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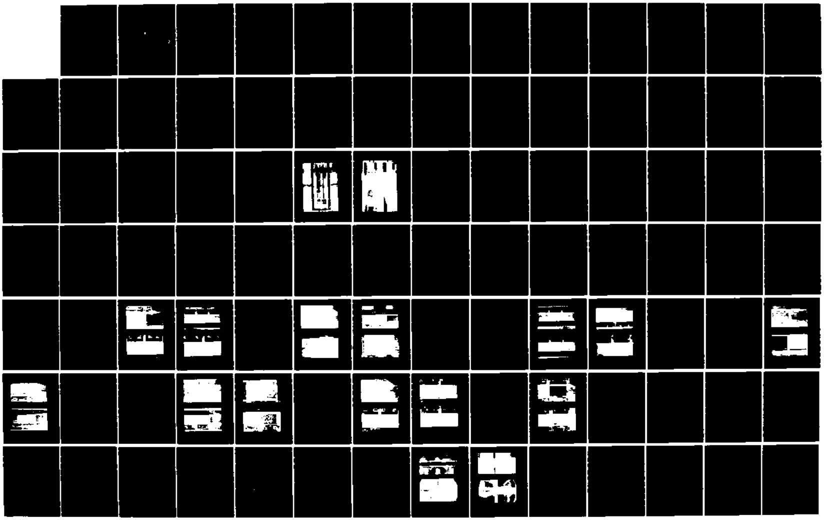

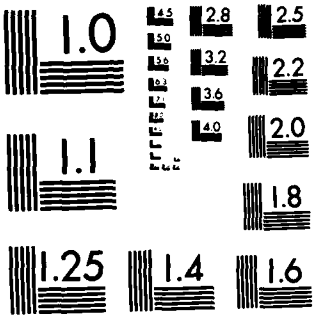

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN EVALUATION OF POLYMER COATINGS FOR THE PROMOTION OF DROPWISE CONDENSATION OF STEAM

by

Kenneth M. Holden II

March 1984

Thesis Advisor: P. J. Marto

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Fifteen polymer coatings were evaluated for their ability to promote and sustain dropwise condensation of steam to enhance the heat transfer capability of steam condensers. Of the fifteen coatings, nine employed a fluoropolymer as a major constituent. Of the other six, four were hydrocarbons, one a chlorocarbon and one a silicone. Each coating was applied to four different metal substrates: brass, copper, naval brass, and titanium. While exposed to steam at atmospheric pressure, each coating was visually evaluated for its ability to promote dropwise condensation. Observations were conducted over a period of 4000 hours. Hardness and adhesion tests were performed on selected specimens both before and after exposure.

On the basis of sustained performance, six coatings were selected for heat-transfer performance evaluation. A separate apparatus was used in which coated copper tubes were mounted horizontally in a test section through which steam flowed vertically downward. Vapor-side heat-transfer coefficients were inferred from overall measurements. Test results indicate that the outside condensing coefficient can be increased by a factor of five to eight through the use of polymer coatings to promote dropwise condensation.

A 1

An Evaluation of Polymer Coatings for the Promotion of Dropwise Condensation of Steam

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NOMENCLATURE

A_i	Inside area $l(D_i)\pi$, m^2
A_o	Outside area $l(D_o)\pi$, m^2
AD	As delivered
Br	Brass
c_p	Specific heat, kJ/kg K
Cu	Copper
D_i	Inner diameter, m
D_o	Outer diameter, m
h_i	Inside heat-transfer coefficient, W/m^2K
h_o	Outside heat-transfer coefficient, W/m^2K
k	Thermal conductivity, W/m K
k_l	Thermal conductivity of the liquid, W/m K
l	Length of tube, m
m	Mass flow rate of cooling water, kg/s
NBr	Naval brass
Pr	Prandtl number
Q	Heat-transfer rate, W
q	Heat flux, W/m^2
R	Rough surface finish
Re	Reynolds number
Rw	Wall thermal resistance, m^2K/W
S	Smooth surface finish
T	Temperature, K
T_i	Coolant inlet temperature, K
T_o	Coolant outlet temperature, K
Ti	Titanium
ΔT	Coolant Temperature rise, K
Tlm	LMTD, ($T/\ln((T_{sat}-T_{ci})/(T_{sat}-T_{co}))$, K
U	Unknown or proprietary
U_o	Overall heat-transfer coefficient, W/m^2K

w	Inside wall

GREEK SYMBOLS

Δ	Differential
μ	Dynamic viscosity, N s/m^2
υ	Kinematic viscosity, m^2/s
σ	Surface Tension, dynes/cm

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I. INTRODUCTION

A. BACKGROUND INFORMATION

The realization that the earth's resources are finite and not equally distributed has been amply demonstrated by the dramatic rise in the cost of energy and raw materials within the past ten years. In addition, the cost of construction for the basic Rankine cycle power plant, whether marine or stationary, has also increased. These facts have pointed to the need to apply advanced technology to boilers and condensers.

Marine applications pose the greatest problems since the power plant is limited by both size and cost. In the past, most of the effort in increasing efficiency has been directed at boiler design, while marine condensers have remained basically unchanged. For naval applications, the increased use of gas turbine and diesel engines for main propulsion has diminished the importance of the improvements achieved in fossil fueled boiler design. However, with the introduction of the Rankine Cycle Energy Recovery System (RACER) and the existence of numerous nuclear propulsion systems, the time has come to direct attention to the improvement of marine condensers.

Search [Ref. 1] performed a feasibility study to determine what improvements could be made in marine condensers. His research indicates that an increase of more than thirty percent in heat transfer, a thirty percent reduction in weight, and a twenty per cent reduction in volume could all be achieved if the condensation mode within the condenser were dropwise rather than filmwise. Unfortunately, filmwise condensation is the normal, stable mode of condensation on virtually all condenser materials and steps must therefore be taken to promote the dropwise mode.

B. FILMWISE VS. DROPWISE CONDENSATION

Filmwise condensation is characterized by the formation of a continuous sheet of liquid on the surface of the condenser. Because of the relatively simple shape and flow of the condensate film, the heat-transfer rate can be analytically predicted using the Nusselt analysis. This sheet of liquid forms a relatively high conduction resistance between the condensing vapor and the condenser surface. Under most conditions, it is this resistance which limits the heat transfer rate. For steam, the external heat transfer coefficient associated with filmwise condensation is normally in the range of 10,000 to 14,000 $W/m^2 K$. On the other hand, dropwise condensation can produce heat transfer coefficients up to twenty times that of filmwise condensation. This marked increase is a result of the process of drop formation and removal from the condenser surface.

In 1939, the theory that primary drops formed at submicroscopic nucleation sites on the surface was first proposed. This nucleation theory of drop initiation was later elaborated upon by McCormick and Westwater [Ref. 10] and confirmed by Reisbig [Ref. 11] through the use of microphotography. It is during this phase of drop formation that the major proportion of the heat transfer takes place. As the drop grows, it comes in contact with many other small drops which coalesce to form larger drops. This coalescence uncovers nucleation sites which immediately start to form additional drops. When the drop is approximately 0.15 mm in diameter, the increase in conduction resistance greatly reduces direct condensation. Experimental evidence indicates that over 90% of the heat transfer takes place during the nucleation and growth phase. The drop continues to grow, primarily by coalescence, until it reaches a critical size at which point external forces, such as gravity or vapor shear, overcome the surface tension of the drop with the condenser surface. As the drop departs a vertical surface, it coalesces with drops in its path, wiping them from the surface and exposing additional nucleation sites.

Graham [Ref. 2] has shown that the condenser surface during dropwise condensation can be characterized as follows: 10% bare surface, 30% active drops (less than 0.15 mm in diameter) and 60% dead drops (greater than 0.15 mm in diameter). It is important to note that vapor condenses only on the surface of the drops and not on the bare surface areas. In addition, very little heat is transferred through the dead drops. Therefore, at any point in time, only 30% of the condenser surface is transferring over 90% of the heat. The large heat-transfer rates associated with dropwise condensation are due to the fact that the average condensate thickness is much less then that associated with filmwise condensation, thus greatly reducing the conduction resistance. Figure 1.1 [Ref. 14] depicts the relative sizes of the various stages and modes of condensation.

C. DROP FORMATION

In 1804 Thomas Young first proposed the following equation to describe the equilibrium condition of a drop on a solid surface:

$$\sigma_{sv} - \sigma_{sl} = \sigma_{lv} \cos \Theta \qquad (1.1)$$

where σ_{sv} is the surface tension at the solid-vapor interface, σ_{sl} the surface tension at the solid liquid interface, σ_{lv} the surface tension at the liquid vapor interface and

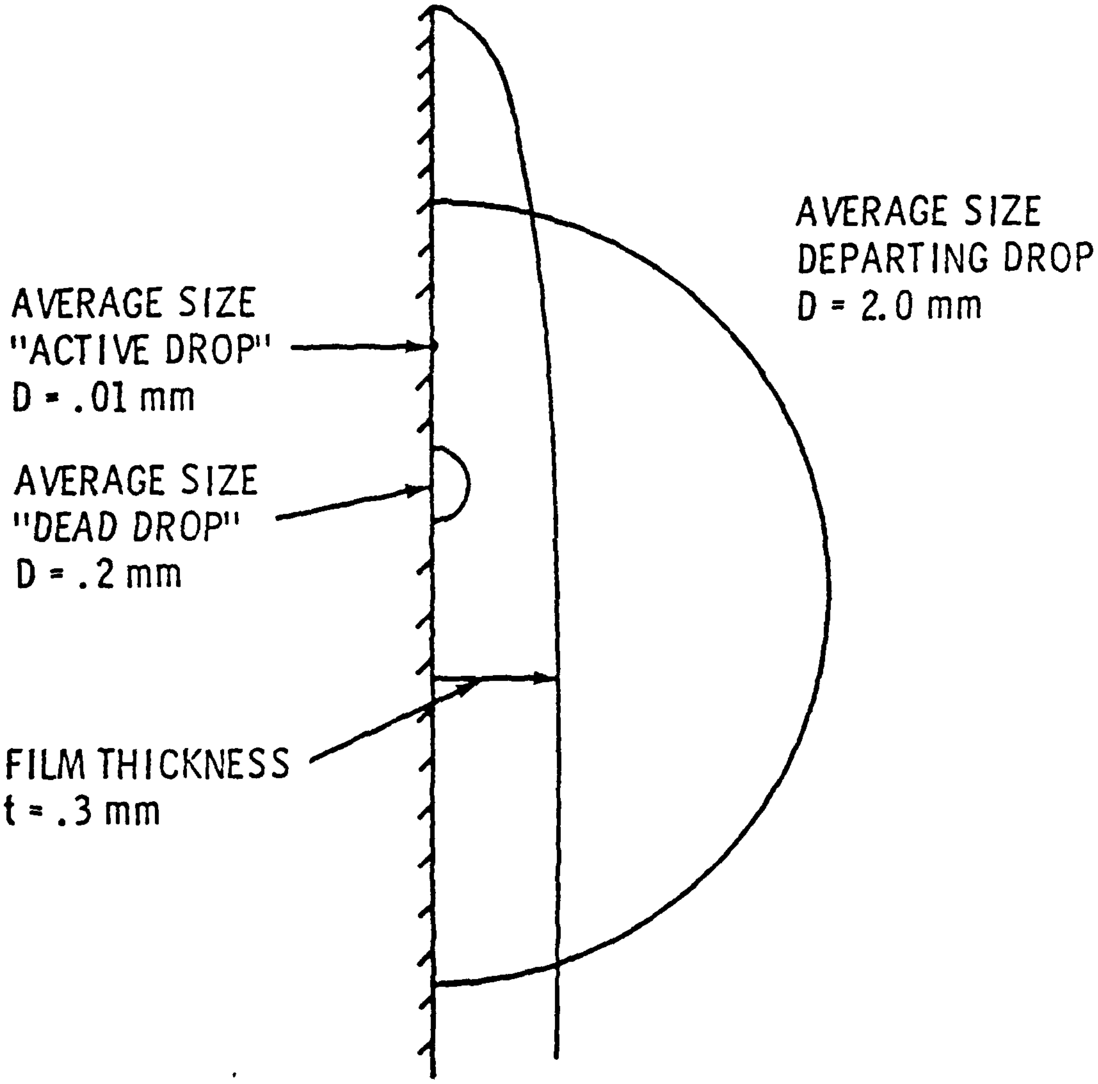


Figure 1.1 Relative Sizes of Condensation Modes.

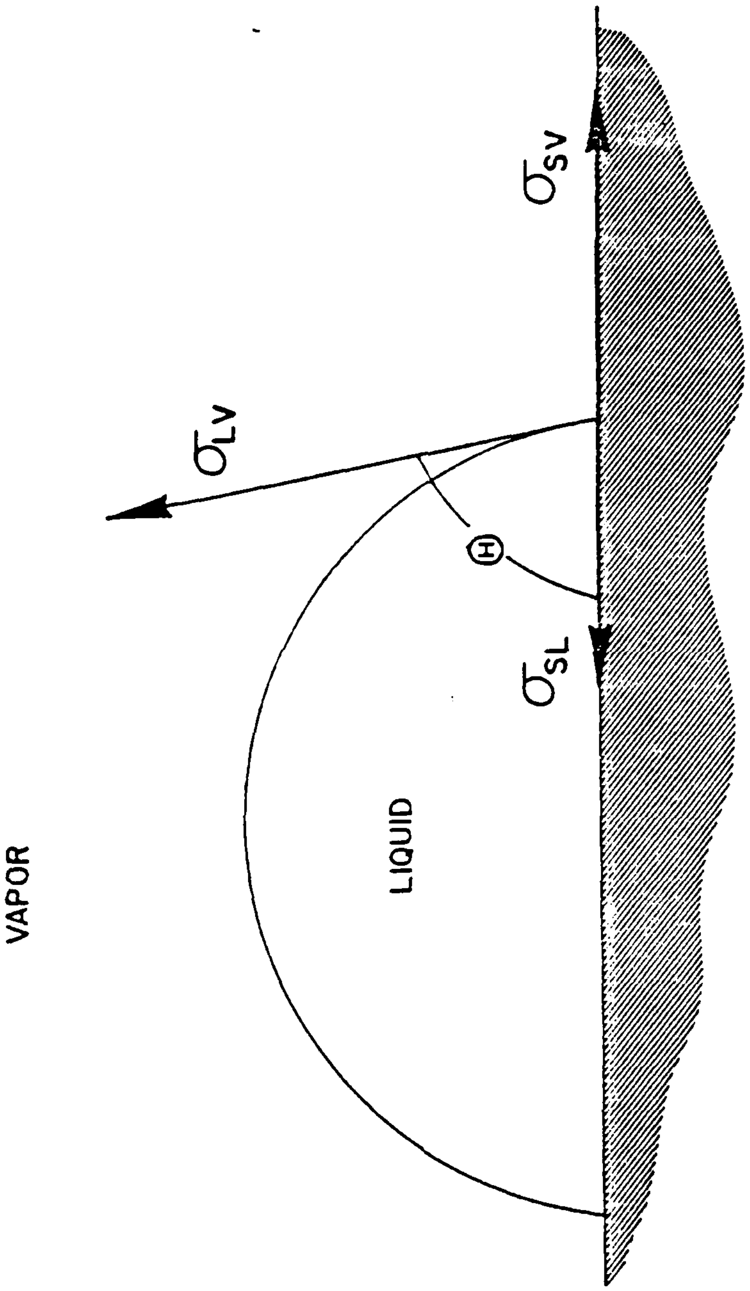


Figure 1.2 Contact Angle

Θ is defined as the contact angle (Figure 1.2). This equation is deceptively simple and poses many experimental and conceptual problems. However, the notion of a contact angle to characterize the degree to which a surface will wet is extremely useful. Zisman [Ref. 13] and other investigators have shown that there is a rectilinear relationship between σ_{lv} and the contact angle. Extrapolating the data to the point at which cosine Θ =1.0, that point at which the surface completely wets, it is possible to define an empirical value, the critical surface tension, to characterize the wettability of low energy solid surfaces. Table I lists the critical surface tensions for various low-energy organic surfaces. It follows from the definition of the critical surface tension, that a liquid with a surface tension greater than the critical surface tension of the surface will not spread. In addition, the results of many experiments indicate that the wettability of high energy surfaces coated by organic films are essentially determined by the nature and packing of the exposed surface atoms. Thus, a high energy surface can be made hydrophobic if it can be coated with a substance which has a critical surface tension less than that of the condensing liquid. In the case of water, which has a liquid-vapor surface tension of 71.9 dynes/cm at 25 C, all of the surfaces listed in Table I will be hydrophobic with the heavily fluorinated surfaces the most hydrophobic [Ref. 13].

D. FACTORS WHICH INFLUENCE DROPWISE CONDENSATION

Since metal surfaces have a relatively high surface energy, the most important factor is the existence of a low energy barrier or promoter on the condenser such that the critical surface tension of the condenser surface is less than that of the condensing liquid. This is a necessary

TABLE I

Critical Surface Tensions of Low Energy Surfaces

Surface Constitution	dynes/cm at 20 C
	A. Fluorocarbon Surfaces
$-CF_3$	6
$-CF_2H$	15
$-CF_3$ and $-CF_2-$	17
$-CF_2-$	18
$-CH_2-CF_3$	20
$-CF_2-CFH-$	22
$-CF_2-CH_2-$	25
$-CFH-CH_2-$	28
	B. Hydrocarbon Surfaces
$-CH_3$ (crystal)	22
$-CH_3$ (monolayer)	24
$-CH_2-$	31
$-CH_2-$ and $==CH==$	33
$==CH==$ (phenyl ring edge)	35
	C. Chlorocarbon Surfaces
$-CClH-CH_2-$	39
$-CCl_2-CH_2-$	40
$==CCl_2$	43
	D. Nitrated Hydrocarbon Surfaces
$-CH_2ONO_2$ (crystal)	40
$-C(NO_2)_3$ (monolayer)	42
$-CH_2NHNO_2$ (crystal)	44
$-CH_2ONO_2$ (crystal)	45

condition for dropwise condensation. Tanasawa [Ref. 3] noted an additional twenty-one factors which have, to a greater or lesser degree, an influence upon the heat-transfer coefficient of dropwise condensation. Of these additional factors, the most important are: (1) the thermal properties of the condenser material, (2) non-condensing gases, (3) external forces, and (4) condenser surface roughness.

The effect of the thermal properties from which the condenser is manufactured on the heat transfer coefficient of dropwise condensation is not completely resolved. Hanneman and Mikic [Ref. 4] have proposed the theory that the non-uniformity of drop size and spacing produces a non-uniformity in the surface wall temperature since the large drops act as insulators while the small drops are highly conductive. The net result is a thermal constriction resistance. Materials of low thermal conductivity allow less lateral heat transfer at the surface and therefore have a high constriction resistance. Rose [Ref. 5] believes that the non-uniformities are rapidly homogenized by the frequent coalescence between drops. Therefore, the constriction resistance will be small. Data are available to support both points of view. Regardless of whether the constriction resistance is large or small, the material selected for condenser construction will be limited by other constraints such as durability, machineability, availability and cost.

The effects of the second and third factors, non-condensing gases and external forces, can be minimized by proper design. The condenser must be able to operate under vacuum conditions without producing stagnant regions within the bundle where non-condensing gases can concentrate. The design should be such that gravity and vapor shear work together to remove the condensate drops.

The forth factor is surface roughness. For liquids exhibiting contact angles less than 90 degrees, a rough surface decreases the contact angle. This produces poorer quality condensation by causing the larger drops to occupy a greater surface area than would be normal. There is less room for active drops and more potential nucleation sites are covered. Both Griffith [Ref. 15] and Graham [Ref. 14] reported reduced heat transfer as a result of surface roughness. However, as will be pointed out later in this thesis, a certain amount of surface roughness is necessary for the proper adhesion of some of the organic polymers tested.

E. PROMOTION OF PERMANENT DROPWISE CONDENSATION

Dropwise condensation can be promoted by: (1) direct application of a suitable chemical, such as oleic acid or montan wax, to the condenser surface, (2) injecting non-wetting chemicals into the vapor which adsorb on the condenser surface, and (3) using a low energy polymer or noble metal coating.

Both the first and second method are limited in that neither produces a permanent hydrophobic coating. Results vary widely but usually the effectiveness of these promoters is measured in the hundreds of hours. The third method, the use of permanent coatings, has been the subject of considerable interest. At present, there are two types of coatings which can be used to promote permanent dropwise condensation: noble metals and organic polymers.

1. Noble Metals

Of the noble metals, only gold has been shown to consistently produce excellent dropwise condensation. This would appear to contradict theory since the surface energy of gold is relatively high. Recent experiments have shown that a "clean" gold surface applied under carefully controlled conditions will spontaneously wet as predicted. However, gold has the ability to attract and retain organics which render the surface hydrophobic. For this reason, gold is referred to as a "self-promoter." An extensive investigation by Woodruff [Ref. 12] concluded that the promotion of dropwise condensation of a gold-plated surface was directly related to the surface gold and carbon concentrations and inversely related to the copper, aluminum and oxygen concentrations.

Although gold has been shown to produce excellent dropwise condensation, its behavior over extended periods under varying conditions is uncertain. In addition, practical considerations such as cost and availability make gold unattractive for this purpose.

2. Organic Polymers

The second method of producing permanent dropwise condensation is to apply an organic polymer with a low surface energy to the condensing surface. Although many experiments have been conducted, virtually all of the research has been done using a fluorocarbon or silicone polymer.

Fluorocarbon polymers exhibit the desirable characteristics of high thermal stability, very low surface energy, and are highly resistant to chemical attack. However, they also have the undesirable characteristic of a relatively low thermal conductivity usually on the order of 0.3 W/m K. Assuming a realistic value of a tenfold increase in the outside heat-transfer coefficient due to dropwise rather than filmwise condensation and a nominal value of 0.3 W/m K for thermal conductivity, the maximum film thickness which could be employed to produce an increase in the overall heat-transfer coefficient would be on the order of

20 micrometers. Films of greater thickness would impose a thermal barrier so large that it would negate any benefi- derived from altering the mode of condensation. The most common polymer which has been employed is PTFE (polytetrafluoroethylene). PTFE is commonly referred to as Teflon, DuPont's registered trademark for a non-stick finish.

In 1956, Smith [Ref. 7] concluded that, when applied by utilizing the existing application techniques, thin Teflon coatings were not satisfactory for increasing overall heat-transfer rates for Naval applications. In 1964, Fox [Ref. 21] reported on tests conducted with a small condenser in which the tubes had been coated by Teflon to a thickness of 12.5 micrometers (0.0005 in). Performance was not significantly increased. Shortly thereafter, further studies into dropwise condensation by the Navy were suspended. In 1966, Brown and Thomas [Ref. 24] conducted experiments with tubes of Admiralty brass coated with 2.5 micrometers (0.0001 inch) of PTFE. The outside heat-transfer coefficient for dropwise condensation averaged approximately three times that of filmwise condensation. In 1969, Graham [Ref. 14] also achieved a threefold increase using flat, copper plates coated with a Teflon film estimated to be 1.5 micrometers (0.00006 inches) thick. This represented the practical limit for the application of Teflon films using standard techniques. In 1979, both Manvel [Ref. 8] and Perkins [Ref. 22] used vacuum-deposition sputtering to apply ultra-thin layers of PTFE. Thicknesses ranged from a minimum of 0.04 micrometers to a maximum of 0.13 micrometers. The results were disappointing and unexpected. Although the dropwise performance was good, the steam-side heat- transfer coefficient was increased by a maximum of only 1.6. This result was attributed to the presence of non-condensing gases. In addition, all of the coatings showed signs of physical deterioration after very short operating periods.

The use of silicones to promote dropwise condensation began in the 1950's and continued into the early 1960's. In 1959, Kullberg and Kendall [Ref. 25] experimented with a commercially-available, semi-permanent silicone release agent, R-671. With a film thickness estimated to be 10 micrometers (0.0004 in), an increase of 1.5 in the overall heat-transfer coefficient was obtained. Preliminary endurance tests indicated that the coating was capable of producing dropwise condensation for periods in excess of 1500 hours. A subsequent study conducted by the Westinghouse Corporation for the U. S. Navy investigated five silicon compounds, including R-671, and Teflon. These tests produced only moderate increases in the overall heat-transfer coefficient. Most important, all of the silicone coatings exhibited limited endurance. The best silicone compound had been reduced to 80% dropwise and 20% filmwise within 135 hours of operation. From these tests, it was concluded that Teflon was the only coating of the group that exhibited a life expectancy sufficient to warrant investigation.

In 1966, Erb and Thalen [Ref. 23] conducted an extensive investigation of permanent hydrophobic coatings. Although they were primarily concerned with sulfide films and noble metals, they also investigated organic polymers. One of the polymers investigated was PTFE and another was a relatively new compound developed by the Union Carbide Corporation, parylene-N. Parylene-N is a polymer of para-xylylene which can be vapor deposited in very thin films. Unlike PTFE, parylene-N contains no fluorine and therefore would not be expected to be as hydrophobic as the fluoropolymers. However, a one-micrometer- thick film produced good dropwise condensation in excess of 2400 hours of continuous operation. The overall heat transfer coefficient was increased by a factor of approximately 1.5.

Recent developments in techniques for the application of ultra-thin coatings, in addition to the development of new materials, has put the use of organic polymers to promote dropwise condensation within the realm of feasibility.

F. PURPOSE OF STUDY

The overall purpose of this study was to evaluate the performance of various organic polymers as effective dropwise promoters. This was accomplished in two distinct stages.

1. Endurance

Fifteen different coatings, which were applied to four different substrates with two different surface preparations, were subjected to an endurance test. The test consisted of continuous exposure to steam at atmospheric pressure. Visual observations were made to determine which coatings could sustain dropwise condensation. Those coatings which showed little or no degradation after a minimum of 2000 hours of exposure were used in the second stage of this study.

2. Heat-Transfer Evaluation

On the basis of the endurance tests, six coatings were selected for quantitative evaluation: (1) Nedox, a coating system developed by the General Magnaplate Corporation, (2) No-Stik, a coating developed by Plasma Coatings, Inc., (3) parylene-N, (4) parylene-D, (5) NRL C-6 fluoroepoxy, and (6) NRL fluoroacrylic. These coatings were applied to copper tubes in order to quantify their effect on the outside heat-transfer coefficient.

II. EXPERIMENTAL APPARATUS

A. INTRODUCTION

Tests and evaluations were conducted in two stages. During the first stage, prepared samples of selected coatings were subjected to a rigorous endurance test prior to the second stage, heat-transfer evaluation. During the endurance test, the coatings were visually evaluated for their ability to promote and sustain dropwise condensation. Those coatings which performed satisfactorily in excess of 2000 hours were selected for the second stage, heat-transfer evaluation. During this stage, the effect of the coating on the outside heat-transfer coefficient was determined.

B. ENDURANCE TEST FACILITY

The endurance test consisted of exposing prepared samples to steam at atmospheric pressure while mounted on a heat sink. The heat sink was necessary to provide a thermal gradient of sufficient magnitude to induce vigorous condensation. The endurance test was to run continuously for an indefinite period. Therefore, a principle concern was to design and construct a facility which was simple, reliable, and could be left unattended for extended periods. In addition, since photography would be used to assess the quality of the dropwise condensation and provide a visual record of changes with time, it was essential that the specimens be displayed with an unobstructed view. These objectives were accomplished by the construction of an endurance testing apparatus consisting of three major components: (1) steam chamber, (2) heat sink, and (3) de-superheater. Figure 2.1 depicts a schematic of this system.

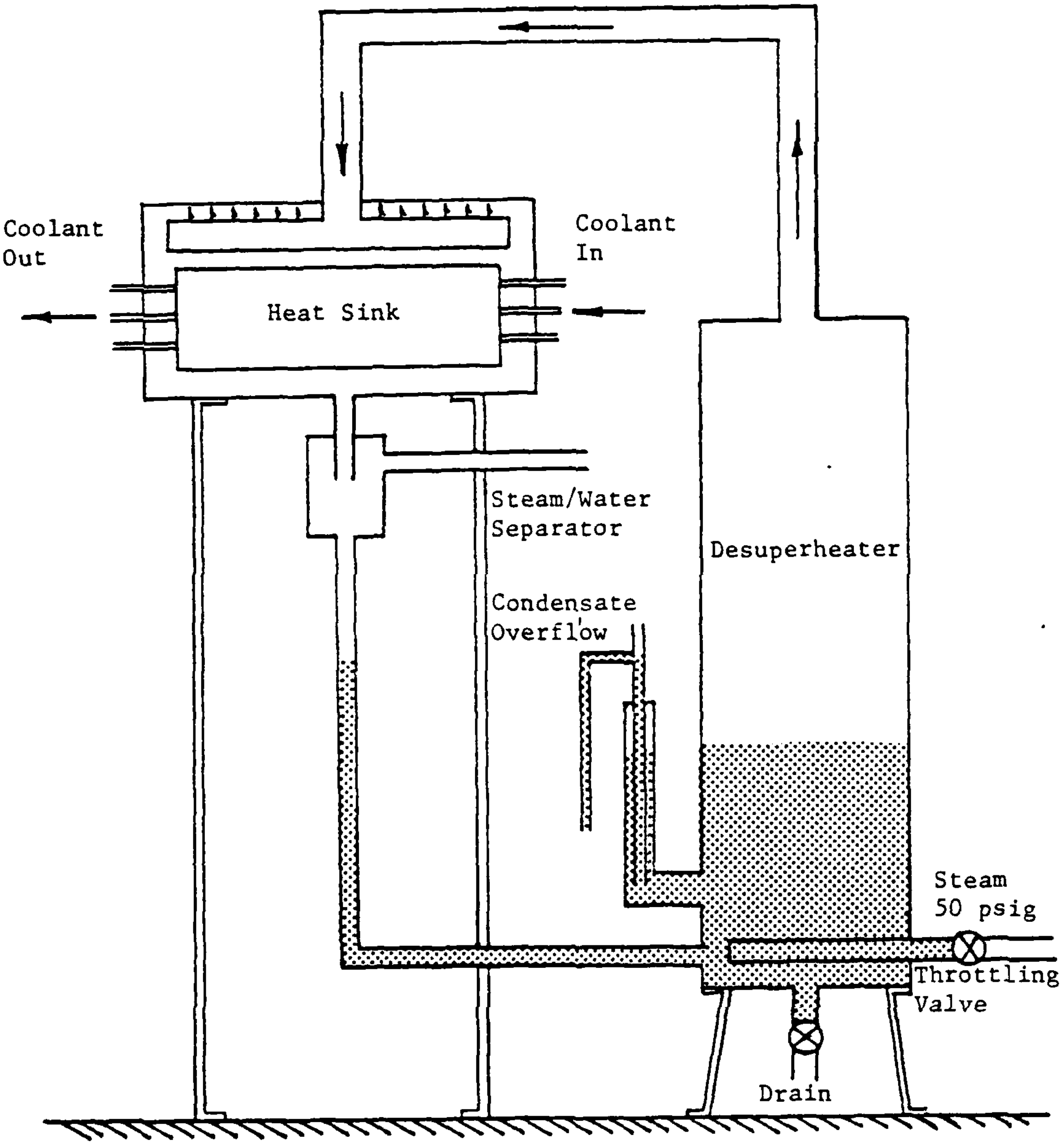


Figure 2.1 Endurance Test Apparatus Schematic.

1. Steam Chamber

The steam chamber was a rectangular box with overall dimensions 0.457 m (18 in) in length, 0.127 m (5 in) in depth and 0.165 m (6.5 in) in height. The main body of the chamber, top, bottom and end plates, was constructed from 4.8 mm (0.1875 in) thick, stainless-steel plate. The side panels were constructed from two pieces of 6.3 mm (0.25 in) thick borrosilicate glass. The inner glass was recessed into the body of the chamber while the outer glass was inlaid in a stainless-steel frame. Twenty-four threaded, stainless steel studs were butt welded along the periphery of each side to hold the glass panels in place. To provide for an adequate dead air space between the glass panels, a 6.3 mm (0.25 in) thick aluminum spacer was used. The entire assembly, the inner glass, spacer, and outer frame, was held in place by bolting the outer frame to the main chamber. A Neoprene "O" ring was used to provide a seal between the inner glass and the chamber. Both sides of the chamber were identical. Figure 2.2 shows the assembled chamber in operation.

Steam was introduced through 25.4 mm (1.0 in) OD stainless steel tubing at the top center of the chamber. The steam was distributed along the centerline through a perforated stainless steel manifold running the length of the chamber. A drain in the center of the bottom of the chamber returned the condensate to the de-superheater. A horizontal branch line located in the return line directly beneath the chamber was open to atmosphere. This prevented the chamber from becoming pressurized. In addition, a continuous jet of steam issuing from this tube indicated that the supply to the chamber was adequate.

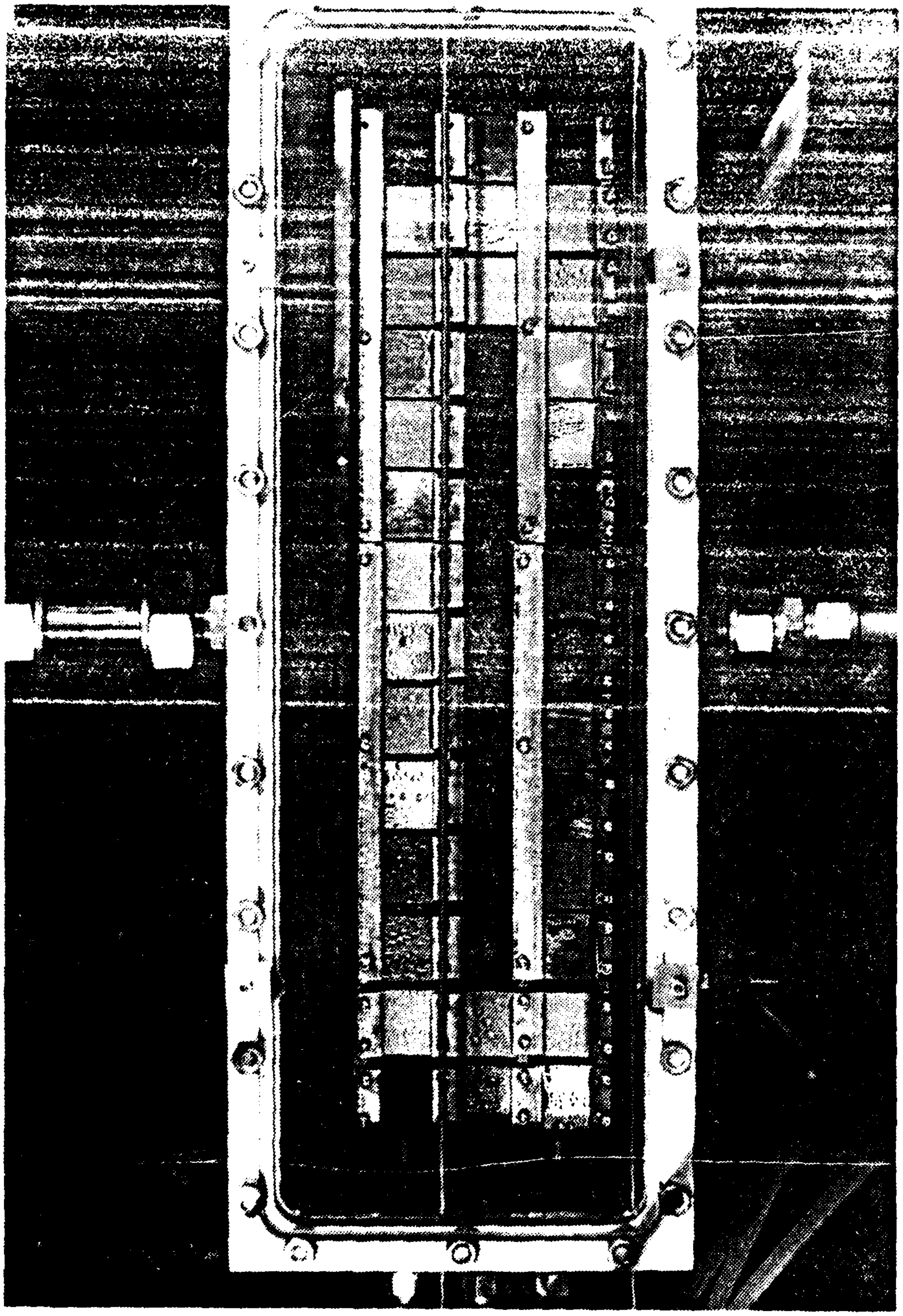


Figure 2.2 Steam Chamber

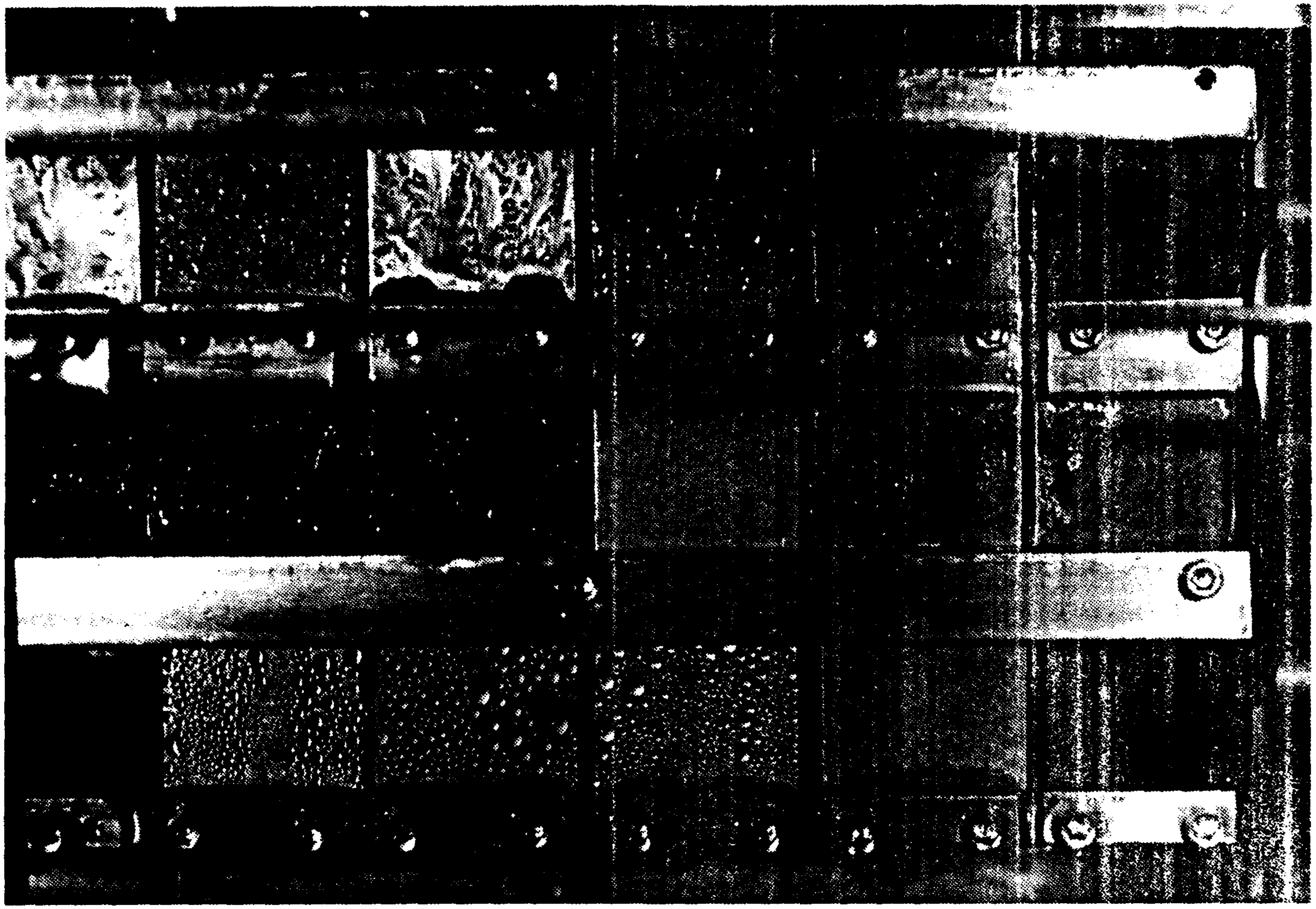


Figure 2.3 Steam Chamber Close-up Showing Rod Heater

In order to have a clear field of view for taking pictures, it was necessary to prevent condensation on the inside of the inner glass panel. This was accomplished by heating the air space between the glass panels with rod heaters. The heaters were 0.438 m (19.0 in) long and 3.0 mm (0.125 in) in diameter with a power output of 165 Watts each. The heaters were inserted through holes drilled in the ends of the spacer frame. Two heaters were required per side; one was placed along the bottom of the air space and the other approximately half way up. All four heaters were controlled with one rheostat. The heaters are visible in Figure 2.2.

2. Heat Sink

The test specimens were mounted on a heat sink which was centered within the chamber. The heat sink was fabricated from two sheets of copper 0.388 m (15.25 in) long, 95 mm (3.75 in) wide and 6.35 mm (0.25 in) thick held apart along the periphery by 6.35 mm (0.25 in) square, brass bar stock. The interior was divided into three longitudinal chambers by brass baffles. Cooling water entered and exited each chamber through 6.35 mm (0.25 in) OD stainless steel tubes which protruded from the ends of the heat sink. After installing the internal baffles, the entire unit was brazed along the periphery to form a single, leak-free unit. Once assembled, the large flats were lapped to provide a smooth, uniform contact surface. The heat sink was suspended in the center of the steam chamber by passing the water inlet and outlet tubes into bulkhead fittings mounted in the end plates. The end plates were bolted in place before tightening the compression nuts on the bulkhead fittings. The coolant, tap water making a single pass, was supplied and discharged through 6.35 mm (0.25 in) diameter nylon tubing.

The heat sink was designed to hold eighty-four 25.4 mm (1 in) square specimens. The thickness of the specimens was nominally 0.76 mm (0.03 in) or 1.5 mm (0.060 in) depending upon the substrate material and coating system. A primary concern was the ability to hold the specimens tightly against the heat sink in order to minimize contact resistance. In order to accomplish this, four equispaced stainless steel tracks, 3.2 mm (0.125 in) by 4.7 mm (0.1875 in), were fastened to each face of the heat sink with counter-sunk machine screws. The tracks were pre-drilled and tapped to receive stainless-steel clips which were held in place by set screws. The clips were designed to securely clamp each specimen against the heat-transfer surface by the upper and lower edges.

3. De-Superheater

An additional concern was the ability to provide a reliable steam supply. House steam from a central boiler was available, but the service pressure was greatly in excess of atmospheric. Therefore, when throttled to atmospheric pressure, the steam entering the chamber would be superheated by approximately 60 K. In addition, contaminants such as rust and scale were common in the system. In order to reduce the pressure and the degree of superheat and provide a sediment trap for non-volatile contaminants, a stainless-steel tank was fabricated. The tank was 0.66 m (26 in) in length and 0.33 m (13 in) in diameter. The bottom of the tank was situated 1.82 m (72 in) below the bottom of the steam chamber. The steam supply line from the de-superheater to the chamber was 25.4 mm (1 in) OD stainless-steel tubing, while the condensate return line was 12.7 mm (0.5 in) OD stainless-steel tubing. The combination of elevation and steam line diameters made a gravity return possible, thus eliminating the need for a condensate return pump.

Operation commenced by injecting steam into the bottom of the de-superheater through a sparger tube. The amount of steam was controlled by a throttling valve. The steam passed through the de-superheater to the chamber, condensed on the heat sink and the condensate returned to the de-superheater. After one hour, steady-state conditions prevailed in which the de-superheater was approximately one-third full of water and the return condensate was balanced by overflow from the de-superheater.

C. HEAT-TRANSFER EVALUATION FACILITY

The apparatus used to determine the quantitative effect of a coating on the outside heat-transfer coefficient was described in detail by Poole [Ref. 20]. A brief description of the apparatus will be given here. A schematic of the system is shown in Figure 2.4.

Steam was generated in a 0.305 m (12 in) diameter glass boiler using ten 4000-watt immersion heaters. The steam then passed through a 0.305 m (12 in) to 0.152 m (6 in) reducer into a 2.44 m (8 ft) vertical section, through a 180 degree bend, and then down a 1.52 m (5 ft) vertical section before entering the stainless steel test section. The tube to be tested was mounted horizontally in the center of the test section behind a viewing port. Steam that did not condense on the tube passed on to an auxiliary coil condenser. All condensate was returned to the boiler by gravity through stainless steel tubing. Operating under vacuum conditions of 0.012 MPa (1.62 psia), the test apparatus produced vapor velocities of approximately 2.0 m/s (6.5 ft/s) past the tube.

Cooling water for the tubes was provided by a centrifugal pump. A throttling valve was employed to control the flow through the tube from zero to a maximum of 0.52

liters/s (8.3 gal/min) which produced a maximum velocity of 4.3 m/s (14.0 ft/s) through the tube. A continuous supply of tap water was used for cooling the auxiliary condenser. By throttling the flow of tap water to the auxiliary condenser, the pressure within the system could be regulated.

As previously stated, the presence of non-condensing gasses can have a relatively large effect on the heat-transfer rate. Extreme care was taken to ensure that the heat transfer test apparatus was virtually leak free. As documented in [Ref. 20], the experimental apparatus was successively improved until it could be repeatedly demonstrated that the rise in pressure due to the ingress of non-condensing gasses was less than 5.0 mm Hg (0.1 psia) in twenty-four hours with a system pressure of 80.0 mm Hg (1.6 psia).

After the installation of the test tube, an air ejector was used to reduce the system pressure to roughly 100.0 mm Hg (1.9 psia). At this point, the air ejector was secured and the boiler was energized. After boiling had commenced, the air ejector was again activated for approximately 10 minutes. Over many data runs, this purging procedure was validated by the absence of any improvement in the heat-transfer by additional purging.

1. Instrumentation

The power to the heaters was regulated through a silicon-controlled rectifier. This provided precise control and an accurate measure of the power being consumed. A mercury-in-glass manometer, calibrated in millimeters, was used to measure the internal pressure of the system. The temperature rise through the tube was measured by a dual channel Hewlett-Packard 2804A quartz thermometer. In order to provide in situ verification of the readings from the

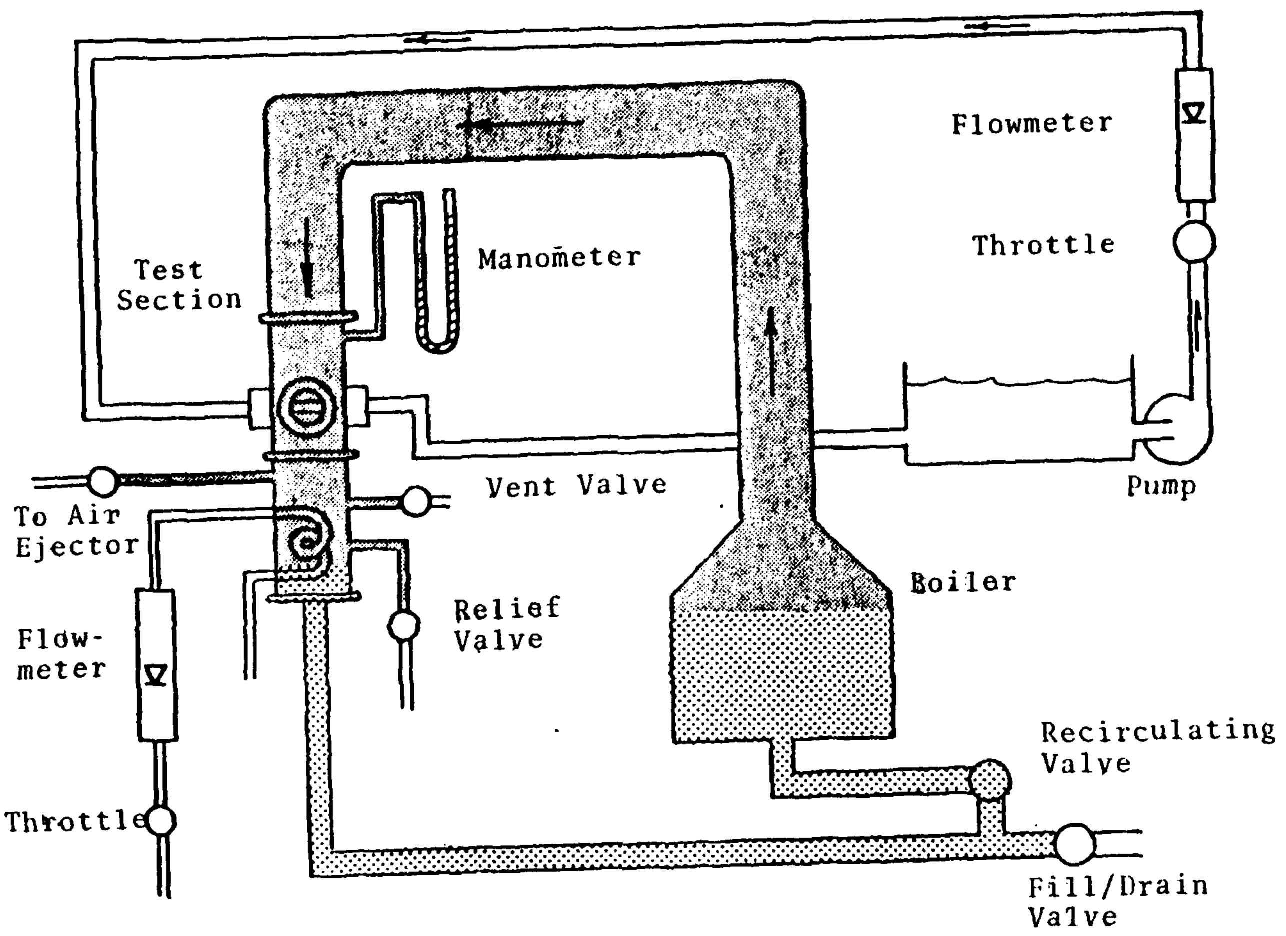


Figure 2.4 Heat-Transfer Test Apparatus Schematic

quartz thermometer, a ten-junction thermopile was also used to measure the temperature rise. Proper shielding of the thermopile wires eliminated the considerable rf frequency interference generated by the boiler rectifier at low voltages. The significance of this problem documented by Poole [Ref. 20]. Throughout all of the data runs, the quartz thermometer and the thermopile agreed to within ±0.03 K. A calibrated rotameter was used to measure the coolant flow rate through the tube.

All raw data were recorded on disk by a Hewlett Packard 9826A computer. With the exception of the manometer and rotameter, all data were interfaced through a Hewlett Packard 3497A Data Acquisition/Control Unit. The rotameter and manometer readings were manually entered from the keyboard into an interactive data logging and reduction program.

D. TEST SPECIMENS

1. Endurance Test

Four metals used in the construction of condensers were selected for use as test specimen substrates: copper, brass (70% copper, 30% zinc), Naval brass (60% copper, 39.25% zinc, 0.75% tin), and titanium. The copper, brass and titanium specimens were 0.76 mm (0.03 in) thick, while the Naval brass was 1.52 mm (0.06 in). The sheets were sheared into 25.4 mm (1.0 in) squares. Care was exercised to ensure that the shearing operation did not warp the specimens. Prior to surface preparation, the edges were lightly dressed with a file to remove the slight burr left by the shearing process.

Two surface finishes were used during this stage of testing. A "smooth" surface finish was produced by lapping the front face on a belt sander using 180 grit silicon carbide abrasive paper. This was followed by hand stroking the specimens on 400 grit followed by 600 grit abrasive paper mounted on a glass table. When changing grit, the specimen was rotated 90 degrees and stroked in only one direction until the markings from the previous abrasive were removed. The specimen was then placed in an ultra-sonic bath containing methanol for fifteen minutes and then blown dry. For adhesion purposes, a mirror-like finish was deemed undesirable. The procedure described was designed only to provide a uniform surface free of gross irregularities.

A "rough" surface was prepared by grit blasting with size 40 glass beads with the air pressure set at 0.138 MPa (20 psig). The surface roughness produced by this procedure was determined by means of a surface profilemeter. Representative samples were found to have a surface roughness ranging from thirty to fifty microinches RMS. These specimens were also cleaned in the ultra-sonic bath as previously described.

The surface preparation for the commercial coatings that were tested was dictated by the manufacturer. In most cases, the preparation was considered to be proprietary information. Therefore, if the actual surface preparation is not known, this fact will be noted. Otherwise, the terms "smooth" and "rough" refer to the procedures described in this section.

2. Heat-Transfer Test

The tubes used in the heat-transfer tests were machined from thick wall, low-oxygen copper pipe. The tubes were 0.129 m (9 in) long with an inside diameter of 12.7 mm (0.5 in) and an outside diameter of 19.0 mm (0.75 in). All of the tubes were machined at the Naval Postgraduate School and then shipped to various laboratories and commercial concerns for application of the particular coating.

E. POLYMER COATINGS

Fifteen organic coating systems were considered for endurance testing. Ten of the coatings are commercially available, while the remaining five are strictly experimental. A preliminary screening procedure was necessary to identify which coatings were likely to produce dropwise condensation. The principle characteristics for consideration were: (1) critical surface energy, (2) thermal stability, (3) the ability to be applied in ultra-thin layers, and (4) method of application.

The critical surface tension is not a parameter which is normally measured. However, knowing the chemical structure of the polymer, it was possible to estimate how well the coating could be expected to perform. Knowing that water has a surface tension of approximately 71.9 dynes/cm and referring to Table I, it can be seen that the fluorinated polymers could be expected to produce the best dropwise condensation, with the hydrocarbon surfaces the next best option. For this reason, nine of the coating systems selected contained fluorine. All of the coating systems had maximum recommended service temperatures in excess of 150 C. In addition, all but one system was advertised as being possible to apply in thicknesses of twelve micrometers (0.0005 in) or less.

It is important to note that the endurance test was designed to be rather harsh. None of the coatings tested were formulated or developed specifically for the purpose of promoting dropwise condensation. Therefore, qualitative assessments such as "poor dropwise" or "degraded with time" should not be construed as a critical statement of a coating's ability to perform satisfactorily under the environmental conditions for which it was intended. Simply stated, such comments are meant only to indicate that a coating did not perform satisfactorily under severe conditions for which it was not designed. After the evaluation of considerable product and research data, the following coatings were selected for evaluation:

1. No-Stik

No-Stik is a thermally conducting coating, impregnated with PTFE, which is applied by a thermal or plasma spray technique. No-Stik was developed by Plasma Coatings, Inc. for use as a hard-wearing, corrosion-resistant mold release for the paper, food and plastics industries. The actual process is proprietary information. Thermal conductivity is enhanced by loading the spray with copper during application. No-Stik has superior hardness and the ability to withstand temperatures in excess of 200 C (400 F). Unfortunately, the coating cannot be applied in thicknesses of less then 50 micrometers (0.002 in). If the coating were strictly an organic polymer, a thickness of this magnitude would provide a thermal resistance far greater than the reduction in thermal resistance due to dropwise condensation. However, since the coating is heavily doped with copper, it's thermal conductivity is difficult to estimate. Therefore, although the thickness of the coating did not fall below the estimated payback value of 20 micrometers (0.0015 in), it was still included for evaluation.

2. Nedox

Nedox is a commercially-available coating developed by the General Magnaplate Corporation for use as a corrosion-resistant mold release. The coating technique is a proprietary process in which a very porous, hard surface of chrome-nickel alloy is electro-deposited on the substrate surface. The pores are enlarged through a series of processes to accept the infusion of PTFE which forms a clear, ultra-thin coating over the entire surface. Precise control allows the coating to be applied as thin as five micrometers (0.0002 in). This was the thickness selected for testing.

3. Emralon 333

Emralon, a registered trademark of the Acheson Colloids Company, refers to a family of resin-based, fluoropolymer coatings. Emralon 333 is a one component blend of fluorocarbon lubricants in an organic resin binder. This coating was developed to provide dry-film lubrication and release properties for a variety of industrial purposes. In addition to a service temperature in excess of 200 C, the coating exhibits excellent resistance to abrasion, humidity, and chemical attack. Application is achieved with an external atomizer gun using an MBC #30 nozzle. The optimum thickness for wear and abrasion resistance is advertised to be twenty-five micrometers (0.001 in). The film thickness used for endurance testing was 20 micrometers (.0008 in).

4. Isonel 472

Isonel is a registered trademark of Schenectady Chemicals, Inc. Isonel 472 is a clear, thermosetting, modified polyester insulating varnish. Although not expected to perform as well as the fluorinated compounds, ease of application, availability, and low cost made investigation worthwhile. Application was accomplished by fastening a substrate to a horizontal turntable, placing a small amount of the varnish in the center followed by spinning at 5000 rpm for sixty seconds. A viscosity of 0.235-0.3 kg/m s at 25 C produced a film thickness of 5 to 10 micrometers (0.0002-0.0004 in). The specimen was then cured at 150 C for two hours. Application was performed at the Naval Postgraduate School.

5. Isonel 31-398

Isonel 31-398 is similar to Isonel 472. The varnish was applied in the same manner as previously described, but curing was accomplished at 100 C for one hour.

6. NRL C-6 Fluoroepoxy

For the past fifteen years, development of fluorinated polymers has been a continuing research effort at Naval Research Laboratory located in Washington, D.C. The C-6 fluoroepoxy was developed by Dr. James Griffith at the Naval Research laboratory in an effort to produce a thin, tough protective coating which would also provide extremely low fluid absorption. At present, the coatings are experimental and not available to the general public. All of the NRL coatings referenced in this thesis were formulated and applied by Dr. Griffith.

C-6 fluoroepoxy is a thermosetting polymer. It is so named because of the perfluorinated, straight-chain hexyl group present on the five position of the central benzene ring (see Figure 2.5). Thermosetting compounds are characterized by being insoluble in virtually all commercial solvents and by the lack of a melting point. When exposed

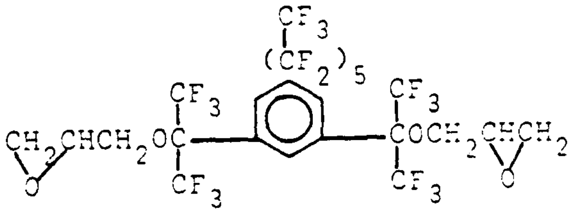


Figure 2.5 Chemical Structure of NRL C-6 Fluoroepoxy.

to high temperatures, thermosetting compounds decompose rather than melt. These characteristics dictate that polymerization take place on the surface after application. It is important to note that the fluorine is not located in the vicinity of the reactive epoxy groups and therefore plays no role in the polymerization reaction. In addition, each carbon-bearing fluorine is totally fluorinated. This results in maximum stability with regard to environmental degradation.

The C-6 fluoroepoxy had previously been tested by both Manvel [Ref. 8] and Perkins [Ref. 22]. The results were disappointing because of the rapid degradation of the coating. Manvel [Ref. 8] reported that the coating appeared to dissolve after a short period of exposure to steam. Since the epoxy is a thermosetting polymer, dissolution is virtually impossible under the test conditions stated. More likely, these earlier results were caused by an inadequate bond between the substrate and the coating, allowing it to be physically removed, or by an insufficient cure which allowed the coating to remain intact but lose its hydrophobic properties. After discussing these problems with Dr. Griffith, a modified C-6 was supplied for the endurance test. The catalyst used was ethylene-diamine. Curing took place at room temperature for eight hours followed by forty-eight hours at 90 C.

7. NRL BCE-7 Fluoroepoxy

The BCE-7 fluoroepoxy has an chemical structure as depicted in Figure 2.6. Although similar to the C-6, there are basic differences in the group attached to the five position on the central ring. In addition, a fluoro anhydride curing agent was utilized with the following cure schedule: three days at room temperature, twenty-four hours at 70 C and seventy-two hours at 120 C.

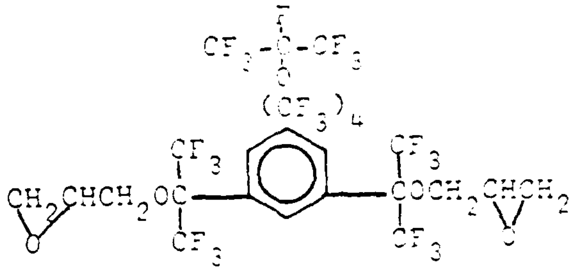


Figure 2.6 Chemical Structure of NRL BCE-7 Fluoroepoxy.

8. NRL C-6' Fluoroepoxy

The C-6' fluoroepoxy was a variation of the BCE-7 fluoroepoxy formulated by using an adduct of the C-6 fluoroepoxy as the curing agent. The curing process was the same as that of the BCE-7 coating.

9. NRL Fluoroacrylate

Like the fluoroepoxies, the NRL fluoroacrylate is a thermosetting polymer. After application, the specimens were subjected to a nitrogen purge at 50 C. Catalysis was

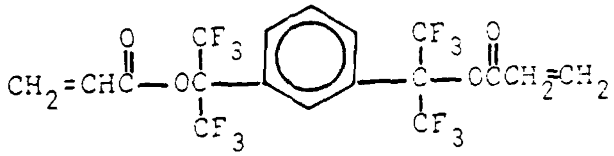


Figure 2.7 Chemical Structure of NRL Fluoroacrylate.

accomplished by exposure to long wave length, ultraviolet light at 80 C for 30 minutes. The chemical arrangement of the fluoroacrylate is shown in Figure 2.7.

10. NRL Fluoroacrylic

The NRL Fluoroacrylic was characteristic of a linear thermoplastic. The acrylic differs from the epoxies and the acrylate in that there is no three dimensional, cross-linking between the polymer chains. This makes the acrylic inherently less tough. In addition, being a thermoplastic rather than a thermosetting plastic, polymerization takes place prior to application. After polymerization, the acrylic can be dissolved in a commercial solvent and then applied. In this case, freon was used as the carrier. Curing was accomplished at room temperature by evaporation of the carrier. Unlike a thermosetting plastic, the acrylic can be removed by dissolving it with freon. The chemical structure of the fluoroacrylic is shown in Figure 2.8.

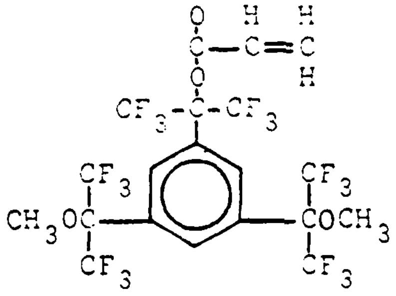


Figure 2.8 Chemical Structure of NRL Fluoroacrylic.

11. Sputtered PTFE

PTFE was sputter deposited on the various substrates at the Lewis Research Center, National Aeronautics and Space Administration. Briefly, sputtering is accomplished by placing a target, in this case PTFE, and the substrate to be coated in a vacuum chamber. The chamber is evacuated and then backfilled at low pressure with an inert gas. An RF power supply is utilized to provide a negative voltage on the target which causes it to become a cold cathode electron emitter. The emitted electrons ionize atoms of the gas which are then accelerated toward the negatively charged target. The positive ions strike the target with sufficient force to dislodge atoms or molecules. These dislodged molecules move through the plasma and re-polymerize on the substrates and the exposed surfaces of the chamber. A thorough description of the glow discharge process is given Ref. 9.

This process has the ability to deposit ultra-thin coatings of uniform thickness on virtually any substrate. The process does have some drawbacks. Deposition is basically line-of-sight and relatively slow. These characteristics make it somewhat difficult to coat a round object such as a tube. The one-inch-square sputter coated specimens had a coating thickness of approximately 0.4 micrometers which required approximately one hour of deposition time.

12. Parylene-N

Parylene is a generic name for a family of thermoplastic polymers developed by the Union Carbide Company for use as a conformal, insulating coating for the electronics industry. The most basic parylene member, parylene-N, has the simple chemical structure shown in Figure 2.9. Because it is not practical to melt or extrude and because it is

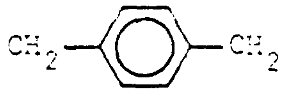


Figure 2.9 Chemical Structure of Parylene-N.

insoluble in conventional solvents, parylene is not produced as a polymer like most thermoplastics. Instead, it is produced as a dimer. The dimer is put through a two-step heating process under vacuum. This process produces a reactive monomer vapor which, when passed over an object at room temperature, polymerizes on the surface forming a uniform coating. Parylene is tough, can be applied as thin as 0.1 micrometer (4.0×10^{-6} in), has excellent chemical resistance, and is thermally stable up to 120 C. Most importantly, unlike most other vacuum deposition processes, the process is not "line-of-sight." The process will produce a uniform coating on the top, bottom, and edges, inside and out, on virtually any object.

The parylene coatings were applied by the Lawrence Livermore National Laboratory (LLNL), which is licensed by the Union Carbide Corporation. Two sets of samples were coated with parylene-N; one set with a thickness of 0.5 micrometer (2.0×10^{-5} in) and the other 1.0 micrometer (4.0×10^{-5} in).

13. Parylene-D

Parylene-D, a double chlorinated parylene, is applied in the same manner as parylene-N. It has the chemical structure shown in Figure 2.10. Parylene-D was selected for evaluation because it possesses a moisture-vapor transmission rate only one-sixth that of parylene-N. As before, two sets of samples with thicknesses of 0.5 and 1.0 micrometer were supplied by LLNL.

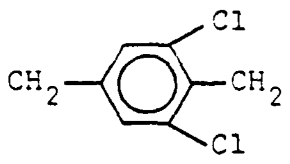


Figure 2.10 Chemical Structure of Parylene-D.

14. Pepco 6122

Pepco 6122 is a graphite-based, solid film lubricant developed for the nuclear industry by Power and Engineered Products, Co. This coating is stable to 300 C, has a coefficient of friction of 0.08, is chemically resistant, and can be applied by spray as thin as 12.0 micrometers (0.0005 in).

15. Silicone

Silicone polymers possess unusually low surface tensions. Silicones are available as oils, greases, rubbers and as thermoplastic or thermosetting polymers depending upon the monomer and polymerizing conditions. The basic silicone structure consists of a silicon-oxygen-silicon backbone combined with organic groups. By varying the organic side chains, the properties of the polymer can be varied. For example, methyl groups have been used to promote thermal stability and water repellency in silicone fluids. An examination of Table I indicates that a critical surface tension as low as 21 dynes/cm could be expected from this combination.

The silicone tested was Silgan J-500, a high quality commercial coating manufactured by the SWS Silicones, Inc., known for its durability and toughness. Application of this coating was performed at the Naval Research Laboratory. Unfortunately, the coating proved to be somewhat difficult to apply which resulted in a rather thick, uneven coating. It was decided to test the coating for its endurance and hydrophobic characteristics before attempting to develop a procedure for applying a thin, uniform layer.

III. EXPERIMENTAL PROCEDURES

A. ENDURANCE TEST

Forceps were used to hold the specimens against the heat sink while they were clamped in place. The glass side panels were then placed in position and the nuts secured finger-tight. The three coolant control valves were opened to their maximum positions allowing water to pass through the heat sink. The steam regulating valve was opened until steam issued from the branch line beneath the chamber. As the steam condensed, the condensate would return and commence filling the de-superheater. Steady-state was reached in approximately one hour when the de-superheater was roughly one-third full. At this point the returned condensate was balanced by overflow from the de-superheater discharge. The steam regulating valve was then adjusted to provide a steady flow of steam from the branch line. This ensured that the chamber was receiving the maximum amount of steam which could be condensed.

Visual observations were conducted daily. In order to provide a permanent, visual record, photographs were taken at the following intervals: 0, 260, 790, 1500, and 2000 hours. Periodically, the system was shut down in order to remove specimens which were not performing satisfactorily. These were set aside for examination under the scanning electron microscope (SEM), and new samples were installed in their places.

B. HEAT-TRANSFER EVALUATION PROCEDURE

With one exception, Poole [Ref. 20] provides a detailed description of the operational procedures, data reduction, and computer programs utilized during the heat-transfer evaluation stage. The one exception concerns the use of a spiral insert placed within the tube being tested in order to enhance the inside heat-transfer coefficient. The justification for enhancement of the inside coefficient can be explained by examining the manner in which the outisde heat-transfer coefficient was determined.

The total heat transfer can be computed from equation (3.1); the right-hand side being measured or known quantities.

$$Q=mc_p\Delta T \qquad (3.1)$$

The overall heat-transfer coefficient can now be computed using equation (3.2):

$$U = Q/A_o\Delta Tlm \qquad (3.2)$$

Since the inside of the tube was thoroughly cleaned before testing, and all of the noncondensing gases were effectively eliminated, the resistances due to these two factors were considered negligible.

Since the inside heat-transfer coefficient had previously been established using the Sieder-Tate correlation and the wall resistance was well established, the outside heat-transfer coefficient, which is a combination of the condensation resistance and the coating resistance, can be computed from equation (3.3):

$$1/h_o = 1/U_o - A_o/h_iA_i - R_w \qquad (3.3)$$

During filmwise condensation on a smooth tube, the outside and inside resistances are of the same order of magnitude. However, with dropwise condensation, it was anticipated that the outside resistance would be much smaller than the inside resistance and the inside resistance would control the process. Therefore, small uncertainties in the determination of the inside resistance would produce relatively large variations in the computed value of the outside resistance. In order to minimize this effect, the inside coefficient was enhanced by utilizing a concentric spiral insert which ran the length of the tube. The increased turbulence produced by the insert resulted in a decrease in the internal thermal resistance. Utilizing a plain copper tube instrumented with six wall thermocouples and the spiral insert, the inside coefficient was determined using a Sieder-Tate-type correlation of the form shown in equation (3.4):

$$Nu = C_i Re^{0.8} Pr^{1/3} (\mu/\mu_w)^{0.14} + B \qquad (3.4)$$

Details regarding the determination of this coefficient are provided in Ref. 20 and Ref. 26.

C. PHYSICAL PROPERTIES TESTS

Two standard testing procedures were employed to assess specific physical characteristics of each coating; ASTM specifications D 3359-78 <u>Measuring Adhesion by Tape Test</u> and D3363-74, <u>Film Hardness by Pencil Test</u>. Since both of these tests are destructive, it was not possible to subject specimens which were to be tested for endurance. Therefore, at least one specimen from each group of coatings was held back for destructive testing. The results derived from the testing one specimen per set were assumed to be representative of all samples in that set.

To provide statistically valid results which would ensure repeatability and reproducibility, these tests should be performed on a large number of samples. Due to the limited availability of many of the coatings, this was not possible. These tests were performed to provide a relative indication of toughness and durability and to indicate the likelihood of the degradation of these characteristics upon exposure to steam for extended periods.

IV. RESULTS AND DISCUSSION

A. ENDURANCE TEST

During this stage of the thesis, evaluation was limited to visual observation supported by periodic photographic sessions. With ideal dropwise condensation, the drops should appear spherical in shape, exhibit a large contact angle and grow to no more than two to three mm in diameter before departure. Departure from a vertical surface should be swift, straight down and the drop should retain its spherical shape. A flat appearance with irregularly-shaped edges during growth and the presence of a "tail" during departure are indications of "less-than-ideal" dropwise condensation. Although ideal dropwise condensation was the most desirable characteristic, durability and ease of application were also important considerations. Therefore, a of number coatings which exhibited somewhat less than ideal dropwise condensation were still considered for heat-transfer measurements. A summary of all the coatings and the results of this stage of testing are provided in Table II.

1. No-Stik

Two identical sets, each consisting of four samples representing the four different substrates, were tested. Application and surface preparation were performed by the manufacturer. In order to verify previous observations, the second set was installed in the steam chamber approximately 2000 hours after the first set. Micrometers were used to determine a mean coating thickness of approximately 60 micrometers (0.0025 in). Due to the uneven texture of the

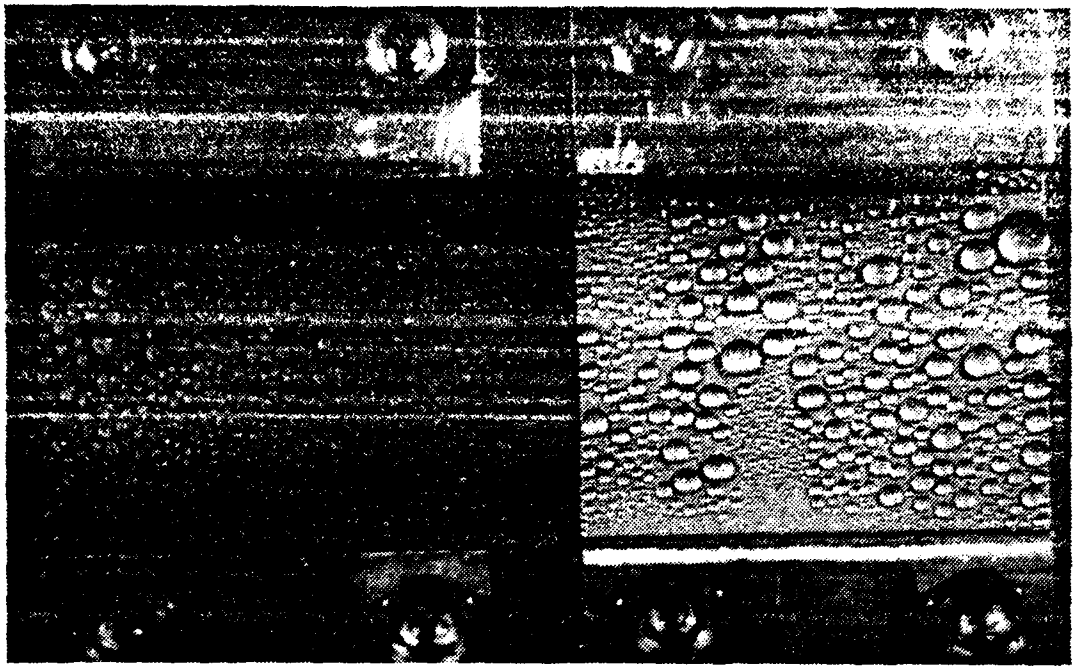


Figure 4.1 No-Stik and Nedox on NBr 0 hrs.

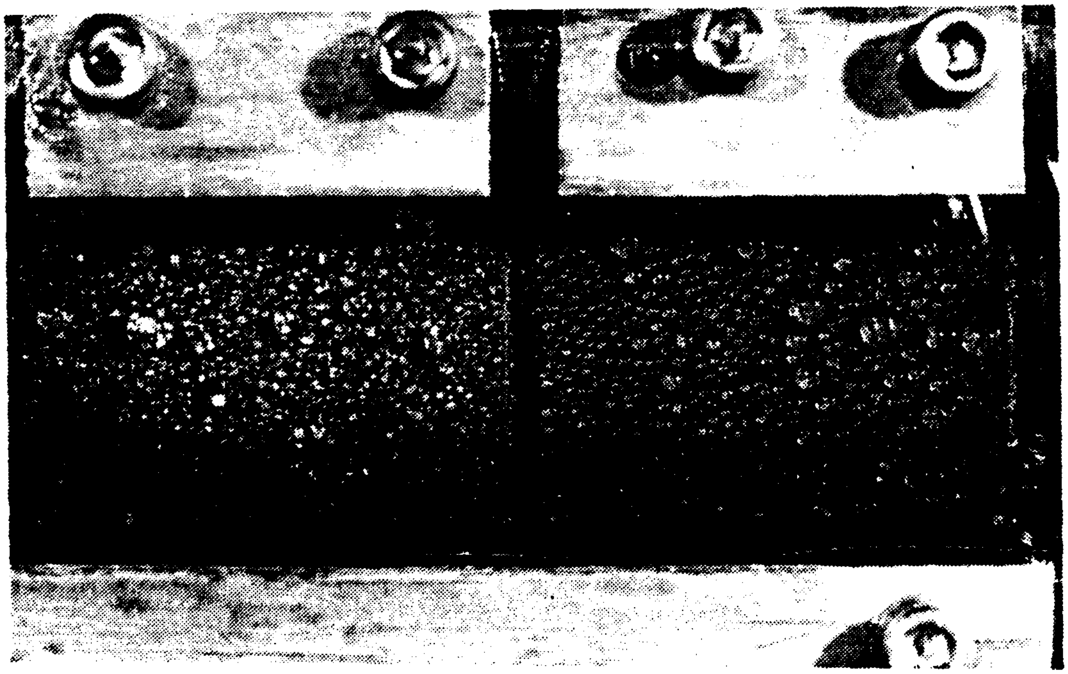


Figure 4.2 No-Stik Br Ti 790 hrs.

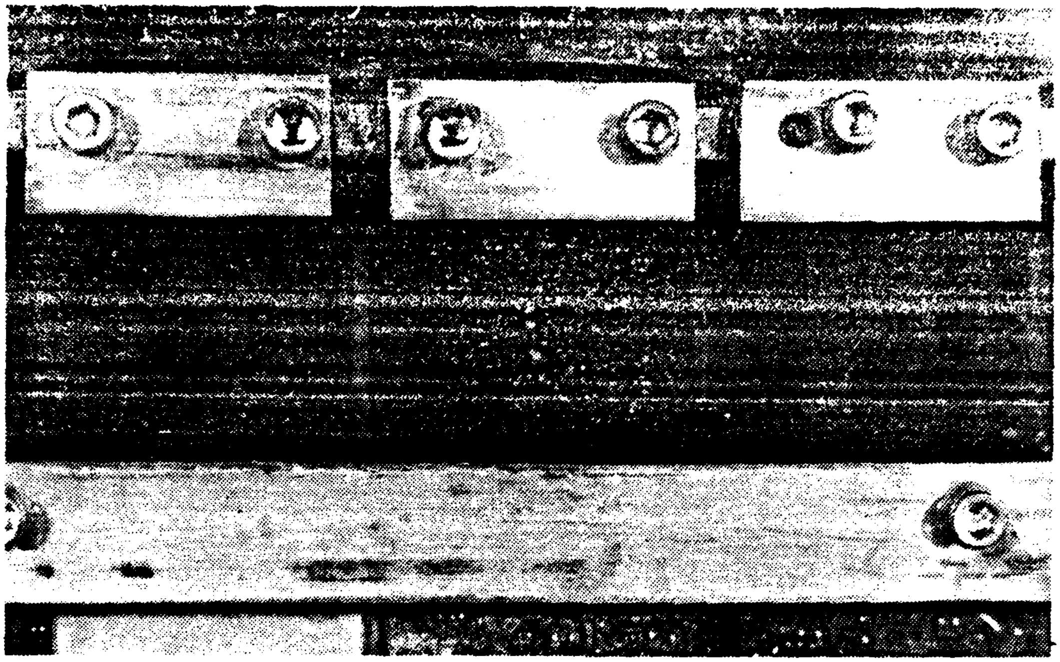


Figure 4.3 No-Stik Cu Br Ti 1500 hrs.

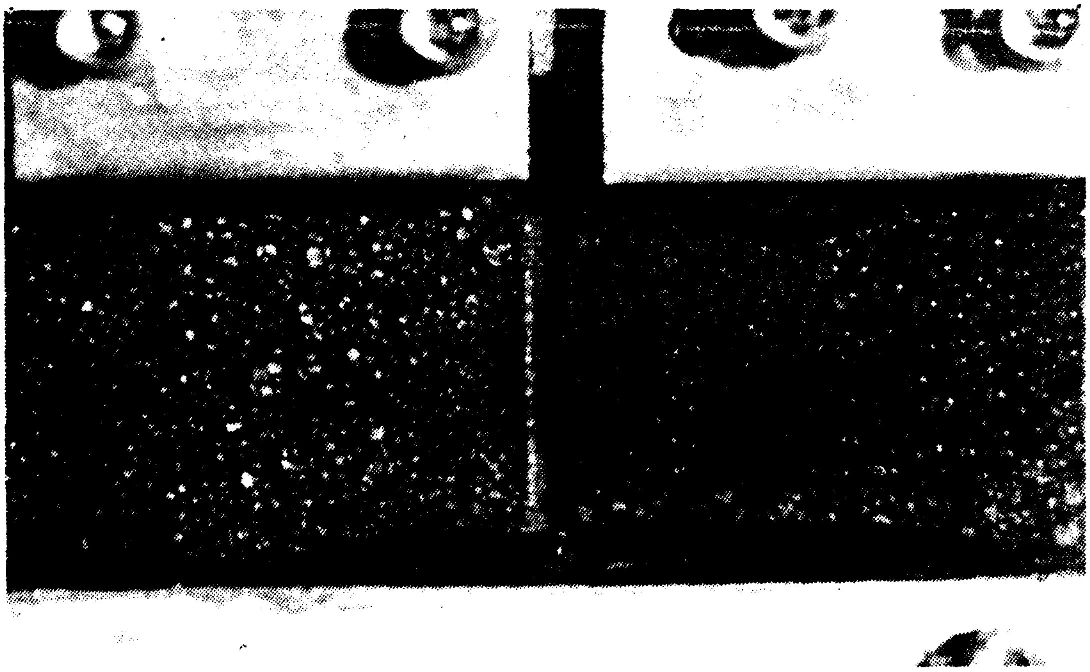


Figure 4.4 No-Stik Cu Br 4000 hrs.

coating, an exact measurement of the coating thickness was not possible. The excellent quality of the dropwise condensation is readily apparent in Figures 4.1 through 4.4. The drops are nearly spherical, exhibit a relatively large contact angle, and grow to approximately 2.5 mm before departure. However, the rate at which the drops departed the surface was noticeably less than that of other specimens with thinner coatings. This indicated a lower heat flux caused by the thermal barrier imposed by the coating.

After more than 4000 hours of continuous exposure, this coating showed virtually no signs of physical degradation. The brass and copper samples were lightly speckled with green which was attributed to oxidation of the copper. An examination of an "as delivered" sample with the SEM revealed small holes in the coating which exposed the substrate. Examination of an exposed specimen revealed that, although the coating was not affected, the substrate was being attacked at these void sites. However, this did not appear to affect the quality of the dropwise condensation, nor did the oxidation appear to undermine the coating in the immediate vicinity of the voids.

Based upon the quality of the condensation and the durability of the coating, No-Stik was selected for heat-transfer measurements.

2. Nedox

A total of eight Nedox samples were tested, two sets of the four different substrates. Surface preparation and application were performed by the manufacturer. The coating thickness, supplied by the manufacturer, was approximately 5.0 micrometers (0.0002 in). This was confirmed by viewing a sectioned sample under the SEM.

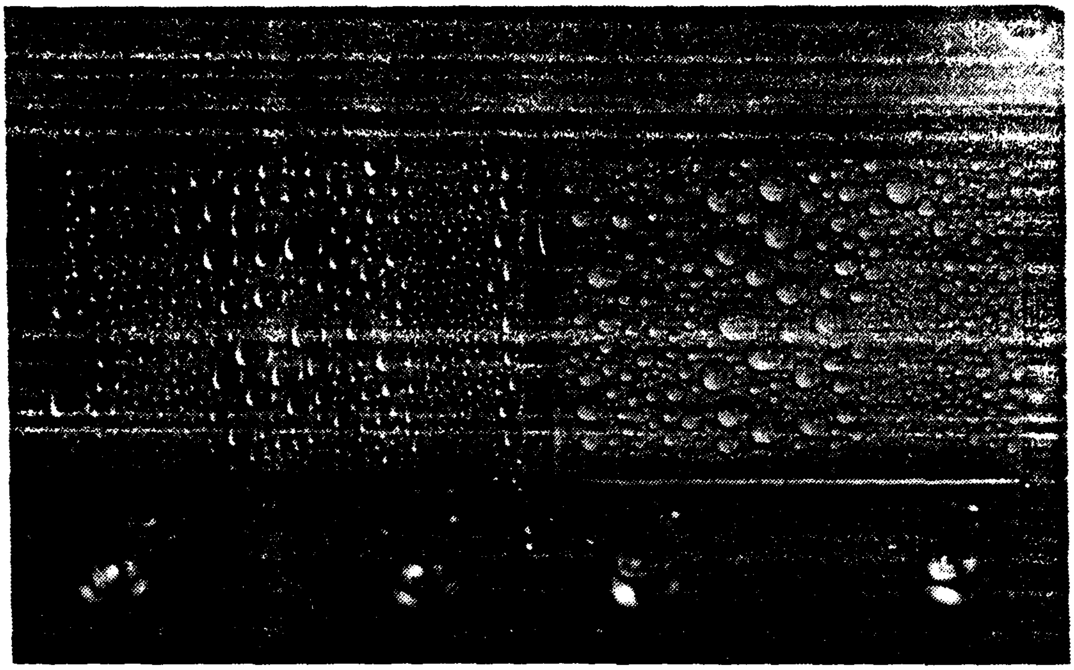


Figure 4.5 Nedox Br Ti 0 hrs.

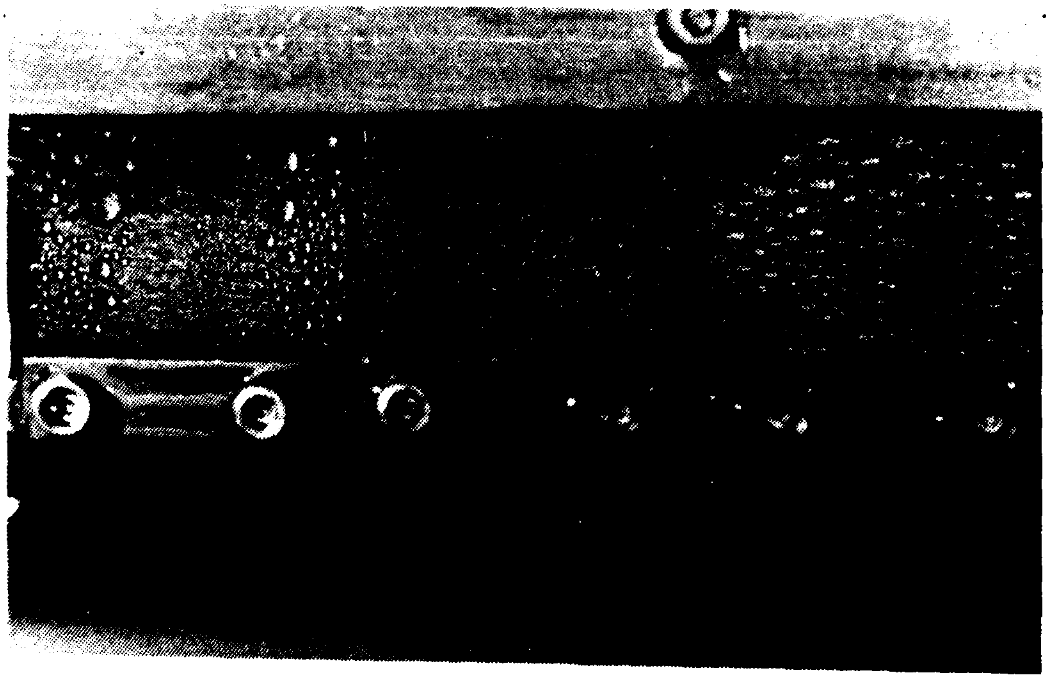


Figure 4.6 Nedox Br Ti Cu 264 hrs.

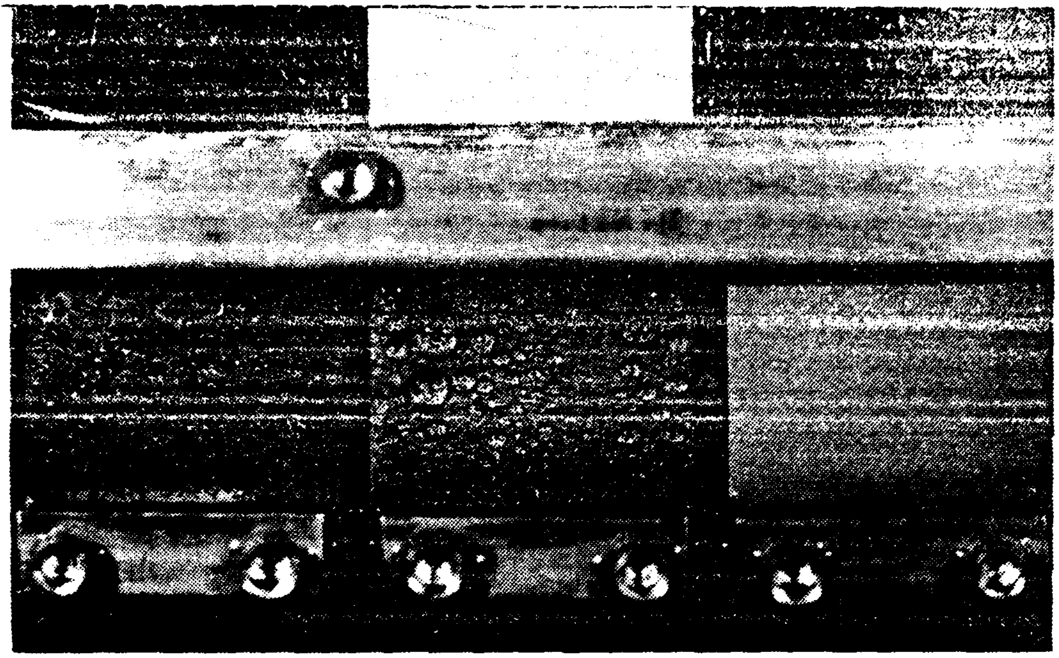


Figure 4.7 Nedox Ti Cu Blank 790 hrs.

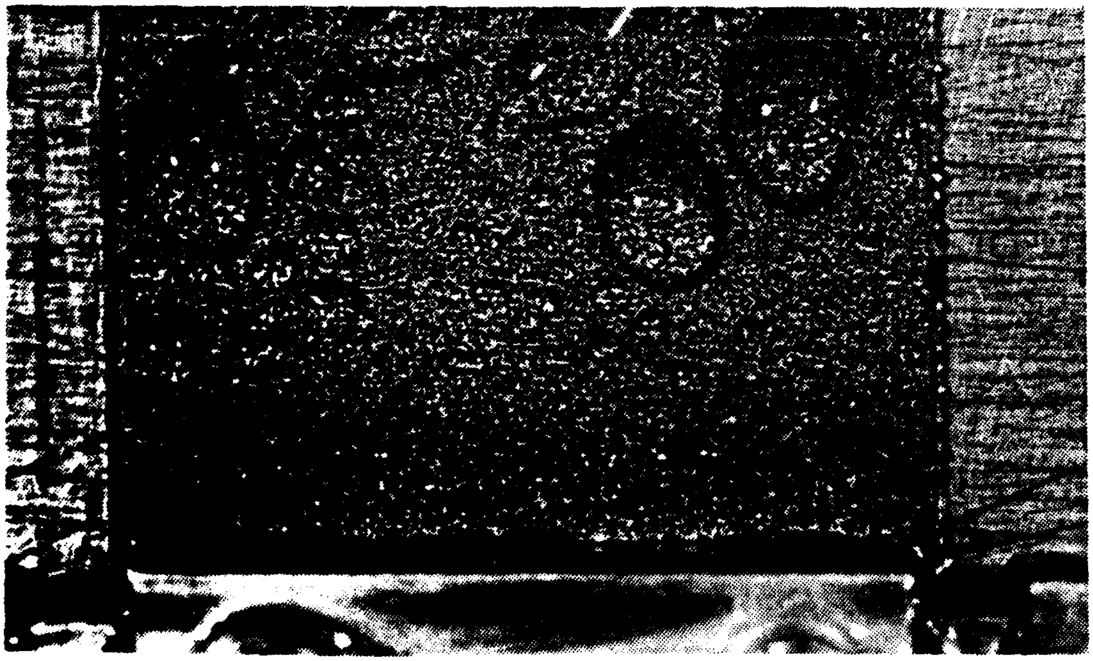


Figure 4.8 Nedcx Cu 2000 hrs.

As can be seen in Figure 4.5, the initial dropwise condensation was very good to excellent. This was true for all specimens. However, after forty-eight hours, all of the samples were noticeably darker in color, indicating a reaction of the substrate with the environment. At this point, the quality of the dropwise condensation was not noticeably affected. After 240 hours, the condensation mode on the upper-half of the naval brass specimen was filmwise. This specimen was removed for examination. After 1200 hours, only the copper specimen exhibited any degree of dropwise condensation. The changes in the quality of the condensation mode is readily evident from Figures 4.5 through 4.8. After 3000 hours, the remaining specimens were removed and the second set was installed. Although the exposure time varied, the pattern of performance was virtually the same; very good to excellent dropwise condensation occurred initially, with a gradual darkening of the substrate followed by a gradual degradation in dropwise performance.

Examination of an unexposed specimen under the SEM revealed a mottled surface covered by a thin, smooth, transparent film. The transparent film was presumed to be the Teflon coating while the mottled appearance was due to the chrome-nickel plating. Examination of an exposed specimen revealed that although the chrome-nickel plating was intact, the film had been peeled back or completely removed. Pieces of the film still partially attached were visible with the naked eye. The loss of the Teflon film accounted for the loss of the hydrophobic characteristics of the coating. However, the exact cause of this loss could not be determined.

Despite reservations about the durability of this coating, the excellent nature of the dropwise condensation made this coating a candidate for the heat-transfer experiments.

3. Emralon 333

A total of seven Emralon samples were tested. Application and surface preparation were accomplished by the manufacturer of the coating. A set of four samples, one for each substrate, was initially loaded into the chamber while the second set of three samples, copper, titanium, and brass, was installed approximately 2000 hours later. The naval brass sample was withheld for destructive testing.

On startup, all of the samples behaved predictably: condensation was mixed to filmwise. This behavior was anticipated because the fluorocarbon lubricants are bonded to the substrate with an organic resin binder which was not likely to possess a particularly low surface energy. Examination under the SEM revealed fluorocarbon particles imbedded in a resin matirx. However, with one exception, the mode of condensation gradually began to change after approximately 500 hours of exposure. Except for the copper sample, the condensation first turned from mixed to poor dropwise and then to good dropwise. After 1000 hours, the titanium, brass and naval brass samples were producing fair to excellent dropwise condensation (see Figures 4.9 through 4.12). An SEM examination of the exposed specimens revealed that the resin binder had been washed or eroded away, thereby exposing more of the imbedded fluorocarbons. This effectively lowered the critical surface tension of the condensing surface. The copper specimen never produced dropwise condensation. In fact, since faint copper colored areas could be seen with the naked eye, it was evident that the coating had been almost completely removed. These results were consistent for both sets of specimens.

Although the brass, titanium and naval brass specimens produced good to excellent dropwise condensation in excess of 4000 hours, Emralon 333 was not considered for

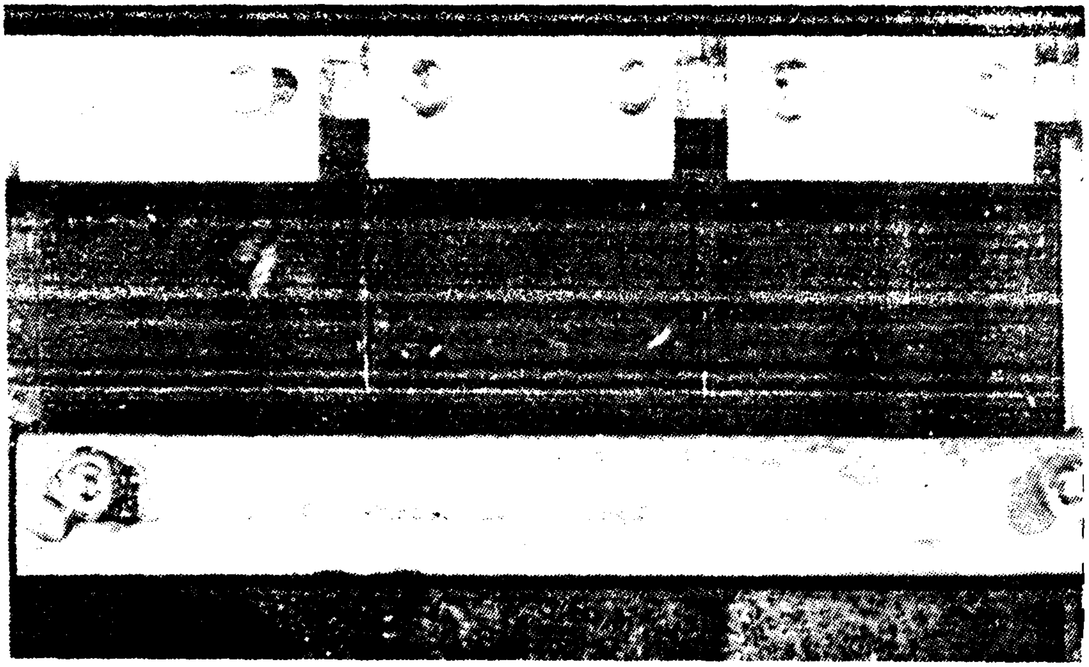


Figure 4.9 Emralon 333 Br Cu Ti 1500 hrs.

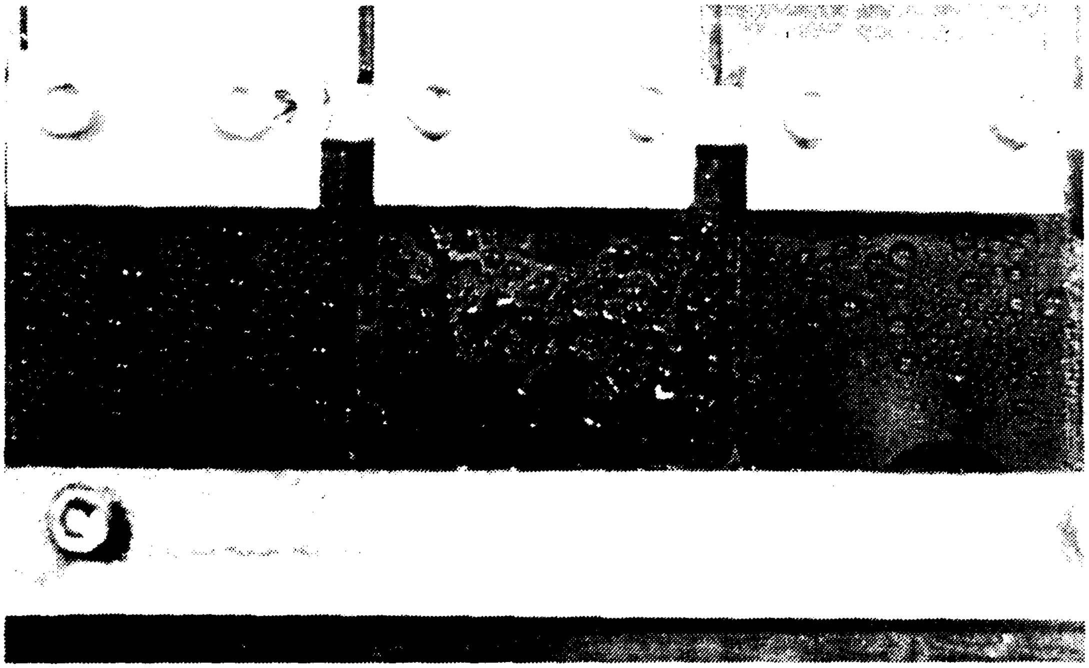


Figure 4.10 Emralon 333 Br Cu Ti 2000 hrs.

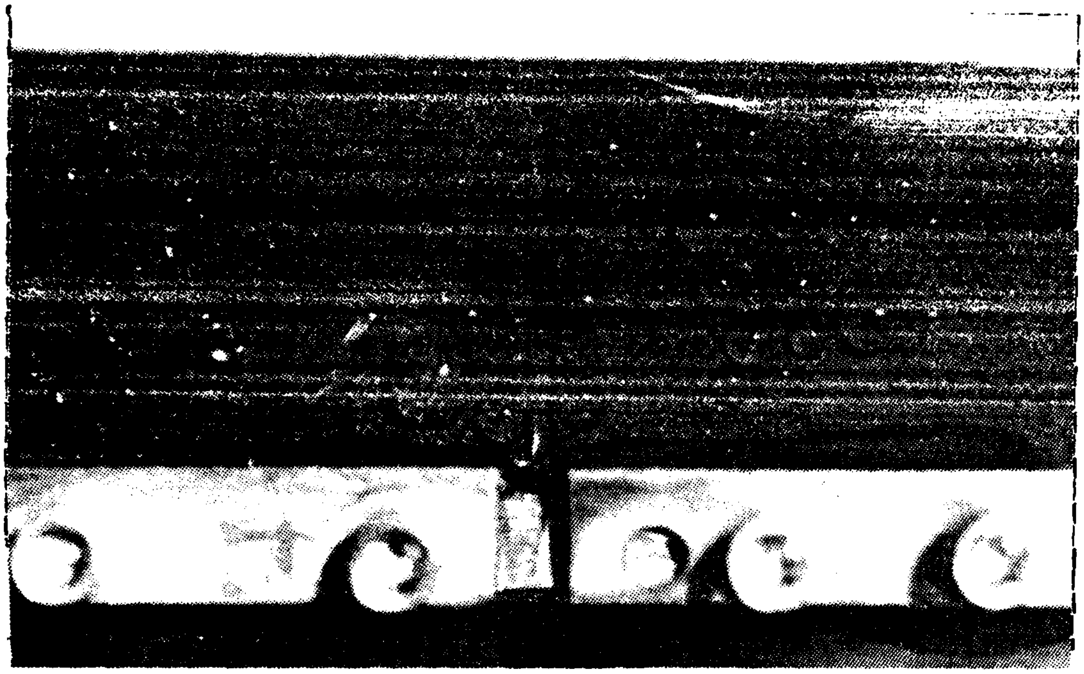


Figure 4.11 Emralon 333 Cu Ti 2700 hrs.

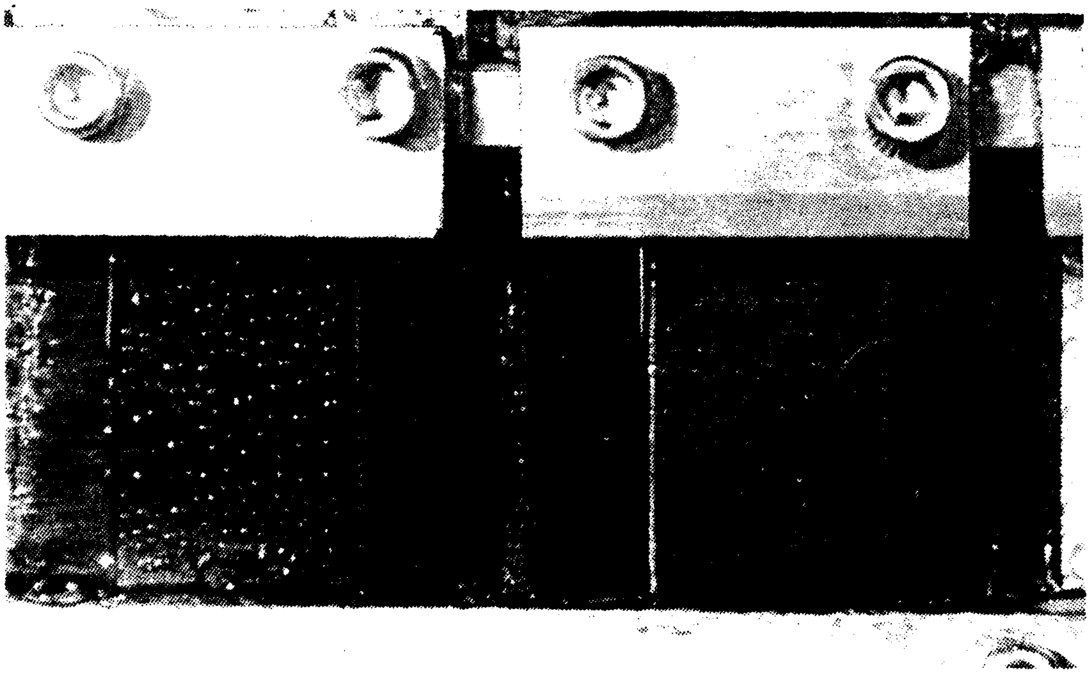


Figure 4.12 Emralon 333 Br Ti 3000 hrs.

heat transfer measurements because of the necessity of "ageing" the coating and the undesirable effect of contamination of the heat transfer apparatus due to the removal of the binder.

4. Isonel 472

A total of eight Isonel 472 samples were tested; four substrates, each with rough and smooth surface finishes. The initial condensation mode was characterized as fair to poor dropwise. The drops exhibited a relatively low contact angle, were irregular in shape, and grew to approximately 5.0 mm (0.2 in) before slowly departing the surface. After twenty-four hours of exposure, the condensation mode had changed to filmwise. This indicated a change in the critical surface tension of the condensing surface. This change was attributed to absorption of water by the coating. This result was the same for all samples. After 1000 hours, the samples were removed. No further observations were conducted.

5. Isonel 31-398

A total of eight samples were tested. The results were virtually identical with those of the Isonel 472. No further observations were conducted.

The performance of the 472 and the 31-398 was not unexpected. These polyesters could be expected to present basically a hydrocarbon surface to the condensing steam. Therefore, these compounds could be expected to have a relatively high critical surface tension which should produce relatively poor quality dropwise condensation. Other physical characteristics, such as ease of application and availability, made polyesters an attractive candidate. However, their inability to sustain dropwise condensation eliminated them from further consideration. No further tests were performed with these compounds.

6. NRL C-6 Fluoroepoxy

Six C-6 samples were tested; substrates of copper, naval brass, and titanium were used with the two surface finishes previously described. The brass samples were reserved for destructive testing. Because this compound is only available in limited quantities, application was by brush rather than by spraying or spinning. This resulted in an uneven surface texture estimated to be 5.0 to 10.0 micrometers thick. The estimate of the coating thickness was determined with micrometers and confirmed by viewing a sectioned portion of a specimen with the SEM.

All of the test specimens produced fair to good dropwise condensation. As can be seen in Figures 4.13 through 4.16, the drops are somewhat flat, irregular in shape, and grow to 4.0 mm (0.16 in) in diameter before slowly departing the surface. After 100 hours of exposure, the surfaces of the copper and naval brass specimens showed signs of oxidation. The oxidation grew progressively worse until after 1000 hours the surfaces were completely black. The oxidation of the surfaces of the reactive substrates indicated that the coating was incapable of completely insulating the substrate from the environment. However, this did not seem to adversely affect the performance of the coating which remained virtually unchanged during the first 2000 hours of operation. After 2400 hours, all of the smooth samples exhibited some degree of separation of the coating from the substrate. After 3000 hours, the coating became unbonded from the smooth samples causing blisters and bare spots over 20% to 30% of the surface. This condition existed in excess of 4000 hours.

Although the oxidation of the copper and naval brass surfaces could be blamed for the deterioration of the adhesive qualities of the epoxy, this is not the case for

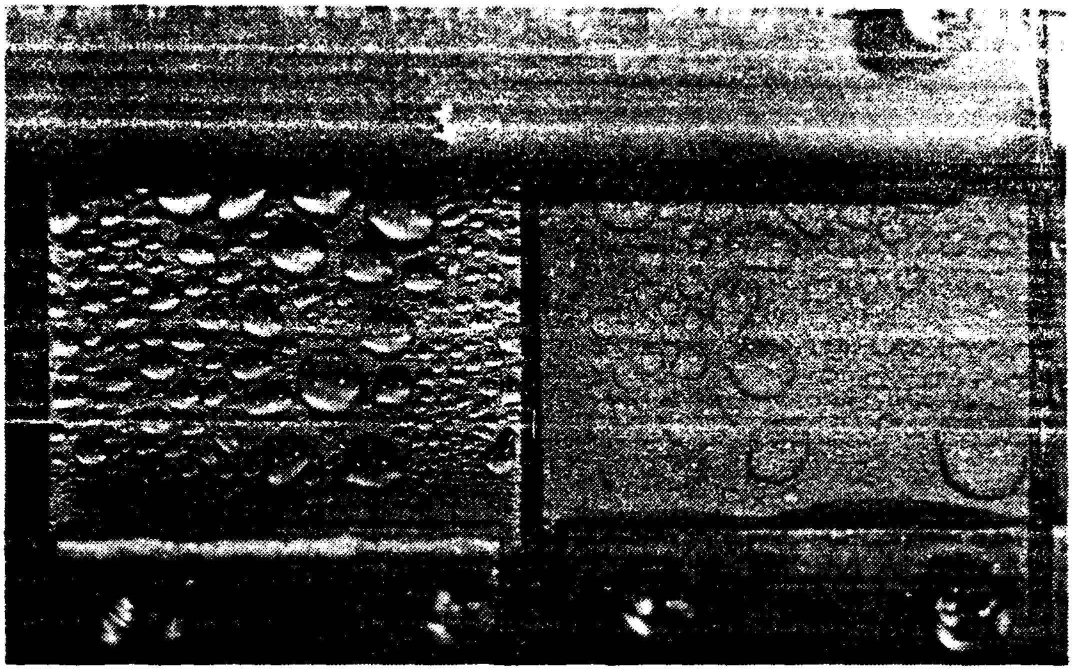


Figure 4.13 NRL C-6 Cu/S Cu/R 0 hrs.

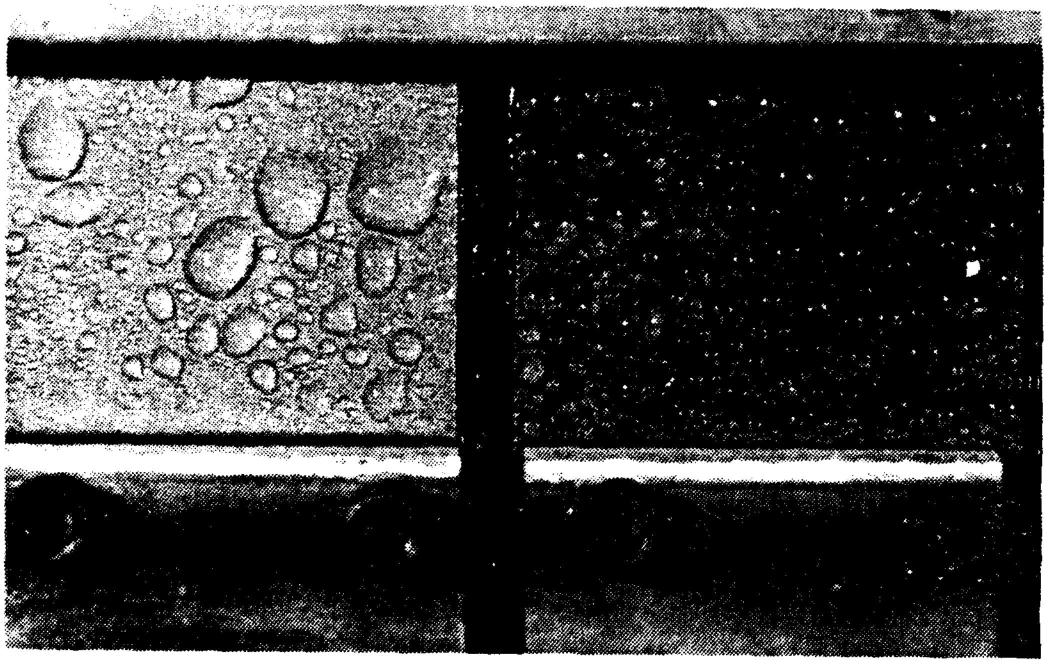


Figure 4.14 NRL C-6 Ti/R Cu/S 790 hrs.

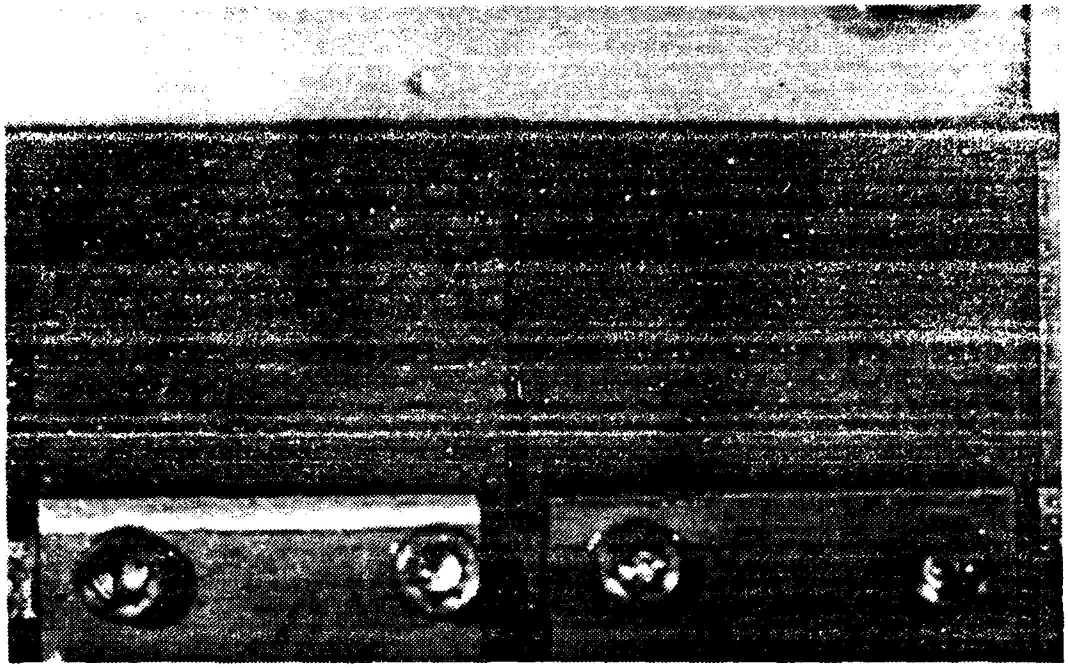


Figure 4.15 NRL C-6 Cu/S Cu/R 1500 hrs.

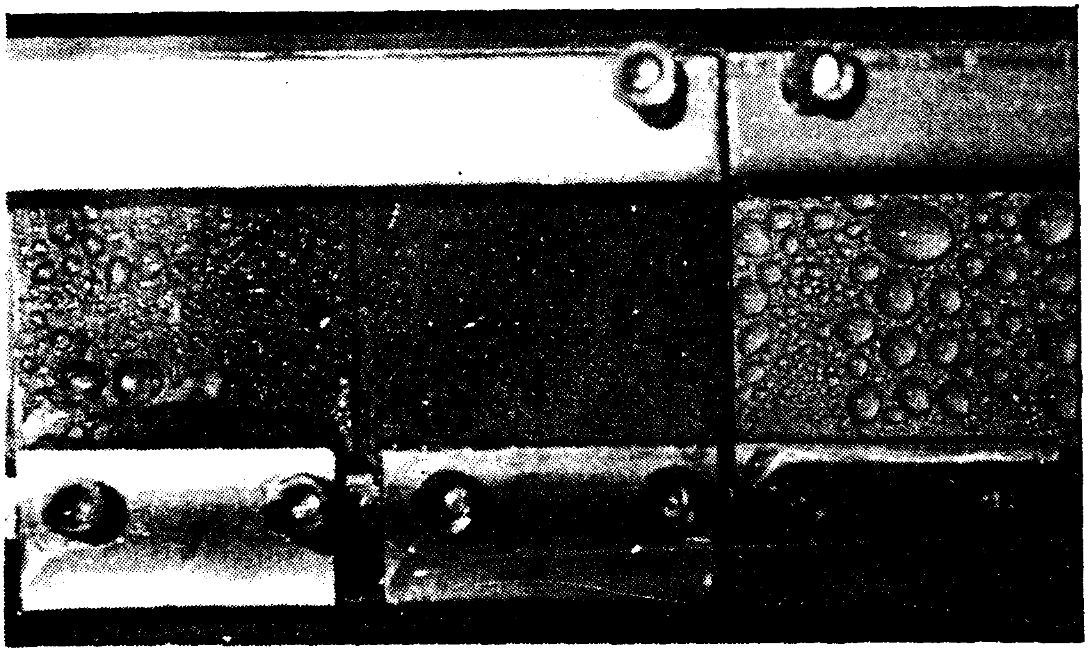


Figure 4.16 NRL C-6 Cu/S Cu/R 4000 hrs.

titanium. Rather, this condition seems to indicate an inadequate bond with the smooth surfaces. Although the rough specimens did not experience any delamination over the 4000 hours of testing, it is anticipated that the effect of the oxide layer will eventually have a deleterious upon the adherence of the coating.

Based upon durability and good dropwise performance, this coating was selected for heat-transfer evaluation.

7. NRL C-6' Fluoroepoxy

The specimen arrangement for the C-6' fluoroepoxy as well as the application and thickness of the coating were identical to the C-6 epoxy. In addition, the endurance test results were virtually the same. The reactive surfaces experienced progressive oxidation, changing in color from a bright copper or brass to a uniform dull black. After roughly 1000 hours, the coatings on the smooth specimens showed signs of deterioration. Approximately 30% of the coating had been removed from the smooth titanium sample, while on the smooth copper and naval brass samples, although physically present, the coating had blistered and cracked allowing condensate to pass between the coating and the substrate. After 2400 hours, the rough specimens were still performing well. The departure size and shape of the drops did not differ markedly from the C-6. Therefore, this coating was not selected for heat-transfer measurements.

8. NRL BCE-7 Fluoroepoxy

A total of six BCE-7 specimens were tested including both rough and smooth surfaces of the copper, naval brass and titanium substrates. Although this coating should have been highly hydrophobic because of the high concentration of $-CF_3$ groups, the dropwise condensation was judged to be only fair. Within two hours, the condensation mode had changed to filmwise. Closer examination revealed that over 90% of the coating had been removed from the substrate. The rapid deterioration of this coating was entirely unexpected. An explanation for the inadequate bonding of the coating to the substrate was not apparent. However, the performance was consistent for all substrates and surface finishes. No further tests were attempted with this coating.

9. NRL Fluoroacrylate

A total of six fluoroacrylate specimens were tested including both rough and smooth surfaces of the copper, titanium and naval brass substrates. As with the BCE-7 fluoroepoxy, this coating was virtually non-existent on any of the substrates within two hours. Since both coatings are thermosetting polymers, they cannot be dissolved. Therefore, this behavior appears to indicate an inadequate bond between the coating and the substrate. An adequate explanation for this behavior could not be discerned from the limited number of samples involved. No further testing of this particular coating was attempted.

10. NRL Fluoroacrylic

As with the fluoroepoxies, six samples were tested. The three smooth samples failed almost immediately. Small patches of the coating could be seen floating away with the condensate. However, all of the rough specimens produced good to excellent condensation in excess of 2500 hours with no signs of physical or hydrophobic degradation (see Figures 4.17 through 4.20). Although the drops are somewhat large, 3.8 mm (.15 in) in diameter before departure, they exhibit a larger contact angle and a more uniform shape than either of the epoxies. In addition, the oxidation rate of the reactive surfaces was noticeably less than either of the epoxy coated surfaces. This indicates that the acrylic was

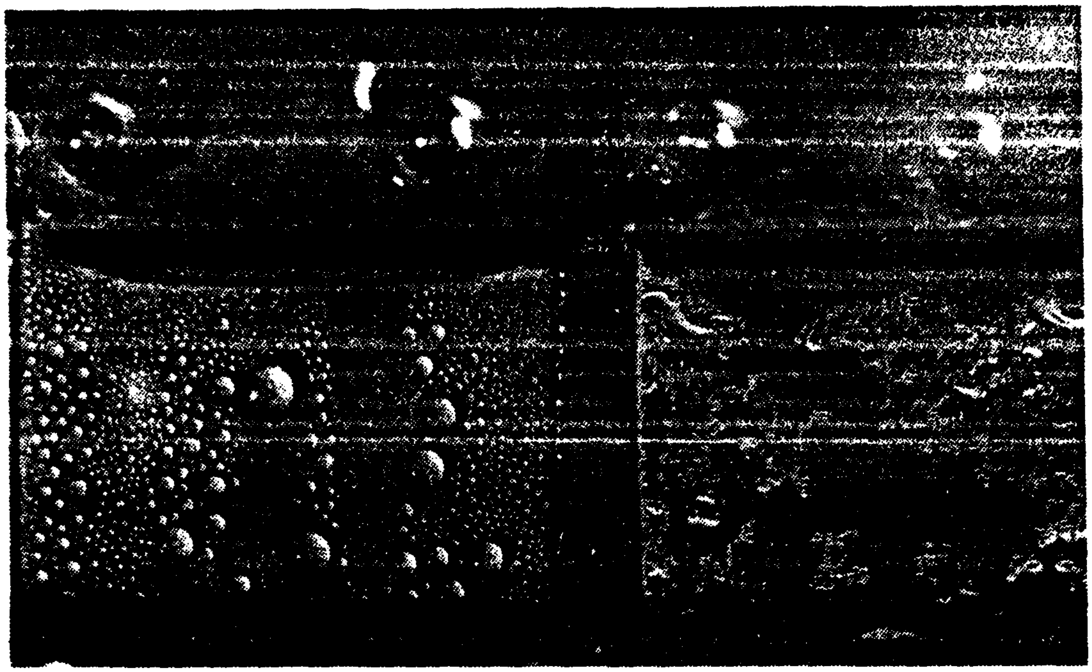


Figure 4.17 NRL Acrylic Cu/S Ti/R 0 hrs.

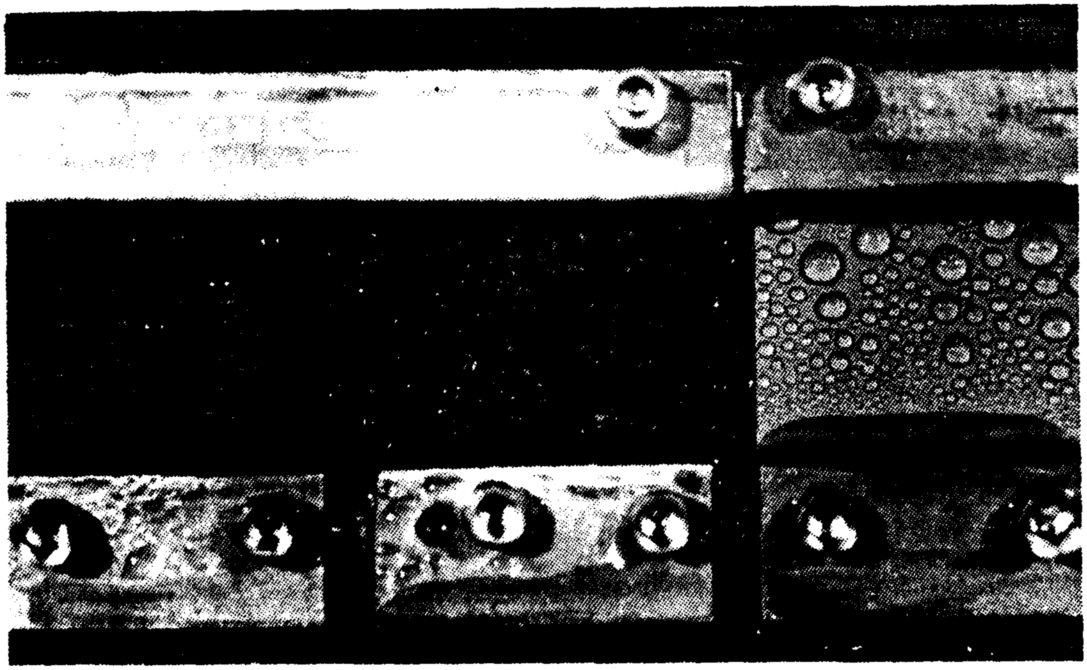


Figure 4.18 NRL Acrylic Cu/R Cu/S Ti/R 700 hrs.

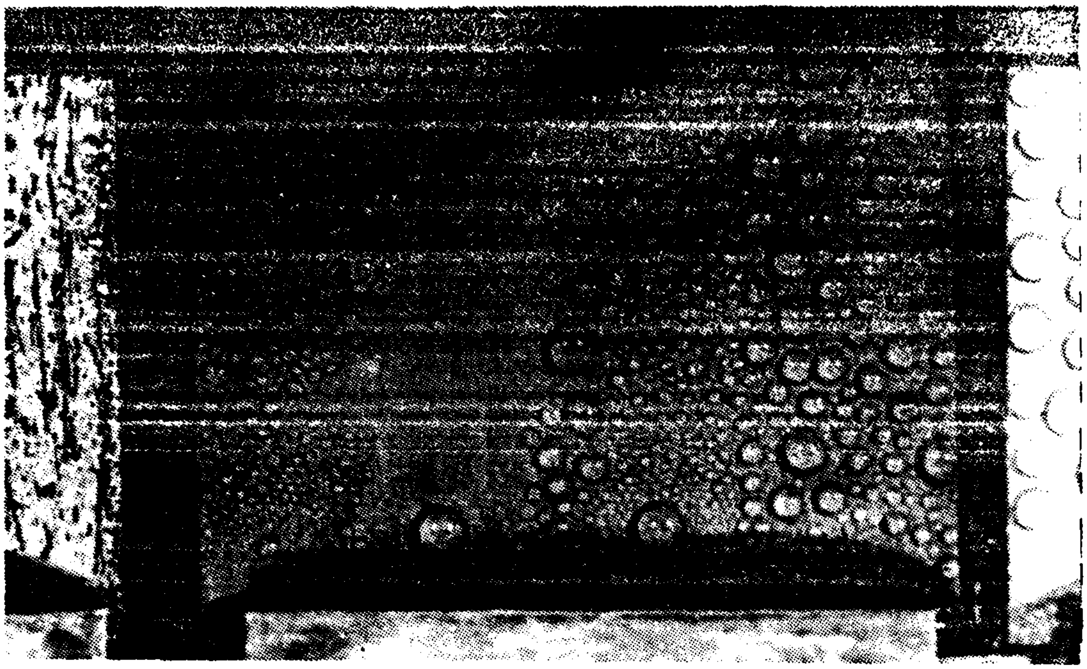


Figure 4.19 NRL Acrylic Cu/R 1000 hrs.

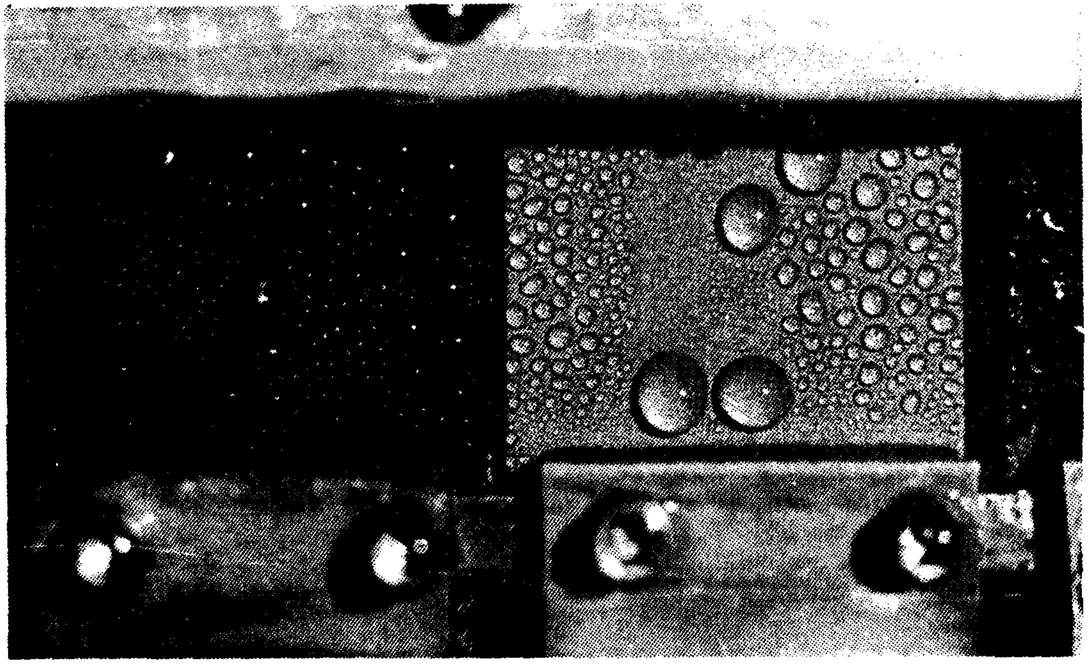


Figure 4.20 NRL Acrylic Cu/R Ti/R 2000 hrs.

better able to insulate the substrate from the environment. On the basis of performance and durability, the coating was selected for heat-transfer measurements.

11. PTFE

A total of sixteen PTFE samples, two complete sets of four substrates and two surface finishes, were tested. Specimens from the first set were tested for a total of 3000 hours before being replaced by the second set to verify previous observations.

Immediately after startup, all of the specimens produced excellent dropwise condensation. However, within four hours, the condensation mode on the brass and naval brass specimens had changed from dropwise to almost completely filmwise. The titanium samples also showed signs of failing. After forty-eight hours, only the copper specimens continued to promote dropwise condensation. After 240 hours of exposure, the non-performing specimens were removed for examination under the SEM.

The copper specimens were exposed in the test chamber for 3000 hours. The performance of these specimens during this period is shown in Figures 4.21 through 4.24 Throughout the test, the copper substrates showed signs of oxidation; their color gradually turned from a bright copper to a dull black. As can be seen in Figure 4.24, both copper specimens were performing poorly at the end of the test. At this point, the copper specimens were removed for examination and the second set was installed. None of the samples from the second set produced dropwise condensation after four hours of exposure.

Examination of various specimens under the SEM revealed different modes of failure. In the case of titanium, the PTFE was not adequately bonded to the substrate. After a short period of exposure, the coating flaked off in

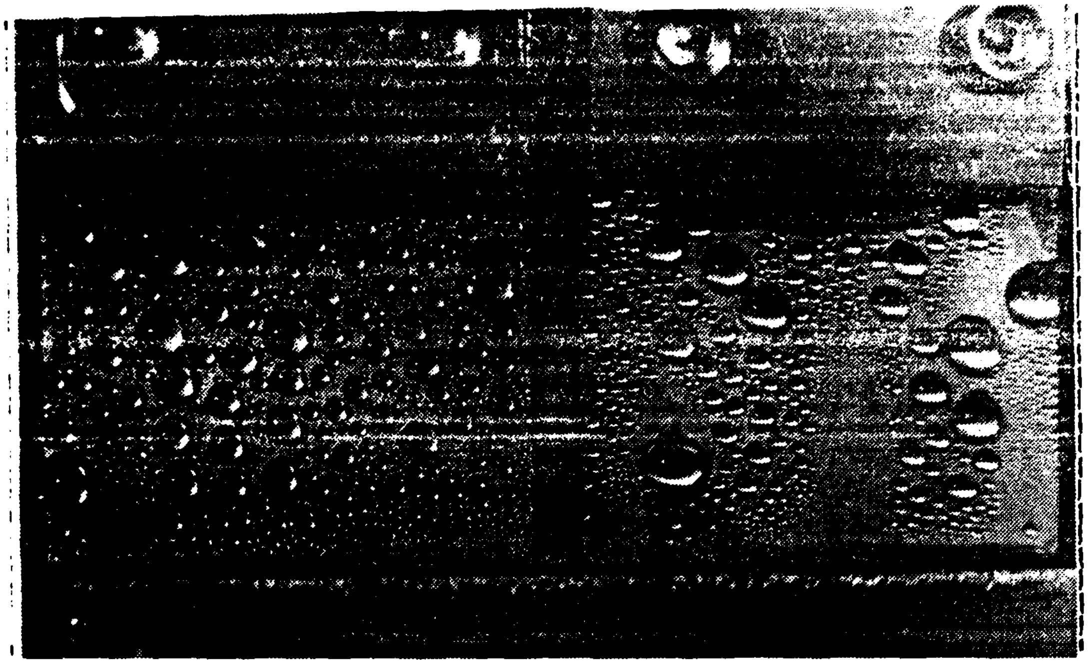


Figure 4.21 Sputtered PTFE Cu/S Cu/R 0 hrs.

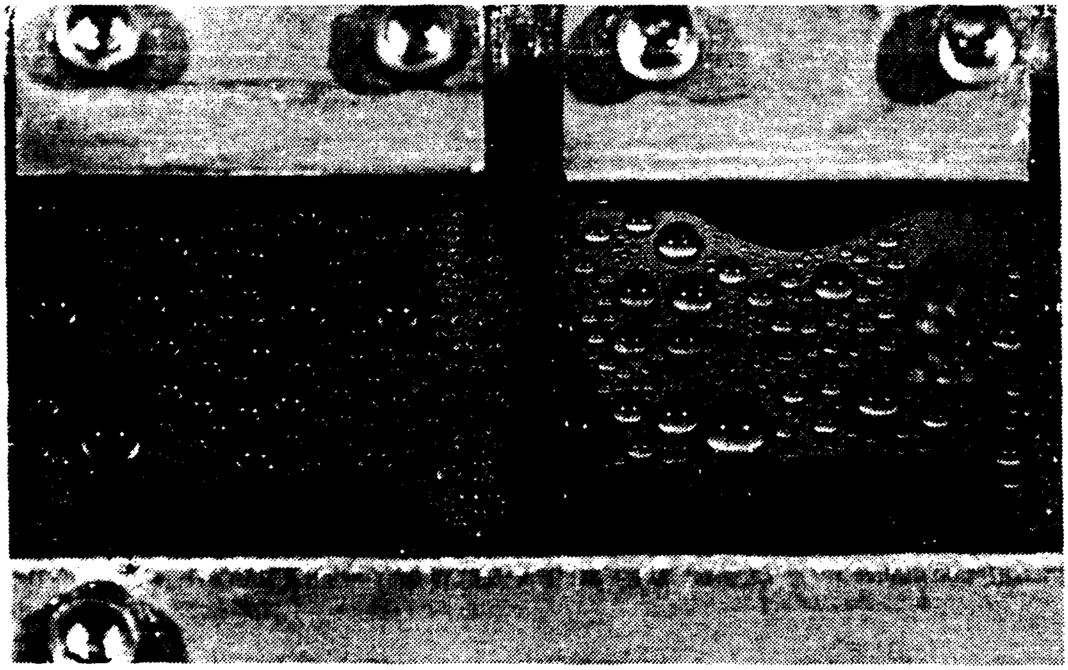


Figure 4.22 Sputtered PTFE Cu/S Cu/R 790 hrs.

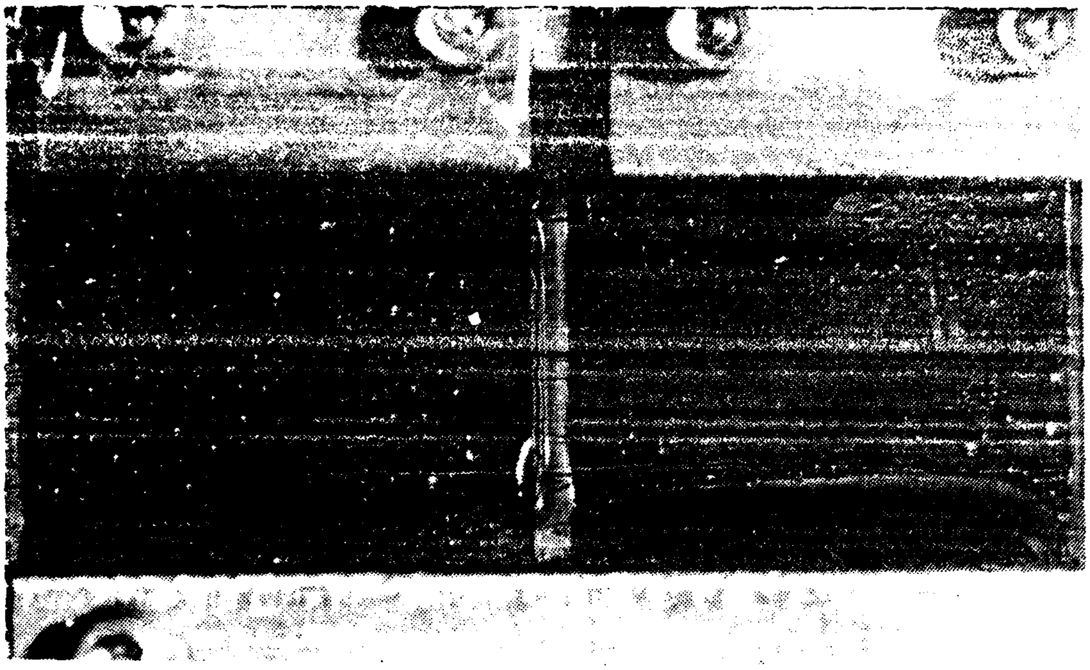


Figure 4.23 Sputtered PTFE Cu/S Cu/R 2000 hrs.

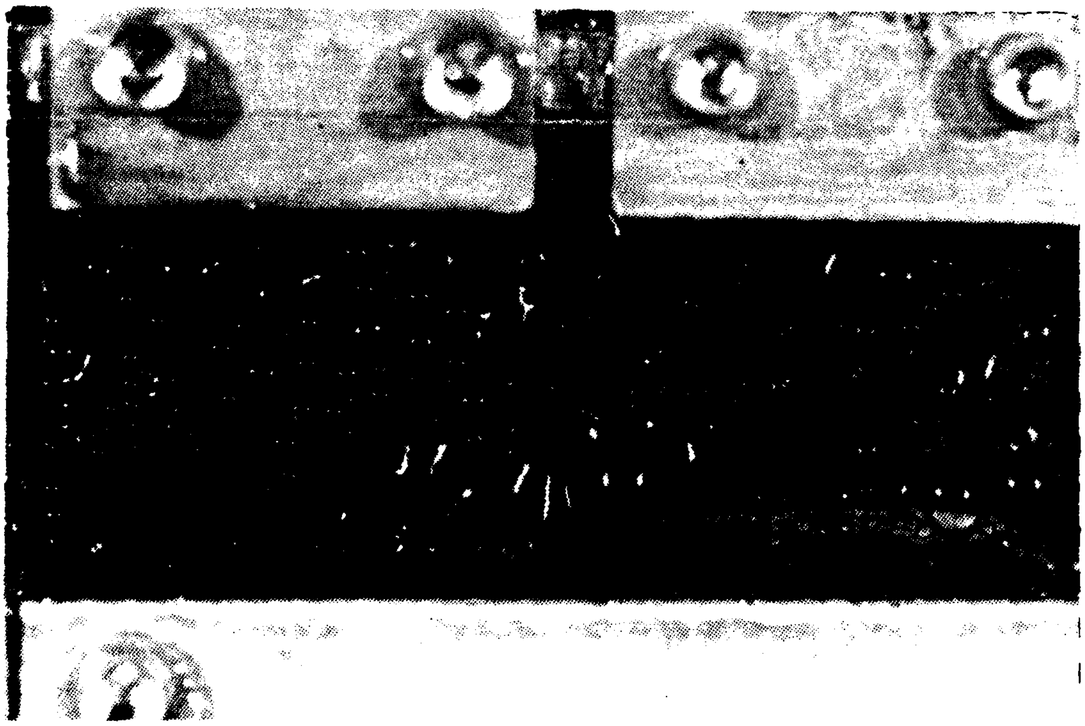


Figure 4.24 Sputtered PTFE Cu/S Cu/R 2700 hrs..

small patches exposing the bare substrate. This was consistent for all of the titanium specimens. The failure mode of the brass and naval brass specimens was similar. Only the copper specimens exhibited adequate adhesion throughout the duration of the test. However, SEM photographs revealed that the ultra-thin coating of PTFE was incapable of insulating the substrate from the environment. Numerous small, broken blisters caused by the oxidation of the substrate beneath the coating, covered much of the surface. This condition was revealed macroscopically by a gradual darkening of the surface and a degradation of the hydrophobic characteristics of the coating. The rapid failure of the second set can only be attributed to poor adhesion.

As pointed out in Ref 9, adhesion is dependent upon many factors some of which are not fully understood. Although some film-substrate combinations exhibit good adhesion, some of the more interesting combinations are incompatible in terms of adhesion. The results of this test indicate that the adhesion qualities of sputtered PTFE on the various substrates must be thoroughly investigated before utilizing this process to deposit thin films on condenser tubes. Based upon these results, this coating technique was not pursued for heat transfer measurements.

12. Parylene-N

A total of eight samples, four different substrates with two coating thicknesses of 0.5 micrometers and 1.0 micrometer, were tested. The coatings were applied by the Lawrence Livermore National Laboratory on an "as available" basis. Due to scheduling difficulties, it was not possible to prepare the substrate surfaces prior to coating. Therefore, unlike the other specimens, none of the specimens to be coated with parylene-N underwent any surface preparation. All of the specimens were plated in the "as

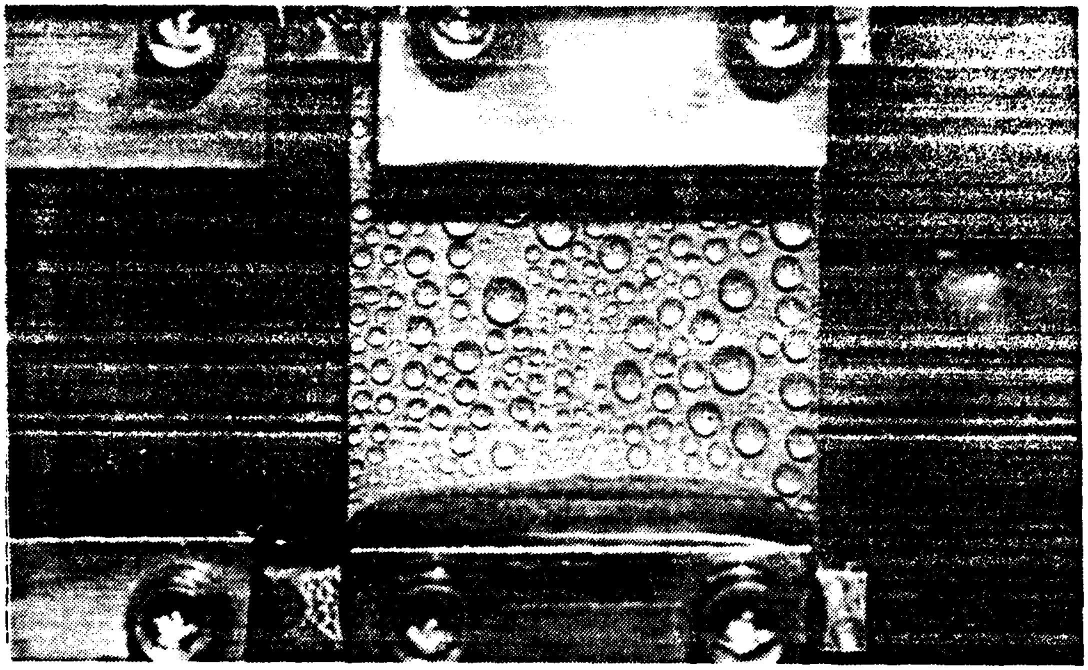


Figure 4.25 Parylene-N NBr 0 hrs.

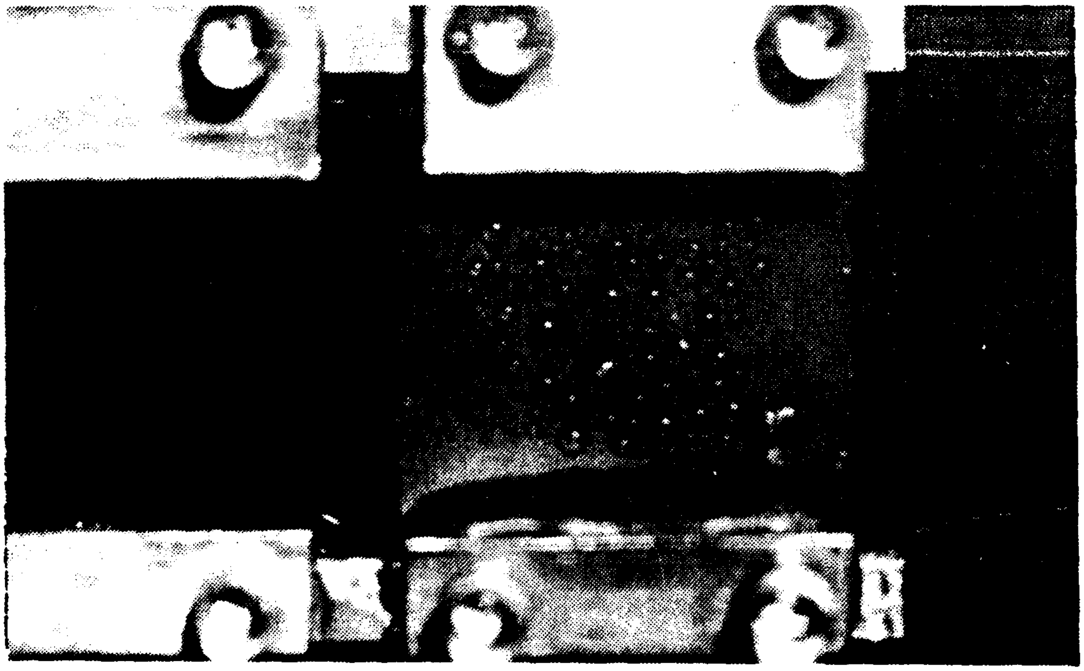


Figure 4.26 Parylene-N NBr 800 hrs.

delivered" condition. For the copper, brass and titanium substrates the "as delivered" condition was similar to the "smooth" surface previously described. However, the naval brass was received with a surface similar to the "rough" surface of the prepared specimens.

Upon exposure to steam, seven of the specimens failed within twenty-four hours. Large, water-filled blisters covered as much as 90% of the substrate surfaces. The only specimen to perform satisfactorily was the one-micrometer-thick coating on the naval brass substrate. As can be seen in Figures 4.25 and 4.26, this coating produced dropwise condensation which could be characterized as fair to good. The drops are somewhat irregular but grew to only 3.5 mm (.14 in) in diameter before quickly departing the surface. After 1500 hours of exposure, this specimen showed no signs of physical or hydrophobic degradation.

Based upon the limited number of parylene samples involved and observations of other coatings under similar conditions, failure can be attributed to two causes: surface finish and coating thickness. The fact that only the naval brass specimen with the 1.0 micrometer coating endured, indicates that a rough surface is necessary to insure proper bonding. This finding is consistent with observations of other coatings. In addition, thicknesses of less than one micrometer appear to be incapable of withstanding the test environment. It is surmised that water vapor can penetrate the ultra-thin coatings in sufficient quantity to eventually undermine the bond between the coating and the substrate surface. This observation is supported by the failure of the 0.5 micrometer coating on the rough, naval brass substrate and the appearance of water filled blisters on all of the failed specimens. The bilsters indicated that, although the coating was continuous and firmly attached at the edges, condensate had somehow collected between the film and the substrate.

Based upon the performance of the one good sample with consideration given to its unique application process, parylene-N was selected for heat-transfer measurements.

13. Parylene-D

The parylene-D specimens were received too late for the test results to be included in this thesis. However, sixteen parylene-D specimens, four substrates with both surface finishes and thicknesses of 0.5 and 1.0 micrometer are currently undergoing endurance testing during the writing of this thesis.

14. Pepco 6122

Since the application and substrate preparation for this coating were proprietary, only four specimens representing the different substrates were tested. Although the initial condensation mode was dropwise, it gradually turned to mixed condensation, part dropwise and part filmwise, within 100 hours. This remained the steady-state mode of condensation for over 2000 hours. The most likely explanation for the gradual change was the absorption and retention of water by the coating. This had the effect of gradually altering the critical surface tension. Although the coating did not promote dropwise condensation to a degree that would warrant further investigation, the coating did not suffer physical degradation by exposure to steam at atmospheric pressure in excess of 2000 hours.

15. Silicone

The silicone compound tested produced only fair dropwise condensation. The drops were relatively large, flat, and irregular in shape. In addition, the coating did not adhere to either the rough or smooth surfaces of any substrate. Blisters, filled with water, appeared within twenty-four hours. These blisters continued to grow while undermining the coating and forcing it to separate from the substrate. Because the quality of the dropwise condensation was only fair and adherence appeared to be inadequate, no further testing was done.

B. PHYSICAL PROPERTIES TESTS

The results of the physical properties tests as well as the endurance test results are summarized in Table II.

C. HEAT-TRANSFER RESULTS

A total of six coatings were selected for heat-transfer measurements. Realizing that, for dropwise condensation, the determination of the outside heat-transfer coefficient is very sensitive to variations in the inside coefficient, extreme care was exercised in establishing a reliable, repeatable Sieder-Tate coefficient for an internally enhanced smooth tube. A coefficient (C_i) of 0.0638 with an intercept of (B) 26.9 was established for the Sieder-Tate equation through the analysis of data taken from a plain copper tube instrumented with six thermocouples. Although not normally associated with the Sieder-Tate equation, the presence of an intercept was necessitated by the low L/D ratio of the test tubes. These values were used for determining the inside heat-transfer coefficient for all subsequent data runs. A description of the data acquisition and reduction for determining these values is provided in Ref. 20 and Ref. 26. Figure 4.29 shows the variation of the Nusselt number as a function of the Sieder-Tate parameter for the instrumented tube. All of the data runs, a minimum of two for each coating, were made under vacuum conditions, approximately 0.012 MPa (1.6 psia). The mass concentration of the non-condensing gases was maintained at ±0.5% (i.e.

TABLE II

Endurance Test Results

Coating	Substrate/ Surface	Thick- ness m	Hard- ness	Adhesion	Dropwise Performance	Hours of Operation
No-Stik	Cu/U	60	4F	5B	Excellent	>4000
No-Stik	Ti/U	60	4F	5B	Excellent	>4000
No-Stik	Br/U	60	4F	5B	Excellent	>4000
No-Stik	NBr/U	60	4F	5B	Excellent	>4000
Nedox	Cu/U	5	F	5B	Excellent	>2000
Nedox	Ti/U	5	F	5B	Excellent	<1000
Nedox	Br/U	5	F	5B	Excellent	<400
Nedox	NBr/U	5	F	5B	Excellent	<300
Emralon 333	Cu/U	20	F	5B	Poor	<500
Emralon 333	Ti/U	20	F	5B	Excellent	>4000
Emralon 333	Br/U	20	F	5B	Fair/Good	4000
Emralon 333	NBr/U	20	F	5B	Fair/Good	>4000
C-6 Fluoroepoxy	Cu/S	1-10	2H	5B	Fair/Good	2000
C-6 Fluoroepoxy	Cu/R	1-10	2H	5B	Fair/Good	>4000
C-6 Fluoroepoxy	Ti/S	1-10	2H	5B	Fair/Good	2000
C-6 Fluoroepoxy	Ti/R	1-10	2H	5B	Fair/Good	>4000
C-6 Fluoroepoxy	NBr/S	1-10	2H	5B	Fair/Good	2000
C-6 Fluoroepoxy	NBr/R	1-10	2H	5B	Fair/Good	>4000

TABLE II

Endurance Test Results

Coating	Substrate/ Surface	Thick- ness m	Hard- ness	Adhesion	Dropwise Performance	Hours of Operation
C-6' Fluoroepoxy	Cu/S	1-10	2H	5B	Fair/Good	1000
C-6' Fluoroepoxy	Cu/R	1-10	2H	5B	Fair/Good	>2000
C-6' Fluoroepoxy	Ti/S	1-10	2H	5B	Fair/Good	1000
C-6' Fluoroepoxy	Ti/R	1-10	2H	5B	Fair/Good	>2000
C-6' Fluoroepoxy	NBr/S	1-10	2H	5B	Fair/Good	1000
C-6' Fluoroepoxy	NBr/R	1-10	2H	5B	Fair/Good	>2000
BCE-7 Fluoroepoxy	Cu/S	1-10	HB	5B	Failed	<20
Fluoroacrylate		1-10	HB	4B	Failed	<20
Fluoroacrylic	Cu/S	1-10	F	3B	Failed	<20
Fluoroacrylic	Cu/R	1-10	F	3B	Good	>2500
Fluoroacrylic	Ti/S	1-10	F	3B	Failed	<20
Fluoroacrylic	Ti/R	1-10	F	3B	Good	>2500
Fluoroacrylic	NBr/S	1-10	F	3B	Failed	<20
Fluoroacrylic	NBr/R	1-10	F	3B	Good	>2500
Pepco 6122	Cu/U	5-10	HB	5B	Poor	>2000
Pepco 6122	Ti/U	5-10	HB	5B	Poor	>2000
Pepco 6122	NBr/U	5-10	HB	5B	Poor	>2000

TABLE II

Endurance Test Results

Coating	Substrate/ Surface	Thickness m	Hardness	Adhesion	Dropwise Performance	Hours of Operation
Isonel 472	All	5-10	H	5B	Failed	<24
Isonel 31-398	All	5-10	H	5B	Failed	<24
Sputtered PTFE	Cu/S	.4	F	4B	Excellent	2000
Sputtered PTFE	Cu/R	.4	F	4B	Excellent	2000
Sputtered PTFE	Ti/S	.4	F	4B	Excellent	<48
Sputtered PTFE	Ti/R	.4	F	4B	Excellent	<48
Sputtered PTFE	Br/S	.4	F	4B	Excellent	<48
Sputtered PTFE	Br/R	.4	F	4B	Excellent	<48
Sputtered PTFE	NBr/S	.4	F	4B	Excellent	<48
Sputtered PTFE	NBr/R	.4	F	4B	Excellent	<48
Parylene-N	All	.5	B	4B	Failed	<20
Parylene-N	Cu/AD	1.0	B	4B	Failed	<100
Parylene-N	Ti/AD	1.0	B	4B	Failed	<100
Parylene-N	Br/AD	1.0	B	4B	Failed	<100
Parylene-N	NBr/AD	1.0	B	4B	Good	>1500
Silicone	All	U	4B	5B	Poor	<50

zero to within the accuracy of the temperature and pressure measurements) during all data runs.

The results of all the data runs with a least-squares curve fit are plotted in Figures 4.27 and 4.28. For comparison purposes, data representing the performance of a plain, smooth tube are also plotted. Because the program used for reducing and plotting the data was slightly different from that used in Ref. 20, a listing of the program (DRP3) and a sample of the reduced data are provided in Appendix A. Photographs of the tubes under actual test conditions are provided in Figures 4.30 through 4.33. The performance of each coating was as follows:

1. No-Stik

Even though this coating produced excellent dropwise condensation, the outside heat-transfer coefficient was reduced by a factor of two-thirds when compared with a smooth tube undergoing filmwise condensation. This result is explained by the thickness of the coating which averaged 75 to 100 micrometers (0.003 to 0.004 in) thick. Although the coating was heavily doped with copper to improve conductivity, the thermal resistance imposed by the coating was far too great to be offset by the beneficial effects of dropwise condensation.

2. Nedox

The Nedox coating improved the outside heat-transfer coefficient by 700% to 900%. This represented the best enhancement produced by any coating. However, questions as to the durability of this coating, which were raised during the endurance test, still remain. No degradation was evident during the heat-transfer tests.

3. Parylene-N

Two thicknesses of parylene-N were tested: 0.5 and 1.0 micrometer. The 0.5 micrometer coating enhanced the outside coefficient from 600% to 750%. As expected, due to the increased thickness, the 1.0 micrometer coating produced a lower enhancement of 500% to 600%. However, close inspection of the 0.5 micrometer coating after the heat-transfer tests, revealed small areas in which the coating was beginning to peel or crack. The one-micrometer coating showed no signs of deterioration. This result was consistent with the endurance test which indicates that 0.5 micrometers is too thin to produce reliable durability.

4. C-6 Fluoroepoxy

The NRL C-6 fluoroepoxy produced an improvement of 200% to 240%. Although considerably greater than a smooth tube undergoing filmwise condensation, these results are less than those achieved by fin tubes (See Ref. 20). This disappointing performance was probably a result of the coating thickness. Application by brush produces a coating which is slightly too thick. The thickness on the test tube was estimated to be 10.0 to 20.0 micrometers. Although very durable, an application technique which will consistently produce an ultra-thin, uniform coating must be utilized if this coating is to be exploited for enhancing heat transfer.

5. Fluoroacrylic

Since the NRL fluoroacrylic is a thermoplastic polymer, it can be easily thinned prior to application. This makes a thin, uniform coating more easily obtainable when compared to the epoxies. In this case, the coating was estimated to be 5.0 to 10.0 micrometers. Therefore, the fluoroacrylic was capable of producing enhancements of 500% to 600%.

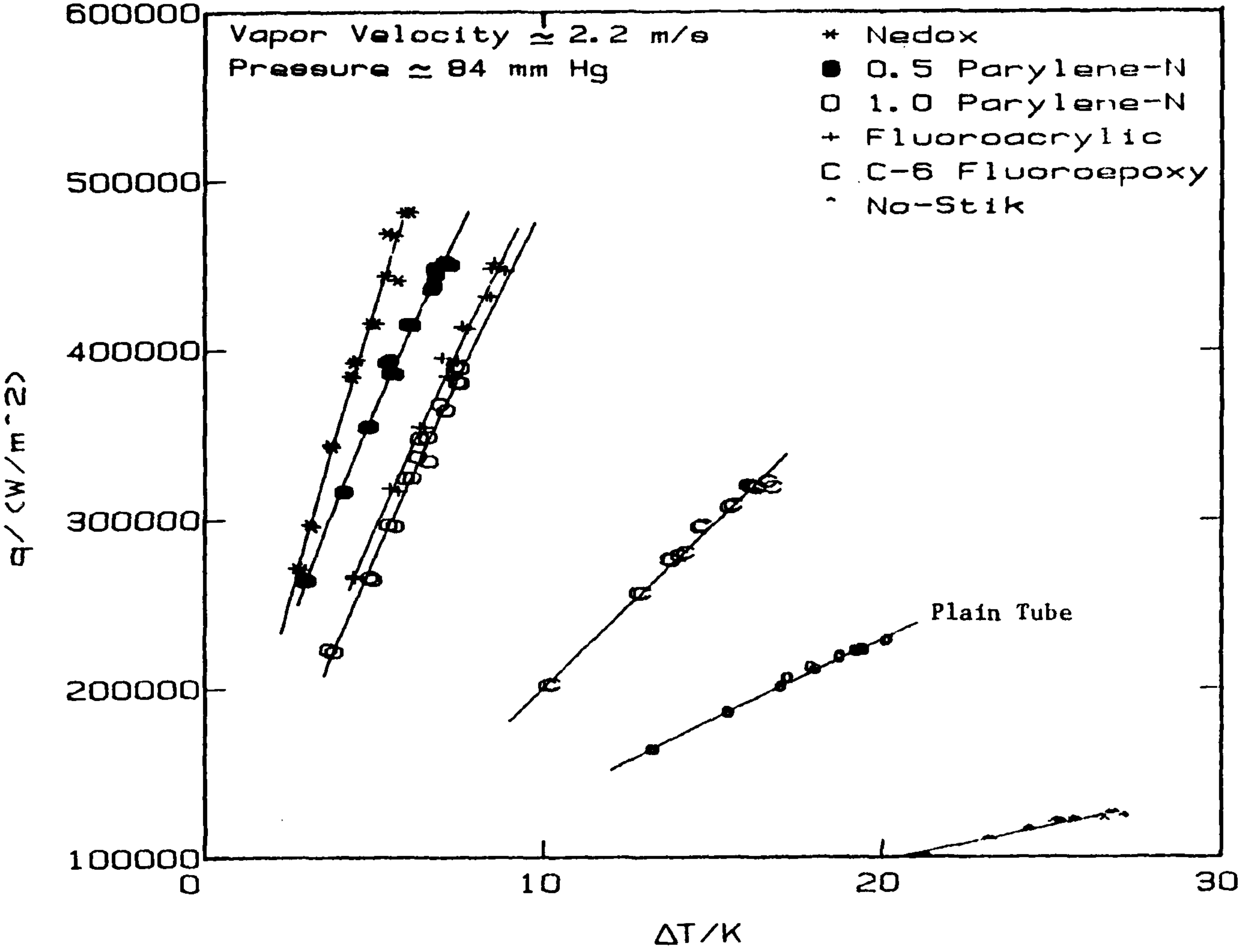


Figure 4.27 Variation of Heat Flux with Vapor-Side Temperature Difference for Tubes Coated with Polymers.

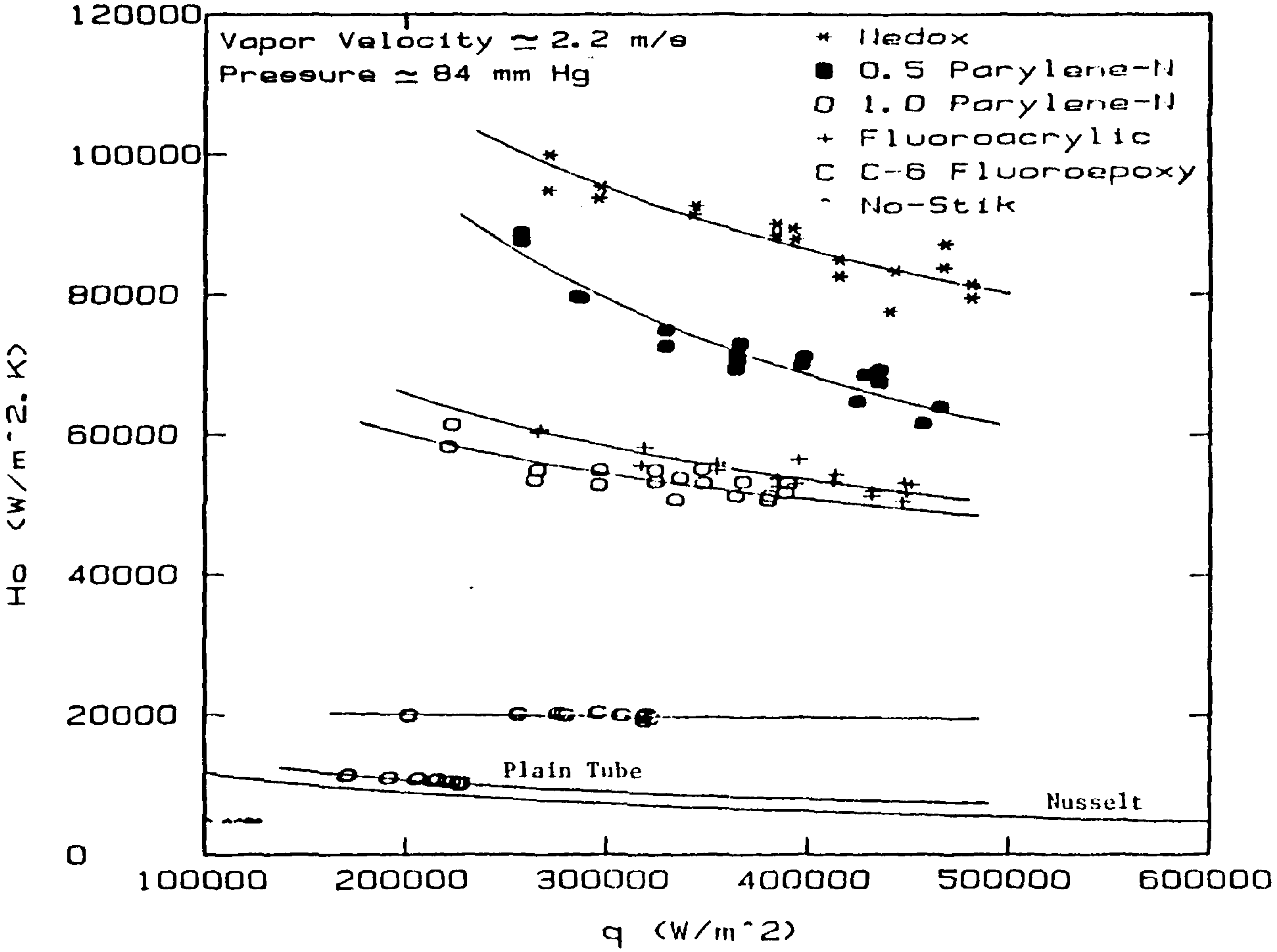


Figure 4.28 Outside Heat-Transfer Coefficient for Tubes Coated with Polymers.

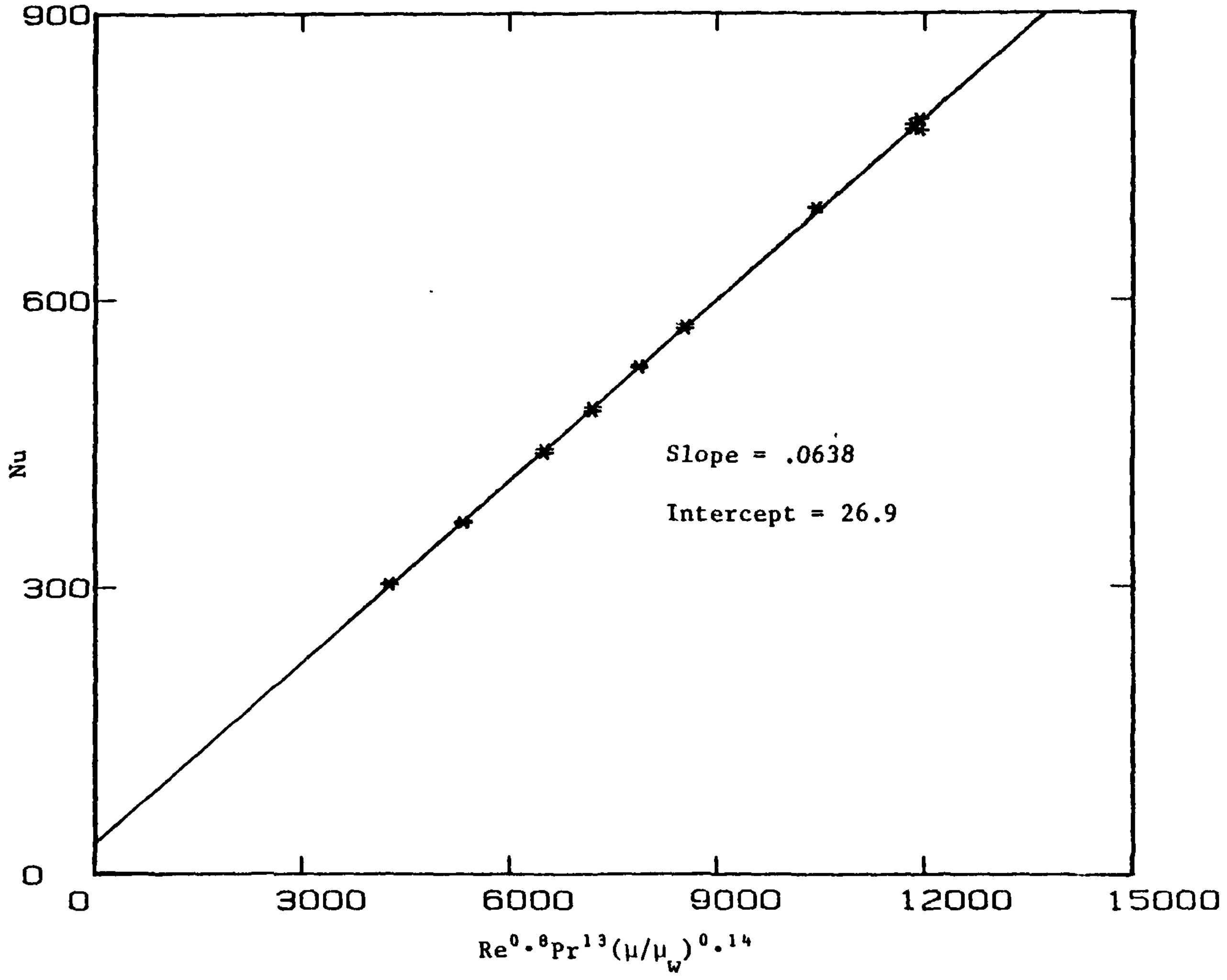


Figure 4.29 Inside Nusselt Number Plot for the Instrumented Tube.

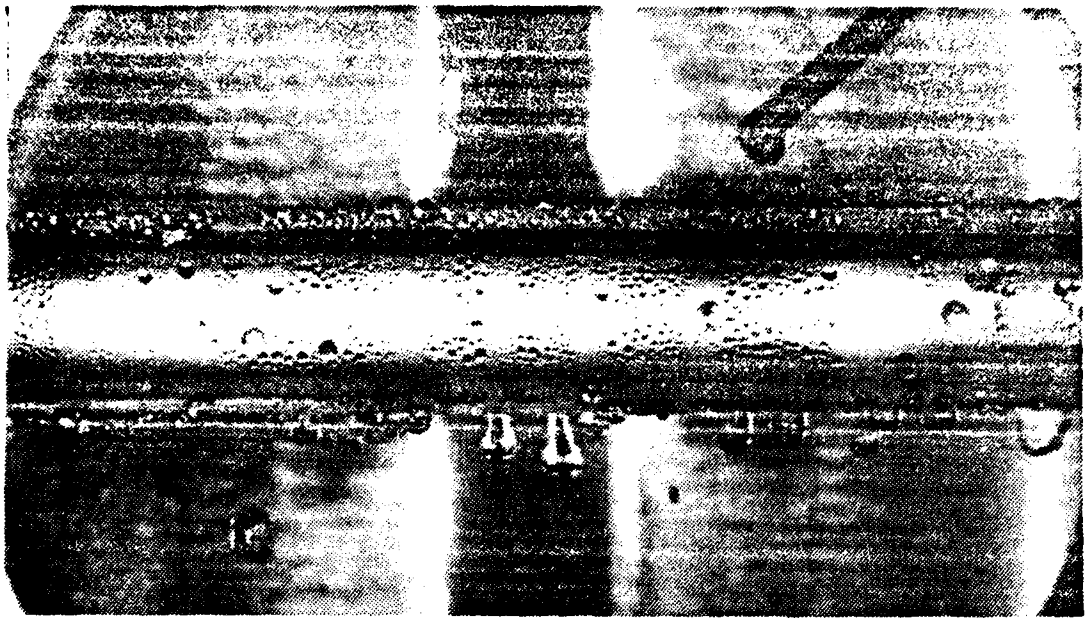


Figure 4.30 Nedox.

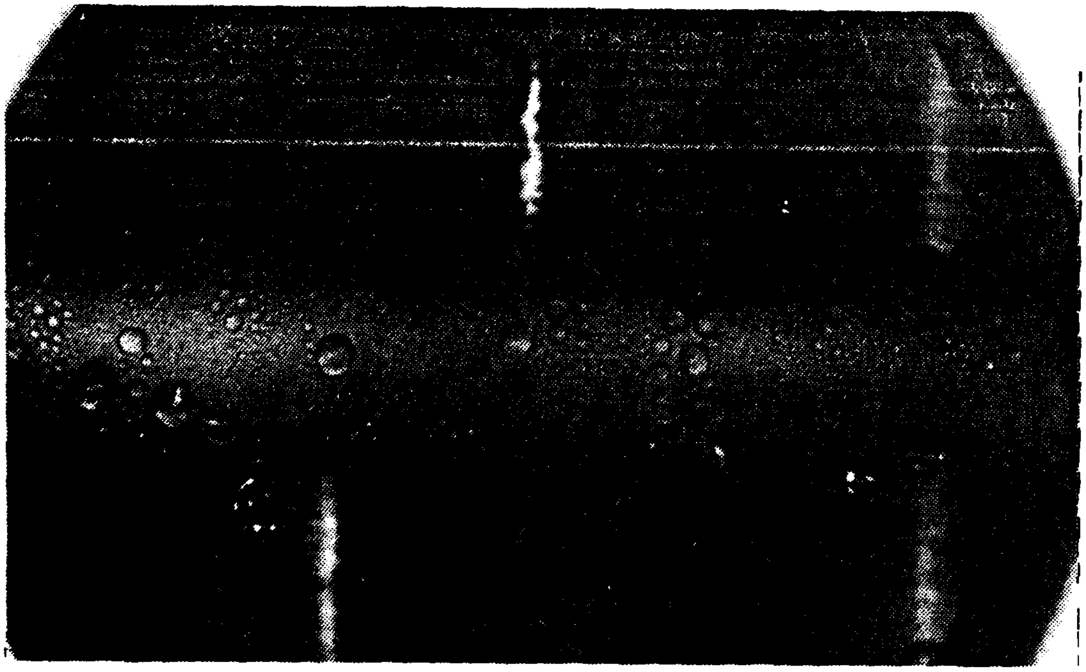


Figure 4.31 NRL Fluoroacrylic.

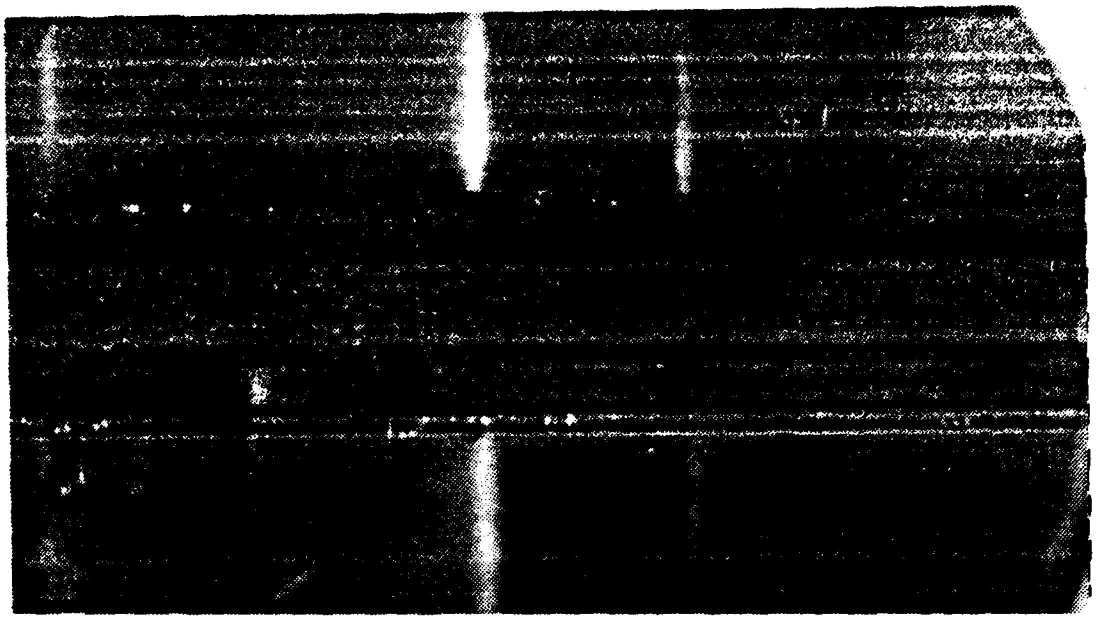


Figure 4.32 No-Stik.

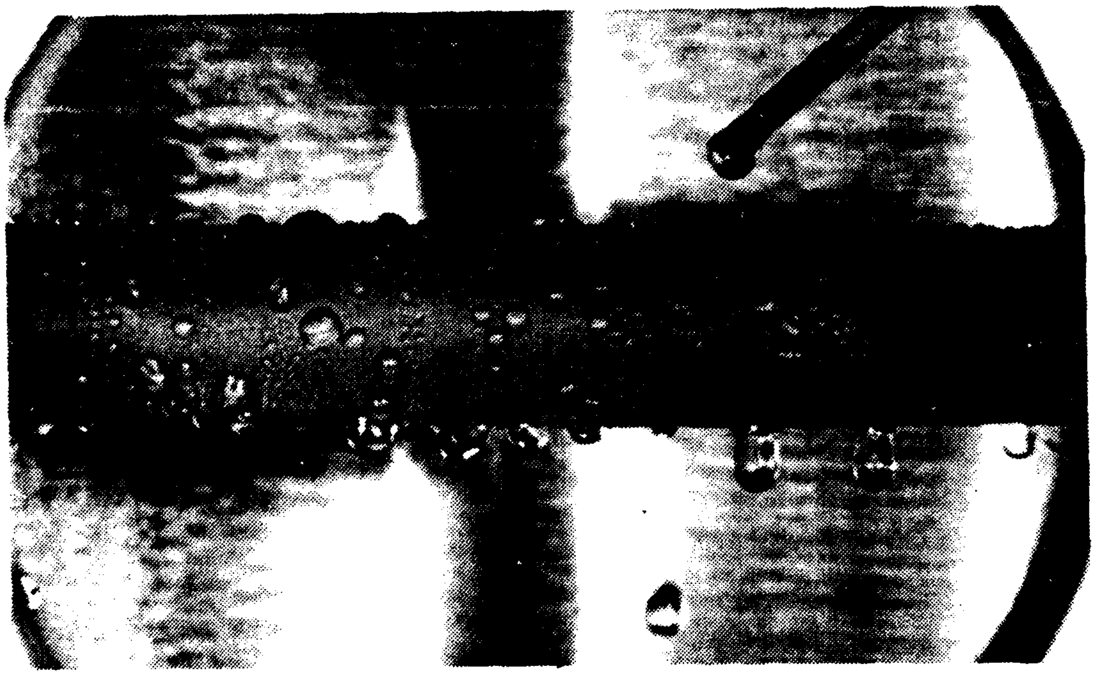


Figure 4.33 Parylene-N.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. During the condensation of steam on horizontal tubes, the outside heat-transfer coefficient can be enhanced five to eight times through the use of organic polymer coatings. A 500% increase can be achieved with coatings of demonstrated durability, (i. e. coatings which showed no degradation over a minimum period of 2000 hours), whereas the higher rates can be achieved only by coatings of questionable durability.

2. Because of their hydrophobic characteristics, ease of application and the ability to be applied in ultra-thin layers, the fluoroepoxies and fluoroacrylics represent the best alternative for the application of a low energy, fluorocarbon surface.

3. Both the Nedox coating and the parylenes offer possible alternatives to the epoxies and acrylics once their durability is firmly established.

4. A rough surface is essential for the proper bonding of the polymer coatings tested.

5. The ultra-thin polymer coatings tested were incapable of completely insulating reactive substrates from the environment.

6. The outside heat-transfer coefficient is highly sensitive to uncertainties in the inside coefficient. Therefore, the inside coefficient must be clearly established before attempting to infer the outside coefficient from overall measurements.

B. RECCMMENDATIONS

1. Continue the evaluation of the fluoroepoxies and fluoroacrylics. New compounds have been developed and those previously tested can be modified to enhance durability, while maintaining most of their hydrophobic characteristics.

2. Devise a method for applying a controlled, uniform, repeatable thickness for the fluoroacrylics and fluoroepoxies.

3. Continue to evaluate the parylenes for durability. When compared to the other parylenes, parylene-C has relatively low water vapor and oxygen transmission rates. Therefore, parylene-C should be included in the evaluation.

4. Attempt to reduce the thickness of the No-Stik coating.

5. Determine and eliminate the cause for the deterioration of the NEDOX coating.

6. Apply selected coatings to tubes made of materials with low thermal conductivities, such as stainless steel or titanium, to determine the effect of the constriction resistence upon thermal performance.

7. In order to prevent oxidation and eventual coating failure, use non-reactive substrates. If this is not possible, the substrate should be plated with a non-reactive sub-layer.

APPENDIX A

COMPUTER PROGRAM LISTING

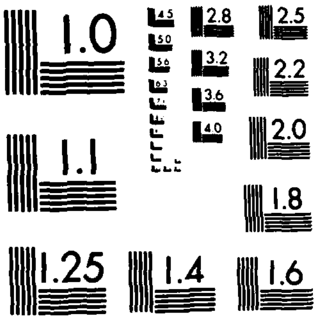
The following pages contain a listing of the computer program used for data acquisition, data reduction and plotting.

```
1000! FILE NAME: DRP3
1010! REVISED:  December 19, 1983
1020!
1030  COM /Cc/ C(7)
1040  DIM Emf(10)
1050  DATA 0.10086091,25727.94369,-767345.9295,78025595.81
1060  DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1070  READ C(*)
1080  Di=.0127       ! Inside diameter of test tube
1090  Do=.01905      ! Outside diameter of test tube
1100  Dr=.015875     ! Outside diameter of the outlet end
1110  Dssp=.1524     ! Inside diameter of stainless steel test section
1120  Ax=PI*Dssp^2/4-PI*Do*L
1130  L=.130175      ! Condensing length
1140  L1=.050325     ! Inlet end "fin length"
1150  L2=.034925     ! Outlet end "fin length"
1160  Kcu=385        ! Thermal conductivity of Copper
1170  Rm=Do*LOG(Do/Di)/(2*Kcu) ! Wall resistance based on outside area
1180  PRINTER IS 1
1190  CLEAR 709
1200  BEEP
1210  PRINT USING "4X,""SELECT OPTION:"""
1220  PRINT USING "6X,""1 Taking data or re-processing previous data"""
1230  PRINT USING "6X,""2 Plotting data"""
1240  INPUT Iop
1250  PRINTER IS 701
1260  IF Iop=2 THEN 4620
1270  BEEP
1280  INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1290  OUTPUT 709:"TD":Date$
1300  OUTPUT 709:"TD"
1310  ENTER 709:Date$
1320  PRINT "           Month, date and time :";Date$
1330  PRINT
1340  PRINT USING "10X,""NOTE: Program name : DRP3"""
1350  BEEP
1360  INPUT "ENTER DISK NUMBER",Dn
1370  PRINT USING "16X,""Disk number  = "",DD";Dn
1380  BEEP
1390  INPUT "ENTER INPUT MODE (1=3054A,2=FILE)",Im
1400  IF Im=1 THEN
1410  BEEP
1420  INPUT "GIVE A NAME FOR THE RAW DATA FILE",D_file$
1430  PRINT USING "16X,""File name    : "",14A";D_file$
1440  CREATE BDAT D_file$,15
1450  ASSIGN @File TO D_file$
1460  Ifg=0
1470  Inn=1
1480  Iwt=0
1490  OUTPUT @File:Ifg,Inn
1500  IF Ifg=0 THEN OUTPUT @File:Iwt
1510  ELSE
1520  BEEP
1530  INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D_file$
1540  PRINT USING "16X,""This analysis was performed for data in file "",10A";D_
file$
1550  BEEP
1560  INPUT "ENTER THE NUMBER OF RUNS STORED",Nrun
1570  ASSIGN @File TO D_file$
1580  ENTER @File:Ifg,Inn
1590  IF Ifg=0 THEN ENTER @File:Iwt
1600  END IF
1610  BEEP
```

```
1620  INPUT "ENTER OPTION (1=QCT,2=T-PILE,3=AVE)",Itm
1630  BEEP
1640  INPUT "ENTER OPTION FOR END-FIN EFFECT (1=Y,0=N)",Ife
1650  IF Itm=1 THEN PRINT USING "16X,""This analysis uses QCT readings"""""
1660  IF Itm=2 THEN PRINT USING "16X,""This analysis uses T-PILE readings"""""
1670  IF Itm=3 THEN PRINT USING "16X,""This analysis uses average of QCT and T-P
ILE readings"""""
1680  IF Ife=1 THEN PRINT USING "16X,""This analysis includes end-fin effect"""""
1690  IF Ife=0 THEN PRINT USING "16X,""This analysis neglects end-fin effect"""""
1700  IF Ife=1 AND Inn=0 THEN Ci=.0284
1710  IF Ife=0 AND Inn=0 THEN Ci=.032
1720  IF Ife=1 AND Inn=1 THEN Ci=.070
1730  IF Ife=0 AND Inn=1 THEN Ci=.075  ! This value is arbitrary
1740  IF Ife=1 AND Inn=3 THEN Ci=.042
1750  IF Ife=0 AND Inn=3 THEN Ci=.0482
1760  PRINT USING "16X,""Sieder-Tate coefficient   = "",Z.4D":Ci
1770  BEEP
1780  INPUT "GIVE A NAME FOR PLOT DATA FILE",P_file$
1790  CREATE BDAT P_file$,5
1800  ASSIGN @Filep TO P_file$
1810  BEEP
1820  INPUT "ENTER OUTPUT VERSION (1=SHORT,2=LONG)",Iov
1830  J=0
1840  IF Iov=1 THEN
1850  PRINT
1860  IF Inf=1 THEN
1870  PRINT USING "10X,""Data  Vw       Uo        Ho         Qp       Vv    F      Nr
"""""
1880  PRINT USING "10X,"" #  (m/s) (W/m^2-K)(W/m^2-K)  (W/m^2) (m/s)"""""
1890  ELSE
1900  PRINT USING "10X,""Data  Vw         Uo             Ho            Qp          Vv"""""
1910  PRINT USING "10X,"" #  (m/s)   (W/m^2-K)     (W/m^2-K)    (W/m^2)   (m/s)"""
""
1920  END IF
1930  END IF
1940  Go_on=1
1950 Repeat:!
1960  Ok3=1
1970  J=J+1
1980  IF Im=1 THEN
1990  BEEP
2000  INPUT "LIKE TO CHECK NG CONCENTRATION (1=Y,0=N)?",Ng
2010  BEEP
2020  INPUT "ENTER FLOWMETER READING",Fm
2030  OUTPUT 709:"AR AF60 AL63 VR5"
2040  OUTPUT 709:"AS SA"
2050  ENTER 709:Etp
2060  OUTPUT 709:"AS SA"
2070  Vtran=0
2080  FOR I=1 TO 50
2090  ENTER 709:Vt
2100  Vtran=Vtran+Vt
2110  NEXT I
2120  Vtran=Vtran/50
2130  OUTPUT 709:"AS SA"
2140  BEEP
2150  INPUT "CONNECT VOLTAGE LINE",Ok
2160  ENTER 709:Bvol
2170  BEEP
2180  INPUT "DISCONNECT VOLTAGE LINE",Ok
2190  OUTPUT 709:"AS SA"
```

AD-A144 018 AN EVALUATION OF POLYMER COATINGS FOR THE PROMOTION OF 2/2
DROPWISE CONDENSATION OF STEAM(U) NAVAL POSTGRADUATE
SCHOOL MONTEREY CA K M HOLDEN MAR 84 NPS-69-84-003
UNCLASSIFIED F/G 13/1 NL

END



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
2200  ENTER 709:Bamp
2210  OUTPUT 709:"AR AF20 AL24 VR1"
2220  FOR I=0 TO 4
2230  OUTPUT 709:"AS SA"
2240  Se=0
2250  FOR K=0 TO 10
2260  ENTER 709:E
2270  Se=Se+E
2280  NEXT K
2290  Emf(I)=ABS(Se/10)
2300  NEXT I
2310  OUTPUT 709;"AS SA"
2320  OUTPUT 713:"T1R2E"
2330  WAIT 2
2340  ENTER 713;T11
2350! OUTPUT 713:"T2R2E"
2360! WAIT 2
2370! ENTER 713;T2
2380  BEEP
2390  INPUT "ENTER T2",T2
2400  T2=9.0378E-2+T2*1.0034511
2410  OUTPUT 713;"T1R2E"
2420  WAIT 2
2430  ENTER 713:T12
2440  T1=(T11+T12)*.5
2450! OUTPUT 713;"T3R2E"
2460  IF Ng=0 THEN 2590
2470  BEEP
2480  INPUT "ENTER MANOMETER READINGS (HL.HR,HRW)".H1,Hr,Hrw
2490  BEEP
2500  INPUT "OK TO ACCEPT THIS RUN (1=Y=DEFAULT,0=N)",Ok3
2510  IF Ok3=0 THEN
2520  J=J-1
2530  GOTO 1960
2540  END IF
2550  Phg=H1+Hr
2560  Pwater=Hr-Hrw
2570  ELSE
2580  ENTER @File:Bvol.Bamp.Vtran.Etp.Emf(0).Emf(1).Emf(2).Emf(3).Emf(4).Fm.T1,T
2.Phg.Pwater
2590  IF J=1 OR J=10 OR J=20 OR J=Nrun THEN
2600  Ng=1
2610  ELSE
2620  Ng=0
2630  END IF
2640  END IF
2650  Tsteam=FNTvsv(Emf(0))  ! COMPUTE STEAM TEMPERATURE
2660  Troom=FNTvsv(Emf(3))
2670  IF Iwt=1 THEN
2680  Twm=0.
2690  FOR I=0 TO 5
2700  Tw(I)=FNTvsv(Emf(I+5))
2710  Twm=Twm+Tw(I)
2720  NEXT I
2730  Twm=Twm/6
2740  END IF
2750  Tcon=FNTvsv(Emf(4))
2760  Psat=FNPvst(Tsteam)
2770  Rohg=13529-122*(Troom-26.95)/50
2780  Rowater=FNRhow(Troom)
```

```
2790  Ptest=(Phg*Rohg-Pwater*Rowater)*9.799/1000
2800  Pmm=Ptest/133.322
2810  Pkm=Ptest*1.E-3
2820  Pks=Psat*1.E-3
2830  Pkt=FNPvsv(Vtran)*1.E-3
2840  Tsat=FNTvsp(Ptest)
2850  Vst=FNVvst(Tsteam)
2860  Ppng=(Ptest-Psat)/Ptest
2870  Ppst=1-Ppng
2880  Mfng=1/(1+18.015/28.97*Psat/(Ptest-Psat))
2890  Vfng=Mfng/(1.608-.608*Mfng)
2900  Mfng=Mfng*100
2910  Vfng=Vfng*100
2920  BEEP
2930  IF Iov=2 THEN
2940  PRINT
2950  PRINT USING "10X,""Data set number              = "",DD":J
2960  END IF
2970  IF Iov=2 AND Ng=1 THEN
2980  PRINT USING "10X,""        P          Psat     Ptran    Tmeas     Tsat         N
G %"""
2990  PRINT USING "10X,"" (mm)     (kPa)    (kPa)    (kPa)     (C)      (C)     Molal
   Mass"""
3000  PRINT USING "10X,5(3D.DD,2X),2(3D.DD,2X),2(M3D.D,2X)":Pmm,Pkm,Pks,Pkt,Tste
am,Tsat,Vfng,Mfng
3010  PRINT
3020  END IF
3030  IF Mfng>.5 THEN
3040  BEEP
3050  PRINT
3060  IF Im=1 AND Ng=1 THEN
3070  BEEP
3080  PRINT
3090  PRINT USING "10X,""Energize the vacuum system """
3100  BEEP
3110  INPUT "OK TO ACCEPT THIS RUN (1=Y,0=N)?",Ok
3120  IF Ok=0 THEN
3130  BEEP
3140  DISP "NOTE: THIS DATA SET WILL BE DISCARDED!! "
3150  WAIT 5
3160  GOTO 1980
3170  END IF
3180  END IF
3190  END IF
3200  IF Im=1 THEN
3210  IF Fm<10 OR Fm>100 THEN
3220  Ifm=0
3230  BEEP
3240  INPUT "INCORRECT FM (1=ACCEPT,0=DELETE)",Ifm
3250  IF Ifm=0 THEN 1960
3260  END IF
3270  IF Ifg=1 OR Iwt=0 THEN
3280  OUTPUT @File:Bvol,Bamp,Vtran,Etp,Emf(0),Emf(1),Emf(2),Emf(3),Emf(4),Fm,T1,
T2,Phg,Pwater
3290  END IF
3300  IF Ifg=0 AND Iwt=1 THEN OUTPUT @File:Bvol,Bamp,Vtran,Etp,Emf(*),Fm,T1,T2,P
hg,Pwater
3310  END IF
3320  IF Ifg=0 AND Iwt=1 THEN OUTPUT @File1:Tw(*)
3330! ANALYSIS BEGINS
3340  T1=FNTvsv(Emf(2))
```

```
3350  Grad=FNGrad((T1+T2)*.5)
3360  To=Ti+ABS(Etp)/(10*Grad)*1.E+6
3370  Er1=ABS(Ti-T1)
3380  PRINTER IS 1
3390  PRINT USING """T1 (QCT)     = "",DD.3D";T1
3400  PRINT USING """Ti (TC)      = "",DD.3D";Ti
3410  IF Er1>.5 THEN
3420  BEEP
3430  PRINT "QCT AND TC DIFFER BY MORE THAN 0.5 C"
3440  BEEP
3450  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok1
3460  END IF
3470  PRINT USING """DT (QCT)     = "",Z.3D";T2-T1
3480  PRINT USING """DT (T-PILE) = "",Z.3D";To-Ti
3490  IF Ok1=0 AND Er1>.5 THEN 4640
3500  Er2=ABS((T2-T1)-(To-Ti))/(T2-T1)
3510  IF Er2>.05 THEN
3520  BEEP
3530  PRINT "QCT AND T-PILE DIFFER BY MORE THAN 5%"
3540  BEEP
3550  INPUT "OK TO GO AHEAD (1=Y,0=N)?",Ok2
3560  IF Ok2=0 AND Er2>.05 THEN 4640
3570  END IF
3580  PRINTER IS 701
3590  IF Itm=1 THEN
3600  T1i=T1
3610  T2o=T2
3620  END IF
3630  IF Itm=2 THEN
3640  T1i=Ti
3650  T2o=To
3660  END IF
3670  IF Itm=3 THEN
3680  T1i=(T1+Ti)*.5
3690  T2o=(T2+To)*.5
3700  END IF
3710  Tavg=(T1i+T2o)*.5
3720  Cpw=FNCpw(Tavg)
3730  Rhow=FNRhow(Tavg)
3740  Md=5.00049E-3+6.9861937E-3*Fm
3750  Md=Md*(1.0365-1.96644E-3*Tavg+5.252E-5*Tavg^2)/.995434
3760  Mf=Md/Rhow
3770  Vw=Mf/(PI*Di 2/4)
3780  IF Inn=0 THEN T2o=T2o-(.0138+.001*Vw^2)
3790  IF Inn=1 THEN T2o=T2o-.004*Vw 2
3800  IF Inn=3 THEN T2o=T2o-.0018*Vw^2
3810  Q=Md*Cpw*(T2o-T1i)
3820  Qp=Q/(PI*Do*L)
3830  Kw=FNKw(Tavg)
3840  Muw=FNMuw(Tavg)
3850  Rei=Rhow*Vw*Di/Muw
3860  Prw=FNPrw(Tavg)
3870  Fe1=0.
3880  Fe2=0.
3890  Cf=1.
3900  Hi=Kw*Ci/Di*Rei .8*Prw .3333*Cf
3910  Dt=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
3920  Cfc=(Muw/FNMuw(Tavg+Dt)) .14
3930  IF ABS((Cfc-Cf)/Cfc)>.01 THEN
3940  Cf=(Cf+Cfc)*.5
```

```
3950  GOTO 3900
3960  END IF
3970  IF I[illegible] THEN GOTO [illegible]
3980  P1=PI*(Di+Do)
3990  A1=(Do-Di)*PI*(Di+Do)*.5
4000  M1=(Hi*P1/(Kcu*A1)) .5
4010  P2=PI*(Di+Dr)
4020  A2=(Dr-Di)*PI*(Di+Dr)*.5
4030  M2=(Hi*P2/(Kcu*A2)) .5
4040  Fe1=FNTanh(M1*L1)/(M1*L1)
4050  Fe2=FNTanh(M2*L2)/(M2*L2)
4060  Lmtd=(T2o-T1i)/LOG((Tsteam-T1i)/(Tsteam-T2o))
4070  Uo=Q/(Lmtd*PI*Do*L)
4080  Ho=1/(1/Uo-Do*L/(Di*(L+L1*Fe1+L2*Fe2)*Hi)-Rm)
4090  Dtc=Q/(PI*Di*(L+L1*Fe1+L2*Fe2)*Hi)
4100  IF ABS((Dtc-Dt)/Dtc)>.01 THEN 3900
4110  Hfg=FNHfg(Tsteam)
4120  OUTPUT @Filep;Qp,Ho
4130  Ql=500
4140  Qloss=Ql/(100-25)*(Tsteam-Troom)
4150  Hfc=FNHf(Tcon)
4160  Hf=FNHf(Tsteam)
4170  Mdv=0
4180  Bp=(Bvol*100) 2/5.76
4190  Mdvc=((Bp-Qloss)-Mdv*(Hf-Hfc))/Hfg
4200  IF ABS((Mdv-Mdvc)/Mdvc)>.01 THEN
4210  Mdv=(Mdv+Mdvc)*.5
4220  GOTO 4190
4230  END IF
4240  Mdv=(Mdv+Mdvc)*.5
4250  Vg=FNVvst(Tsteam)
4260  Vv=Mdv*Vg/Ax
4270  IF Iov=2 THEN
4280  PRINT USING "10X,""  T (Inlet)      Delta-T"""
4290  PRINT USING "10X,"" QCT     TC    QCT  T-PILE"""
4300  PRINT USING "10X,2(DD.DD,2X),2(Z.3D,2X)":T1,Ti,T2-T1,To-Ti
4310  PRINT USING "10X,"" Vw       Rei          Hi          Uo          Ho          q
       Vv"""
4320  PRINT USING "10X,Z.DD,1X,5(MZ.3DE,1X),MZ.DD":Vw,Rei,Hi,Uo,Ho,Qp,Vv
4330  END IF
4340  IF Iov=1 THEN
4350  IF Inf=1 THEN
4360  PRINT USING "11X,DD,2X,Z.DD,2X,2(5D.D,2X),Z.3DE,1X,Z.DD,2(1X,3D.DD)":J,Vw,
Uo,Ho,Qp,Vv,F,Nr
4370  ELSE
4380  PRINT USING "11X,DD,2X,Z.DD,2X,2(MD.4DE,2X),Z.3DE,3X,Z.DD":J,Vw,Uo,Ho,Qp,V
v
4390  END IF
4400  END IF
4410  IF Im=1 THEN
4420  BEEP
4430  INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
4440  Nrun=J
4450  IF Go_on=1 THEN Repeat
4460  ELSE
4470  IF J<Nrun THEN Repeat
4480  END IF
4490  IF Im=1 THEN
4500  BEEP
4510  PRINT
4520  PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file "",10A":J,
```

```
P_File$
4530  END IF
4540  BEEP
4550  PRINT
4560  PRINT USING "10X,""NOTE: "",ZZ,"" X-Y pairs were stored in plot data file
"",10A";J,P_File$
4570  ASSIGN @File TO *
4580  ASSIGN @Filep TO *
4590  BEEP
4600  INPUT "LIKE TO PLOT DATA (1=Y,0=N)?",Ok
4610  IF Ok=1 THEN
4620  CALL Plot
4630  END IF
4640  END
4650  DEF FNPvst(Tsteam)
4660  DIM K(8)
4670  DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
4680  DATA 4.16711732,20.9750676,1.E9,6
4690  READ K(*)
4700  T=(Tsteam+273.15)/647.3
4710  Sum=0
4720  FOR N=0 TO 4
4730  Sum=Sum+K(N)*(1-T) (N+1)
4740  NEXT N
4750  Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2))-(1-T)/(K(7)*(1-T)^2+K(8))
4760  Pr=EXP(Br)
4770  P=22120000*Pr
4780  RETURN P
4790  FNEND
4800  DEF FNHfg(T)
4810  Hfg=2477200-2450*(T-10)
4820  RETURN Hfg
4830  FNEND
4840  DEF FNMuw(T)
4850  A=247.3/(T+133.15)
4860  Mu=2.4E-5*10 A
4870  RETURN Mu
4880  FNEND
4890  DEF FNVvst(Tt)
4900  P=FNPvst(Tt)
4910  T=Tt+273.15
4920  X=1500/T
4930  F1=1/(1+T*1.E-4)
4940  F2=(1-EXP(-X)) 2.5*EXP(X)/X .5
4950  B=.0015*F1-.000942*F2-.0004882*X
4960  K=2*P/(461.52*T)
4970  V=(1+(1+2*B*K)^.5)/K
4980  RETURN V
4990  FNEND
5000  DEF FNCpw(T)
5010  Cpw=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
5020  RETURN Cpw*1000
5030  FNEND
5040  DEF FNRhow(T)
5050  Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
5060  RETURN Ro
5070  FNEND
5080  DEF FNPrw(T)
5090! Prw=10 (1.09976605-T*(1.3749326E-2-T*(3.968875E-5-3.45026E-7*T)))
5100  Prw=FNCpw(T)*FNMuw(T)/FNKw(T)
5110  RETURN Prw
```

```
5120  FNEND
5130  DEF FNKw(T)
5140! Kw=.5625894+T*(2.2984546E-3-T*(1.509756E-5-4.0581652E-8*T))
5150  X=(T+273.15)/273.15
5160  Kw=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
5170  RETURN Kw
5180  FNEND
5190  DEF FNTanh(X)
5200  P=EXP(X)
5210  Q=EXP(-X)
5220  Tanh=(P-Q)/(P+Q)
5230  RETURN Tanh
5240  FNEND
5250  DEF FNTvsv(V)
5250  COM /Cc/ C(7)
5270  T=C(0)
5280  FOR I=1 TO 7
5290  T=T+C(I)*V^I
5300  NEXT I
5310  T=T+4.73386E-3+T*(7.692834E-3-T*8.077927E-5)
5320  RETURN T
5330  FNEND
5340  DEF FNHf(T)
5350  Hf=T*(4.203849-T*(5.88132E-4-T*4.55160317E-6))
5360  RETURN Hf*1000
5370  FNEND
5380  DEF FNGrad(T)
5390  Grad=37.9853+.104388*T
5400  RETURN Grad
5410  FNEND
5420  DEF FNTvsp(P)
5430  Tu=110
5440  Tl=10
5450  Ta=(Tu+Tl)*.5
5460  Pc=FNPvst(Ta)
5470  IF ABS((P-Pc)/P)>.001 THEN
5480  IF Pc<P THEN Tl=Ta
5490  IF Pc>P THEN Tu=Ta
5500  GOTO 5450
5510  END IF
5520  RETURN Ta
5530  FNEND
5540  DEF FNPvsv(V)
5550  P=8133.5133+2.236051E+4*V
5560  RETURN P
5570  FNEND
5580  SUB Plot
5590  DIM C(9)
5600  PRINTER IS 705
5610  BEEP
5620  INPUT "OK TO SELECT DEFAULT VALUES FOR CAGE ".Okd
5630  IF Okd=1 THEN
5640  BEEP
5650  INPUT "ENTER PRESSURE CONDITION (1=V.2=A)".Iva
5660  END IF
5670  BEEP
5680  INPUT "SELECT OPTION (1=Ho.2=Dt)".Iht
5690  IF Okd=1 THEN
5700  IF Iva=1 AND Iht=1 THEN
5710  Xmin=100000
5720  Xmax=600000
```

```
5730  Ymin=0
5740  Ymax=120000
5750  Xstep=100000
5760  Ystep=20000
5770  END IF
5780  IF Iva=2 AND Iht=1 THEN
5790  Xmin=400000
5800  Xmax=1.6E+6
5810  Ymin=0
5820  Ymax=120000
5830  Xstep=400000
5840  Ystep=20000
5850  END IF
5860  IF Iva=1 AND Iht=2 THEN
5870  Xmin=0
5880  Xmax=30
5890  Ymin=100000
5900  Ymax=600000
5910  Xstep=10
5920  Ystep=100000
5930  END IF
5940  IF Iva=2 AND Iht=2 THEN
5950  Xmin=0
5960  Xmax=30
5970  Ymin=400000
5980  Ymax=1.6E+6
5990  Xstep=10
6000  Ystep=400000
6010  END IF
6020  END IF
6030  IF Okd=0 THEN
6040  BEEP
6050  INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
6060  BEEP
6070  INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
6080  BEEP
6090  INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
6100  BEEP
6110  INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
6120  END IF
6130  BEEP
6140  PRINT "IN:SP1:IP 2300,1800,8300,6800:"
6150  PRINT "SC 0,100,0,100:TL 2,0:"
6160  Sfx=100/(Xmax-Xmin)
6170  Sfy=100/(Ymax-Ymin)
6180  BEEP
6190  Icg=0
6200  INPUT "LIKE TO BY-PASS CAGE (1=Y,0=N=DEFAULT)?",Icg
6210  IF Icg=1 THEN 6650
6220  PRINT "PU 0,0 PD"
6230  FOR Xa=Xmin TO Xmax STEP Xstep
6240  X=(Xa-Xmin)*Sfx
6250  PRINT "PA":X,",0: XT:"
6260  NEXT Xa
6270  PRINT "PA 100,0:PU:"
6280  PRINT "PU PA 0,0 PD"
6290  FOR Ya=Ymin TO Ymax STEP Ystep
6300  Y=(Ya-Ymin)*Sfy
6310  PRINT "PA 0,":Y,"YT"
6320  NEXT Ya
6330  PRINT "PA 0,100 TL 0 2"
```

```
6340  FOR Xa=Xmin TO Xmax STEP Xstep
6350  X=(Xa-Xmin)*Sfx
6360  PRINT "PA":X.".100: XT""
6370  NEXT Xa
6380  PRINT "PA 100.100 PU PA 100.0 PD"
6390  FOR Ya=Ymin TO Ymax STEP Ystep
6400  Y=(Ya-Ymin)*Sfy
6410  PRINT "PD PA 100.".Y."YT"
6420  NEXT Ya
6430  PRINT "PA 100.100 PU"
6440  PRINT "PA 0.-2 SP 1.5.2"
6450  FOR Xa=Xmin TO Xmax STEP Xstep
6460  X=(Xa-Xmin)*Sfx
6470  PRINT "PA":X.".0:"
6480  IF Iht=1 THEN PRINT "CP -4.-1:LB":Xa:""
6490  IF Iht=2 THEN PRINT "CP -2.-1:LB":Xa:""
6500  NEXT Xa
6510  PRINT "PU PA 0.0"
6520  FOR Ya=Ymin TO Ymax STEP Ystep
6530  Y=(Ya-Ymin)*Sfy
6540  PRINT "PA 0.":Y.""
6550  PRINT "CP -7.-.25:LB":Ya:""
6560  NEXT Ya
6570  BEEP
6580  INPUT "ENTER X-LABEL".Xlabel$
6590  BEEP
6600  INPUT "ENTER Y-LABEL".Ylabel$
6610  PRINT "SR 1.5.2:PU PA 50.-10 CP":-LEN(Xlabel$)/2:"0:LB":Xlabel$:""
6620  PRINT "PA -18.50 CP 0.":-LEN(Ylabel$)/2*5/6:"DI 0,1:LB":Ylabel$:""
6630  PRINT "CP 0.0 DI"
6640 Repeat:!
6650  BEEP
6660  INPUT "LIKE TO PLOT DATA FROM A FILE (1=Y,0=N)?".Ok
6670  Okp=0
6680  IF Ok=1 THEN
6690  BEEP
6700  INPUT "WANT TO CHANGE PEN (1=Y.0=N)".Okp
6710  IF Okp=1 THEN
6720  BEEP
6730  PRINT "SP0"
6740  BEEP
6750  INPUT "CHANGE PEN AND HIT CONTINE".Okc
6760  PRINT "SP1"
6770  END IF
6780  BEEP
6790  INPUT "ENTER THE NAME OF THE DATA FILE".D_file$
6800  ASSIGN @File TO D_file$
6810  Sx=0
6820  Sy=0
6830  Sx2=0
6840  Sxy=0
6850  BEEP
6860  INPUT "ENTER THE BEGINNING RUN NUMBER".Md
6870  BEEP
6880  INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED".Npairs
6890  BEEP
6900  INPUT "SELECT A SYMBOL FOR THE PLOTTER (1=*.2=+.3=c.4=o.5= )".Sym
6910  PRINT "PU DI"
6920  IF Sym=1 THEN PRINT "SM*"
6930  IF Sym=2 THEN PRINT "SM+"
6940  IF Sym=3 THEN PRINT "SMc"
```

```
6950  IF Sym=4 THEN PRINT "SMc"
6960  IF Sym=5 THEN PRINT "SM "
6970  IF Md>Npairs THEN
6980  FOR I=1 TO (Md-1)
6990  ENTER @File:Xa,Ya
7000  NEXT I
7010  END IF
7020  FOR I=1 TO Npairs
7030  ENTER @File:Xa,Ya
7040  Yt=Xa
7050  Xa=Xa/Ya
7060  Ya=Yt
7070  Yc=LOG(Ya)
7080  Xc=LOG(Xa)
7090  Sx=Sx+Xc
7100  Sy=Sy+Yc
7110  Sx2=Sx2+Xc^2
7120  Sxy=Sxy+Xc*Yc
7130  IF Iht=1 THEN
7140  Xt=Ya
7150  Ya=Ya/Xa
7160  Xa=Xt
7170  END IF
7180  X=(Xa-Xmin)*Sfx
7190  Y=(Ya-Ymin)*Sfy
7200  IF Y>100 OR Y<0 THEN 7220
7210  PRINT "PA",X,Y,""
7220  NEXT I
7230  BEEP
7240  INPUT "WANT TO PLOT A LEAST-SQUARES LINE",Ils
7250  IF Ils=1 THEN
7260  PRINT "SM"
7270  Bb=(Npairs*Sxy-Sy*Sx)/(Npairs*Sx2-Sx 2)
7280  Aa=(Sy-Bb*Sx)/Npairs
7290  Aa=EXP(Aa)
7300  PRINTER IS 1
7310  PRINT USING "10X,""a = "",Z.4DE":Aa
7320  PRINT USING "10X,""n = "",Z.4DE":Bb
7330  PRINTER IS 705
7340  FOR Xa=Xmin TO Xmax STEP Xstep/40
7350  IF Iht=2 THEN Ya=Aa*(Xa) Bb
7360  IF Iht=1 THEN Ya=Aa (1/Bb)*Xa ((Bb-1)/Bb)
7370  Y=(Ya-Ymin)*Sfy
7380  X=(Xa-Xmin)*Sfx
7390  IF Y<0 THEN Y=0
7400  IF Y>100 THEN GOTO 7420
7410  PRINT "PA",X,Y,"PD"
7420  NEXT Xa
7430  PRINT "PU"
7440  END IF
7450  ASSIGN @File TO *
7460  GOTO 6650
7470  END IF
7480  PRINT "PU SM"
7490  BEEP
7500  INPUT "WANT TO PLOT NUSSELT LINE (1=Y,0=N)?",Inp
7510  IF Inp=0 THEN 7620
7520  BEEP
7530  INPUT "ENTER SLOPE FOR CONSTANT IN HNu vs q",Sl
7540  BEEP
```

```
7550  INPUT "ENTER INTERCEPT FOR CONSTANT IN [illegible] CURVE",Ac
7560  FOR Xa=Xmin TO Xmax STEP Xstep/50
7570  Ya=(Ac+Sl*Xa)/Xa^.33
7580  X=(Xa-Xmin)*Sfx
7590  Y=(Ya-Ymin)*Sfy
7600  PRINT "PA",X,Y,"PD"
7610  NEXT Xa
7620  PRINT "PU PA 0,0"
7630  BEEP
7640  INPUT "LIKE TO DRAW A STRAIGHT LINE (1=Y,0=N)?",Go_on
7650  IF Go_on=1 THEN
7660  BEEP
7670  INPUT "ENTER THE SLOPE",Sl
7680  BEEP
7690  INPUT "ENTER THE INTERCEPT",Ac
7700  FOR Xa=Xmin TO Xmax STEP (Xmax-Xmin)
7710  Ya=Ac+Sl*Xa
7720  Y=(Ya-Ymin)*Sfy
7730  X=(Xa-Xmin)*Sfx
7740  IF Y<0 THEN
7750  Xam=(Ymin-Ac)/Sl
7760  X=(Xam-Xmin)*Sfx
7770  Y=0
7780  END IF
7790  IF Y>100 THEN
7800  Xam=(Ymax-Ac)/Sl
7810  X=(Xam-Xmin)*Sfx
7820  Y=100
7830  END IF
7840  PRINT "PA",X,Y,"PD"
7850  NEXT Xa
7860  END IF
7870  BEEP
7880  INPUT "WANT TO PLOT A POLYNOMIAL (1=Y,0=N)?",Go_on
7890  IF Go_on=1 THEN
7900  BEEP
7910  INPUT "ENTER THE ORDER OF POLYNOMIAL",M
7920  FOR J=0 TO M
7930  BEEP
7940  IF J>0 THEN INPUT "ENTER THE NEXT COEFFICIENT",C(J)
7950  IF J=0 THEN INPUT "ENTER THE FIRST COEFFICIENT",C(0)
7960  NEXT J
7970  Ya=C(0)
7980  FOR Xa=Xmin TO Xmax STEP Xstep/10
7990  FOR J=1 TO M
8000  Ya=Ya+C(J)*Xa^J
8010  NEXT J
8020  Y=(Ya-Ymin)*Sfy
8030  X=(Xa-Xmin)*Sfx
8040  IF Y<0 THEN Y=0
8050  IF Y>100 THEN GOTO 8070
8060  PRINT "PA",X,Y,"PD"
8070  NEXT Xa
8080  END IF
8090  PRINT "PU PA 0,0 SP0"
8100  SUBEND
```

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