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CONDENSATION OF REFRIGERANTS ON
SMALL TUBE BUNDLES

by

Burlin Davis Mabrey

December 1988

Thesis Co-advisors: P.J. Marto
A.S. Wanniarachchi

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Condensation of Refrigerants on Small Tube Bundles

by

Burlin Davis Mabrey
Lieutenant, United States Navy
B.S., U.S. Naval Academy, 1977
B.A., University of Laverne, 1980

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requirements for the degree of

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NAVAL POSTGRADUATE SCHOOL
December 1988

Author:

B.D. Mabrey

B.D. Mabrey

Approved by:

P.J. Marto

P.J. Marto, Thesis Co-advisor

A.S. Wanniarachchi

A.S. Wanniarachchi, Thesis Co-advisor

A.J. Healey

A.J. Healey, Chairman
Department of Mechanical Engineering

G.E. Schacher

G.E. Schacher,
Dean of Science and Engineering

ABSTRACT

The construction of an apparatus for the condensation performance testing of a horizontal bundle of four tubes with various refrigerants was completed. The apparatus was instrumented, and data reduction software was developed to provide bundle and single tube condensation data.

Two tube bundles were tested, smooth copper tubes and low integral-fin copper-nickel tubes, with two refrigerants, R-114 and R-113. An enhancement ratio of about 2.0 for the overall heat transfer coefficient was demonstrated for the finned tubes over the smooth tubes.

Internal contamination, possibly due to a breakdown of the refrigerant molecules when subjected to high temperatures in the boiling chamber, inhibited further meaningful data collection. Recommendations for improvement of the test apparatus are made.

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NOMENCLATURE

A_{ef}	Effective outside area of the tube (m^2)
A_f	Actual area of a finned tube (m^2)
A_i	Tube inside area (m^2)
A_o	Tube outside area (m^2)
A_r	Surface area of tube at the base of the fin (m^2)
C_i	Inside correlation coefficient
C_o	Outside correlation coefficient
C_p	Specific heat of coolant (J/kg K)
D_{eq}	Equivalent diameter of finned tube (m)
D_i	Inside diameter of test tube (m)
D_o	Outside diameter of test tube (m)
D_r	Root diameter of finned tube (m)
g	Acceleration due to gravity (m/s^2)
L	Length of the condenser tube (m)
LMTD	Log mean temperature difference (K)
N	Number of the tube from top of bundle
Ph	Phase Change Number
Pr	Prandtl Number
Q	Heat-transfer rate (W)
Q''	Heat-flux (W/m^2)
Re	Reynolds Number
R_m	Tube wall thermal resistance ($m^2 \cdot K/W$)
Res	Swirl Reynolds Number

T_{c_i}	Coolant inlet temperature (K)
T_{c_o}	Coolant exit temperature (K)
T_{sat}	Vapor saturation temperature (K)
U_o	Overall heat-transfer coefficient ($W/m^2 \cdot K$)

Greek

α_i	Inside heat-transfer coefficient ($W/m^2 \cdot K$)
α_i	Average inside heat-transfer coefficient ($W/m^2 \cdot K$)
α_o	Outside heat-transfer coefficient ($W/m^2 \cdot K$)
α_o	Average outside heat-transfer coefficient ($W/m^2 \cdot K$)
Δh_v	Specific enthalpy of vaporization (J/kg)
ΔT	Temperature rise of coolant across condensing length (K)
λ	Thermal conductivity ($W/m \cdot K$)
Γ	Mass flow rate of coolant (kg/s)
ρ	Density (kg/m^3)
η_{eff-f}	Fin efficiency
η	Dynamic viscosity ($N \cdot s/m$)

I. INTRODUCTION

A. BACKGROUND

With the advent of more complex shipboard weapons/combat systems and increasing fuel costs, the United States Navy has increasingly recognized a need for an energy-efficient, light-weight, and high-capacity air-conditioning system. Such an advanced system has been proposed and is currently in its test and evaluation phase for the DDG-51 program [Ref. 1].

Among the substantial differences in the advanced air-conditioning plant over extant systems is the use of titanium finned tubes in the condenser, in place of the smooth copper-nickel alloyed tubes previously used. The use of titanium in the air-conditioner's condenser presents two significant advantages. First, since the United States Navy uses ambient seawater as a heat sink, the corrosion resistance of titanium should measurably improve system integrity and reliability. Secondly, the advanced air-conditioning system expects to realize a weight savings per unit of 2286 kg (5040 lbs) and the major portion of this weight savings will come from the use of the lighter-weight titanium condenser tubes [Ref. 1].

Since the early 1970's the United States Navy has used R-114 as its primary refrigerant. The advantages of R-114 over the more-widely-used commercial refrigerants in a naval application derive from its low toxicity, temperature

stability, stability when in contact with moisture, and its applicability to lower-pressure systems [Ref. 1]. R-114¹ will be the refrigerant utilized in the advanced air-conditioning plant.

As no substantial data base on the heat-transfer capacity exists for a system utilizing titanium condenser tube bundles configured as proposed in the advanced air conditioning plant and consequently, no way exists to measure this design's performance against competing designs, the need arose to develop a test apparatus to provide this data base in order to accurately predict future system performance. The design and subsequent construction of this test apparatus at the Naval Postgraduate School began in 1987 and is documented in the Theses of LCDR David S. Zebrowski [Ref. 2] and of LCDR Thomas J. Murphy [Ref. 3]. The test apparatus was also intended to serve as a test platform for advanced boiling surfaces proposed for use in the advanced air-conditioning plant. The incorporation of the advanced boiling surface test platform and a condenser tube test platform into a single test apparatus allows the widest latitude in examining the effects of various heat inputs, coolant flow rates, and various levels of refrigerant contaminants on individual components and overall system performance. Zebrowski and Murphy constructed

¹New refrigerants may have to be used in the future due to the "ozone problem."

the basic apparatus, and Murphy operated the system for preliminary evaporator measurements.

B. OBJECTIVES

The major objectives of this thesis were:

1. Refine the design and complete the fabrication of the apparatus for the testing of condenser tube bundles utilizing R-114 as the working fluid.
2. Develop and instrument a data-acquisition system with the associated software to provide a data base on the heat-transfer capacity of the condenser section of the test apparatus.
3. Validate the test apparatus by comparing condenser performance against extant data bases derived from conventional condenser tube bundles.

II. LITERATURE SURVEY

A. GENERAL OBSERVATIONS

Condensation is the phase transformation process in which a vapor is transformed to liquid by removal of latent heat. The promotion of condensation in heat exchangers is used extensively in applications for propulsion engineering and air-conditioning/refrigeration cycles. Due to its importance in the aforementioned fields, considerable research has been directed at the factors influencing the process and ways in which the process can be enhanced. Such factors as various modes of condensation, surface orientation to vapor flow, the shear forces exerted on condensate film, various external and internal surface enhancements, turbulent effects due to cascading condensate flow from another surface, and the effects of fluid properties on the process are detailed extensively in various reviews. This thesis deals exclusively with film condensation of refrigerants on small horizontal tube bundles in a quiescent vapor where tubes with external fins are compared to smooth tubes.

B. SINGLE TUBE INVESTIGATIONS

1. Smooth Horizontal Tube Studies

The first comprehensive condensation model was developed by Nusselt in 1916 [Ref. 4] based on the assumption that a quiescent vapor at saturation temperature coming into

contact with a wall surface below saturation temperature would condense and form a continuous film of condensate growing in thickness as the film flowed off the surface under the influence of gravity. The condensate film at the vapor-liquid interface would be at the vapor saturation temperature with a temperature gradient in the film down to the wall surface temperature. No radiation or convection would take place at the liquid-vapor interface as both liquid and vapor are at the same temperature, however the amount of vapor condensing corresponds to the quantity of heat flowing through the film by thermal conduction. In the case of a horizontal tube, he assumed that condensate flows in a laminar manner around the sides of the tube and off the tube in a continuous sheet. The heat transfer coefficient would be maximum at the top center of the tube decreasing gradually around the surface of the tube, as the inherent thermal resistance in the film grows with the thickness of the film, and eventually goes to zero at tube bottom. Nusselt's model is limited by disregarding surface tension forces that tend to hold up condensate at the tube bottom until overcome by gravity, resulting in the production of condensate droplets rather than a continuous sheet. Nusselt's expression for the average heat transfer coefficient for a single tube subjected to a constant heat flux is given by:

$$\bar{\alpha}_O = .655 [\lambda_f^3 \cdot \rho_f^2 \cdot g \cdot \Delta h_v / \eta_f \cdot D_O \cdot Q"]^{1/3} \quad (2.1)$$

Although constrained by the aforementioned limitations, Nusselt's model remains the conservative bench-mark against which all other models are compared.

2. Exterior Surface Enhanced Tubes

Research into ways to improve condensation performance in condensers is motivated by the idea that any force that acts to thin the condensate film promotes an enhancement of heat transfer by minimizing the resistance to heat flow. General enhancement techniques include the fabrication of surfaces that promote dropwise condensation, wrapping exterior surfaces with wire, installation of porous drainage strips, and the fabrication of finned tubes with fins of various geometries and various spacings along the tube. This thesis deals with a low integral-fin tube and its heat transfer enhancement over a smooth tube.

In considering a low integral-fin tube during condensation, there exists two distinguishable regions on the circumference of the tube; a flooded region and an un-flooded region. The flooded portion of the tube defines the condensate retention angle of the tube with respect to the tube circumference. The smaller the condensate retention angle of the tube, the larger the heat transfer capacity of the tube. The fin can be divided into three regions; the fin tips, the sides of the fins, and the fin root area. The majority of heat transfer takes place at the fin tips. Surface tension forces pull the condensate from the tips down

the fin sides into the flooded root area, where gravity drains the condensate to the bottom of the tube. The amount of condensate retained along the circumference of the tube is dependent upon the ratio of surface tension forces to gravity forces.

Beatty and Katz [Ref. 5], in 1948, developed a comprehensive model for the prediction of the heat transfer coefficient of finned tubes based on their experimental results for various test fluids (including R-22) and finned tubes of various metallic compositions, and various fin geometries. Their model assumes gravity-dominated flow and neglects surface tension effects completely. Subsequent experimental results from other sources indicate that the Beatty and Katz model overpredicts the heat transfer coefficient as surface tension increases or as fin density increases. Nevertheless, the Beatty and Katz model conformed to their reported overall heat transfer enhancement of up to 2.3 for R-22 on finned tubes compared to smooth tube data. The Beatty and Katz model is given by:

$$\bar{\alpha}_O = .689 \cdot [\lambda_f^3 \cdot \rho_f^2 \cdot g \cdot \Delta h_{vf} / \eta_f \cdot \Delta T_{vf}]^{1/4} \cdot [\frac{1}{D_{eq}}]^{1/4} \quad (2.2)$$

where,

$$[\frac{1}{D_{eq}}]^{1/4} = \frac{A_r}{A_{ef}} \cdot \frac{1}{D_r^{1/4}} + 1.30 \cdot [\eta_{eff-f}] [\frac{A_f}{A_{ef}}] [\frac{1}{L^{1/4}}] \quad (2.3)$$

and,

$$\bar{L} = \pi \cdot (D_o^2 - D_r^2) / 4 \cdot D_o$$

A three-region theoretical model, based on their experimental results with three rectangular finned tubes, was presented by Karkhu and Borovkov [Ref. 6], in 1971, including surface tension forces. Measured heat-transfer coefficients demonstrated a 50 to 100 percent increase in vapor-side heat transfer coefficients for steam and R-113 condensing on finned tubes compared to smooth tubes. Unfortunately, they did not report enhancements separately for the two fluids. In 1980, results reported by Carnavos [Ref. 7] condensing refrigerants on various finned tubes demonstrated an enhancement of up to 400 percent in the heat transfer coefficient over smooth tube results. Work done by Sauer and Williams [Ref. 8], in 1982, on the condensing performance of finned tubes with oil-contaminated R-113 demonstrated a serious degradation of performance when the surface tension to density ratio was large. The conclusion formed was that the higher-surface-tension oil remained in the fin gaps rendering the finned surface ineffective. Results reported by Honda et al. [Ref. 9], in 1983, condensing R-113 on finned tubes of various geometries showed improvements of 900 percent for the vapor-side heat transfer coefficients at a constant vapor-to-tube-wall temperature difference. The results reported by Kabov

[Ref. 10] in 1984 with refrigerants R-12 and R-21, indicated that the bulk of the latent heat was in fact removed on the lateral fin surfaces and that an optimum fin height and spacing was dependent upon the ratio of surface tension to gravity forces. The results published by Masuda and Rose [Ref. 11] in 1985 in experiments with R-113 condensing on low integral-fin tubes, confirmed that the overall heat transfer coefficient increases, in general, with decreasing fin spacing. Their results showed a 600 percent increase in enhancement over smooth tube performance. More recent results by Marto et al. [Ref. 12] with R-113, demonstrated a 700 percent enhancement in performance over a smooth tube and gave an optimum fin spacing of 0.5 mm for that fluid. Work performed and published in the same time frame by Sukhatme et al. [Ref. 13] with R-11 on conventional integral-fin tubes and special pyramid-shaped fin tubes, reported enhancement ratios of 5 to 7 for the low integral fin tubes and 10.3 to 12.3 for the pyramid-shaped fin tubes.

C. TUBE BUNDLE INVESTIGATIONS

1. Smooth Tube Bundles

In smooth tube bundles, two conflicting factors play a role in determining bundle performance. First, the condensate flowing from the tubes above a given tube in a bundle tends to thicken the condensate film on that tube, hence increasing the resistance to heat transfer. This effect is known as the condensate inundation effect. Secondly,

droplets from other tubes striking the film surface on a tube with a velocity provided by gravity or vapor flow, can create ripples or waves in the condensate film imparting a turbulence within the condensate film that produces an enhancement of heat transfer performance.

In 1949, Jakob [Ref. 14] elaborating on Nusselt's model, predicted that the vapor-side heat transfer coefficient for a tube in a bundle, compared to the first tube in the bundle, was a function of that tube's relative position in the bundle. This model was based upon the assumption that a continuous laminar sheet of condensate flowing off the tube directly above the tube considered and striking the top of this tube further thickened the condensate film on this tube. Jakob's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/4} \quad (2.4)$$

In 1958, Kern [Ref. 15] proposed a model based on the assumption that discrete droplets or jets of fluid from other tubes caused ripples in the condensate film diminishing the inundation effect. Kern's model is less conservative than Nusselt's and, in many cases, remains the applied industrial design standard. Kern's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/6} \quad (2.5)$$

Work by Chen [Ref. 16], published in 1961, proposed a model that considered the momentum gain of falling condensate as well as the condensation of vapor on sub-cooled condensate droplets or sheets. Chen's model which is essentially Nusselt's model times a factor that incorporates the phase change number is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = N^{-1/4} [1 + 2 \cdot Ph \cdot (N-1)] \quad (2.6)$$

where the Phase Change number is given by:

$$Ph = \frac{C_p \Delta T}{\Delta h_v}$$

Equation (2.6) is valid provided,

$$Ph \cdot (N-1) \leq 2.0$$

A model proposed by Eissenberg [Ref. 17] in 1972, assumes that condensate does not always drain in a vertical direction but may be diverted sideways due to local vapor flow conditions. In this case, the condensate strikes subsequent tubes on their sides rather than on their tops, minimizing inundation effects on the condensate film in the top portion of the tube. Eissenberg's model is given by:

$$\frac{\bar{\alpha}_N}{\alpha_1} = .60 + .42 \cdot (N^{-1/4}) \quad (2.7)$$

2. Enhanced Tube Bundles

Katz and Geist [Ref. 18] in 1948, studying six fin tubes in a vertical row, using R-12 among other working fluids, found that the effect of condensate inundation was over-predicted by Jakob's model and proposed that the exponent in Equation (2.4) be changed to 0.06 for finned tubes.

A theoretical model was proposed by Honda et al. [Ref. 19] in work published in 1987, for finned tube bundles that showed good agreement, within 5 to 7%, for data taken condensing acetone and R-12 on finned tubes. Their model relies upon solving a set of algebraic equations describing the vapor-to-coolant conjugate heat transfer problem. A compendium of the aforementioned models, both single tube and bundles, is provided by Marto [Ref. 20].

As of the date of this writing, the author is unaware of any comprehensive model, substantiated by experimental results, that accurately predicts heat transfer performance for enhanced tube bundles with varying fin geometries and varying pitch.

III. EXPERIMENTAL APPARATUS

A. CONDENSER/BOILER TUBE BANK TEST PLATFORM

1. Overview

The composite test platform, with associated support systems, is depicted schematically in Figure 3.1. The boiler/condenser unit was fabricated from 6.35 mm thick, rolled stainless steel plates designed to withstand an absolute pressure of 308 kPa. The top cylinder which serves as the condenser for the apparatus is 1.30 m in length with an external diameter of 0.61 m. The effective condensing length is 1.22 m. The condensing chamber is capped on either end with circular stainless steel plates of 0.71 m diameter and connected to the chamber with a flange and stud assembly. System integrity is maintained with a 3.20 mm thick rubber gasket. The end caps support the nylon block condenser tube mounts, stainless steel backing plates, auxiliary condenser coils (coolant entrance side), and mixing chambers (coolant exit side). The condenser chamber has five 12.7 mm thick Pyrex glass view ports backed with 12.7 mm thick Plexiglas. The view ports are 127 mm in diameter and are located axially along the main chamber, angled so as to provide top to bottom views of the test tubes at various locations along the effective condensing length. The condenser chamber and

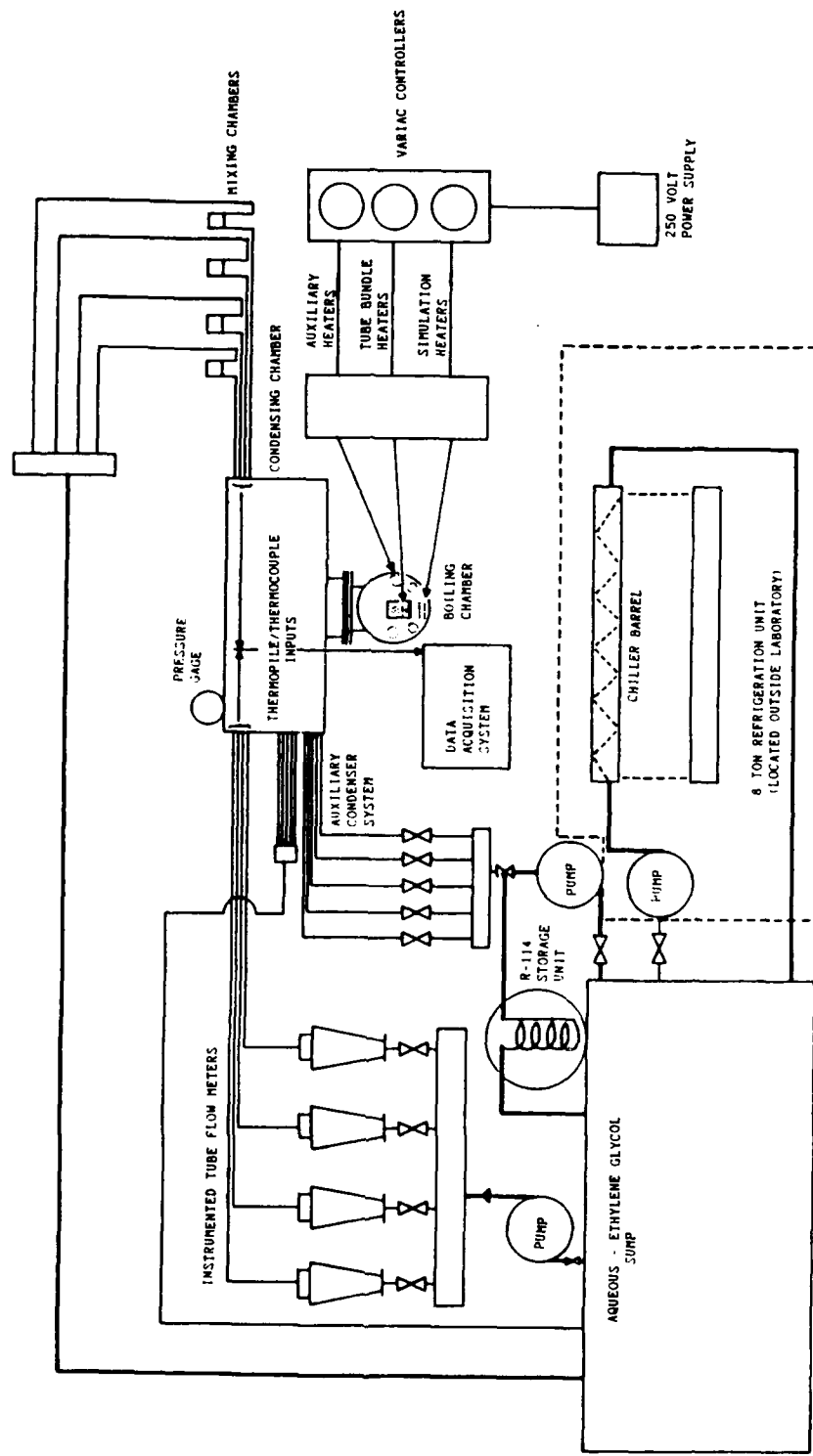


Figure 3.1 System Schematic

ancillary equipment are depicted graphically and in photographs in Figures 3.2 through 3.5.

Internal to the condenser chamber, a stainless steel shroud is fitted over the effective condensing length of the instrumented test tubes (see Figure 3.6). The purpose of the shroud is to channel refrigerant vapor along the inside circumference of the shell, collecting vapor at the top, and then forcing vapor through the vertical axis of the instrumented tube bank into the shroud's well, where condensate is collected and the remaining vapor is condensed by an auxiliary condenser. The auxiliary condenser is composed of five helically wound copper tubes of 9.53 mm diameter suspended inside the shroud well by cantilevered rods welded to the entrance end cap. The stainless steel shroud was fabricated with a glass panel serving as one side of its stem to permit viewing of the instrumented tubes through the view ports.

The condenser chamber is attached to the boiler chamber by a rolled stainless-steel cylinder nominally 280 mm in diameter and 203 mm in length, located mid-way along the condenser chamber's length allowing condensate to drain by gravity. A collar dam was fitted at the connecting flange, for the initial purpose of providing a condensate drain point to send condensate to the auxiliary storage unit. Subsequently, a faster, more-efficient method of transferring refrigerant was devised that allowed refrigerant vapor to be



Figure 3.2 Photograph of Apparatus and Support Systems

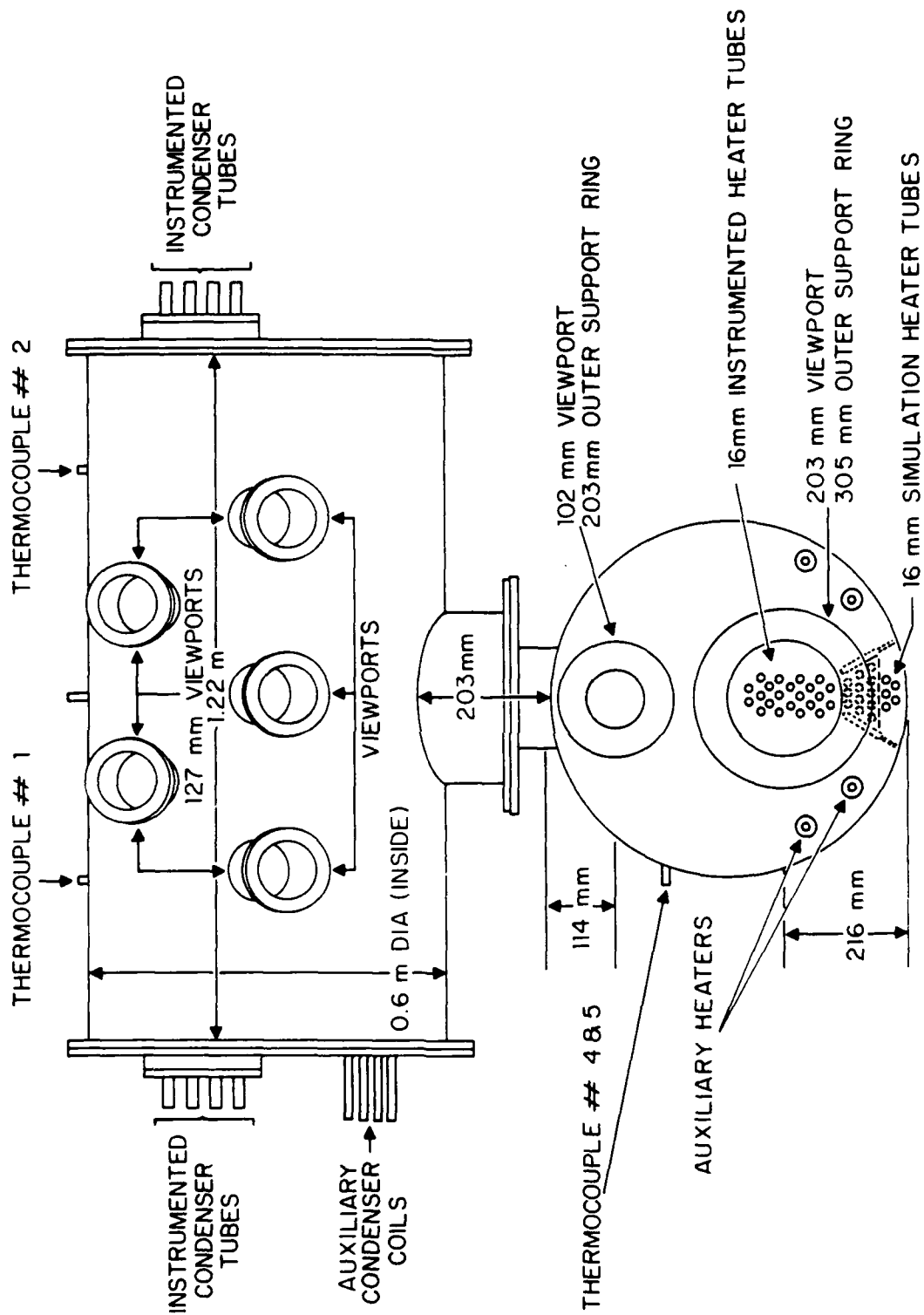


Figure 3.3 Apparatus Schematic



Figure 3.4 Photograph of Coolant Entrance Endcap



Figure 3.5 Photograph of Coolant Exit Endcap

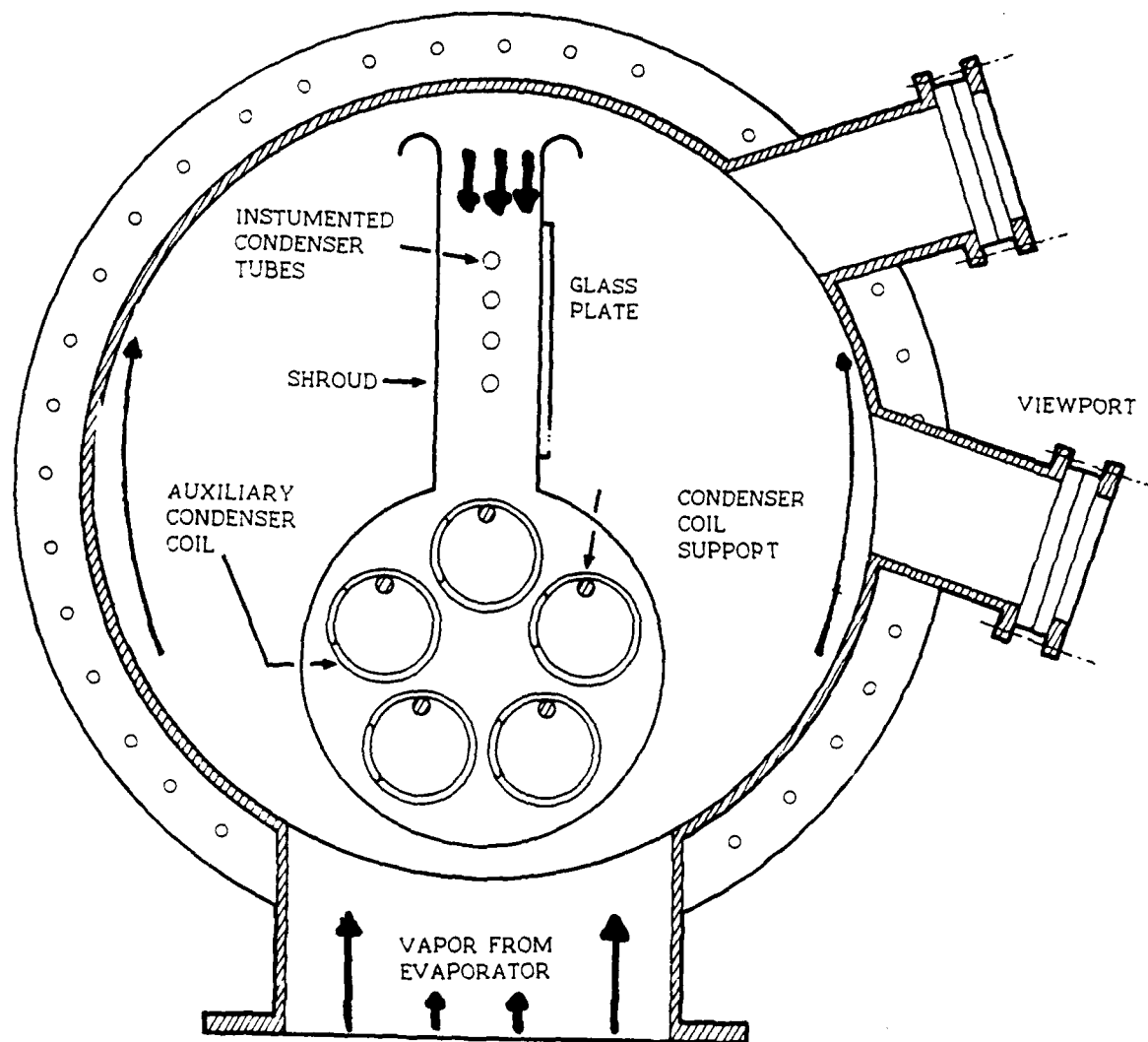


Figure 3.6 Cross-section of Condensing Chamber Schematic

sent and condensed in the auxiliary storage unit. A 9.53 mm diameter copper tubing was provided for the vapor flow from the top of the condenser chamber to the storage tank. A similar tubing was provided between the storage tank and the boiling chamber to allow liquid flow via gravity.

The boiling chamber is connected to the condenser unit via the interconnecting riser as previously discussed. The boiling chamber was also fabricated from rolled stainless-steel and is cylindrical with an outside diameter of 0.61 m and a length of 0.279 m. The boiling chamber is fitted with two Pyrex view ports, strengthened by Plexiglas plates, for observation during operation. The boiling unit is comprised of three groups of tubes (see Figure 3.3). In the simulation tube bundle, there are five boiling tubes each nominally rated at 1.5 kW and located at the bottom of the boiler unit. In the auxiliary tube bundle, there are four boiling tubes each nominally rated at 4 kW and located two on either side of the instrumented tube bundle. The instrumented tube bundle is located in the lower center of the boiling unit and is comprised of 35 tubes, with ten active tubes rated at one kW each, five instrumented tubes, and 20 dummy tubes. The power provided to these tubes is controlled by three variac controllers located on a console adjacent to the test platform and fed by a 208 volt power supply. The variac controllers are graduated in one percent increments of maximum power for each tube bundle. The exact location of each tube bundle is

apparent in Figures 3.2 through 3.5. It is a unique feature of this test platform that both boiling and condensation phenomena in a closed loop system can be evaluated simultaneously. Details on the design and construction of the basic test platform are available from Zebrowski [Ref. 2] and Murphy [Ref. 3]. Lightoff and securing procedures for the apparatus are listed in Appendix B.

2. Ancillary Systems

Component equipment that support the R-114 tube bundle test platform and are located external to the apparatus include: (1) an R-114 storage and transfer system, (2) a condenser cooling and flow control system, (3) a coolant (62.4% by weight mixture of ethylene glycol and water) sump, and (4) an eight-ton refrigeration unit.

The R-114 storage and transfer system, as previously described, consists of a stainless-steel cylindrical tank 0.350 m in diameter and 0.91 m in length located on a rack above the coolant sump. Transfer of the refrigerant is accomplished by boiling in the main boiling chamber with vapor being sent to the storage tank via 9.53 mm diameter copper tubing located in the top center of the condenser chamber. The vapor is condensed in the storage cylinder by means of a helical copper coil, suspended the length of the cylinder on a cantilevered bar, that is kept cooled by the water-ethylene glycol mixture. Liquid refrigerant can be returned by gravity to the test platform from the bottom of the storage tank

through a 9.53 mm diameter copper tubing to the boiling chamber. Faster transfer of R-114 liquid was also possible if the system pressure was at or below the atmospheric pressure. Notice that the storage tank experiences an absolute pressure of about 210 kPa.

Coolant and flow control to the test apparatus and ancillary equipment is accomplished by two different flow path systems. Both flow systems are driven by two 0.5 HP constant-speed pumps that take suction on the main coolant sump. The coolant for the test condenser tube bank passes from the pump discharge through 76 mm diameter PVC piping to a Plexiglas header. At the header, flow is split and proceeds through 15.9 mm diameter Tygon flexible tubing to a bank of rotameters. Flow can be controlled by throttling a gate valve located at the entrance to each flow meter. Coolant flow leaves the exit of each flow meter and proceeds to the instrumented condenser tube bank through flexible Tygon tubing. At the exit of the main condenser chamber, coolant leaves each tube and flows through flexible Tygon tubing to individual mixing chambers (Figure 3.7). From the mixing chambers, coolant passes through flexible Tygon tubing to a central Plexiglas header suspended above the test platform, and the collective coolant is piped back to the main sump through 76 mm diameter PVC pipe. Auxiliary coolant flow leaves the pump discharge through PVC piping and proceeds to a two-way ball valve, where the flow is either sent to the

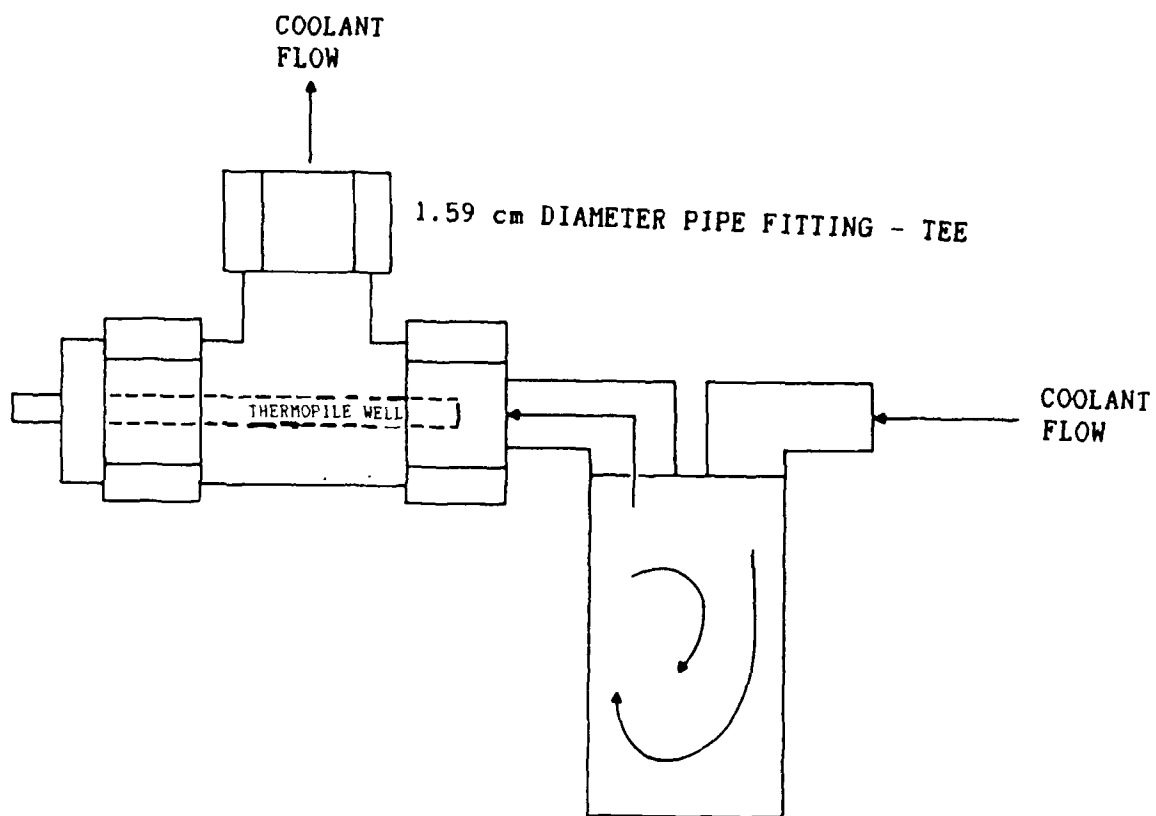


Figure 3.7 Mixing Chamber Schematic

R-114 storage tank and back to the main sump or is sent through PVC pipe to a large rotameter. From the auxiliary flowmeter, coolant enters a central header and is then split to flow to the five auxiliary condenser coils and back to the coolant sump. Flow through each auxiliary condenser coil is controlled by a valve located at the coil inlet. The coolant sump has a 1.81 cubic meter capacity and is constructed of 12.7 mm thick sheets of Plexiglas. The coolant is approximately 62.4% ethylene glycol and 37.6% water (by weight).

The coolant is chilled by an externally-located, 8 ton refrigeration system that continually re-circulates sump coolant with a 0.75 HP pump. The refrigeration system is capable of maintaining a sump temperature between -21 C and ambient temperature.

3. Instrumentation

The coolant temperature rise is measured by series-connected thermopiles having ten junctions on either end. These thermopiles were fabricated using type-T thermocouple wire. The ends of the thermopiles are inserted in stainless steel wells with copper-plugged tips located at the entrance to each individual condenser tube and at the exit of this tube's mixing chamber. Inlet coolant temperature is measured with type-T thermocouples also located in the entrance wells. Refrigerant liquid and vapor temperatures are measured with

type-T thermocouples inserted in stainless-steel wells at the locations indicated in Figures 3.2 through 3.5.

System pressure is monitored through a calibrated pressure-vacuum gage valid over a range of 30 inches mercury (vacuum) to 30 pounds per square inch (gage pressure).

4. Tube Bundle Data Acquisition and Reduction

A Hewlett-Packard 9816A computer was used to control a Hewlett-Packard 3497A Automatic Data Acquisition System, which read the output of the thermopiles and thermocouples. Readings were made in millivolts and were converted to temperature readings in the data reduction program. The channels read by the data acquisition system are listed in Table 3.1.

5. Tubes Tested

Two sets of tubes were tested. The first was a smooth copper tube (inside diameter 13.26 mm, outside diameter 15.88 mm) and the second was a low integral-fin copper-nickel tube (inside diameter 10.16 mm, root diameter 14.00 mm, outside diameter 15.88). These two sets of tubes were tested, in bundles and individually, with R-114 and R-113.

TABLE 3.1

CHANNEL ASSIGNMENTS ON DATA ACQUISITION SYSTEM

<u>Channel Numbers</u>	<u>Measurement</u>
0-2	Vapor Saturation Temperature
3-4	Liquid Temperature
5	Inlet Temperature coolant 1st Tube
6	Inlet Temperature coolant 2nd Tube
7	Inlet Temperature coolant 3rd Tube
8	Inlet Temperature coolant 4th Tube
20	Thermopile 1st Tube
21	Thermopile 2nd Tube
22	Thermopile 3rd Tube
23	Thermopile 4th Tube

IV. SYSTEM OPERATION AND DATA REDUCTION

A. TEST PLAN AND MODIFICATION OF DESIGN FOR CONDENSER TEST APPARATUS

1. Ability to Change Working Fluids

Although envisioned in the original apparatus design by Zebrowski [Ref. 2] and Murphy [Ref. 3], no physical system existed for the change-out and storage of working fluids. The system was designed as a general test platform to evaluate the performance of various refrigerants and steam during condensation on a variety of test tubes.

The R-114 storage and transfer system as described in Chapter III, ancillary systems, was designed and built to allow for the storage of refrigerants that evaporate at atmospheric temperature and pressure. This additional capability not only conserves expensive refrigerants but facilitates speedy change of these working fluids during the evaluation of a particular tube with a variety of refrigerants.

2. Tube Alignment and Reduction of Tubes in Test Bundle

Visual inspection, during preliminary experimental runs, revealed that bowing of the tube bundle was detrimentally affecting condensation patterns. As a result of misalignment of the endcaps during fabrication, bending moments of varying magnitudes and directions resulted in

condensate flow striking subsequent tubes in the vertically-oriented bundle at different positions around the circumference of the tubes. Upon disassembly of the end plates of the apparatus and comparison with the proposed drawings for the DDG-51 refrigeration condenser provided by the David Taylor Research Center, miscalculations in the tube pitch were revealed. The vertical pitch required for the project is 35.74 mm, centerline to centerline. The nylon bundle plates, as manufactured, had a pitch that was considerably less. In an effort to correct the tube misalignment problem, a low-powered laser was proposed to align the bundle tubes. A new nylon endplate was fabricated for the exit endcap, at the correct pitch with the tube bundle reduced to four vertical tubes, due to constraints in the endcap openings. An aluminum mount for the laser was fabricated by machine shop personnel that fit snugly into the tube penetrations of the nylon block. Several test projections were conducted on a plastic template fitted to the entrance endcap to minimize misalignment possibilities. The plastic template was scribed and cut with particular attention paid to correct pitch and used to manufacture the entrance nylon endplate. Subsequent visual inspection during experimental runs revealed that misalignments and bowing had been corrected.

3. Vapor Superheat Problems

During initial experimental runs, observed discrepancies in the measured temperature increases across the condenser tube lengths when compared to predicted temperature increases, prompted consideration of the possibility of vapor superheat occurring as vapor (at saturation temperature less than room temperature) flowed from the boiling chamber through the riser and up the sides of the condensing chamber. A two-pronged strategy was developed to minimize this possible effect. First, the apparatus shell was completely insulated with 12.7 mm thick foam insulation and all ancillary tygon tubing was insulated with double-wrapped, 3.18 mm thick foam insulation. Secondly, all experimental runs were performed at vapor saturation temperatures above the ambient temperature.

4. Contamination Problems

Visual inspection of the condensing tubes during operation, correlated with observed disparities in measured temperature increases across condenser tubes, revealed a structured, crystalline surface or matrix formation on the tube surfaces that inhibited heat transfer. The first appearance of the inhibiting matrix occurred during runs with smooth copper tubes and with the coolant inlet temperature at approximately -20 C. The working fluid, R-114, was transferred to the storage unit except for an oily residue that remained in the bottom of the boiling chamber. This residue was not analyzed, but was assumed to be machining oil

that remained after apparatus fabrication. The system was flushed twice, once with acetone and once with R-113, and the boiling chamber was scrubbed out. The smooth copper tubes were re-installed after a complete cleaning of their outside surfaces, and the experimental runs were repeated under the same conditions. Visual inspection again revealed the presence of the matrix formation on the tubes, and the possibility of water contamination in the R-114 was conjectured as a probable cause. The matrix was thought to be ice crystals solidified on the tube surface. The decision was made to continue experimental runs with a different refrigerant (R-113) and a different type of condensing tube (copper-nickel 1024 fpm low integral-fin tube), with the aim of understanding the conditions that caused the phenomena to exist. First, a run was made using R-114 with the copper-nickel finned tube under exactly the same conditions as described in the smooth copper tube runs. Visual inspection, during this run, revealed an apparent thickening of the fins at the top of the tube when compared visually with the second tube (see Figure 4.1(a) fin normal appearance and Figure 4.1(b) fin's thickened appearance). This appearance of thickening gave credence to the belief that water contamination was causing an ice layer to form on the top tube between fins. The refrigerant was then changed to R-113 and the run was repeated, with the inlet cooling temperature at approximately -20 C. Again, a marked thickening of the finned

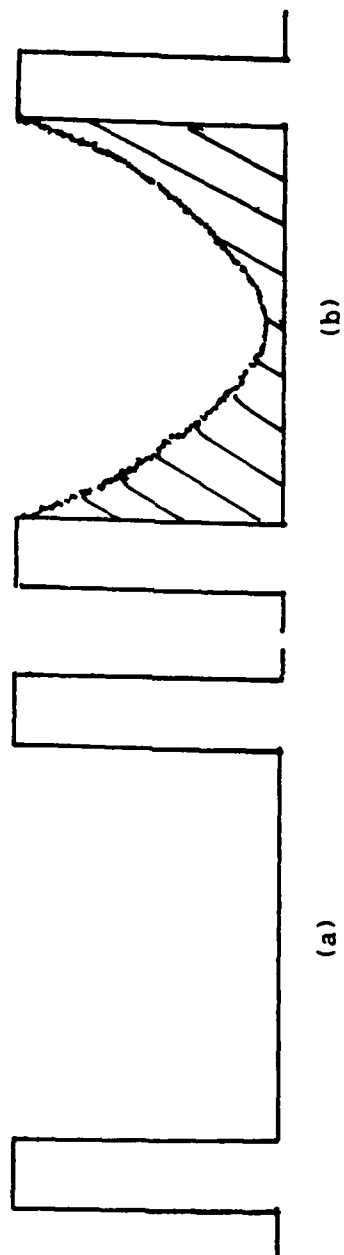


Figure 4.1 Cross-section of Fin Surface Schematic

surface appeared on the top of the first tube. The next experimental run was conducted on the same finned tube with R-113, but at a coolant inlet temperature slightly above 0 C. In this situation, no visible thickening of the finned surface was observed, but disparities in temperature increases across tube lengths persisted. The run was repeated several days later to observe whether the phenomenon consistently repeated itself. Finally, the smooth copper tube was substituted for the finned tube and the experimental run repeated at the higher coolant inlet temperature. Noticeable surface contamination, having an orange peel appearance, recurred. In addition, during this run, there were indications that a pocket of non-condensable gases formed in the top of the condensing chamber. As every effort had been made to evacuate the apparatus prior to commencing the experimental run, and no evidence exists to support outside leakage of air into the system, the possibility exists that contamination within the system produced the non-condensable gases during boiling.

Two possible sources of the contamination are conjectured. The first is that high temperatures on the heater tubes and poor circulation in the boiling chamber are combining to break down the refrigerant molecules producing some type of hydro-carbon. The second is that a chemical reaction is occurring between the refrigerants and gasket material in the apparatus producing a hydro-carbon. Time and

funding limitations have prevented further investigation of the problem.

5. Summary

The original test plan called for the testing of various enhanced surfaces in a simulated bundle during condensation of R-114. The contamination problem described above, coupled with the time delays inherent in achieving solutions to the other aforementioned encountered problems, severely limited the results of this thesis.

B. DATA REDUCTION

1. Description of Program Capabilities

The computer program, DRP1F, that collects and processes raw data, in conjunction with a Hewlett-Packard computer/data acquisition system described in Chapter II, is listed in its entirety in Appendix C. The program is designed to calculate and plot heat transfer parameters for a variety of different tube bundles, utilizing R-114, R-113, or steam as the working fluid. The program has the added capability of allowing testing for single tube performance. The program consists of five main sections, as follows:

1. Driver Program,
2. Main Program,
3. Property Subroutines,
4. Modified Wilson Plot Subroutine.
5. Plotting Subroutines.

Of these five sections, only the modified Wilson Plot subroutine will be described in lengthy detail.

The driver program permits the user to take data, reprocess data, or plot re-processed data through various subroutines. The driver program is listed in lines 1000 through 1125, in Appendix C.

The main subroutine (lines 1130-2315) can be divided into five parts. The first part allows the user to select the physical parameters used in data reduction. The selection of parameters consists of the working fluid to be used (R-114, R-113, or steam), the vapor saturation temperature to be used (derived from averaged thermocouple readings in either the vapor section or liquid region of the apparatus), the instrumented test tube type, and whether data will be taken on a bundle or individual tubes. The second part allows the user to reprocess data with the same selection of physical parameters described above, but calls the modified Wilson Plot subroutine to calculate the inside and outside coefficients used in the correlations. Basic data reduction takes place in the third part (lines 1945-2125). Subroutines are called to calculate the properties of the ethylene glycol-water solution. These properties, with the physical tube dimensions, are used to calculate velocities and Reynolds numbers. Low coolant velocities and high viscosities prompted the use of twisted tape inserts (thickness 0.559 mm, with a pitch for a 180 degree twist of three times the tube's inner

diameter) to increase the inside heat flux. The inside Nusselt number with a twisted tape insert, provided by Hong and Bergles [Ref. 21], is given by the correlation:

$$\overline{Nu}_i = \frac{\overline{\alpha}_i D_i}{\lambda} = 5.172 [1 + 5.4838 \cdot 10^{-3} \cdot (Pr)^{0.7} \cdot \left(\frac{Re_s}{Y}\right)^{1.25}]^{1/2} \quad (4.1)$$

where the Reynolds number for coolant flow was given by:

$$Re_s = 4 \cdot \dot{\Gamma} / \pi \cdot \eta \cdot (D_i - 4\delta) \quad (4.2)$$

where, δ is tape thickness.

The outside heat transfer coefficient is then given by the well-known summation of resistances to heat transfer:

$$\frac{1}{U_o A_o} = \frac{1}{\overline{\alpha}_o A_o} + R_f + R_m + \frac{1}{\overline{\alpha}_i A_i} \quad (4.3)$$

which algebraically reduces to:

$$\overline{\alpha}_o = \frac{1}{\frac{1}{U_o} - R_m \frac{A_o}{A_i} - R_f \frac{A_o}{A_i} - \frac{1}{\overline{\alpha}_i} \left(\frac{A_o}{A_i}\right)} \quad (4.4)$$

The heat transferred to the coolant (Q) is given by the relationship:

$$Q = \dot{\Gamma} \cdot C_p \cdot (\Delta T) \quad (4.5)$$

The heat flux (Q'') is subsequently calculated by dividing by the outside surface area:

$$Q'' = \frac{Q}{A_o} \quad (4.6)$$

where $A_o = \pi D_o \cdot L$. And, the overall heat transfer coefficient (U_o) is given by:

$$U_o = \frac{Q''}{LMTD} \quad (4.7)$$

where the Log Mean Temperature Difference (LMTD) is defined to be:

$$LMTD = \frac{\Delta T}{\log \left[\frac{T_{sat} - T_{c_i}}{T_{sat} - T_{c_o}} \right]} \quad (4.8)$$

It should be noted that the wall resistance due to fouling was assumed to be negligible for the purposes of calculation.

The fourth part of the main subroutine creates a raw data file (lines 1680-1835), allowing subsequent reprocessing by the modified Wilson subroutine. The fifth part of the main subroutine provides a printed output both while taking initial data and subsequently after reprocessing data.

The third major section of the computer program calculates fluid properties through called functions for both the working fluid and the coolant. The calculated coolant

properties as a function of temperature (lines 2330-2615), are kinematic viscosity, specific heat, density, Prandtl number, and conductivity.

The fifth major section of the program provides plotting routines for the output files generated in the program. The relationships graphically displayed are heat-transfer coefficient ratios (either based on the first tube in the bundle or as a ratio of the Nusselt value) plotted against tube position, heat transfer coefficient plotted against either the heat flux or temperature rise of the coolant, and the X-Y plot generated from the modified Wilson Plot results.

2. Modified Wilson Plot

The modified Wilson Plot, as outlined by Marto [Ref. 22], accomplishes an indirect measurement of the outside heat-transfer coefficient. The implicit assumption is that the overall heat transfer coefficient (U_o) is reliably known from data and, therefore a summation of heat transfer resistances is assumed. This summation relationship is given by:

$$\frac{1}{U_o} = \frac{1}{\alpha_o} + R_{fO} + R_{mO} + \frac{1}{\alpha_i} \left(\frac{A_o}{A_i} \right) \quad (4.9)$$

where resistance due to wall fouling is assumed equal to zero. The summation equation is transformed to a linear relationship, as follows:

$$\left[\frac{1}{U_o} - R_{mO} \right] = \left(\frac{A_o}{A_i} \right) \frac{1}{\alpha_i} + \frac{1}{\alpha_o} \quad (4.10)$$

where:

$$\bar{\alpha}_i = C_i \left(\frac{\lambda}{D_i} \right) ; \quad \bar{\alpha}_o = C_o F \quad (4.11)$$

which results in the simple linear form, $Y = mX + b$. It should be noted that Theta (defined in line 3290) is derived from the Hong and Bergles [Ref. 20] relationship for the inside Nusselt number, given by:

$$\overline{Nu}_i = \frac{\bar{\alpha}_i D_i}{\lambda} = C_i [1 + 5.4838 \cdot 10^{-3} (Pr^{0.7}) \cdot \left(\frac{Re_s}{Y} \right)^{1.25}]^{1/2} \quad (4.12)$$

hence,

$$\theta = [1 + 5.4838 \cdot 10^{-3} (Pr^{0.7}) \cdot \left(\frac{Re_s}{Y} \right)^{1.25}]^{1/2} \quad (4.13)$$

Further, F (defined in line 3330), is derived from Nusselt's relationship for a horizontal cylinder subjected to a constant heat flux [Ref. 4], given by:

$$\bar{\alpha}_o = .655 [\lambda^3 \cdot \rho^2 \cdot g \cdot \Delta h_v / \eta \cdot D_o \cdot Q'']^{1/3} \quad (4.14)$$

Hence,

$$F = [\lambda^3 \cdot \rho^2 \cdot g \cdot \Delta h_v / \eta \cdot D_o \cdot Q'']^{1/3} \quad (4.15)$$

X and Y values are calculated from raw data and the data are fit with a least squares approximation. Initial assumed values are taken from the aforementioned correlations, and the solutions iterated to find the inside coefficient (C_i) and the outside coefficient (C_o) that fit the data, where:

$$Y = \left[\frac{1}{U_o} - R_m(A_o) \right] F ; \quad X = \frac{D_o \cdot F}{\lambda} \quad (4.16)$$

the slope (m) is given by:

$$m = \frac{1}{C_i}$$

and the intercept (b) is given by:

$$b = \frac{1}{C_o}$$

The accuracy of this method relies heavily upon the number of data points taken and the range of velocities utilized.

V. RESULTS AND DISCUSSION

A. EXPERIMENTAL SEQUENCE

The data runs are summarized in Table 5.1 according to tube type, refrigerant used, and approximate operating parameters. Specifics for each run are provided in the following section under the run title.

TABLE 5.1
SEQUENTIAL LISTING OF DATA RUNS

<u>Run Title</u>	<u>Tube Type</u>	<u>Refrigerant Used</u>	<u>Coolant T inlet</u>	<u>Vapor T saturation</u>
SMT02	smooth	R-114	-20 C	17.8 C
CNFT01	finned	R-114	-21 C	18.3 C
CNFT02	finned	R-113	-21 C	64.4 C
CNFT03	finned	R-113	-3 to +6 C	52.2 C
CNFT04	finned	R-113	-3 to +6 C	46.3 C
SMT03	smooth	R-113	-1 to +6 C	56.7 C

B. EXPERIMENTAL RESULTS

1. Smooth Tubes with R-114 and Low Coolant Temperature

SMT02 was an experimental run made with four smooth copper tubes while condensing R-114. Vapor saturation temperature was 17.8 C. Ambient temperature was 20 C. The ethylene glycol coolant inlet temperature was -20 C. The

experiment was conducted following a cleaning of the boiling chamber, two flushings of the apparatus, once with acetone and once with R-113, evacuation to 27.5 in Hg., and filling the system from an unopened cylinder of R-114. After filling the system, the apparatus pressure stabilized at 17 psig. The system pressure was lowered to 10 psig by opening the coolant flow through the auxiliary condenser. When the desired gage pressure was reached, the lowest flow rate was set through the instrumented tube bundle, and all three heater units were set for power levels corresponding to approximately 10 kW total. Gage pressure was maintained nearly constant by controlling coolant flow through the auxiliary condenser. The system required approximately 35 minutes from lightoff to reach a steady state condition, indicated by nearly constant gage pressure. The R-114 appeared clear at the commencement of the data run. By the time the apparatus reached a steady state condition, the contamination matrix was fully formed and visible on the top two tubes in the bundle. Data were taken at nine different coolant velocities, after the voltage indicator on the data acquisition system for the bottom tube thermopile appeared to reach a fixed value following each velocity change. Data for the tube bundle run (Figure 5.1) clearly demonstrates an observed uncertainty of about 7% in the overall heat transfer coefficient (U_o) at velocities close to 0.9 m/s. This observed uncertainty, in contrast to the maximum calculated uncertainty of 4.5% (see Appendix A),

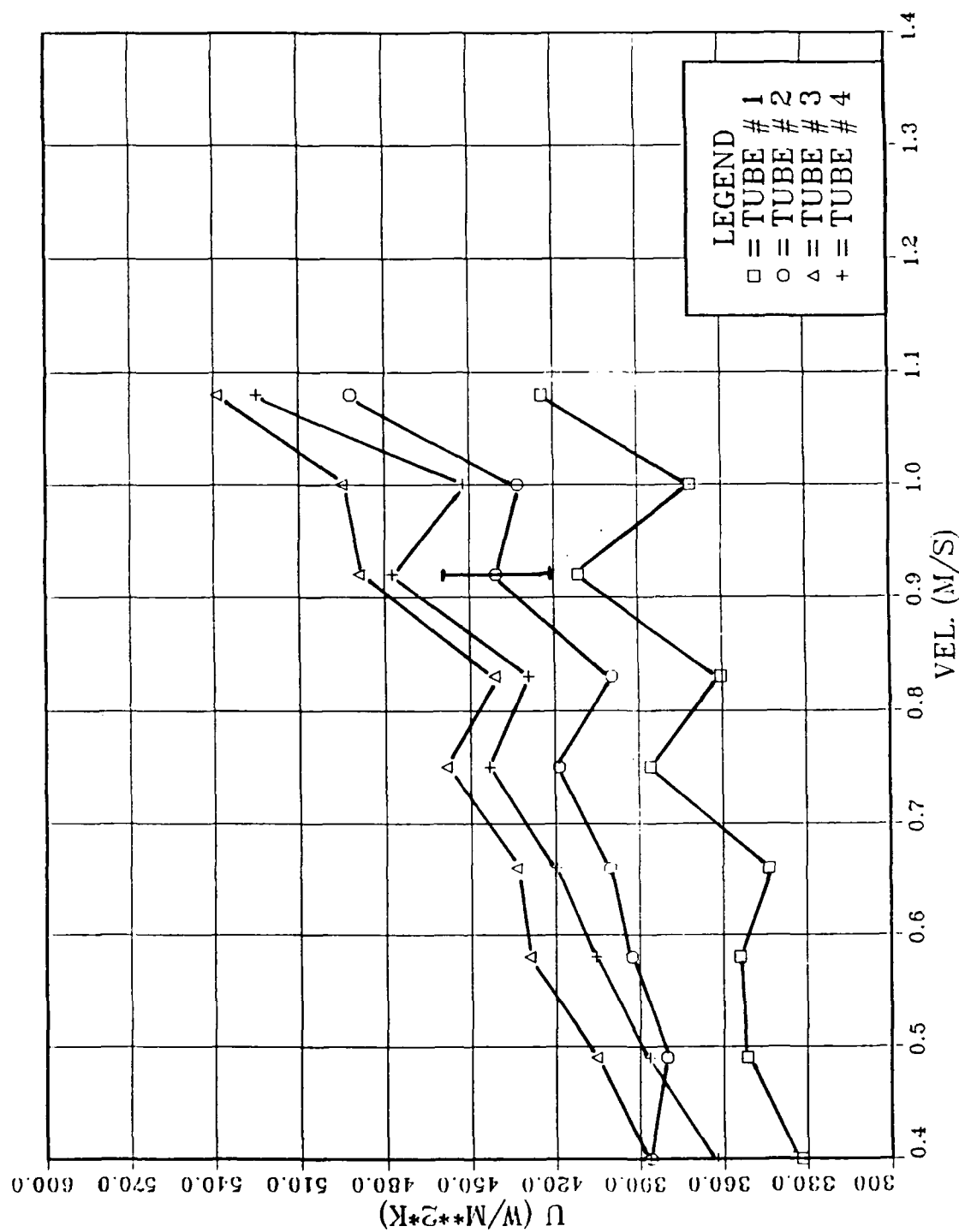


Figure 5.1 SMT02--Tube Bundle Performance

indicates the effect of the contamination on the measurement of the overall heat transfer. The most significant result of the contamination is the addition of an un-quantifiable resistance to heat-transfer that has produced heat-transfer coefficients approximately half of those predicted by the Nusselt correlation. Further, it is apparent that during bundle operation, the contamination degrades the performance of the tubes in a graduated manner with the first tube being the most adversely affected and the third tube appearing the least affected.

Upon completion of the bundle run, the flow in all of the instrumented tubes was shut off. Gage pressure was maintained at 10 psig by controlling coolant flow through the auxiliary condenser. The coolant inlet temperature remained approximately -20 C. The apparatus remained in this condition until the tube surfaces appeared to dry off, which took normally about ten minutes. Data were then taken at the same nine flow rates, as for the bundle, but with flow through only one instrumented tube at a time, starting with the top tube. Between velocity changes, approximately 10 minutes was allowed for the temperature changes in the tube to take effect. Data runs were made only after inundation from the previously tested tube was no longer present. The R-114 in the boiling chamber remained visually clear for all single tube runs. Again, as in the bundle data, data from the single tube runs (Figure 5.2) fall within an acceptable uncertainty band.

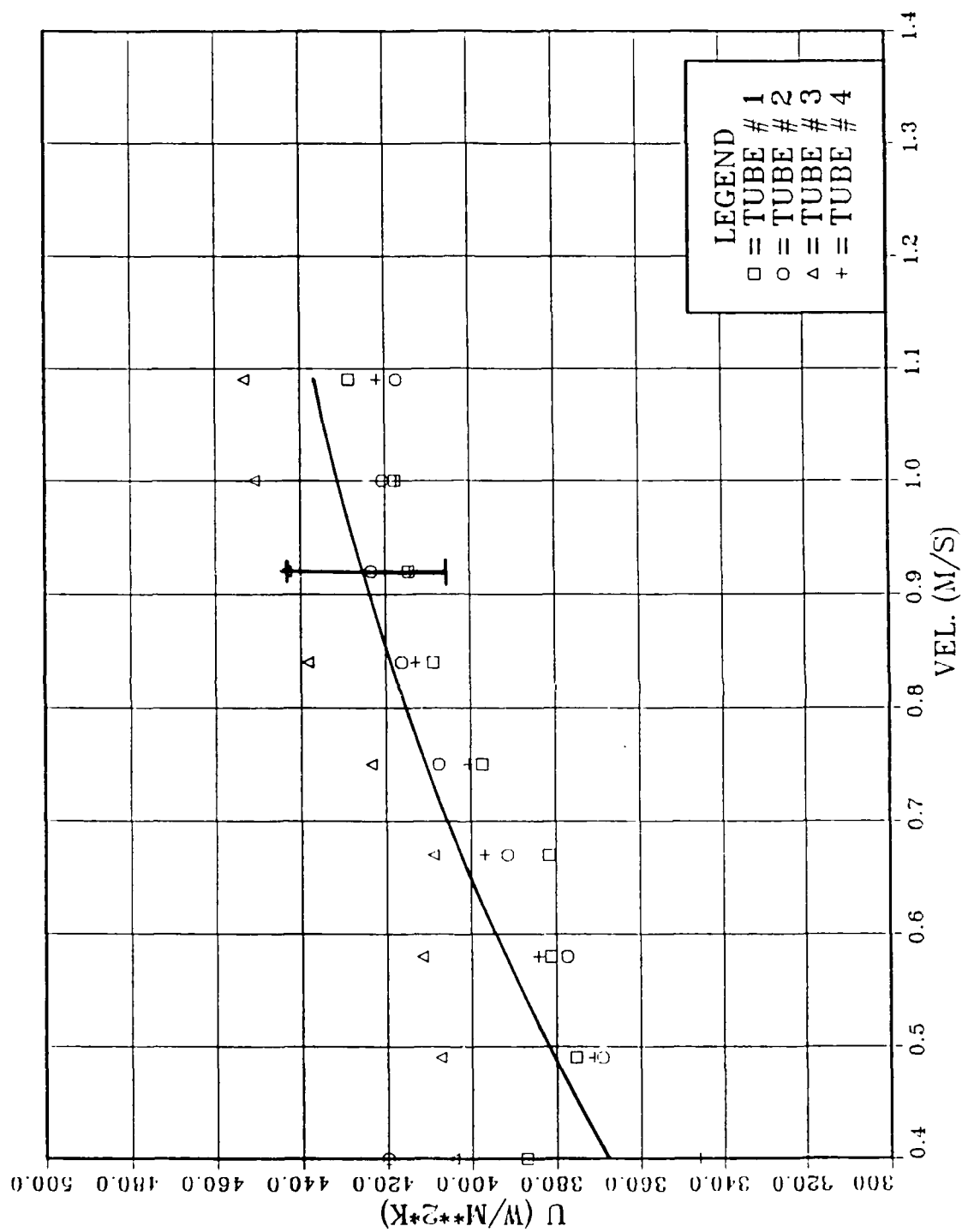


Figure 5.2 SMT02--Individual Tube Performance

From the conditions under which these runs were made, it is noteworthy and logical that the effect of the contamination increases in magnitude as a run progresses. The first tube gives the lowest results possibly because of residual contamination from the bundle run. The first and second tubes produced approximately the same results as previously discussed in the bundle run, however the third and fourth tubes gave lower results when operating as single tubes than when operating in a bundle, possibly because condensate inundation that provides a rinsing effect in the bundle operation, is no longer present during single tube operation.

2. Finned Tubes with R-114 and Low Coolant Temperature

CNFT01 was an experimental run made with copper-nickel low integral-fin tubes condensing R-114. Vapor saturation temperature was 18.3 C. The ethylene glycol coolant inlet temperature was at -21 C. The experiment commenced following the completion of the SMT02 single tube runs, transfer of the R-114 to the auxiliary storage unit, installation of the copper-nickel finned tubes, evacuation of the apparatus to 27.5 in Hg, and a refill of R-114 from the storage unit. This process took approximately six hours to complete. The same data taking procedure as outlined for the smooth tube runs was followed. The appearance of the R-114 was clear at the commencement of the run. By the time the system reached steady state, a marked thickening of the fin areas on the top tube when compared to the fins of the second tube was apparent

(see Figure 4.1). The R-114 appeared clear at the end of the bundle run. Data from the bundle run (Figure 5.3) show an increase in the overall heat transfer coefficient of approximately 100% when compared to the bundle results for the smooth tubes SMT02 (Figure 5.1). The coolant velocity differences between the smooth tubes and the finned tubes is due to the smaller inside diameter of the finned tubes at the prescribed mass flow rate. There is no disparity between calculated and observed uncertainties given the calculated uncertainty band, but performance remains approximately half of that expected when compared to the values obtained with the Nusselt correlation and enhancement ratios reported by other investigations. Once again, the first and second tubes demonstrate the greatest degradation in performance due to the contamination. The third and fourth tubes either receive less contamination or derive enhancement from condensate inundation flow. From observations, the unknown contaminant had a higher surface tension than R-114, but to what extent the contaminant kept fin root areas flooded and subsequently negated the enhanced surface effect, remains obscured in the uncertainties of the measurements.

The single tube runs followed the procedures outlined for the single tube runs of the smooth copper tubes. However at the end of each single tube run, a marked thickening of the fin surface at the top of the tube was noticeable. Vapor saturation temperature and coolant inlet temperature were the

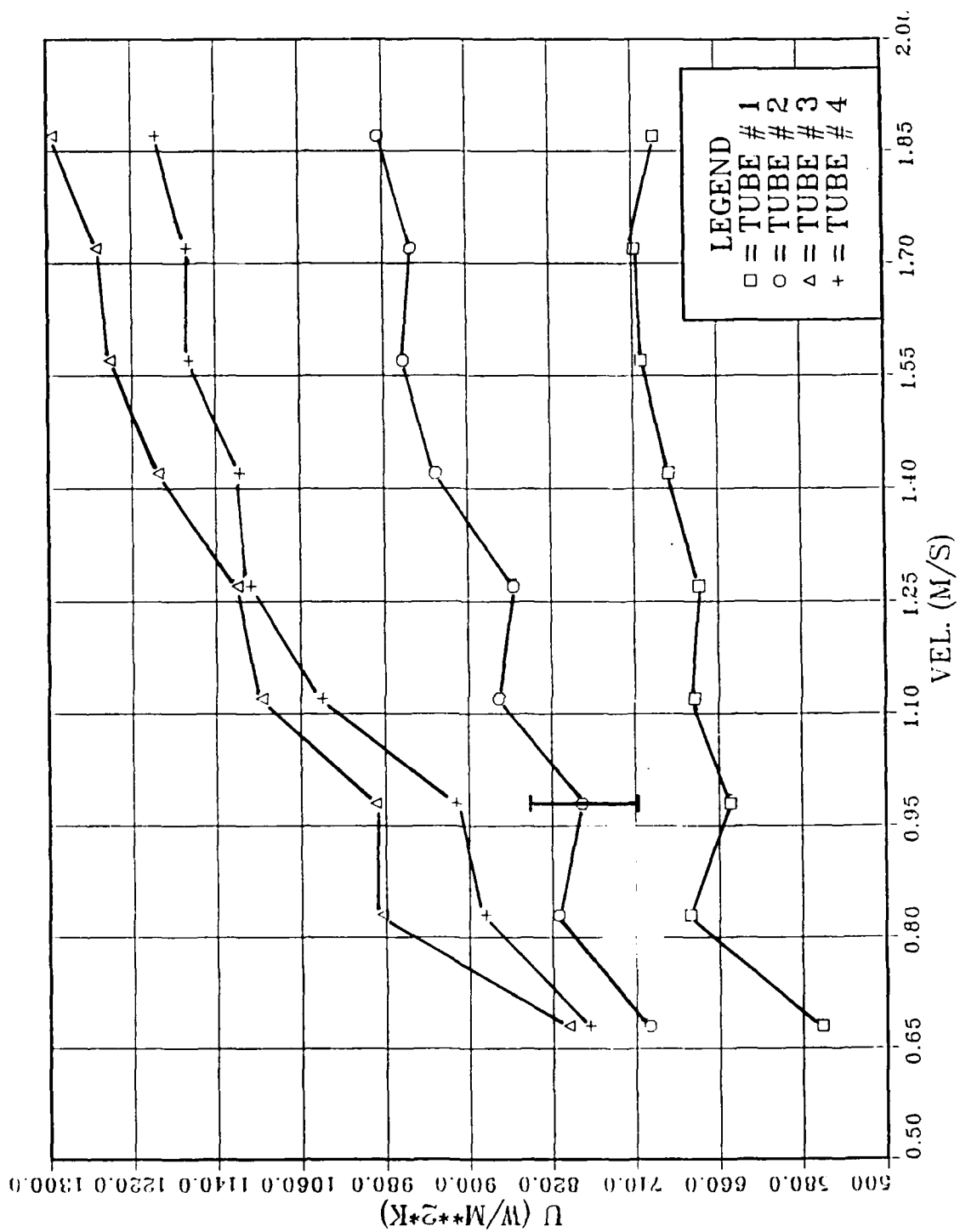


Figure 5.3 CNFT01--Tube Bundle Performance

same as in the bundle run. Data from the single tube runs (Figure 5.4) demonstrate an enhancement of approximately 76% in the overall heat transfer coefficient when compared to its counterpart in SMT02. The spread in the data is approximately 7% and, given the calculated uncertainty band, appears reasonable. Performance remains lower than expected from existing studies, and clearly the magnitude of the contamination effect increases as each run proceeded.

3. Finned Tubes with R-113 and Low Coolant Temperature

Upon completion of the single tube runs described in CNFT01, R-114 was transferred to the storage unit. The apparatus was drained of residual refrigerant, the system was evacuated to 27.5 in Hg, and filled with freshly distilled R-113 by using apparatus vacuum to promote flow from the R-113 container. After filling, system vacuum was at 11 inches Hg. The system was brought to a gage pressure of 5 psig corresponding to a vapor saturation temperature of 64.4 C. Coolant inlet temperature remained the same as described in CNFT01, -21 C. Vapor saturation temperature was monitored through the system pressure, and controlled by regulating coolant flow through the auxiliary condenser. The same nine data points described previously were taken in accordance with the stated procedure. The appearance of the R-113 at the beginning of the run was clear and clean. Upon the conclusion of the run, however, the R-113 had a slight yellowish tinge. During the run, the same marked thickening of the fin surface

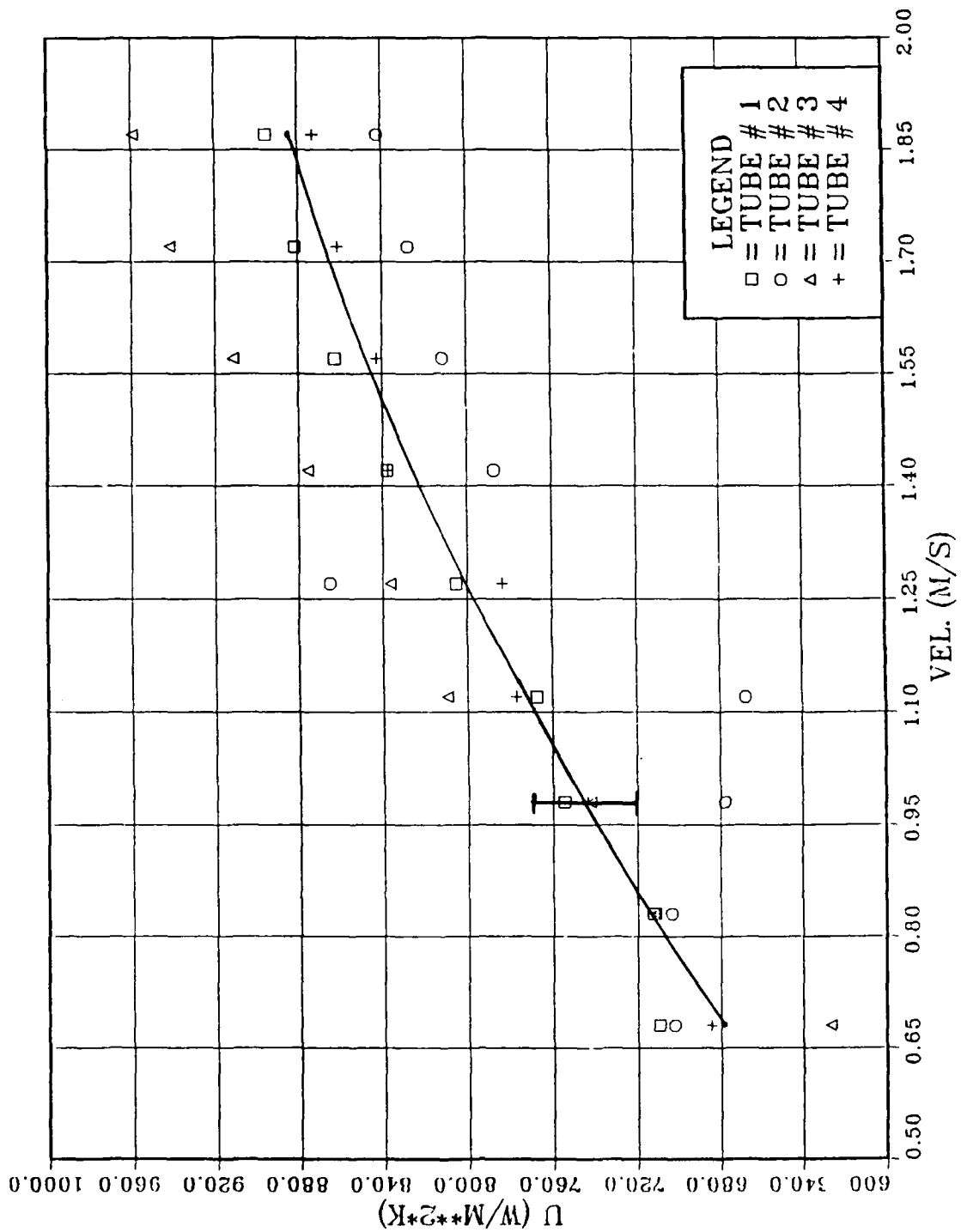


Figure 5.4 CNFT01--Individual Tube Performance

described in CNFT01, and shown schematically in Figure 4.1 occurred on the top tube. The data from the bundle run (Figure 5.5) demonstrates only a slight improvement in the overall heat transfer coefficient when compared to the bundle data for SMT02 (Figure 5.1), and in fact represents an approximate 80% decrease in the overall heat transfer coefficient when compared to the performance of the bundle in CNFT01 (Figure 5.3). In view of the fact that these data were collected after transferring the R-114 to the storage unit and filling with freshly distilled R-113, it can only be assumed that the contamination was freshly created with the R-113 and, in fact is associated with the apparatus. It is also possible, based on these results, to infer the presence of non-condensable gases generated by the contamination, although no indications of non-condensable gases were detected during the run. In view of these facts, the reliability of the calculated values for the overall heat transfer coefficient is extremely doubtful even though data spread falls within the acceptable uncertainty band.

Upon completion of the bundle run, data were taken for each of the tubes individually at the same system conditions described for the bundle run, and in accordance with the procedure described for single tube runs. The appearance of the R-113 at the completion of the single tube runs was slightly-darkened, with a yellow tinge, but otherwise appeared free from any floating contaminants. On each of the single

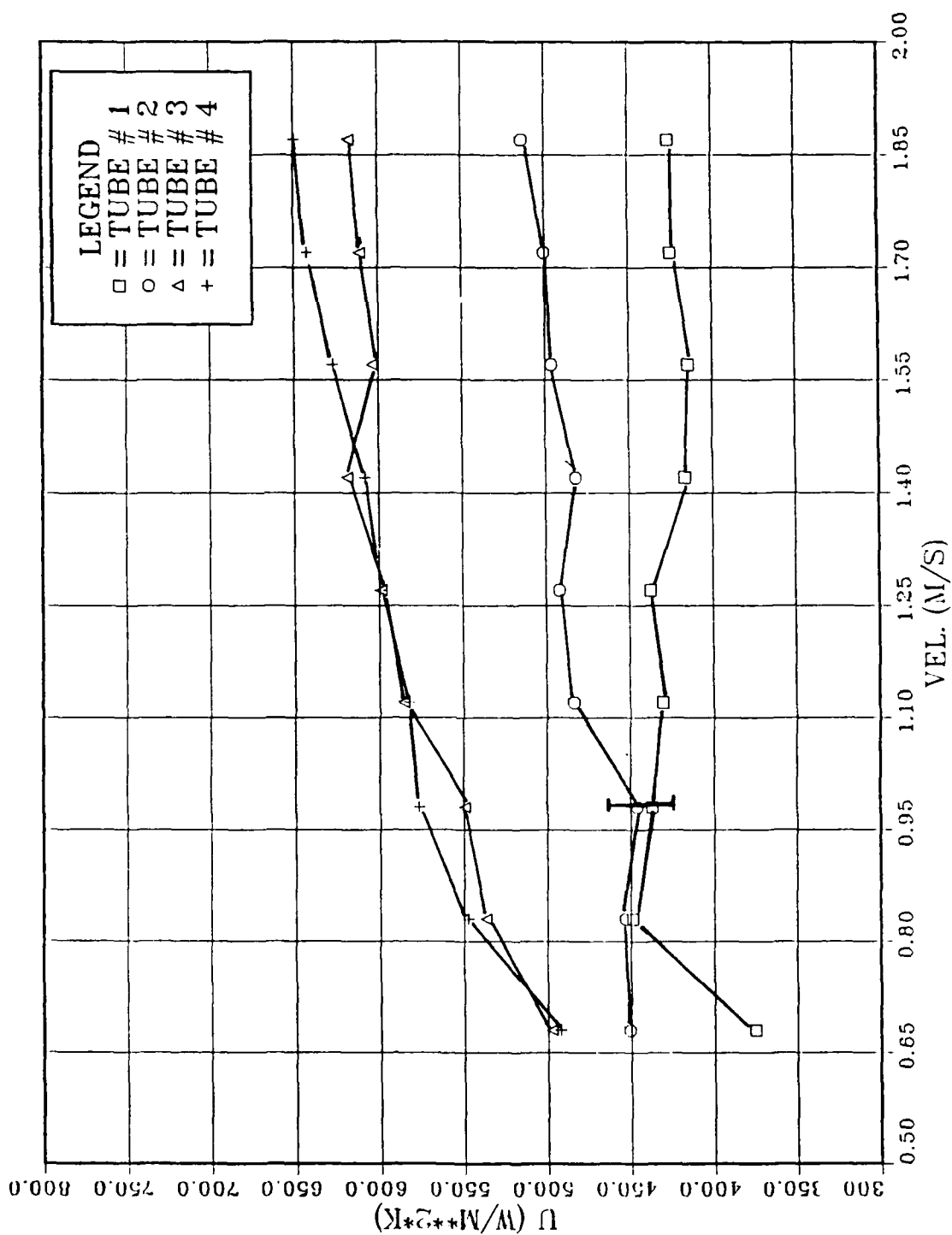


Figure 5.5 CNFT02--Tube Bundle Performance

tube runs, a marked thickening of the fin surface developed in the course of the run. There exists reasonably good agreement between the single tube data (Figure 5.6) and the single tube data from CNFT01 in the calculation of the overall heat transfer coefficient, and no disparity exists between the data spread and the calculated uncertainty band. The apparatus was evacuated for five minutes prior to beginning the single tube runs and if non-condensable gases were present during the bundle run, this explains the improved performance of the tubes during individual runs.

4. Finned Tubes with R-113 and High Coolant Temperature

This data run was made with the same copper-nickel tubes described in CNFT01 and CNFT02. The system was allowed to sit overnight at 11 in Hg, while the sump temperature was brought to an operating range of -3 C to +6 C. No change in the system vacuum over this 12 hour period occurred. The decision to run the system at a higher coolant temperature was motivated by a belief that the contamination of the system was water, and that at the colder coolant temperature, an ice sheath was forming on the tubes inhibiting heat transfer. The appearance of the R-113 before commencement of the bundle run was a medium yellow tinge. The system was brought to a steady state pressure corresponding to a vapor saturation temperature of 52.2 C. Difficulty was encountered in maintaining positive system pressure with the auxiliary condenser operating. The auxiliary condenser was therefore turned off and steady state

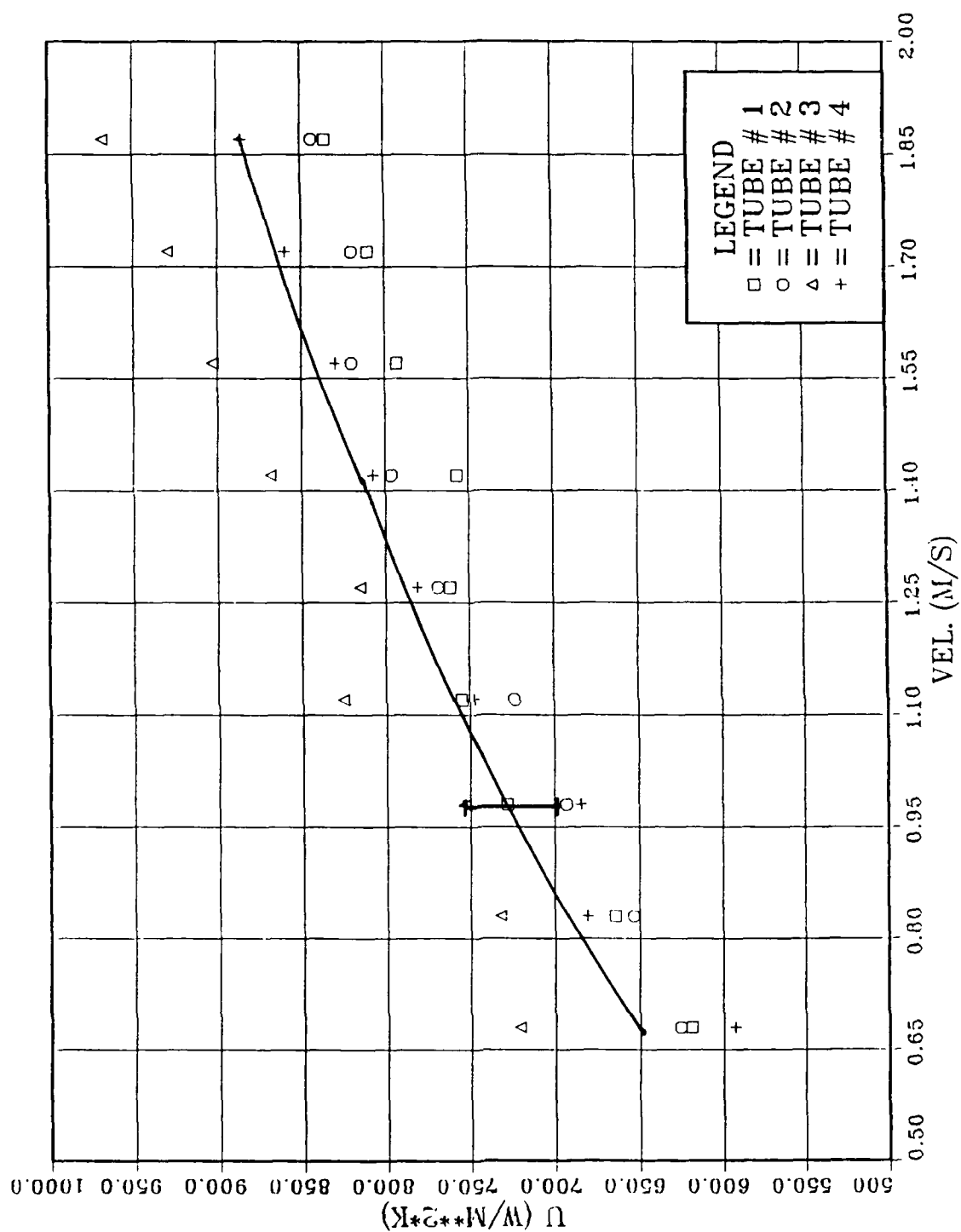
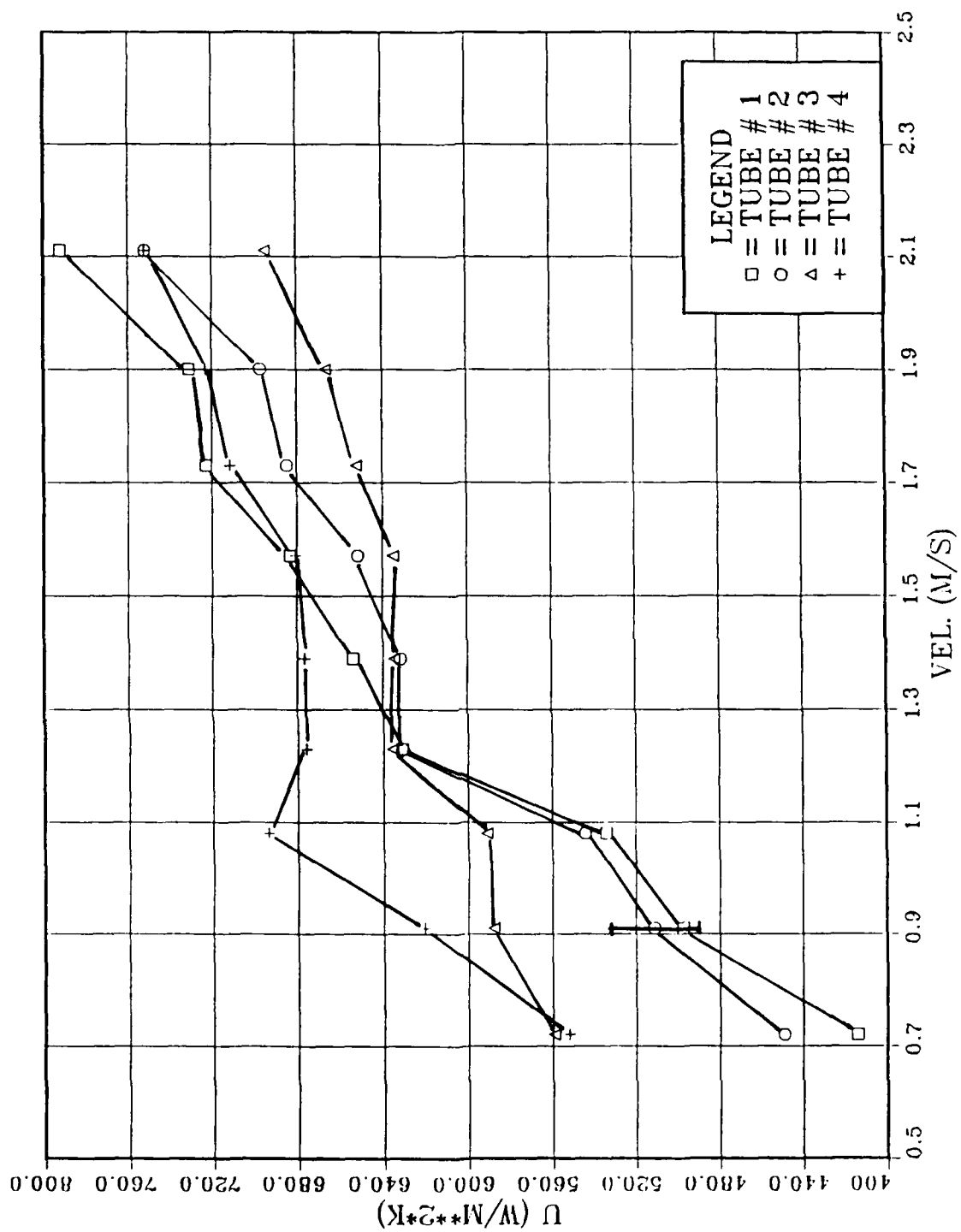
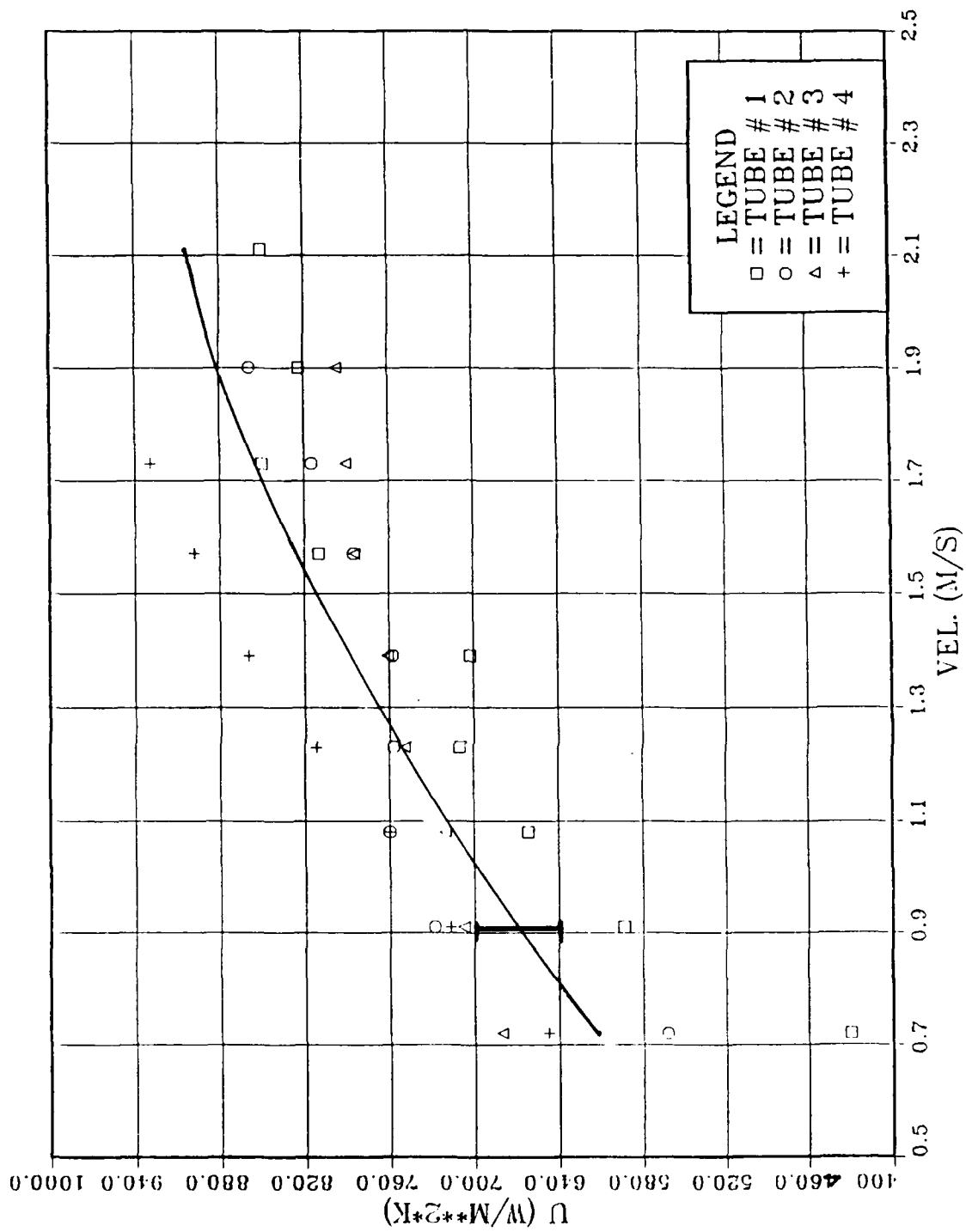


Figure 5.6 CNFT02--Individual Tube Performance

was maintained by slight power adjustments to the heating elements in the boiling chamber. Nine sets of data were taken in accordance with the procedure for bundle runs previously described. No observable thickening of fin surfaces during the run occurred. The data from the bundle run (Figure 5.7) shows a slight increase in overall heat transfer coefficient over the bundle results obtained in CNFT02 (Figure 5.5) and this is possibly explained by a decrease in the viscosity of the contaminant when exposed to the warmer tube surface.

Single tube runs were made on each of the tubes, in accordance with procedures outlined previously, at the same coolant inlet temperature as in the bundle run, but at a system pressure corresponding to a vapor saturation temperature of 64.4 C. No change in the appearance of the R-113 was detected. Again no thickening of the fin surfaces was detected. The single tube results (Figure 5.8) demonstrate a corresponding range of values in the overall heat transfer coefficient when compared to the results for single tubes in CNFT02 (Figure 5.6), but is significantly higher than the bundle results. It is possible that non-condensable gases were present in bundle operation, but were eliminated by evacuation prior to single tube data being taken. No indications of non-condensable gases were detected during bundle or single tube operation.





5. Finned Tubes with R-113 and High Coolant Temperature

This data run was made in order to see if the results produced in CNFT03 were repeatable. The system operating pressure corresponded to a vapor saturation temperature of 46.3 C, and the coolant inlet temperature remained unchanged from the coolant temperature in CNFT03. Nine data sets were taken in accordance with the bundle run procedures outlined previously. No thickening of fin surfaces during the run was observed. The color of the R-113, at the completion of the run, was amber. The bundle data (Figure 5.9) does demonstrate that the results of CNFT03 were repeatable at least within the calculated uncertainty.

Single tube runs were made in accordance with the procedures discussed previously. Nine data sets were taken on each tube, at the same conditions specified in the bundle run. No thickening of fin surfaces was observed during the runs, and the R-113 color remained amber. There is no major disparity between the single tube results (Figure 5.10), and the single tube results for CNFT03, given the calculated uncertainty band. The single tube results were significantly higher than bundle performance, and the build up of non-condensable gases during bundle operation and evacuation of the apparatus prior to commencing single tube runs is conjectured as a possible explanation. At no time during bundle or single tube operation were indications of non-condensable gases detected.

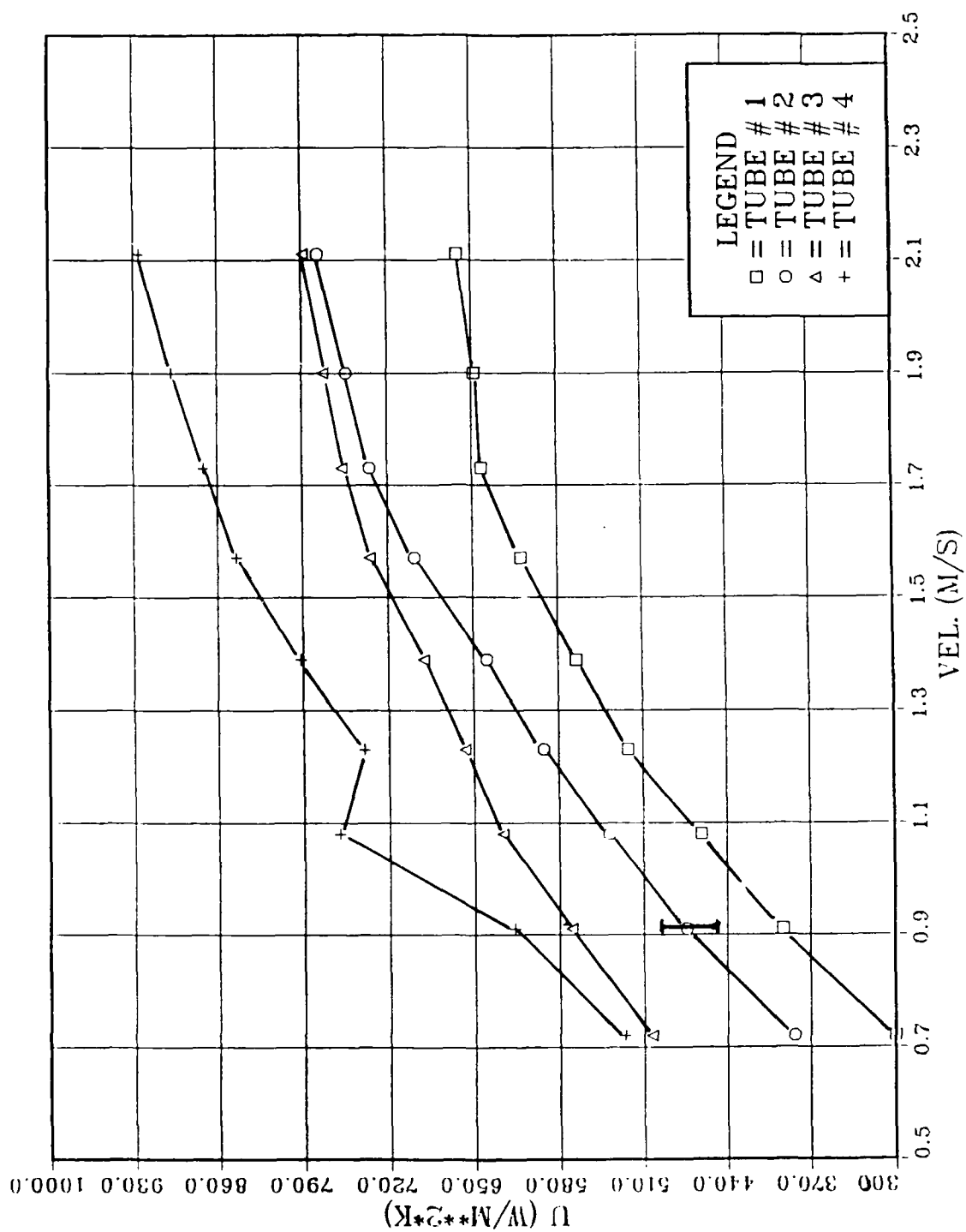


Figure 5.9--CNFT04--Tube Bundle Performance

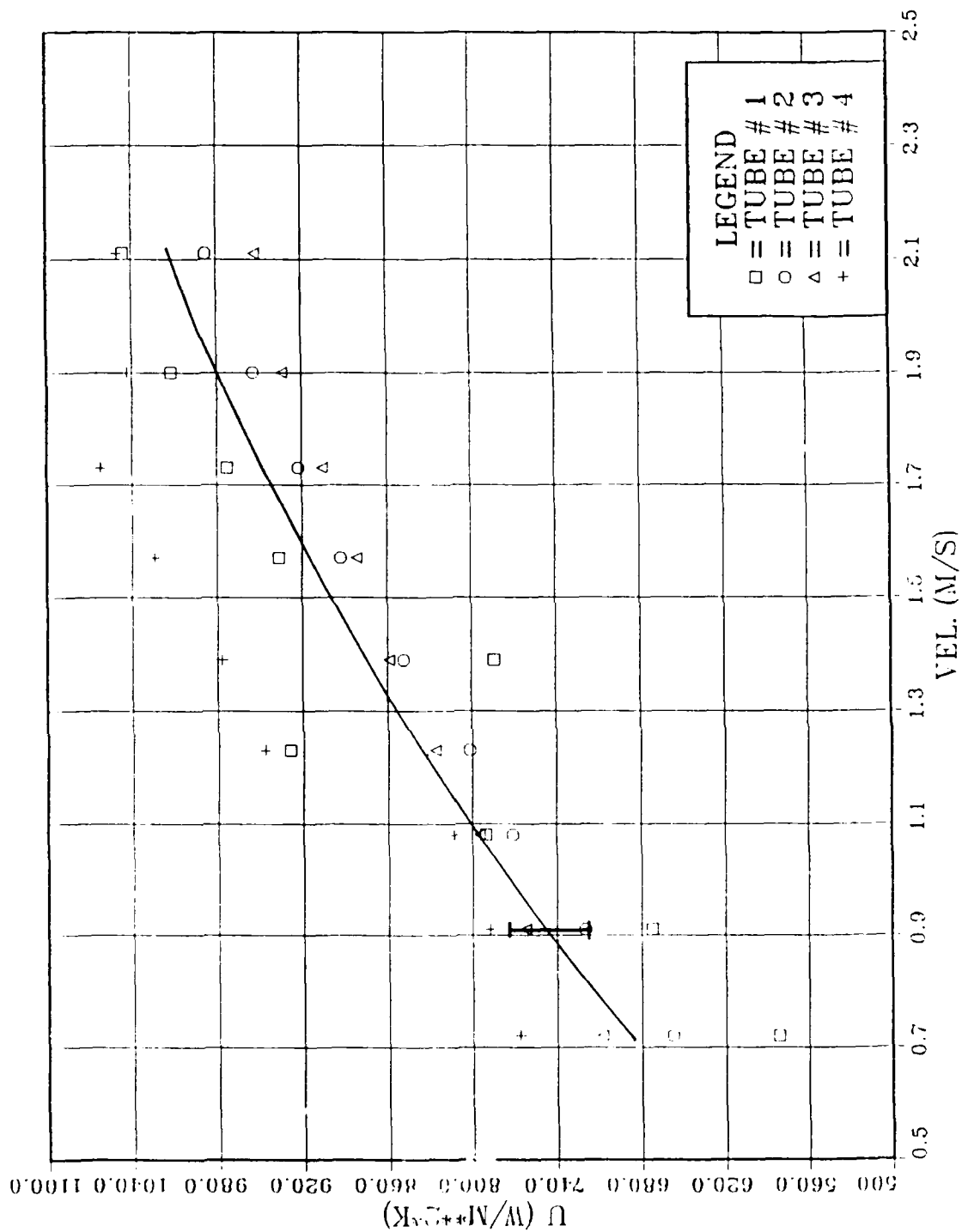


Figure 5.10--CNFT04--Individual Tube Performance

6. Smooth Tubes with R-113 and High Coolant Temperature

SMT03 was a data run made on the same aforementioned copper tubes, but with R-113. Vapor saturation temperature was 56.7 C. Coolant inlet temperature ranged between -1 C and +6 C. The experiment was conducted following a test run with R-113 and finned tubes and subsequent replacement of the finned tubes, and evacuation to 11 in Hg. While the tube change was being made, the R-113 remained in the boiling chamber exposed to the atmosphere for a two hour period. The R-113 appeared light amber in color at the commencement of the bundle run. The desired gage pressure was maintained by controlling the boiling chamber heaters through their corresponding variac controllers. The auxiliary condenser was not utilized because the additional coolant flow provided by the auxiliary condenser made it difficult to maintain the desired system pressure. During the data run, the top two instrumented tubes assumed an orange peel textured or dimpled appearance. The R-113 had a darker amber appearance at the completion of the bundle run. Again, data were taken at the same nine coolant flow settings following the procedure outlined previously. Data taken during bundle operation (Figure 5.11), while falling within the acceptable uncertainty bands, clearly demonstrates the presence of non-condensable gases as well the presence of the contamination acting to inhibit the overall heat-transfer performance. The top tube's very poor performance can be attributable to its location in

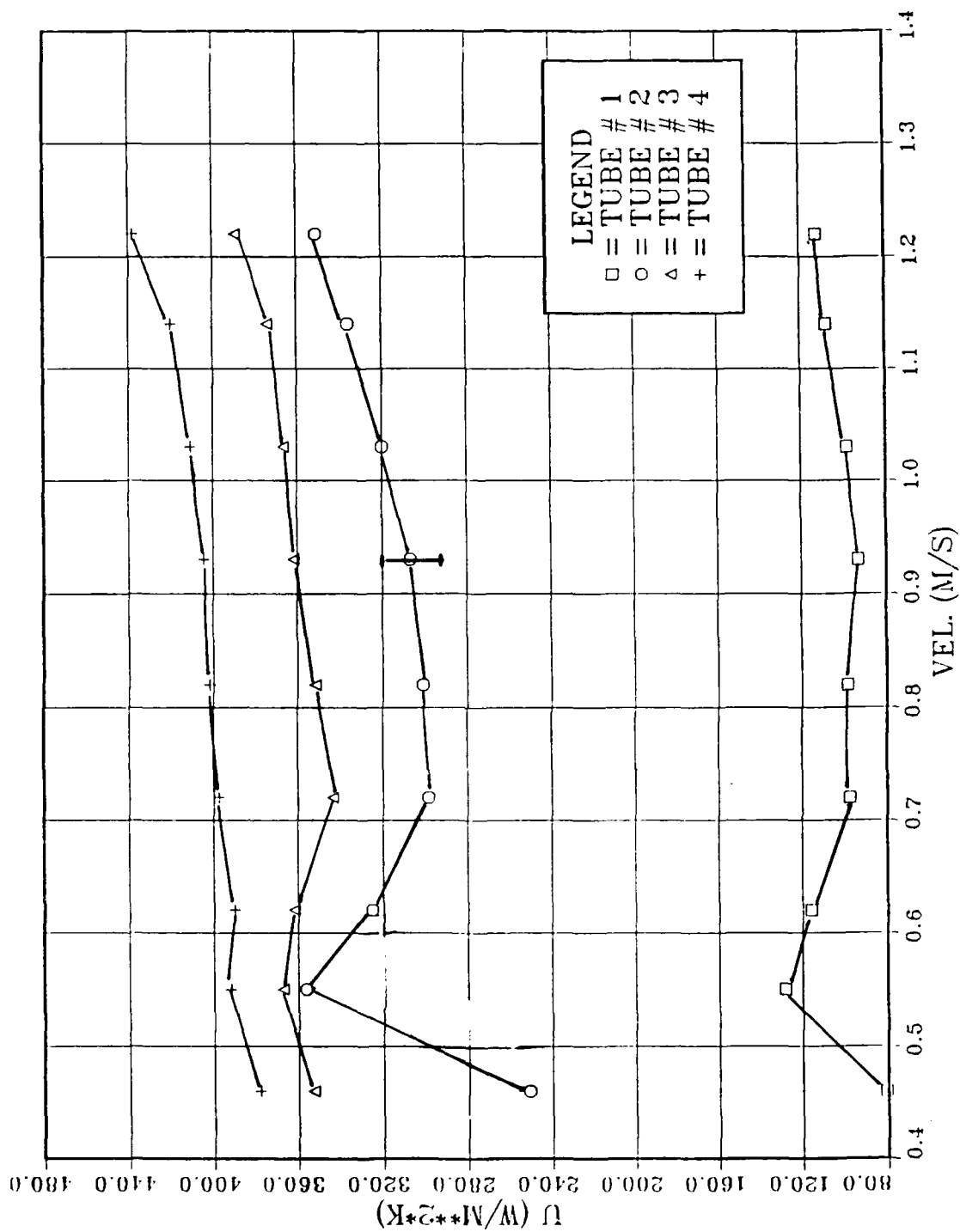


Figure 5.11--SMT03--Tube Bundle Performance

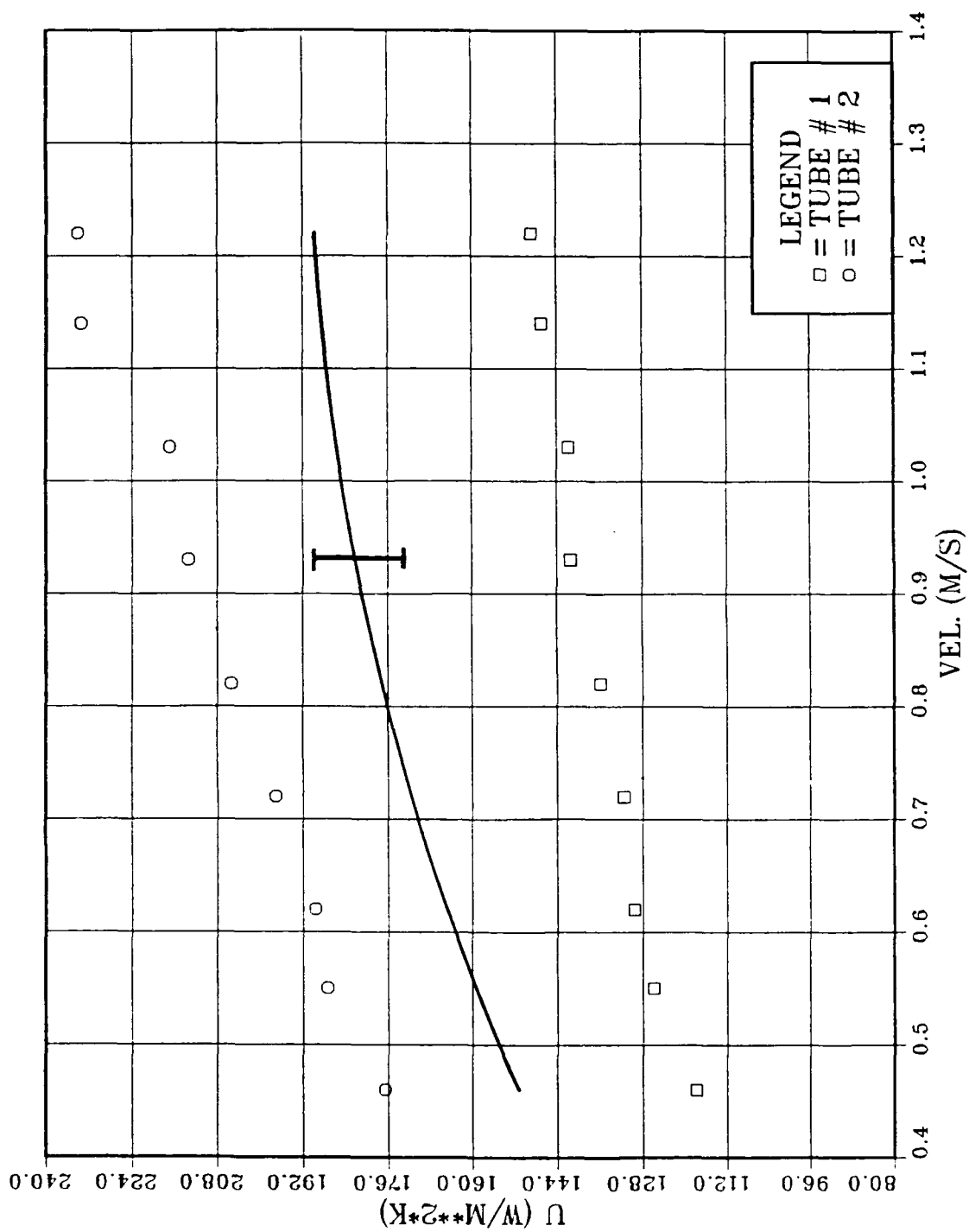
a pocket of non-condensable gases. And the bundle performance as a whole, when taken in comparison with the performance demonstrated in the bundle run of SMT02, indicates an increased concentration of the contamination and the presence of non-condensable gases.

Upon completion of the bundle run, coolant flow through the instrumented tubes was shut off and gage pressure maintained by controlling flow through the auxiliary condenser. While no coolant flowed through the instrumented tubes, the textured appearance noted during the bundle operation gradually transformed to small droplets on the top two tubes which then coalesced into larger ellipsoid shaped droplets that were held on the tube by surface tension forces. Data was taken on the first two tubes in the bundle following the procedure outlined previously for single tube runs. At the completion of the second run, it was noticed that the top view port flanges were cold to the touch while the bottom view port flanges were warm to the touch. The assumption was therefore made that non-condensable gases had collected in the top of the condensing chamber. Before evacuation of the apparatus could be effected, the pyrex glass in the top center view port cracked. As a result, the apparatus was secured and no further data taken. It should be noted that, prior to the view port breaking, there was no evidence to suggest that the apparatus was other than air tight, so that the source of non-condensable gases was most probably due to their generation

within the boiling chamber. Data taken in the single tube runs (Figure 5.12) reflects not only the effects of the contamination, but also the effects of the presence of non-condensable gases as well. This data showed the greatest variance between calculated and observed uncertainties in the overall heat transfer coefficient. This data is limited to the performance of only the top two tubes, due to the aforementioned breakage of the view port and the presence of non-condensable gases.

C. SUMMARY OF RESULTS

The comparison between finned and smooth tubes shows an enhancement ratio in the overall heat transfer coefficient for the finned tubes compared to the smooth tubes of approximately 2.0. While this enhancement in the overall heat-transfer coefficient might translate to a vapor-side heat-transfer coefficient enhancement ratio of approximately 4.0 to 4.5, based upon the calculated values for the vapor-side heat-transfer coefficient for the tested smooth tubes when compared against the Nusselt's correlation for smooth horizontal tubes and the reported enhancement ratios from other finned-tube investigations [Refs. 5-13], it is estimated that the effect of the contamination during these tests has been a degradation of up to 50% in the vapor-side heat-transfer coefficient. The contamination has resulted in the promotion of another resistance to heat transfer that has no predictable characteristics and can not be quantified. This contamination



must therefore be removed before any quantifiable heat-transfer results can be obtained.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the data gathered during this investigation for condensation of refrigerants R-114 and R-113 in the multi-tube apparatus, the following conclusions are reached:

1. The construction of a multi-tube condensation test apparatus begun by Murphy [Ref. 3] and Zebrowski [Ref. 4] has been completed, instrumented and integrated with the various support systems.
2. Data reduction software has been developed that produces high confidence results from experimental readings.
3. Data were collected from condensation experiments with R-114 and R-113 on smooth and finned tubes demonstrating an enhancement ratio of approximately 2.0 in the overall heat transfer coefficient for the finned tubes over the smooth tubes.
4. Serious apparatus internal contamination has degraded the value of the overall heat-transfer beyond acceptable limits, making further data reduction meaningless.

B. RECOMMENDATIONS

Based upon the data gathered during the operation of the multi-tube condensation test apparatus, and the experience gained in construction of this apparatus, the following recommendations are made:

1. Samples should be taken from the R-114 and R-113 used in the experimental runs and a chemical analysis performed on these samples to assist in determining the source of the contamination in the system.
2. Modifications to the apparatus, as dictated by the results of the chemical analysis of the refrigerants, should be made.

3. New flow meters allowing a greater range in coolant velocities should be installed. The greater range in coolant velocities will enhance the accuracy of the modified Wilson plot method in calculating the outside heat-transfer coefficient.
4. The temperature control system for the eight ton refrigeration unit should be re-evaluated to determine if tighter control of sump temperature can be maintained.
5. After appropriate modifications to the apparatus have been made, the smooth tube and finned tube experiments should be repeated and contrasted with the results presented here, in order that baseline tube performance might be established.
6. During operation of the system, flow should be throttled to the coolant supply pumps with the valves on the coolant inlet side. This will increase the pump life and reduce noise in the laboratory space.

APPENDIX A
UNCERTAINTY ANALYSIS

A certain amount of uncertainty exists in any engineering measurement. These uncertainties arise both from known sources, such as calibration and measurement errors from sensing devices, and also unknown sources, such as operator experience and unexpected experimental reactions. The procedure used in this uncertainty analysis is based on the Kline-McClintock [Ref. 21] method. This method assumes that a result R is a function of the variables that contribute to that result. Therefore the uncertainty in a result is a function of the uncertainties in each of the variables. This method is expressed mathematically by:

$$\frac{\partial R}{R} = [(\frac{\partial R}{\partial V_1} \cdot \frac{\partial V_1}{R})^2 + (\frac{\partial R}{\partial V_2} \cdot \frac{\partial V_2}{R})^2 + \dots]^{1/2} \quad (A.1)$$

The measurement of the overall heat transfer coefficient (U_o) performed in this thesis is given by:

$$U_o = \frac{Q}{A_o \cdot \text{LMTD}} \quad (A.2)$$

where the heat transferred (Q) is given by:

$$Q = \dot{m} \cdot C_p \cdot (\Delta T) \quad (A.3)$$

and the Log Mean Temperature Difference (LMTD) is defined as:

$$\text{LMTD} = \frac{(\Delta T)}{\log \left[\frac{T_{\text{sat}} - T_{c_i}}{T_{\text{sat}} - T_{c_o}} \right]} \quad (\text{A.4})$$

Therefore the uncertainty in the measurement of the overall heat transfer coefficient (U_o) is given by:

$$\frac{\delta U_o}{U_o} = \left[\left(\frac{\delta \dot{Q}}{\dot{Q}} \right)^2 + \left(\frac{\delta C_p}{C_p} \right)^2 + \left(\frac{\delta \Delta T}{\Delta T} \right)^2 + \left(\frac{\delta D_o}{D_o} \right)^2 + \left(\frac{\delta \text{LMTD}}{\text{LMTD}} \right)^2 \right]^{1/2} \quad (\text{A.5})$$

where $\frac{\delta A_o}{A_o}$ reduces to $\frac{\delta D_o}{D_o}$, and the uncertainty in the LMTD is given by:

$$\frac{\delta \text{LMTD}}{\text{LMTD}} = [A^2 + B^2 + C^2]^{1/2} \quad (\text{A.6})$$

where A is given by the expression:

$$A = \delta T_{\text{sat}} \left[\frac{\Delta T}{(T_{\text{sat}} - T_{c_i})(T_{\text{sat}} - T_{c_o})} \cdot \frac{1}{\log \left[\frac{T_{\text{sat}} - T_{c_i}}{T_{\text{sat}} - T_{c_o}} \right]} \right]$$

where B is given by the expression:

$$B = \frac{\delta T_{c_i}}{(T_{\text{sat}} - T_{c_i})} \cdot \frac{1}{\log \left[\frac{T_{\text{sat}} - T_{c_i}}{T_{\text{sat}} - T_{c_o}} \right]}$$

where C is given by the expression:

$$C = \frac{\delta T_{c_o}}{(T_{sat} - T_{c_o})} \cdot \frac{1}{\log \left[\frac{T_{sat} - T_{c_i}}{T_{sat} - T_{c_o}} \right]}$$

It should be noted that the uncertainties for mass flow rate ($\dot{m}$) and the coolant temperature rise across the condensing tubes (ΔT) were calculated during calibration of the flow meters and thermopiles respectfully. Reference material providing data on thermophysical properties, specifically the specific heat (C_p), listed no uncertainties associated with the curves for aqueous-ethylene glycol solutions. The composition of the aqueous-ethylene glycol solution by weight percentages was calculated by measurement of the specific gravity and the change in this composition over the experimental period was determined to be negligible and therefore this uncertainty has been ignored.

The uncertainty in the overall heat transfer coefficient represents the maximum uncertainty present from the calibration of the four flow meters and the maximum uncertainty in the calibration of the four thermopiles, regardless of association, and therefore represents a conservative estimate of the uncertainty present in each calculation of the overall heat transfer coefficient (U_o). This maximum uncertainty was calculated to be 4.5 percent.

The disparity between the calculated uncertainties and the uncertainties observed by the spread in data particularly in the single tube runs, can be accounted for by the as-yet

undetermined chemical or phase reactions generated by the contamination in the system.

The values of the uncertainties in the measured variables that were used to calculate the uncertainty by the Kline-McClintock method are listed in Table A.1.

TABLE A.1
UNCERTAINTY VARIABLES

VARIABLE	VALUE	REMARKS
$\frac{\delta \dot{F}}{\dot{F}}$	0.01	From flow meter calibration data
$\frac{\delta C_p}{C_p}$	0.00	Not available
$\frac{\delta \Delta T}{\Delta T}$	0.01	From thermopile calibration data
$\frac{\delta D_o}{D_o}$	0.002	From micrometer name plate data
$\frac{\delta LMTD}{LMTD}$		Listed below by run title
SMT02	0.005	
CNFT01	0.002	
CNFT02	0.001	
CNFT03	0.003	
CNFT04	0.002	
SMT03	0.017	

APPENDIX B

LIGHTOFF AND SECURING PROCEDURES

A. SYSTEM LIGHTOFF

1. Push the starter button in the control box for the re-circulation pump. This control box is located on the bulkhead above the re-circulation pump in the outside area adjacent to the refrigeration unit.

2. Turn the switch on the refrigeration unit control panel, located in front of the refrigeration unit to the "auto" position after passing through "on" position.

3. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately four hours to chill the sump 40 degrees C. The thermometer located on the side of the ethylene glycol sump must be monitored to ensure the desired sump temperature is attained and maintained. Slight adjustments in the refrigeration unit thermostat can be expected due to the coarseness of its scale.

4. Energize the heater variacs by switching on the breakers in the breaker panel located in the laboratory space on the bulkhead next to the counter.

5. Set the heater variacs to the desired position, after ensuring that the switch panel for the heater tubes located on the apparatus has all switches in the "on" position. Monitor

apparatus pressure through the pressure gage at the top of the apparatus, ensuring system pressure does not exceed 30 psig.

6. Turn on the pump motors by pushing down on the arm of the appropriate breaker box for the pumps located on the bulkhead next to the ethylene glycol sump. The pumps are marked "auxiliary condenser" and "instrumented tube condenser," respectively. Flow in the auxiliary condensate system can be controlled with the individual gate valves located at the coil penetrations on the apparatus. The auxiliary condenser will produce the fastest adjustments to system pressure if pressure is rising too quickly. Flow through the instrumented tubes can be controlled by the ball valves located at the bottom of the respective flow meter.

7. Throttle down coolant flow to the supply pumps with the valve located before the pump suction. This will increase the pump life and reduce noise in the laboratory space.

B. SECURING PROCEDURES

1. Turn all variacs to the zero position and switch off all breakers in the power panel on the bulkhead.

2. Turn the breakers for the pumps to the off position at the switch boxes near the ethylene glycol sump.

3. If apparatus will not be operated for an extended period, turn the switch on the refrigeration control panel to the "off" position after passing through "on."

4. Allow the re-circulation pump to operate for at least ten minutes after switching off the refrigeration unit to

dissipate any back pressure in the system; then secure the pump.

APPENDIX C

DATA REDUCTION PROGRAM

```

1000 : FILE: DRPIF
1005 : PURPOSE: This program collects and processes condensation data for
1010 :           the R-114 tube-bundle apparatus.
1015 : CREATED: NOVEMBER 2, 1988
1020 : UPDATED: November 8, 1988
1025 : CHANGE MOD=3 AND USING CALCULATED CI FROM WILSON
1030 : BEEP
1035 : PRINTER IS 1
1040 : PRINT USING "4X," "SELECT OPTION""
1045 : PRINT USING "6X," "0 TAKING DATA OR REPROCESSING PREVIOUS DATA"
1050 : PRINT USING "6X," "1 PLOTTING H VS DELTA-T""
1055 : PRINT USING "6X," "2 PLOTTING HRAT VS N""
1060 : PRINT USING "6X," "3 PLOTTING WILSON""
1065 : PRINT USING "6X," "4 PURGE FILES""
1070 : PRINT USING "6X," "5 XYREAD""
1075 : PRINT USING "6X," "6 NUSSELT ESTIMATE""
1080 : PRINTER IS 701
1085 : INPUT Icall
1090 : IF Icall=0 THEN CALL Main
1095 : IF Icall=1 THEN CALL Plot2
1100 : IF Icall=2 THEN CALL Plot1
1105 : IF Icall=3 THEN CALL Plot3
1110 : IF Icall=4 THEN CALL Purge
1115 : IF Icall=5 THEN CALL Xyread
1120 : IF Icall=6 THEN CALL Nusseilt
1125 : END
1130 : SUB Main
1135 : COM /Cci/ C(7)
1140 : COM /Fid/ Ift
1145 : COM /Nus/ Iin,Tsat,Gdpl,Hnus
1150 : COM /Wil1/ Doa(4),Dia(4),Kma(4),Iact
1155 : COM /Wil2/ Delta,Isat,Nsets,Hod,Cia(3),Alpaa(3)
1160 : DIM Fma(8,4),Fm(4),Emf(8),Tp(3),T(8),Ho(3),Gdp(3),Uo(3)
1165 : DATA 33.4,20,34.4,34.5,23.5
1170 : DATA 41.3,25,41.3,41.6,28.8
1175 : DATA 49.1,30,48.4,48.6,34.1
1180 : DATA 57.0,35,55.3,55.6,38.4
1185 : DATA 64.8,40,62.3,62.7,44.6
1190 : DATA 72.7,45,69.2,69.7,48.8
1195 : DATA 80.6,50,76.3,76.7,55.2
1200 : DATA 88.4,55,83.3,83.8,60.5
1205 : DATA 96.3,60,90.2,90.8,65.6
1210 : READ Fma(*)
1215 : DATA 5.172,5.172,5.172,5.172
1220 : READ Cia(*)
1225 : DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1230 : DATA -9247486589,6.97688E11,-2.66192E13,3.94078E14
1235 : READ C(*)
1240 : DATA 0.015875,0.014000,0.0,0.0,0.0

```

```

1245 DATA 0.010259,0.010150,0.0,0.0,0.0
1250 DATA 386.0,42.975,0.0,0.0,0.0
1255 DATA 0.0005589,3
1260 READ Ddat(*),Diat(*),Kmat(*),Delta,Hod : Hod=H*Di
1265 L=1.2192 : Condensing length
1270 Jset=0
1275 BEEP
1280 INPUT "ENTER MONTH, DATE AND TIME (MM-DD HH-MM-SS)",Dtg$
1285 OUTPUT 709,"D":Dtg$
1290 BEEP
1295 INPUT "SELECT OPTION (0=DAQ, 1=FILE)",Im
1300 Ihard=1
1305 BEEP
1310 INPUT "WANT A HARDCOPY PRINTOUT (1=DEF=YES,0=NO)",Ihard
1315 BEEP
1320 INPUT "SELECT (0=R-114,1=STEAM,2=R-113,3=EG)",If
1325 Iin=1
1330 Isat=2
1335 BEEP
1340 INPUT "SELECT SAT TEMP MODE (0=LIQ,1=VAP,2=(LIQ+VAP)/2=DEF)",Isat
1345 IF Ihard=1 THEN PRINTER IS 701
1350 IF Im=0 THEN
1355 BEEP
1360 INPUT "GIVE A NAME FOR THE NEW DATA FILE",File$
1365 CREATE BDAT File$,20
1370 ASSIGN @File TO File$
1375 BEEP
1380 INPUT "ENTER TUBE CODE",Itube
1385 BEEP
1390 INPUT "ENTER EG CONCENTRATION (WT PERCENT)",Egrat
1395 ENTER 709,Dtg$
1400 OUTPUT @File:Dtg$
1405 OUTPUT @File:Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
1410 Iact=10
1415 BEEP
1420 INPUT "SELECT (0=TOP,1=SECOND,...,10=BUNDLE=DEFAULT)",Iact
1425 PRINT
1430 PRINT USING "10X,""FILE NAME """,12A",File$
1435 PRINT
1440 ELSE
1445 BEEP
1450 INPUT "ENTER NAME OF EXISTING FILE",File$
1455 BEEP
1460 INPUT "ENTER NUMBER OF DATA SETS STORED",Nsets
1465 Iw1=1
1470 BEEP
1475 INPUT "WANT TO CALL WILSON? (1=DEFAULT=YES,0=NO)",Iw1
1480 IF Iw1=1 THEN
1485 BEEP
1490 INPUT "WHICH TUBE (0=TOP,1=SECOND,...,10=BUNDLE)",Iact
1495 CALL Wilson
1500 IF Ihard=1 THEN PRINTER IS 701
1505 PRINT
1510 PRINT USING "10X,""FILE NAME """,12A",File$
1515 PRINT
1520 IF Iact>9 THEN
1525 PRINT USING "10X,""INSIDE COEFFICIENTS: """,4(DD.3D,2X)",Diat*)
1530 PRINT USING "10X,""ALPHAS """,4(1X,M2.3DE,2X)",Alp

```

```

aa(*)
1535         ELSE
1540             PRINT USING "10X,""INSIDE COEFFICIENT FOR TUBE ""D,"" """,DD.3
1545             PRINT USING "10X,""ALPHA FOR TUBE ""D,"" """,DD.3
1550         END IF
1555         ELSE
1565             INPUT "ENTER CI VALUES (DEFAULT=5.172)",Cia(*)
1570         END IF
1575         ASSIGN @File TO File$
1580         ENTER @File:Dtg$
1585         ENTER @File:Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
1586         INPUT "ENTER TUBE CODE",Itube
1590     END IF
1595     Iout=1
1600     BEEP
1605     INPUT "WANT TO CREATE AN OUTPUT FILE? (1=DEF=YES,0=NO)",Iout
1610     IF Iout=1 THEN
1615         BEEP
1620         INPUT "ENTER A NAME FOR OUTPUT FILE",Fout$
1625         CREATE BDAT Fout$,5
1630         ASSIGN @Fout TO Fout$
1635     END IF
1640
1645     Do=Doa(Itube)
1650     Di=Dia(Itube)
1655     Km=kma(Itube)
1660     Ax=PI*Di^2/4    ' Cross-sectional area
1665     Ao=PI*Do*L
1670     Rm=Do*LOG(Do/Di)/(2*Km)
1675
1680     IF Im=0 THEN
1685         PRINTER IS 1
1690         BEEP
1695         PRINT "SET FLOWMETER READINGS CORRESPONDING TO:"
1700         PRINT "          ",Fma(Jset,1):"% OF METER 2 AND HIT CONTINUE"
1705         PAUSE
1710         PRINTER IS 701
1715         OUTPUT 709:"AR AF0 AL8 VRS"
1720         Nend=8      ' INCREASE TO 9 IF FIVE TUBES IN BUNDLE
1725         FOR I=0 TO Nend
1730             OUTPUT 709:"AS SA"
1735             Vsum=0
1740             FOR J=1 TO 5
1745                 ENTER 709:E
1750                 Vsum=Vsum+E
1755             NEXT J
1760             Emf(I)=Vsum/5
1765         NEXT I
1770         OUTPUT 709:"AR AF20 AL23 VRS"
1775         FOR I=0 TO 3
1780             OUTPUT 709:"AS SA"
1785             Vsum=0
1790             FOR J=1 TO 50
1795                 ENTER 709:E
1800                 Vsum=Vsum+E
1805             WAIT .25
1810             NEXT J

```

```

1815         Tp(I)=Vsum/50
1820     NEXT I
1825     ELSE
1830         ENTER @File.Fm(*),Emf(*),Tp(*)
1835     END IF
1840
1845 DATA ANALYSIS
1850
1855     Nend=8
1860     FOR I=0 TO Nend
1865         T(I)=FNTvsv(Emf(I))
1870     NEXT I
1875     Tvap=(T(0)+T(1)+T(2))/3
1880     Tliq=(T(3)+T(4))/2
1890     Tsat=Tliq
1895     END IF
1896     IF Isat=1 THEN
1900         Tsat=Tvap
1905     END IF
1906     IF Isat=2 THEN
1907         Tsat=(Tvap+Tliq)/2
1908     END IF
1910     FOR I=0 TO 4
1915         Fm(I)=Fma(Jset,I)
1920     NEXT I
1925     Jset=Jset+1
1930     PRINT
1935     PRINT USING "10X," "Data set number = ",DD,Jset
1940     PRINT
1945     Ibeg=0
1950     Iend=3
1955     IF Iact<10 THEN
1960         Ibeg=Iact
1965         Iend=Iact
1970     END IF
1975     FOR I=Ibeg TO Iend
1980         Grad=FNGrad(Emf(I+5))
1985         Delt=ABS(Tp(I)/(Grad*10))
1990         Tav=T(I+5)+Delt*.5
1995         Rhoeg=FNRhoeg(Tavg,Egrat)
2000         Nueg=FNNueg(Tavg,Egrat)
2005         Mueg=Nueg*Rhoeg
2010         Cpeg=FNCPeg(Tavg,Egrat)
2015         Keg=FNKeg(Tavg,Egrat)
2020         Preg=Cpeg*Mueg/Keg
2025         Mdot=FNFmcal(I,T(I+5),Fm(I))
2030         Veg=Mdot/(Rhoeg*Ax)
2035         Reeg=Veg*D1/Nueg
2040         Res=4*Mdot/(PI*Mueg*(D1-4*Delta))
2045         Qdot=Mdot*Cpeg*Delt
2050         Qdp(I)=Qdot/Ao
2055         IF I=0 OR I=Iact THEN
2060             Qdp1=Qdp(I)
2065             CALL Nusselt
2070         END IF
2075         Lmtd=Delt/LOG((Tsat-T(I+5))/(Tsat-T(I+5)-Delt))
2080         Uo(I)=Qdp(I)/Lmtd
2085         IF Reeg<4000 THEN

```

```

2092     Nueg=Cia*I)*(1+5.484E-3*Preg*.7*(Res/Hod)^1.25)^.5
2095 ELSE
2100     BEEP
2105     PRINT USING "10X,""INCORRECT TURBULENT CORRELATION""
2110     Nueg=.027*Reeg*.8*Preg*.3333*Cfeg
2115 END IF
2120     Hi=Nueg*Keg/Di
2125     Ho(I)=1/((1/Uo(I))-Do/(Di*Hi))-Rm)
2130     IF I=0 OR I=Iact THEN
2135         PRINT USING "10X,""Mass flow rate" = "",MZ.3DE";Mdot
2136         PRINT USING "10X,""Inside Tube Dia. (m.)" = "",MZ.3DE";Dia(Itube
)
2137         PRINT USING "10X,""180 DEG OVER Dia. (HOD)" = "",MZ.3DE";Hod
2140         PRINT USING "10X,""Inlet temperature" = "",MZ.3DE";T(I+S)
2145         PRINT USING "10X,""Saturation temp (Deg C)" = "",MZ.3DE";Tsat
2146         PRINT USING "10X,""DELTA Tape Thickness" = "",MZ.3DE";Delta
2147         PRINT USING "10X,""DELT temp Dif." = "",MZ.3DE";Delt
2148         PRINT USING "10X,""Log. Mean temp Dif." = "",MZ.3DE";LmtD
2150         PRINT USING "10X,""Heat flux" = "",MZ.3DE";Qdp(I)
2151         PRINT USING "10X,""Conductivity E.G." = "",MZ.3DE";Keg
2152         PRINT USING "10X,""Conductivity Tube Metal" = "",MZ.3DE";Km
2155         PRINT USING "10X,""Prandtl number" = "",MZ.3DE";Preg
2160         PRINT USING "10X,""Reynolds number" = "",MZ.3DE";Reeg
2161         PRINT USING "10X,""Reynolds number H&B S" = "",MZ.3DE";Res
2165         PRINT USING "10X,""Inside h.t.c." = "",MZ.3DE";Hi
2166         PRINT USING "10X,""Inside NUSSULT NO." = "",MZ.3DE";Nueg
2167         PRINT USING "10X,""OVERALL H.t.c. (Uo)" = "",MZ.3DE";Uo/I
2170         PRINT
2175         PRINT USING "10X,""TUBE      FM      VEG      DELT      Uo
HO
HNUS""
2180         PRINT USING "10X,"" #      (%)      (m/s)      (K)      (W/m^2.
K)""
2185         PRINT USING "10X,3D,4X,3D,DD,3X,Z,DD,4X,DD,3D,2X,MZ.3DE,3X,MZ.3DE
,3X,MZ.3DE,3X";I+1,Fm(I),Veg,Delt,Uo(I),Ho(I),Hnus
2190     ELSE
2195         PRINT USING "10X,3D,4X,3D,DD,3X,Z,DD,4X,DD,3D,2X,MZ.3DE,3X,MZ.3DE
,3X";I+1,Fm(I),Veg,Delt,Uo(I),Ho(I)
2200     END IF
2205 NEXT I
2210 IF Im=0 THEN
2215     Okacct=1
2220     BEEP
2225     INPUT "OK TO ACCEPT THIS SET (1=DEFAULT=YES, 0=NO)?",Okacct
2230     IF Okacct=1 THEN OUTPUT @File,Fm(*),Emf(*),Tp(*)
2235 END IF
2240 IF (Okacct=1 OR Im=1) AND Iout=1 THEN
2245     FOR I=0 TO 3
2250         OUTPUT @Fout,Ho(I),Qdp(I)
2255     NEXT I
2260 END IF
2265 IF Im=0 THEN
2270     Okrpt=1
2275     BEEP
2280     INPUT "WILL THERE BE ANOTHER RUN (1=YES=DEFAULT,0=NO)",Okrpt
2285     IF Okrpt=1 THEN 1680
2290 ELSE
2295     IF Jset/Nsets THEN 1680
2300 END IF
2305 ASSIGN @File TO *

```

```

2310 IF Iout=1 THEN ASSIGN @File TO *
2315 SUBEND
2320 DEF FNGrad(T)
2325 Grad=-3.877857E-5-2*4.7142857E-8*T
2330 RETURN Grad
2335 FNEND
2340 DEF FNKcu(T)
2345 OFHC COPPER 250 TO 300 K
2350 Tk=T+273.15
2355 K=434-.112*Tk
2360 RETURN K
2365 FNEND
2370 DEF FNNueg(Tc,Egr)
2375 RANGE OF VALIDITY: -20 TO 20 DEG C
2380 Tk=Tc+273.15
2385 Nu1=7.1196507E-3-Tk*(7.4863347E-5-Tk*(2.6294943E-7-Tk*3.0833329E-10))
2390 Nu2=4.9237638E-3-Tk*(4.9213912E-5-Tk*(1.6437534E-7-Tk*1.8333331E-10))
2395 Nu3=8.6586293E-3-Tk*(8.8837902E-5-Tk*(3.0495032E-7-Tk*3.4999996E-10))
2400 A2=(Nu3-2*Nu2+Nu1)/200
2405 A1=(Nu2-Nu1-940*A2)/10
2410 A0=Nu1-42*A1-1764*A2
2415 Nu=A0+Egr*(A1+Egr*A2)
2420 RETURN Nu
2425 FNEND
2430 DEF FNCpeg(Tc,Egr)
2435 RANGE OF VALIDITY: 0 TO 20 DEG C
2440 Tk=Tc+273.15
2445 Cp1=1.6701550E+3+Tk*6.5
2450 Cp2=1.4748125E+3+Tk*6.25
2455 Cp3=9.5800500E+2+Tk*7.3
2460 A2=(Cp3-2*Cp2+Cp1)/200
2465 A1=(Cp2-Cp1-900*A2)/10
2470 A0=Cp1-40*A1-1600*A2
2475 Cp=A0+Egr*(A1+Egr*A2)
2480 RETURN Cp
2485 FNEND
2490 DEF FNRhoeg(T,Egr)
2495 Ro1=1.0607093E+3-T*(3.7031283E-1+T*4.0837183E-3)
2500 Ro2=1.0748272E+3-T*(4.4266195E-1+T*4.0939706E-3)
2505 Ro3=1.0885934E+3-T*(5.7355653E-1+T*6.1261405E-3)
2510 A2=(Ro3-2*Ro2+Ro1)/200
2515 A1=(Ro2-Ro1-900*A2)/10
2520 A0=Ro1-40*A1-1600*A2
2525 Ro=A0+Egr*(A1+Egr*A2)
2530 RETURN Ro
2535 FNEND
2540 DEF FNPneg(T,Egr)
2545 Pr=FNCpeg(T,Egr)*FNNueg(T,Egr)+FNRhoeg(T,Egr)/FNCpeg(T,Egr)
2550 RETURN Pr
2555 FNEND
2560 DEF FNKeg(Tc,Egr)
2565 RANGE OF VALIDITY: -20 TO 20 DEG C
2570 Tk=Tc+273.15
2575 K1=2.2824708E-1+Tk*(5.5989286E-4+Tk*3.5714286E-7)
2580 K2=2.5846616E-1+Tk*(2.3978571E-4+Tk*7.1428571E-7)
2585 K3=3.2138932E-1-Tk*(3.0042857E-4-Tk*1.4285714E-6)
2590 A2=(K3-2*K2+K1)/200
2595 A1=(K2-K1-900*A2)/10
2600 A0=K1-40*A1-1600*A2
2605 K=A0+Egr*(A1+Egr*A2)

```

```

2610 RETURN R
2615 FNEND
2620 DEF FNTanh(X)
2625 F=EXP(X)
2630 Q=1/F
2635 Tanh=(F-Q)/(F+Q)
2640 RETURN Tanh
2645 FNEND
2650 DEF FNTvsv(V)
2655 COM /Ccr/ 0.7)
2660 T=C(0)
2665 FOR I=1 TO 7
2670 T=T+C(I)*V^I
2675 NEXT I
2680 RETURN T
2685 FNEND
2690 DEF FNBeta(T)
2695 Rop=FNRho(T+.1)
2700 Rom=FNRho(T-.1)
2705 Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
2710 RETURN Beta
2715 FNEND
2720 DEF FNPsat(Tc)
2725 0 TO 80 deg F CURVE FIT OF Psat
2730 Tf=1.8*Tc+32
2735 Pa=5.945525+Tf*(.15352082+Tf*(1.4840963E-3+Tf*9.6150671E-6))
2740 Pg=Pa-14.7
2745 IF Pg>0 THEN P+=PSIG,-=-in Hg
2750 Psat=Pg
2755 ELSE
2760 Psat=Pg*29.92/14.7
2765 END IF
2770 RETURN Psat
2775 FNEND
2780 DEF FNFmcal(I,T,Fm)
2785 DIM B1(4),B2(4),B3(4),M1(4),M2(4),M3(4)
2790 DATA 3.48835E-3,6.71749E-3,-5.8103E-3,-5.5079E-3,4.125E-4
2795 DATA -1.47621E-2,2.53207E-3,-2.76396E-3,-4.30913E-3,-3.10937E-3
2796 DATA 1.048E-3,1.01292E-2,1.114E-2,-3.86717E-3,0.0
2800 DATA 1.71625E-3,2.70428E-3,1.93749E-3,1.92237E-3,2.56646E-3
2805 DATA 2.03462E-3,2.86716E-3,2.09517E-3,2.12432E-3,2.93127E-3
2810 DATA 1.7681E-3,2.70622E-3,2.00121E-3,2.2040E-3,0.0
2811 READ B1(*),B2(*),B3(*),M1(*),M2(*),M3(*)
2815 IF T<=7 THEN
2815 Z1=B1(I)+M1(I)*Fm
2820 Z2=B2(I)+M2(I)*Fm
2821 S=(Z2-Z1)/13
2822 C=Z1+S*20
2824 ELSE
2825 Z1=B1(I)+M2(I)*Fm
2826 Z2=B3(I)+M3(I)*Fm
2827 S=(Z2-Z1)/16
2828 C=Z1+S*7
2830 END IF
2835 Mdot=C+S*T
2840 RETURN Mdot
2845 FNEND
2850 SUB xyread
2855 BEEP

```

```

2860 INPUT "ENTER FILE NAME",File$
2865 BEEP
2870 INPUT "ENTER NUMBER OF X,Y PAIRS",N
2875 ASSIGN @File TO File$
2880 FOR I=1 TO N
2885 ENTER @File,X,Y
2890 PRINT X,Y
2895 NEXT I
2900 SUBEND
2905 SUB Purge
2910 BEEP
2915 INPUT "ENTER FILE NAME TO BE DELETED",File$
2920 PURGE File$
2925 GOTO 2910
2930 SUBEND
2935 SUB Wilson
2940 COM /Wil1/ Doa(4),Dia(4),Kma(4),Iact
2945 COM /Wil2/ Delta,Isat,Nsets,Hod,Dia(3),Alpaa(3)
2950 DIM Fm(4),Emf(8),Tp(3),T(8),Xa(20),Ya(20)
2955 BEEP
2960 INPUT "PLEASE RE-ENTER NAME OF FILE",File$
2965 ASSIGN @File TO File$
2970 INPUT "ENTER TUBE CODE",Itube
2975 BEEP
2980 INPUT "GIVE A NAME FOR XY FILE",Xy$
2985 CREATE BDAT Xy$,5
2990 ASSIGN @Xy TO Xy$
2995 L=1.2192
3000 Do=Doa(Itube)
3005 Di=Dia(Itube)
3010 Km=Kma(Itube)
3015 A=PI*Di2/4 : Cross-sectional area
3020 Ao=PI*Do*L
3025 Rm=Do*LOG(Do/Di)/(2*Km)
3030
3035 Initial values
3040 Tf=Tsat
3045 Alpha=.655
3050 Di=5.172
3055 G=9.81
3060 Ibeg=0
3065 Iend=3 : CHANGE TO 4, IF FIVE TUBES IN BUNDLE
3070 IF Iact<10 THEN
3075 Ibeg=Iact
3080 Iend=Iact
3085 END IF
3090
3095 FOR I=Ibeg TO Iend
3100 Sx=0
3105 Sy=0
3110 Sxs=0
3115 Sxy=0
3120 Jset=0
3125 ASSIGN @File TO File$
3130 ENTER @File,Otg$,Itube,Egrat,Dd1,Dd2,Dd3,Dd4,Dd5
3135 ENTER @File,Fm(*),Emf(*),Tp(*)
3140 FOR J=0 TO 8
3145 T(J)=FNTvsv(Emf(J))
3150 NEXT J
3155 Tvp=(T(0)+T(1)+T(2))/3

```

```

3160 Tliq=(T(3)+T(4))/2
3165 IF Isat=0 THEN
3170 Tset=Tliq
3175 ELSE
3180 Tset=Twap
3185 END IF
3190 Grad=FNGrad(T(I+5))
3195 Delt=ABS(Tp-I)/(Grad*10)
3200 Tavg=T(I+5)+Delt*.5
3205
3210 Water/Ethylene Glycol Mixture Properties
3215 Rhoeg=FN Rhoeg(Tavg,Egrat)
3220 Nueg=FN Nueg(Tavg,Egrat)
3225 Mueg=Nueg*Rhoeg
3230 Cpeg=FN Cpeg(Tavg,Egrat)
3235 keg=FN keg(Tavg,Egrat)
3240 Preg=Cpeg*Mueg/keg
3245
3250 Mdot=FN Fmcal(I,T(I+5),Fm(I))
3255 Veg=Mdot/(Rhoeg*Ax)
3260 Reeg=Veg*Di/Nueg
3265 Res=4*Mdot/(Pi*Mueg*(Di-4*Delta))
3270 Qdot=Mdot*Cpeg*Delt
3275 Qdp=Qdot/Ao
3280 Lmtd=Delt/LOG((Tsat-T(I+5))/(Tsat-T(I+5)-Delt))
3285 Uo=Qdp/Lmtd
3290 Omega=(1+5.484E-3*Preg*.7*(Res/Hod)**1.25)**.5
3295
3300 R-114 Properties
3305 Hfg=FN Hfg(Tsat)
3310 Kf=FN Kf(Tf)
3315 RhoF=FN Rho(Tf)
3320 Muf=FN Mu(Tf)
3325
3330 F=(Kf**3*RhoF**2*G*Hfg/(Muf*Do*Qdp))**.33333
3335 Ho=Alpa*F
3340 Two=Tsat-Qdp/Ho
3345 Tf=Tsat/3+2*Two/3
3350 Y=(1/Uo-Rm)*F
3355 X=Do*F/(keg*Omega)
3360 PRINT "OMEGA=",Omega,"F=":F:"X=":X:"Y=":Y
3365 Xa(Jset)=X INEFFICIENT (MODIFY LATER)
3370 Ya(Jset)=Y
3375 Sx=Sx+X
3380 Sy=Sy+Y
3385 Sxs=Sxs+X*X
3395 Jset=Jset+1
3400 IF Jset/Nsets THEN 3135
3405 ASSIGN @File TO *
3410 Slope=(Nsets*Sxy-Sx*Sy)/(Nsets*Sxs-Sx**2)
3415 Intcpt=(Sy-Slope*Sx)/Nsets
3420 Cic=1/Slope
3425 Alpac=1/Intcpt
3430 Cerr=ABS((Ci-Cic)/Cic)
3435 Aerr=ABS((Alpac-Alpa)/Alpac)
3440 IF Cerr>.001 OR Aerr>.001 THEN
3445 Alpa=(Alpa+Alpac)*.5
3450 Ci=(Ci+Cic)*.5
3455 PRINT "CIC=",Cic,"ALPA=",Alpa

```

```

3462         GOTO 3100
3465     END IF
3470     BEEP
3475     BEEP
3480     PRINTER IS 1
3485     PRINT "CIC=";Cic;"ALPA=";Alpa
3490     C1a(I)=C1c
3495     Alpaa(I)=Alpac
3500     PRINTER IS 701
3505     FOR J=0 TO Nsets-1
3510         OUTPUT @xy,Xa(J),Ya(J)
3515     NEXT J
3520     PRINTER IS 1
3525     NEXT I
3530     ASSIGN @xy TO *
3535     SUBEND
3540     SUB Nusseit
3545     COM /Nus= Iin,Tsat,Qdp,Hoc
3550     Do=.0159
3555     Ho=1000
3560     IF Iin=0 THEN
3565         BEEP
3570         INPUT "ENTER TSAT AND HEAT FLUX",Tsat,Qdp
3575     END IF
3580     Hfg=FNHfg(Tsat)
3585     Two=Tsats-Qdp/Ho
3590     Tf=Tsats/3+2*Two/3
3595     Kf=FNK(Tf)
3600     Rhof=FNrho(Tf)
3605     Muf=FNmu(Tf)
3610     Hoc=.655*(Kf^3*Rhof^2*9.81*Hfg/(Muf*Do*Qdp))^-.333333
3615     IF ABS((Ho-Hoc)/Hoc)>.001 THEN
3620         Ho=(Ho+Hoc)*.5
3625         GOTO 3585
3630     END IF
3635     IF Iin=0 THEN PRINT "HO=";Hoc
3640     SUBEND
3645     SUB Plot1
3650     DIM Yaa(4)
3655     PRINTER IS 705
3660     Idv=1
3665     BEEP
3670     INPUT "OK TO USE DEFAULT VALUES (1=DEF=Y,0=N)",Idv
3675     IF Idv=1 THEN
3680         Itn=2
3685         Xmin=1
3690         Xmax=5
3695         Xstep=1
3700         Ymin=0
3705         Ymax=2.0
3710         Ystep=.5
3715     ELSE
3720         INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
3725         BEEP
3730         INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
3735         BEEP
3740         INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
3745         BEEP
3750         INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep

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3760 END IF
3765 PRINT "IN.SF1:IP 2300,1800,8300,6600."
3770 PRINT "SC 0,100,0,100,TL 0,0."
3775 Sfx=100/(Xmax-Xmin)
3780 Sfy=100/(Ymax-Ymin)
3785 PRINT "PU 0,0 PD"
3790 FOR Xa=Xmin TO Xmax STEP Xstep
3795 X=(Xa-Xmin)*Sfx
3800 PRINT "PA",X,"",0,"XT"
3805 NEXT Xa
3810 PRINT "PA 100,0,PU."
3815 PRINT "PU PA 0,0 PD"
3820 FOR Ya=Ymin TO Ymax STEP Ystep
3825 Y=(Ya-Ymin)*Sfy
3830 PRINT "PA 0,"",Y,"YT"
3835 NEXT Ya
3840 PRINT "PA 0,100 TL 0 2"
3845 FOR Xa=Xmin TO Xmax STEP Xstep
3850 X=(Xa-Xmin)*Sfx
3855 PRINT "PA",X,"",100,"XT"
3860 NEXT Xa
3865 PRINT "PA 100,100 PU PA 100,0 PD"
3870 FOR Ya=Ymin TO Ymax STEP Ystep
3875 Y=(Ya-Ymin)*Sfy
3880 PRINT "PD PA 100,"",Y,"YT"
3885 NEXT Ya
3890 PRINT "PA 100,100 PU"
3895 PRINT "PA 0,-2 SR 1.5,2"
3900 FOR Xa=Xmin TO Xmax STEP Xstep
3905 X=(Xa-Xmin)*Sfx
3910 PRINT "PA",X,"",0,""
3915 PRINT "CP -2,-1:LB":Xa:""
3920 NEXT Xa
3925 PRINT "PU PA 0,0"
3930 FOR Ya=Ymin TO Ymax STEP Ystep
3935 Y=(Ya-Ymin)*Sfy
3940 PRINT "PA 0,"",Y,""
3945 PRINT "CP -4,-.25:LB":Ya:""
3950 NEXT Ya
3955 BEEP
3960 INPUT "SELECT MODE (0=HN/H1,1=HN(avg)/H1)",Ism
3965 Ism=Ism+1
3970 IF Idv=1 THEN
3975 IF Ism=1 THEN Ylabel$="HN/H1"
3980 IF Ism=2 THEN Ylabel$="HN(avg)/H1"
3985 Xlabel$="Tube Number"
3990 ELSE
3995 BEEP
4000 INPUT "ENTER X-LABEL",Xlabel$
4005 BEEP
4010 INPUT "ENTER Y-LABEL",Ylabel$
4015 END IF
4020 PRINT "SR 1.5,2:PU PA 50,-10 CP":-LEN(Xlabel$)/2:"0:LB":Xlabel$:""
4025 PRINT "PA -11,50 CP 0,"":-LEN(Ylabel$)/2*5/6:"DI 0,1:LB":Ylabel$:""
4030 PRINT "CP 0,0 DI"
4035 Okp=1
4040 BEEP
4045 INPUT "WANT TO PLOT DATA FROM A FILE (1=DEF=Y,0=N)?",Okp

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4055      BEEP
4060      INPUT "ENTER THE NAME OF THE DATA FILE",Dfile$
4065      ASSIGN @File TO Dfile$
4070      BEEP
4075      INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4080      BEEP
4085      INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Nsets
4090      BEEP
4095      INPUT "SELECT A SYMBOL FOR THE PLOTTER (1=*,2=+,3=c,4=o,5=.)",S,
4100      PRINT "PU DI"
4105      IF Sy=1 THEN PRINT "SM*"
4110      IF Sy=2 THEN PRINT "SM+"
4115      IF Sy=3 THEN PRINT "SMc"
4120      IF Sy=4 THEN PRINT "SMo"
4125      IF Sy=5 THEN PRINT "SM."
4130      FOR I=1 TO Nsets
4135          FOR J=0 TO 3
4140              ENTER @File:Yaa(J),D
4145              IF J=0 THEN Ytop=Yaa(0)
4150              Yaa(J)=Yaa(J)/Ytop
4155          NEXT J
4160          FOR J=0 TO 3
4165              X=(J+1-Xmin)*Sfx
4170              Y=(Yaa(J)-Ymin)*Sfy
4175              PRINT "PA",X,Y,""
4180          NEXT J
4185      NEXT I
4190      BEEP
4195      ASSIGN @File TO *
4200      GOTO 4040
4205  END IF
4210  BEEP
4215  INPUT "LIKE TO PLOT THE NUSSELT RELATION (1=Y,0=N)?",Oknus
4220  PRINT "PU:SM"
4225  IF Oknus=1 THEN
4230      FOR Xa=Xmin TO Xmax STEP Xstep/50
4235          X=(Xa-Xmin)*Sfx
4240          IF Ism=1 AND Xa>Xmin THEN Ya=Xa0.75-(Ya-1)0.75
4245          IF Ism=2 AND Xa>Xmin THEN Ya=Xa(-.25)
4250          IF Xa=Xmin THEN Ya=1
4255          Y=(Ya-Ymin)*Sfy
4260          PRINT "PA",X,Y,"PD"
4265      NEXT Xa
4270      BEEP
4275      PRINT "PU"
4280      INPUT "MOVE THE PEN TO LABEL THE NUSSELT LINE",Ok
4285      PRINT "LBNusselt"
4290  END IF
4295  IF Ism=2 THEN
4300      BEEP
4305      INPUT "LIKE TO PLOT EXPTL CURVE (1=Y,0=N)",Okex
4310      Nq=0
4315      IF Okex=1 THEN
4320          BEEP
4325          INPUT "ENTER THE EXPONENT",Ex
4330          FOR Xa=Xmin TO Xmax STEP Xstep/10
4335              Nq=Nq+1
4340              Ya=Xa(-Ex)
4345              X=(Xa-Xmin)*Sfx
4350              Y=(Ya-Ymin)*Sfy

```

```

4355         IF Na MOD 2=0 THEN
4360             PRINT "PA",X,Y, "PD"
4365         ELSE
4370             PRINT "PA",X,Y,"PU"
4375         END IF
4380         Na = Na + 1
4385         PRINT "PU"
4390         BEEP
4395         INPUT "MOVE PEN TO LABEL AND HIT ENTER",C)
4400         PRINT "LBs=0"
4405         PRINT "PR -1 0"
4410         PRINT "LB",Ex,""
4415         GOTO 4300
4420     END IF
4425 END IF
4430 GOTO 4510
4435 BEEP
4440 INPUT "LIKE TO PLOT KERN RELATIONSHIP (1=Y,0=N)?",Yes
4445 IF Yes=1 THEN
4450     FOR Xa=Xmin TO Xmax STEP Xstep/20
4455         Ya=Xa*(1/6)
4460         X=(Xa-Xmin)*Sfx
4465         Y=(Ya-Ymin)*Sfy
4470         PRINT "PA",X,Y,"PD"
4475     NEXT Xa
4480     PRINT "PU"
4485     BEEP
4490     INPUT "MOVE THE PEN TO LABEL KERN RELATIONSHIP",O)
4495     PRINT "LBkern:PU"
4500 END IF
4505 PRINT "PU PA 0,0"
4510 BEEP
4515 INPUT "LIKE TO PLOT EISSENBERG RELATION (1=Y,0=N)?",O)
4520 IF O) = 1 THEN
4525     FOR Xa=Xmin TO Xmax STEP Xstep/10
4530         Ya=.5+.42*Xa*-.25)
4535         X=(Xa-Xmin)*Sfx
4540         Y=(Ya-Ymin)*Sfy
4545         PRINT "PA",X,Y,"PD"
4550     NEXT Xa
4555     PRINT "PU"
4560     BEEP
4565     INPUT "MOVE THE PEN TO LABEL THE EISSENBERG LINE",O)
4570     PRINT "LBEissenberg:PU"
4575 END IF
4580 PRINT "PU SP0"
4585 SUBEND
4590 DEF FNPvst(Tc)
4595 COM /F1d/ Ift
4600 DIM K(8)
4605 IF Ift=0 THEN
4610     BEEP
4615     PRINT "PVST CORRELATION NOT AVAILABLE FOR R-114"
4620     STOP
4625 END IF
4630 IF Ift=1 THEN
4635     DATA -7.691234564,-26.08023696,-168.1706546,64.23285504,-118.9646225
4640     DATA 4.16711732,20.9750676,1.E9,6
4645     READ K(*)

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4650      T=(Tc+273.15)/647.3
4655      Sum=0
4660      FOR N=0 TO 4
4665          Sum=Sum+K(N)*(1-T)^(N+1)
4670      NEXT N
4675      Br=Sum/(T*(1+K(5)*(1-T)+K(6)*(1-T)^2)-(1-T)/(K(7)*(1-T)^2+K(8)))
4680      Pr=EXP(Br)
4685      P=22120000*Pr
4690  END IF
4695  IF Ift=2 THEN
4700      Tf=Tc*1.8+32+459.6
4705      P=10^(33.0655-4330.98/Tf-9.2635*LGT(Tf)+2.0539E-3*Tf)
4715  END IF
4720  IF Ift=3 THEN
4725      A=9.394685-3066.1/(Tc+273.15)
4730      P=133.32*10^A
4735  END IF
4740  RETURN P
4745  FNEND
4750  DEF FNHfg(T)
4755  COM /FId/ Ift
4760  IF Ift=0 THEN
4765      Tf=T*1.8+32
4770      Hfg=6.1451558E+1-Tf*(6.951079E-2+Tf*(1.3988688E-4+1.9607843E-7*Tf))
4775      Hfg=Hfg*2326
4780  END IF
4785  IF Ift=1 THEN
4790      Hfg=2477200-2450*(T-10)
4795  END IF
4800  IF Ift=2 THEN
4805      Tf=T*1.8+32
4810      Hfg=7.0557857E+1-Tf*(4.838052E-2+1.2619048E-4*Tf)
4815      Hfg=Hfg*2326
4820  END IF
4825  IF Ift=3 THEN
4830      Tk=T+273.15
4835      Hfg=1.35264E+6-Tk*(6.38263E+2+Tk*.747462)
4840  END IF
4845  RETURN Hfg
4850  FNEND
4855  DEF FNMu(T)
4860  COM /FId/ Ift
4865  IF Ift=0 THEN
4870      Tk=T+273.15
4875      Mu=EXP(-4.4636+1011.47/Tk)*1.E-3
4880  END IF
4885  IF Ift=1 THEN
4890      A=247.8/(T+133.15)
4895      Mu=2.4E-5*10^A
4900  END IF
4905  IF Ift=2 THEN
4910      Mu=8.9629819E-4-T*(1.1094609E-5-T*5.566829E-8)
4915  END IF
4920  IF Ift=3 THEN
4925      Tk=1/(T+273.15)
4930      Mu=EXP(-11.0179+Tk*(1.744E+3-Tk*(2.80335E+5-Tk*1.12661E+8)))
4935  END IF
4940  RETURN Mu
4945  FNEND

```

```

4950 DEF FNUVst(Tt)
4955 COM /F1d/ Ift
4960 IF Ift=0 THEN
4965 BEEP
4970 PRINT "UVST CORRELATION NOT AVAILABLE FOR R-114"
4975 STOP
4980 END IF
4985 IF Ift=1 THEN
4990 P=FNPvst(Tt)
4995 T=Tt+273.15
5000 X=1500/T
5005 F1=1/(1+T*.1E-4)
5010 F2=(1-EXP(-X))^2.5*EXP(X)/X^.5
5015 B=.0015*F1-.000942*F2-.0004882*X
5020 K=2*P/(461.52*T)
5025 V=(1+(1+2*B*K)^.5)/K
5030 END IF
5035 IF Ift=2 THEN
5040 If=It*1.8+.54
5045 V=13.955357-Tf*/.16127262-Tf*.5.1726190E-4)
5050 V=V/16.018
5055 END IF
5060 IF Ift=3 THEN
5065 Tk=Tt+273.15
5070 P=FNPvst(Tt)
5075 V=133.95*Tk/P
5080 END IF
5085 RETURN V
5090 FNEND
5095 DEF FNCp(T)
5100 COM /F1d/ Ift
5105 IF Ift=0 THEN
5110 Tk=T+273.15
5115 Cp=.40118+Tk*(1.65007E-3+Tk*(1.51494E-6-Tk*6.67853E-10))
5120 END IF
5125 IF Ift=1 THEN
5130 Cp=4.21120858-T*(2.26826E-3-T*(4.42361E-5+2.71428E-7*T))
5135 END IF
5140 IF Ift=2 THEN
5145 Cp=9.2507273E-1+T*(9.3400433E-4+1.7207792E-6*T)
5150 END IF
5155 IF Ift=3 THEN
5160 Tk=T+273.15
5165 Cp=4.1868*(1.6884E-2+Tk*(3.35083E-3-Tk*(7.224E-6-Tk*7.61748E-9)))
5170 END IF
5175 RETURN Cp*1000
5180 FNEND
5185 DEF FNRho(T)
5190 COM /F1d/ Ift
5195 IF Ift=0 THEN
5200 Tk=T+273.15
5205 X=1-(1.8*Tk/753.95)
5210 Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
5215 Ro=Ro/.062428
5220 END IF
5225 IF Ift=1 THEN
5230 Ro=999.52946+T*(.01269-T*(5.482513E-3-T*1.234147E-5))
5235 END IF
5240 IF Ift=2 THEN

```

```

5245      Ro=1.6207479E+3-T*(2.2186346+T*2.3576291E-3)
5250  END IF
5255  IF Ift=3 THEN
5260      Tk=T+273.15-338.15
5265      Vf=9.24848E-4+Tk*(6.2796E-7+Tk*(9.2444E-10+Tk*3.057E-12))
5270      Ro=1/Vf
5275  END IF
5280  RETURN Ro
5285  FNEND
5290  DEF FNPr(T)
5295  Pr=FNCp(T)*FNMu(T)/FNK(T)
5300  RETURN Pr
5305  FNEND
5310  DEF FNK(T)
5315  COM /Fld/ Ift
5320  IF Ift=0 THEN K=.071-.000261*T
5325  IF Ift=1 THEN
5330      Y=(T+273.15)/273.15
5335      K=-.92247+X*(2.8395-X*(1.8007-X*(.52577-.07344*X)))
5340  END IF
5345  IF Ift=2 THEN
5350      K=6.2095238E-2-T*(2.2214286E-4+T*2.3809524E-8)
5355  END IF
5360  IF Ift=3 THEN
5365      Tk=T+273.15
5375  END IF
5380  RETURN K
5385  FNEND
5390  DEF FNHF(T)
5395  COM /Fld/ Ift
5400  IF Ift=0 THEN
5405      BEEP
5410      PRINT "HF CORRELATION NOT FOR R-114"
5415      STOP
5420  END IF
5425  IF Ift=1 THEN
5430      Hf=T*(4.203849-T*(5.88122E-4+T*4.55160317E-6))
5435  END IF
5440  IF Ift=2 THEN
5445      Tf=T+1.8+32
5450      Hf=8.2078971+Tf*.19467657+Tf*1.3214266E-4)
5455      Hf=Hf*2.326
5460  END IF
5465  IF Ift=3 THEN
5470      Hf=250 TO BE VERIFIED
5475  END IF
5480  RETURN Hf*1000
5485  FNEND
5490  SUB Plot2
5495  COM /Dn1/ Star,Sym,Icon
5500  COM /Fld/ Ift
5505  DIM C(9),Xya(7),Doa(3)
5510  DATA 0.0158,0.0158,0.0158,0.0158
5515  READ Doa(*)
5520  Fw=1
5525  PRINTER IS 1
5530  BEEP
5535  PRINT USING "4X,""Select Option X-Y Limits.""
5540  PRINT USING "6X,""0 Use default values""

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```

5545 PRINT USING "BX,";"1 Use new values"
5550 INPUT Ord
5555 BEEP
5560 INPUT "ENTER TUBE CODE",Icode
5565 Do=Oca-Itube)
5570 Iht=2
5575 BEEP
5580 PRINT USING "4X,";"Select option ""
5585 PRINT USING "BX,";"0 h versus q""
5590 PRINT USING "BX,";"1 q versus Delta-T""
5595 PRINT USING "BX,";"2 h versus Delta-T (default)""
5600 INPUT Iht
5605 PRINTER IS 705
5610 IF Okd=0 THEN IAXIS DEFAULT VALUES
5615     IF Iht=0 THEN I(h vs q)
5620         Ymin=0
5625         Ymax=60
5630         Ystep=10
5635         Xmin=.2
5640         Xmax=1.4
5645         Xstep=.2
5650     END IF
5655     IF Iht=1 THEN I(q vs t)
5660         Xmin=0
5665         Ymin=0
5670         Ymax=.5
5675         Xmax=15
5680         Xstep=3
5685         Ystep=.1
5690     END IF
5695     IF Iht=2 THEN I(h vs t)
5700         Xmin=0
5705         Ymin=0
5710         Xmax=50
5715         Ymax=6
5720         Xstep=10
5725         Ystep=1
5730     END IF
5735 END IF
5740 IF Okd=1 THEN
5745     BEEP
5750     INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
5755     BEEP
5760     INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
5765     BEEP
5770     INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
5775     BEEP
5780     INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
5785 END IF
5790 BEEP
5795 PRINT "IN:SP1:IP 2300,1800,8300,6800:"
5800 PRINT "SC 0,100,0,100,TL 2,0:"
5805 Sfx=100/(Xmax-Xmin)
5810 Sfy=100/(Ymax-Ymin)
5815 BEEP
5820 Icp=0
5825 INPUT "LIKE TO BY-PASS CAGE (1=Y,0=N=DEFAULT)?",Icp
5830 IF Icp=1 THEN 6175
5835 PRINT "PU 0,0 EO"
5840 FOR Xa=Xmin TO Xmax STEP Xstep

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```

5845     X=(Xa-Xmin)*Sfx
5850     PRINT "PA":X,"",0: XT:"
5855 NEXT Xa
5860 PRINT "PA 100,0,PU:"
5865 PRINT "PU PA 0,0 PD"
5870 FOR Ya=Ymin TO Ymax STEP Ystep
5875     Y=(Ya-Ymin)*Sfy
5880     PRINT "PA 0,"",Y,"YT"
5885 NEXT Ya
5890 PRINT "PA 0,100 TL 0 2"
5895 FOR Xa=Xmin TO Xmax STEP Xstep
5900     X=(Xa-Xmin)*Sfx
5905     PRINT "PA":X,"",100: XT"
5910 NEXT Xa
5915 PRINT "PA 100,100 PU PA 100,0 PD"
5920 FOR Ya=Ymin TO Ymax STEP Ystep
5925     Y=(Ya-Ymin)*Sfy
5930     PRINT "PD PA 100,"",Y,"YT"
5935 NEXT Ya
5940 PRINT "PA 100,100 PU"
5945 PRINT "PA 0,-2 SR 1.5,2"
5950 FOR Xa=Xmin TO Xmax STEP Xstep
5955     X=(Xa-Xmin)*Sfx
5960     PRINT "PA":X,"",0:"
5965     IF Xa<1 AND Xa>0 THEN PRINT "CP -1.5,-1:LB0:PR -1,0:LB":Xa:""
5970     IF Xa=0 THEN PRINT "CP -.5,-1:LB0"
5975     Xin=0
5980     IF Xa MOD 1=0 THEN Xin=1
5985     IF Xa>=10 THEN PRINT "CP -2,-1:LB":Xa:""
5990     IF Xa>1 AND Xa<10 AND Xin=1 THEN PRINT "CP -1.25,-1:LB":Xa:""
5995     IF Xa>1 AND Xin=0 THEN PRINT "CP -2,-1:LB":Xa:""
6000     IF Xa=1 THEN PRINT "CP -1,-1:LB1.0"
6005 NEXT Xa
6010 PRINT "PU PA 0,0"
6015 FOR Ya=Ymin TO Ymax STEP Ystep
6020     Y=(Ya-Ymin)*Sfy
6025     PRINT "PA 0,"",Y,""
6035     IF Ya<1 AND Ya>0 THEN PRINT "CP -4,-.25:LB0:PR -2,0:LB":Ya:""
6040     IF Ya=0 THEN PRINT "CP -2,-.25:LB0"
6045     IF Ya>1 AND Int<2 THEN PRINT "CP -5,-.25:LB":Ya:""
6050     IF Ya>9 AND Int=2 THEN PRINT "CP -4,-.25:LB":Ya:""
6055     IF Ya>0 AND Ya<10 AND Int=2 THEN PRINT "CP -3,-.25:LB":Ya:""
6060     IF Ya=1 THEN PRINT "CP -4,-.25:LB1.0"
6065 NEXT Ya
6070 IF O+d=1 THEN
6075     BEEP
6080     INPUT "ENTER X-LABEL",Xlabels$
6085     BEEP
6090     INPUT "ENTER Y-LABEL",Ylabels$
6095 END IF
6100 IF Int<>1 THEN
6105     PRINT "SR 1.5,2:PU PA -12,35:DI 0,1:LBh:PR 1,0.5:LB0:PR -1,0.5:LB/("
kW/m"
6110     PRINT "PR -1,0.5:SR 1,1.5:LB2:SR 1.5,2:PR .5,.5:LB.:PR .5,0:LBK)"
6115 ELSE
6120     PRINT "PA -12,39:DI 0,1:LBq/(MW/m:SR 1,1.5:PR -1,0.5:LB2:SR 1.5,2:P
R 1,0.5:LB)"
6125 END IF
6130 IF Int=0 THEN

```

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6135      PRINT "SR 1.5,2:PU PA 40,-10:DI:LBq/(MW/m:PR 0.5,1.SR 1,1.5.LB2.SF
1.5,2.PR .5,-1.LB)"
6140      ELSE
6145      PRINT "DI PA 36,-10:LB(T:PR .5,-1.LB:PR .5,1.LB-T:PR -2.4,3 PD PF
2.0 PU:PR .5,-4."
6150      PRINT "LBwo:PR .5,1:LB)/K"
6155      END IF
6160      PRINT "CP 0,0 DI"
6165      Xlg=1.E+6
6170      Xug=-1.E+6
6175      Xal=50
6180      Yal=95
6185      Nrun=0
6190      BEEP
6195      INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Ok
6200      Xll=1.E+6
6205      Xul=-1.E+6
6210      Okp=0
6215      IF Ok=1 THEN
6220          BEEP
6225          INPUT "ENTER THE NAME OF THE PLOT DATA FILE",D_files
6230          ASSIGN @File TO D_files
6235          IF Icomb<>0 THEN 6265
6240          Sx=0
6245          Sy=0
6250          Sx2=0
6255          Sxy=0
6260          Md=1
6265          BEEP
6270          INPUT "ENTER THE BEGINNING RUN NUMBER (DEF=1)",Md
6275          Npairs=9
6280          BEEP
6285          INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED (DEF=9)",Npairs
6290          Nrun=Nrun+Npairs
6295          PRINTER IS 1
6300          BEEP
6305          PRINT USING "4X," "Select a symbol:"
6310          PRINT USING "4X," " 1 Star 2 Plus sign"
6315          PRINT USING "4X," " 3 Circle 4 Square"
6320          PRINT USING "4X," " 5 Rombus"
6325          PRINT USING "4X," " 6 Right-side-up triangle"
6330          PRINT USING "4X," " 7 Up-side-down triangle"
6335          INPUT Sym
6340          BEEP
6345          INPUT "ENTER TUBE NUMBER FOR PLOTTING (0=TOP,1=SECOND,...)",Itube
6350          PRINTER IS 705
6355          IF Sym=1 THEN PRINT "SM+"
6360          IF Sym=2 THEN PRINT "SM+"
6365          IF Sym=3 THEN PRINT "SMo"
6370          IF Md>1 THEN
6375              FOR I=1 TO (Md-1)
6380                  ENTER @File:Xya(*)
6385              NEXT I
6390          END IF
6395          FOR I=1 TO Npairs
6400              ENTER @File:Xya(*)
6405              Ya=Xya(Itube*2)
6410              Xa=Xya(Itube*2+1)
6415              Yc=LOG(Xa)

```

```

6422      xc=LOG(Xa/Ya)
6425      Sx=Sx+xc
6430      Sy=Sy+Yc
6435      Sx2=Sx2+xc^2
6440      Sxy=Sxy+xc*Yc
6445      IF Int=0 THEN
6450          Xt=Ya
6455          Ya=Ya/Xa
6460          Xa=Xt
6465          IF Xa/1.E+6>Xul THEN Xul=Xa/1.E+6
6470          IF Xa/1.E+6<Xll THEN Xll=Xa/1.E+6
6475      END IF
6480      IF Int=0 THEN
6485          X=(Xa*1.E-6-Xmin)*Sfx
6490          Y=(Ya*1.E-3-Ymin)*Sfy
6495      END IF
6500      IF Int=1 THEN
6505          X=(Xa-Xmin)*Sfx
6510          Y=(Ya*1.E-6-Ymin)*Sfy
6515      END IF
6520      IF Int=2 THEN
6525          X=Xa/Ya-Xmin)*Sfx
6530          Y=(Ya*1.E-3-Ymin)*Sfy
6535      END IF
6540      IF Y>100 OR Y<0 THEN 6585
6545      IF Sym>3 THEN PRINT "SM"
6550      IF Sym<4 THEN PRINT "SR 1.4,2.4"
6555      PRINT "PA",X,Y,""
6560      IF Sym>3 THEN PRINT "SR 1.2,1.6"
6565      IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0:"
6570      IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6:"
6575      IF Sym=6 THEN PRINT "UC0,5,3,99,3,-8,-6,0,3,8:"
6580      IF Sym=7 THEN PRINT "UC0,-5,3,99,-3,8,6,0,-3,-8:"
6585  NEXT I
6590  BEEP
6595  INPUT "WANT TO LABEL (1=Y,0=N)?",I1b1
6600  IF I1b1=1 THEN
6605      IF Sym>3 THEN PRINT "SM"
6610      IF Sym<4 THEN PRINT "SR 1.4,2.4"
6615      PRINT "PA",Xal,Yal,""
6620      IF Sym>3 THEN PRINT "SR 1.2,1.6"
6625      IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0:"
6630      IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6:"
6635      IF Sym=6 THEN PRINT "UC0,5,3,99,3,-8,-6,0,3,8:"
6640      IF Sym=7 THEN PRINT "UC0,-5,3,99,-3,8,6,0,-3,-8:"
6645      PRINT "SM"
6650      IF Sym<4 THEN PRINT "PR 2,0"
6655      PRINT "PR 2,-1.0:SR 1.0,1.8:LB":D_files:""
6660      Yal=Yal-5
6665      BEEP
6675      IF Ias=1 THEN
6680          BEEP
6685          INPUT "ENTER THE STRING",Labels$
6690          PRINT "PR 2,0:SR 1.0,1.8:LB":Labels:""
6695          GOTO 6665
6700      END IF
6705  END IF
6710  BEEP
6715  INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,0=N)",Icomb

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6720 ASSIGN @File TO *
6725 x11=5
6730 xul=45
6735 IF Icomb<>0 THEN 6220
6740 BEEP
6745 INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1=Y,0=N)",Ils
6750 IF Ils=1 THEN
6755 BEEP
6760 INPUT "SELECT EXPONENT: 0=COMPUTE, 1=0.75",Iexp
6765 BEEP
6770 INPUT "SELECT CURVE TYPE (0=SOLID,1=DASHED)",Ilt
6775 Ilt=Ilt+1
6780 PRINT "SM"
6785 IF Iexp=0 THEN
6790 Bb=(Nrun*Sxy-Sy*Sx)/(Nrun*Sx2-Sx^2)
6795 ELSE
6800 Bb=.75
6805 END IF
6810 Aa=(Sy-Bb*Sx)/Nrun
6815 Aa=EXP(Aa)
6820 PRINTER IS 1
6825 PRINT USING "10X,""a = ",Z.4DE":Aa
6830 PRINT USING "10X,""n = ",Z.4DE":Bb
6835 PRINTER IS 705
6840 In=0
6845 IF Iht=0 THEN Xxstep=Xstep/40
6850 IF Iht>0 THEN Xxstep=Xstep/10
6855 FOR Xa=X11 TO Xul STEP Xxstep
6860 IF Xa>.99*Xmax THEN 6995
6865 IF Iht=1 THEN Ya=Aa*Xa^Bb
6870 IF Iht=0 THEN Ya=Aa^(1/Bb)*(Xa*1.E+5)^((Bb-1)/Bb)
6875 IF Iht=2 THEN Ya=Aa*Xa^(Bb-1)
6880 IF Iht=0 THEN
6885 Y=(Ya*1.E-3-Ymin)*Sfy
6890 X=(Xa-Xmin)*Sfx
6895 END IF
6900 IF Iht=1 THEN
6905 Y=(Ya*1.E-6-Ymin)*Sfy
6910 X=(Xa-Xmin)*Sfx
6915 END IF
6920 IF Iht=2 THEN
6925 Y=(Ya*1.E-3-Ymin)*Sfy
6930 X=(Xa-Xmin)*Sfx
6935 END IF
6940 IF Y<0 THEN Y=0
6945 IF Y>100 THEN 6990
6950 IF Ilt=1 THEN
6955 PRINT "PA",X,Y,"PD"
6960 ELSE
6965 In=In+1
6970 Ir=In MOD Ilt
6975 IF Ir=1 THEN PRINT "PA",X,Y,"PD"
6980 IF Ir=0 THEN PRINT "PA",X,Y,"PU"
6985 END IF
6990 NEXT Xa
6995 PRINT "PU"
7000 END IF
7005 Icomb=0
7010 GOTO 6185

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7015 END IF
7020 PRINT "PU SM"
7025 BEEP
7030 INPUT "WANT TO PLOT NUSSELT LINE (1=Y,0=N)?".Inp
7035 IF Inp=0 THEN 7125
7040 BEEP
7045 INPUT "ENTER TSAT (DEFAULT=18 DEG C)".Tsats
7050 Hfg=FNHfg(Tsats)
7055 X11=5
7060 Xul=45
7065 FOR Xa=X11 TO Xul STEP Xstep/50
7070   Tfilm=Tsats-Xa*.5
7075   Kf=FNK(Tfilm)
7080   Rhof=FNRRho(Tfilm)
7085   Muf=FNMu(Tfilm)
7090   Ya=.728*(Kf^3*Rhof^2*9.81+Hfg/(Muf*Do*Xa))^-.25
7095   X=(Xa-Xmin)*Sfx
7100   Y=(Ya*1.E-3-Ymin)*Sfy
7105   PRINT "PA",X,Y,"PD"
7110 NEXT Xa
7115 PRINT "PU PA 0,0"
7120 PRINT "PU PA 0,0 SP0"
7125 SUBEND
7130 SUB Plot3
7135 COM /Dri/ Star,Sym,Icon
7140 COM /Fid/ Ift
7145 DIM C(9)
7150 Fu=1
7155 PRINTER IS 1
7160 BEEP
7165 PRINT USING "4X,""Select Option X-Y Limits ""
7170 PRINT USING "6X,""0 Use default values""
7175 PRINT USING "6X,""1 Use new values""
7180 INPUT Okd
7185 PRINTER IS 705
7190 IF Okd=0 THEN
7195   Xmin=0
7200   Ymin=0
7205   Xmax=15
7210   Ymax=15
7215   Xstep=3
7220   Ystep=3
7225 ELSE
7230   BEEP
7235   INPUT "ENTER MINIMUM AND MAXIMUM X-VALUES",Xmin,Xmax
7240   BEEP
7245   INPUT "ENTER MINIMUM AND MAXIMUM Y-VALUES",Ymin,Ymax
7250   BEEP
7255   INPUT "ENTER STEP SIZE FOR X-AXIS",Xstep
7260   BEEP
7265   INPUT "ENTER STEP SIZE FOR Y-AXIS",Ystep
7270 END IF
7275 BEEP
7280 PRINT "IN:SP1:IP 2300,1800,8300,6800:"
7285 PRINT "SC 0,100,0,100:TL 2,0:"
7290 Sfx=100/(Xmax-Xmin)
7295 Sfy=100/(Ymax-Ymin)
7300 BEEP
7305 Icg=0

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7310 INPUT "LIKE TO BY-PASS CAGE (1=Y,0=N=DEFAULT)?",Icg
7311 IF Icg=1 THEN 7520
7320 PRINT "PU 0,0 PD"
7330 FOR xa=xmin TO xmax STEP xstep
7335 PRINT "PA 0,0,0,0,XT"
7340 NEXT xa
7345 PRINT "PA 100,0,0,0,PT"
7350 PRINT "PU PA 0,0 PD"
7355 FOR ya=ymin TO ymax STEP ystep
7360 ya=ya-ymin+Sfy
7365 PRINT "PA 0,0,y,XT"
7370 NEXT ya
7375 PRINT "PA 0,100,TL 0,2"
7380 FOR xa=xmin TO xmax STEP xstep
7385 xa=xa-xmin+Sfx
7390 PRINT "PA 0,x,0,100,XT"
7395 NEXT xa
7400 PRINT "PA 100,100 PU PA 100,0 PD"
7405 FOR ya=ymin TO ymax STEP ystep
7410 ya=ya-ymin+Sfy
7415 PRINT "PD PA 100,0,y,PT"
7420 NEXT ya
7425 PRINT "PA 100,100 PU"
7430 PRINT "PA 0,0 SF 1.5,2"
7435 FOR xa=xmin TO xmax STEP xstep
7440 xa=xa-xmin+Sfx
7445 PRINT "PA 0,x,0,0"
7450 IF xa=1 AND xa>0 THEN PRINT "CP -1.5,-1,LB0,PR -1,0,LE",xa,""
7455 IF xa=0 THEN PRINT "CP -1.5,-1,LB0"
7460 xin=0
7465 IF xa MOD 1=0 THEN xin=1
7470 IF xa=10 THEN PRINT "CP -2,-1,LB",xa,""
7475 IF xa=1 AND xa=10 AND xin=1 THEN PRINT "CP -1.25,-1,LE",xa,""
7480 IF xa=1 AND xin=0 THEN PRINT "CP -2,-1,LE",xa,""
7485 IF xa=1 THEN PRINT "CP -1,-1,LB1,0"
7490 NEXT xa
7495 PRINT "PU PA 0,0"
7500 iht=0 MOD 10
7505 FOR ya=ymin TO ymax STEP ystep
7510 ya=ya-ymin+Sfy
7515 PRINT "PA 0,0,y,PT"
7520 IF iht=0 AND ya=0 THEN PRINT "PF 2,0"
7525 IF ya=1 AND ya=0 THEN PRINT "CP -4,-.25,LB0,PR -2,0,LE",ya,""
7530 IF ya=0 THEN PRINT "CP -2,-.25,LB0"
7535 IF ya=1 AND iht=2 THEN PRINT "CP -5,-.25,LE",ya,""
7540 IF ya=9 AND iht=2 THEN PRINT "CP -4,-.25,LE",ya,""
7545 IF ya=0 AND ya=10 AND iht=2 THEN PRINT "CP -3,-.25,LE",ya,""
7550 IF ya=1 THEN PRINT "CP -4,-.25,LE1,0"
7555 NEXT ya
7560 IF Old=0 THEN
7565 xlabels="X"
7570 ylabels="Y"
7575 ELSE
7580 BEEP
7585 INPUT "ENTER X-LABEL",xlabels
7590 BEEP
7595 INPUT "ENTER Y-LABEL",ylabels
7600 END IF
7605 PRINT "SF 1.5,2 PU PA 50,-10 CP",-LEN(xlabels)/2,"0,LE",xlabels,""

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7810 PRINT "PA -11.50 CP 0.1 (-LEN Ylabel$) C*516."DI 0.1,1,1B":Ylabel$.
7815 PRINT "CP 0.0 DI"
7820 Nrun=0
7825 BEEP
7830 INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Ok
7835 Ok=0
7840 IF Ok=1 THEN
7845 BEEP
7850 INPUT "ENTER THE NAME OF THE PLOT DATA FILE",C_file$
7855 ASSIGN @File TO D_file$
7860 IF ICOMB=0 THEN GOTO 7865
7865 Sx=0
7870 Sy=0
7875 Sx2=0
7880 Sxy=0
7885 Md=1
7890 BEEP
7895 INPUT "ENTER THE BEGINNING RUN NUMBER (DEF=1)",Md
7900 Npairs=9
7905 BEEP
7910 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED (DEF=9)",Npairs
7915 BEEP
7920 INPUT "SELECT TUBE NUMBER (0=TOP,1=SECOND,...)",Itube
7925 Nrun=Nrun+Npairs
7930 PRINTER IS 1
7935 BEEP
7940 PRINT USING "4X,""Select a symbol:""
7945 PRINT USING "4X,"" 1 Star 2 Plus sign""
7950 PRINT USING "4X,"" 3 Circle 4 Square""
7955 PRINT USING "4X,"" 5 Rhombus""
7960 PRINT USING "4X,"" 6 Right-side-up triangle""
7965 PRINT USING "4X,"" 7 Up-side-down triangle""
7970 INPUT Sym
7975 PRINTER IS 705
7980 IF Sym=1 THEN PRINT "SM+"
7985 IF Sym=2 THEN PRINT "SM+"
7990 IF Sym=3 THEN PRINT "SMo"
7995 Md=Itube+5
8000 IF Md=1 THEN
8005 FOR I=0 TO (Md-1)
8010 ENTER @File,Xa,Ya
8015 NEXT I
8020 END IF
8025 FOR I=1 TO Npairs
8030 ENTER @File,Xa,Ya
8035 Sx=Sx+Xa
8040 Sy=Sy+Ya
8045 Sx2=Sx2+Xa^2
8050 Sxy=Sxy+Xa*Ya
8055 X=(Xa-Xmin)*Sfx
8060 Y=(Ya-Ymin)*Sfy
8065 IF Y>100 OR Y<0 THEN GOTO 7910
8070 IF Sym>3 THEN PRINT "SM"
8075 IF Sym<4 THEN PRINT "SR 1.4,2.4"
8080 PRINT "PA",X,Y,""
8085 IF Sym>3 THEN PRINT "SR 1.2,1.6"
8090 IF Sym=4 THEN PRINT "UC2,4,99.0,-8,-4.0,0.8,4.0:"
8095 IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3.6,3.6,3,-6."
8100 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-5.0,3.8."

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7905         IF Sym=7 THEN PRINT "UC0,-5.3,99,-3.8,6.0,-3,-8;"
7910     NEXT I
7915     BEEP
7920     INPUT "WANT TO LABEL (1=Y,0=N)?",I1b1
7925     IF I1b1=1 THEN
7930         IF Sym>3 THEN PRINT "SM"
7935         IF Sym<4 THEN PRINT "SR 1.4,2.4"
7940         PRINT "PA",Xal,Yal,""
7945         IF Sym>3 THEN PRINT "SR 1.2,1.6"
7950         IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4.0,0.8,4.0;"
7955         IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-2.6,3.6,3,-6;"
7960         IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6.0,3.8;"
7965         IF Sym=7 THEN PRINT "UC0,-5.3,99,-3.8,6.0,-3,-8;"
7970         PRINT "SM"
7975         IF Sym<4 THEN PRINT "PR 2,0"
7980         PRINT "PR 2,-1.0,SR 1.0,1.8;LB";D_files;"
7985         Yal=Yal-5
7995         INPUT "WANT TO ADD ANOTHER STRING (1=Y,0=N)?",Ias
8000         IF Ias=1 THEN
8005             BEEP
8010             INPUT "ENTER THE STRING",Labels$
8015             PRINT "PR 2,0,SR 1.0,1.8;LB",Labels$,""
8020             GOTO 7990
8025         END IF
8030     END IF
8035     BEEP
8040     INPUT "WANT TO COMBINE ANOTHER FILE? (1=Y,0=N)",Icomb
8045     ASSIGN @File TO *
8050     IF Icomb=0 THEN 7645
8055     I1s=1
8060     BEEP
8065     INPUT "WANT TO PLOT A LEAST-SQUARES LINE (1=DEF=YES,0=NO)",I1s
8070     IF I1s=1 THEN
8075         BEEP
8080         INPUT "SELECT CURVE TYPE (0=SOLID,1=DASHED)",I1t
8085         I1t=I1t+1
8090         PRINT "SM"
8095         IF Iexp=0 THEN
8100             Bb=(Nrun*Sxy-Sy*Sx)/(Nrun*Sx2-Sx^2)
8105         ELSE
8110             Bb=.75
8115         END IF
8120         Aa=(Sy-Bb*Sx)/Nrun
8125         PRINTER IS 1
8130         PRINT USING "10X,""a = ",M2.3DE,Aa
8135         PRINT USING "10X,""b = ",M2.3DE,Bb
8140         PRINTER IS 705
8145         In=0
8150         FOR Xa=Xmin TO xmax STEP (Xmax-Xmin)
8155             Ya=Aa+Xa*Bb
8160             Y=(Ya-Ymin)*Sfy
8165             X=(Xa-Xmin)*Sfx
8170             IF Y<0 THEN Y=0
8175             IF Y>100 THEN GOTO 8220
8180             IF I1t=1 THEN
8185                 PRINT "PA",X,Y,"PD"
8190             ELSE
8195                 In=In+1
8200                 Ir=In MOD I1t
8205                 IF Ir=1 THEN PRINT "PA",X,Y,"PD"

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8210             IF Ir=0 THEN PRINT "PA",X,Y,"PU"
8215             END IF
8220             NEXT Xa
8225             PRINT "PU"
8230             END IF
8235             Icomb=0
8240             GOTO 7620
8245             END IF
8250             PRINT "PU PA 0,0"
8255             PRINT "PU PA 0,0 SP0"
8260             SUBEND

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