 32, 178 et seq).

Delivery of microgram quantities of the additive to the hot water surface and its retention by the surface is fraught with uncertainty and compounded by the difficulties of securing and recognizing even distribution, which have dogged (*10*, pp. 28–29) researches on monolayers. The ratio of additive molecules to molecules of water in the surface is far below unity; the competing area of the glass wall above and below the surface is greater than that of the free surface, and the mass of hot water is more than sufficient to dissolve the most "insoluble" additive; all of the reagents studied are more or less volatile in steam and can be carried to the condenser to be expelled, returned with condensate, or deposited on the walls.

The volatility in steam does, however, permit uniform presentation of reagent to the water—the reagents are added by volatilization into the feed steam. The glass spiral included in Fig. 1 is partly withdrawn, the additive in 0.1 ml or less of freshly distilled acetone is applied, and, after the solvent has evaporated, the spiral is returned. This operation is completed within 3 minutes; transfer of additives has been demonstrated to follow rapidly, and response, if any, reaches a maximum in approximately 10 minutes. Relevant background data include the following: mass of H_2O in the flask at 100°C, 190 g; free surface area, 82 cm^2; energy to the superheating ring, 7 watts; measured efficiency of thermal transfer, 55 ± 5 percent; range of superheat, 0.38° to 0.60°C, with 0.813°C full

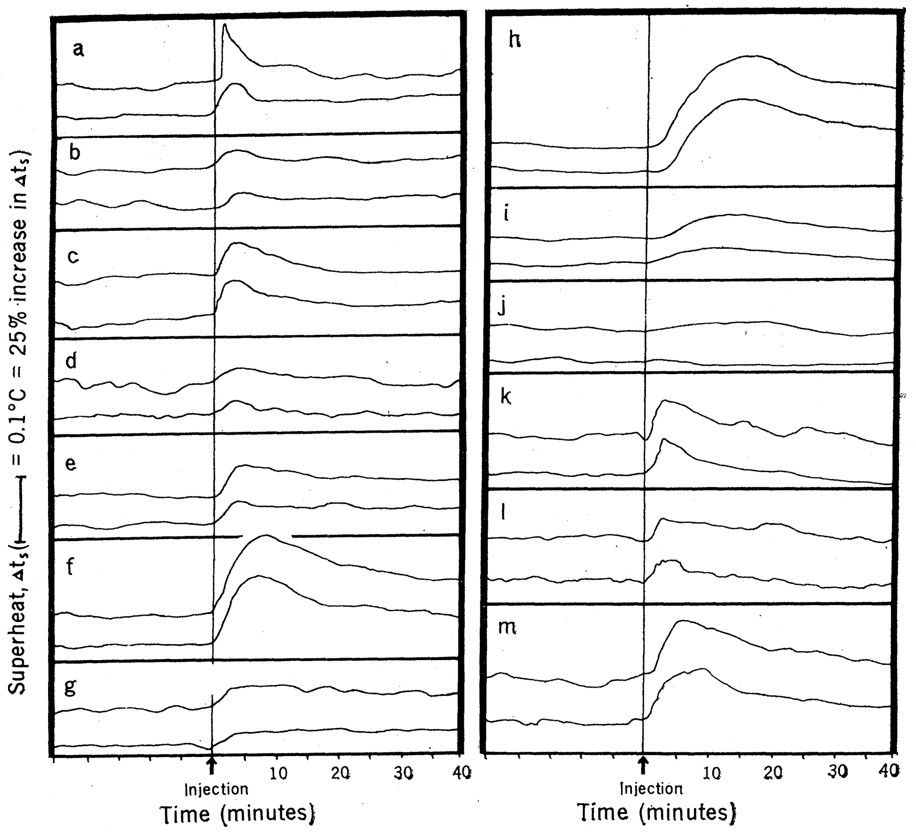


Fig. 5. Lines of mean temperature traced from potentiometric records for the following quantities of compounds: (a) myristic acid, 50 μg; (b) myristic acid, 25 μg; (c) palmitic acid, 12.5 μg; (d) palmitic acid, 2.5 μg (e) erucic acid, 0.1 μg; (f) erucic acid, 0.5 μg; (g) lignoceric acid, 0.1 μg; (h) nervonic acid, 0.5 μg; (i) nervonic acid, 0.1 μg; (j) white mineral oil, 40 μg; (k) erucyl alcohol, 0.5 μg; (l) nervonyl alcohol, 1.0 μg; (m) nervonyl alcohol, 5.0 μg. The upper trace is for thermocouple A; the lower trace is the average value of the three submerged thermocouples.

scale of chart. The period of substantially complete surface scavenging on overflowing was $\geqslant 30$ minutes with boules and $\geqslant 2$ hours without boules.

Boules and superheat were little disturbed by common solvents and aliphatic compounds of low molecular weight (10- to 100-mg additions) except for a brief decrease in the partial pressure of steam. Superheat began to rise when reagents having greater molecular weights and at least one hydrophilic group were added, for example, acids, alcohols, amines, and some esters, and increased noticeably with aliphatic compounds of C_{10} and above. Lauric and myristic acids were active in submilligram quantities, and higher homologs and their unsaturated counterparts were active in microgram quantities. Chart records of the highest sensitivity yet observed, encountered with behenic and erucic acids, are shown in Fig. 4; Fig. 5 displays lines that have been drawn through areas of greatest pen density of the chart records of varying quantities of nervonic acid (*cis*-15-tetracosenoic acid) and other reagents.

The intensity and duration of the signal is determined by the intrinsic "potency" of an additive as modified by volatility; by partition between the water, the water surface, and the container; and by attrition brought about by continuous dilution, overflow, oxidation, or hydrolysis. The areas under each median curve (Fig. 5) reflect this composite of causation and elution and require individual assessment. Only the heights of maximum response to varying doses of an additive have been compared. Some of these, which have been compiled in Table 1 from the pen traces of Figs. 4 and 5 and other data, show that response ratios are nonlinear and are greatest for the smallest additions, tending to a maximum with a compact monolayer or 10 to 100 times the minimum detectable quantity. Responses to cumulative small doses are variable and seldom strictly additive and will require more study. A safe interim conclusion is that the degree of superheat of bulk clean water is perceptibly raised when no more than two molecules of certain compounds are made available to each 1000 molecules of water surface.

It is a reasonable but unproved assumption that the effective moiety of the additive becomes adsorbed to the water surface and that it operates by slowing convective turnover (*16*), perhaps by delaying the spread of hot striae (*17*) which arise from the ring heater. The net result would be the establishment (*18*) of a colder donor-conductive layer (*19*) on the very top of the liquid and the accumulation of a hotter, thicker boundary layer beneath. Since the thermal capacity of the boundary layer is greater than that of the cold donor-conductive layer and both become entrained with the general circulation, the temperature of the bulk liquid would rise. Such a sequence is far more credible than the proposition that there is an alteration of the evaporation coefficient, that is, an alteration of the ability of the large free areas of water surface to accommodate the entrance or exit of energetic H_2O molecules. A "very top" cold layer with depressed temperature T_{tr} (*20*) is a logical necessity if the evaporation coefficient remains near unity. A hotter stratum under the surface, if it extended to the phase boundary, would evaporate faster than the water at the bulk temperature and would reduce the temperature. A hot layer can extend to the interface only when it is hermetically covered, as by a compact monolayer. A consequence is that water in reservoirs becomes hotter at an interface protected by evaporation retardants than at a clean interface, thus increasing the burden on the retardant, as Mansfield pointed out (*21*, *22*). It is the partial monolayer, as in our specialized model, that represses evaporation by maintaining a colder interface with a longer time of residence. On the scale of cleanliness we have been discussing, the surface of waters in natural reservoirs is generally "predirtied" and is also disturbed by wind and wave so that the tenuous-film : cold-layer model is not directly applicable.

In summary, we have described a recycling system in which the concentration of adsorbate on the water surface is neither constant nor precisely known at any instant. This uncertainty is the price paid for the advantage of in-cycle repurification without which the phenomena could scarcely have been noted or exactly repeated. Modifications, nearly completed, should ensure precise delivery of the test sample to the water surface, isolation of the surface and supernatant steam during measurement, and return to the purging routine at will. The test vessel has plane parallel windows which should permit schlieren monitoring of currents in relation to thermocouple records and subsequent mathematical treatment. In the meantime, the simple model is serving to screen various compounds and to confirm that the temperature of purified water resting at the boiling point is measurably responsive to extremely small traces of contaminant.

KENNETH HICKMAN
IAN WHITE
Distillation Research Laboratory,
Rochester Institute of Technology,
Rochester, New York 14623

References and Notes

1. G. L. Gaines, Jr., *Insoluble Monolayers at Liquid-Gas Interfaces* (Interscience, New York, 1966), pp. 179–188.
2. N. K. Adam, *The Physics and Chemistry of Surfaces* (Dover, New York, 1968), pp. 53–68.
3. I. Langmuir, *J. Chem. Phys.* **1**, 756 (1933).
4. D. G. Dervichian, *ibid.* **7**, 931 (1939).
5. W. D. Garrett and J. D. Bullman, *Nav. Res. Lab. Rep. 6003* (1963), pp. ii–18.
6. N. L. Jarvis, C. O. Timmons, W. A. Zisman, in *Retardation of Evaporation by Monolayers*, V. K. LaMer, Ed. (Academic Press, New York, 1962).
7. A. Pockels, *Nature* **46**, 418 (1892); H. Benard, *Ann. Chim. Phys.* **23** (No. 7), 62 (1901); J. A. R. Pearson, *J. Fluid Mech.* **4**, 489 (1958).
8. J. W. Strutt (Baron Rayleigh), *Phil. Mag.* **32** (No. 6), 529 (1916).
9. K. Hickman, paper presented at the meeting of the American Institute of Chemical Engineers, Portland, Ore., 26 August 1969; paper presented at the meeting of the American Institute of Chemical Engineers, Denver, Colo., 30 August 1970.
10. ———, *Office Saline Water Res. Develop. Progr. Rep. No. 585* (1970).
11. P. J. Harris, *ibid.*, p. 22.
12. See O. Mady, *Ind. Eng. Chem.* **59**, 29 (1967).
13. K. Hickman, *Nature* **201**, 985 (1964).
14. ———, *Ind. Eng. Chem.* **56**, 26 (1964), figure 10-A.
15. ———, *Separation Sci.* **3** (No. 6), 551 (Dec. 1968).
16. J. C. Berg and A. Acrivos, *Chem. Eng. Sci.* **20**, 737 (1965).
17. ———, M. Boudart, *Advan. Chem. Eng.* **6**, 105 (1966), figure 17.
18. K. Hickman, *Proc. Int. Symp. Water Desalination, 1st*, 1965 (1967), pp. 180–223.
19. ———, *Desalination* **1**, 13 (1966).
20. See nomenclature in (*22*); see also Jer Ru Maa, *Ind. Eng. Chem. Fundam.* **8**, 560 (1969); *ibid.* **6**, 504 (1967).
21. W. W. Mansfield, *Nature* **172**, 1101 (1953).
22. ———, *ibid.* **175**, 247 (1955).
23. Work supported by grant 14-30-2572 from the Office of Saline Water, U.S. Department of the Interior.

5 February 1971; revised 18 March 1971 ■

Lunar Hadley Rille: Considerations of Its Origin

Abstract. *Geomorphology, topographic configuration, comparisons with terrestrial analogs, and considerations of the chemical and physical characteristics of mare lavas indicate that the Hadley Rille is a lava channel. Some of the structure was roofed to form a lava tube, parts of which have subsequently collapsed.*

Hadley Rille, in a valley of the Apennine Mountains east of Mare Imbrium, has been selected as the Apollo 15 landing site (*1*) (*F* in Fig. 1). Considerations of its origin are essential to geologic interpretation of the site. The rille is about 135 km long and averages 1.2 km in width and 370 m in depth. The northern section (Fig. 1) is 25 km long, shallower than the main rille, and may not be genetically related to it. Rima Fresnel II, a probable graben, intersects the northern section. An increase in elevation at the northern end may reflect adjustments of the mare after formation of the rille, as indicated by lineaments interpreted as step faults. Hadley Rille is in a class of sinuous rilles which characteristically (i) appear to originate in irregularly shaped craters or depressions, (ii) trend generally downslope, (iii) have discontinuous channels and cut-off branches, (iv) are fairly uniform in width or occasionally taper toward the terminus, (v) are restricted to mare surfaces and appear to be controlled by highland or premare topography, and (vi) form topographic highs along the rille axis. These characteristics, with considerations of mare composition and recently derived elevation determinations of the area (*2*), enable speculation on the origin of Hadley Rille and similar lunar structures.

Several diverse modes of origin have been proposed for lunar sinuous rilles —erosion by ash (*3*) or water (*4, 5*), surface collapse resulting from intrusive stoping (*6*), fluidization of regolith by outgassing through fractures (*7*), or that the rilles are lava channels, collapsed lava tubes, or both (*8, 9*). Most investigators agree that fluid flow is involved; controversy arises as to type of fluid—ash, water, gases, or lava. For a particular rille each mode has one or two strong points in its favor, and it is probable that each class of sinuous rille may have a unique origin. The characteristics of the Hadley Rille, however, most closely resemble those of a lava channel and partly collapsed lava tube.

Recent investigations of prehistoric basalt flows (*10*) and observations of active flows (*11*) provide qualitative and quantitative data on the geomorphology of lava tubes and channels. Tubes and channels are morphologically similar, and, because channels frequently form well-defined crusts of solidified lava, it is often difficult to separate channels from tubes in active flows. For convenience, tubes may be defined as having freestanding roofs after drainage of molten lava, while channels result from open (noncrusted) flow, or from crustal collapse during lava drainage. Depending upon gradient and other parameters, a single structure may have both roofed and unroofed segments, giving the appearance from the air of a discontinuous channel similar to Hadley Rille (*A* in Figs. 1 and 2). Lava tubes and channels form commonly in fluid varieties of basalt. Experimental studies of lunar basaltic lavas (*12*) show that the lavas were very fluid, permitting the formation of tubes, and that the thermal conductivity was quite low, permitting long lava flows and hence long lava tubes. It is, therefore, reasonable to expect lava tubes and channels on mare surfaces and to expect that under prolonged meteoroid bombardment many tube roofs would collapse, leaving sinuous trenches.

Lava tubes and channels often originate in vent craters or depressions associated with regional tectonic features, such as faults, fissures, or fracture systems concentric to calderas. Hadley Rille, similarly, is on the mare-highland boundary marked by fault systems concentric to the Imbrium basin (*13*). The apparent source of the rille is a cleft-shaped structure (*B* in Fig. 1) probably of internal, rather than impact, origin. Lingenfelter *et al.* (*4*) proposed sinuous rille formation from erosion by water that originated from subsurface reservoirs tapped by meteoroid impact. Because impact is required for the initial stage, this process is not likely to explain the origin of Hadley Rille. In addition to the lack of initiating impact there are several other objections to erosion of the rille by water. (i) Estimated volume of the rille is 2.8×10^{10} m^3. Although this material should form a significant alluvial fan or outwash plain, there is no indication of sedimentary structures at the terminus. If the material were spread over the surface at the end of the rille and thinned to featheredges, the unit would have no well-defined boundaries and would be younger than the eroded mare surface. Crater count-