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THESIS

**NUCLEATE BOILING CHARACTERISTICS OF R-113
IN A SMALL ENHANCED TUBE BUNDLE**

by

Scott V. Chilman

September 1991

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**Nucleate Boiling Characteristics of R-113
in a Small Enhanced Tube Bundle**

by

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Lieutenant, United States Navy
B.S.M.E.T., California Maritime Academy, 1983**

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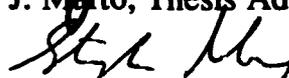


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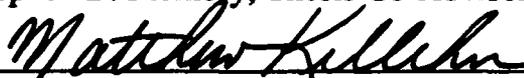
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ABSTRACT

Heat transfer tests were carried out using a small enhanced tube bundle in a pool of R-113. By accurately instrumenting five tubes within the bundle, both the convective and nucleate boiling regions were studied in detail, with emphasis on the 'bundle' effect (i.e. the effect of lower tubes in operation on upper tubes within the bundle). In addition, the effect of surface history and pool height on nucleation site activation/deactivation was studied to see how this affects the overall heat transfer and in particular, the shape of the hysteresis loop. From the results, recommendations can be made to improve start-up procedures on shipboard AC systems.

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NOMENCLATURE

<u>SYMBOL</u>	<u>UNITS</u>	<u>NAME/DESCRIPTION</u>
A _{as}	V	Voltage output from current sensor
A _c	m ²	Tube-wall cross sectional area
A _s	m ²	Area of heated surface
C _p	J/kg K	Specific heat
D _i	m	Inside tube diameter
D _o	m	Outside tube diameter
D _{tc}	m	Thermocouple location diameter
f _{pi}		Fins per inch
g	m/s ²	Gravitational acceleration
h	W/m ² K	Heat transfer coefficient of enhanced tube surface
h _b	W/m ² K	Heat transfer coefficient of tubes unheated ends
ht	m	Height of liquid column above a instrumented tube
k	W/m K	Thermal conductivity of refrigerant
k _{cu}	W/m K	Thermal conductivity of copper
L	m	Heated length of the tube
L _u	m	Unheated length of the tube
L _c	m	Corrected unheated length of the tube
n	1/m	Parameter in calculation of q _f
Pr		Prandtl number
p	m	Perimeter of the tube outside surface
ΔP	Pa	Hydrostatic pressure difference between tube and liquid free surface

q	W	Heat transfer rate
q''	W/m ²	Heat flux
q_f	W	Heat transfer rate from unheated smooth tube ends
t	m	Thickness of the tube wall
T	C	Temperature
T_{film}	C	$(T_{\text{sat}_c} + \bar{T}_{\text{wo}}) / 2$, Film temperature
T_{filmK}	K	Film thermodynamic temperature
T_{ld1}	C	Liquid temperature reading from T(3)
T_{ld2}	C	Liquid temperature reading from T(4)
T_{sat}	C	Saturation temperature
T_{sat_c}	C	Corrected saturation temperature due to hydrostatic pressure difference
\bar{T}_{wi}	C	Average inside wall temperature
$\bar{T}_{\text{wi-K}}$	K	Average inside wall thermodynamic temperature
\bar{T}_{wo}	C	Average outside wall temperature
V_{as}	V	Voltage output from voltage sensor
α	m ² /s	Thermal diffusivity
β	1/K	Thermal expansion coefficient
μ	kg/m s	Dynamic viscosity of liquid
ν	m ² /s	Kinematic viscosity of liquid
ρ	kg/m ³	Density of liquid
Φ	C	Fourier conduction term
θ_b	C	$\bar{T}_{\text{wo}} - T_{\text{sat}_c}$, Wall Superheat

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I. INTRODUCTION

A. BACKGROUND

In September 1987, due to the pressing environmental issues of ozone depletion and global warming, an international conference was held in Montreal, Canada. This conference was viewed by many as a major step toward correcting the critical environmental problems facing the world today. Specifically, one of the problems addressed was chemical products damaging the protective bubble we live in. This bubble or thin layer is known as the ozone layer, and is what makes the earth's atmosphere habitable and hence unique from any other known planet. Without this protective layer, the earth's climate would not support life as we know it today. Protecting this ozone layer from chemical destruction is paramount.

A group of chemicals that deplete the ozone layer is chlorofluorocarbons (CFCs). CFCs are manmade chemicals of chlorine, fluorine and carbon and were developed almost 60 years ago by General Motors. They are unique in that they have a combination of desirable properties not often found in chemistry; low in toxicity, non-flammable, non-corrosive, non-explosive, extremely stable and compatible with many other materials. However, it is this extreme stability which causes problems to the ozone layer, because they only break down in the upper atmosphere (stratosphere) when subjected to intense ultraviolet radiation. This breakdown produces chlorine which has been linked to the depletion of the earth's protective ozone layer. A chlorine atom destroys an ozone molecule (O_3) by reacting with it and converting it to an ordinary oxygen molecule (O_2) and carbon monoxide. More disturbing is the fact that the chlorine atom survives the ozone-destroying reaction and is free to repeat the process - one CFC molecule being able to destroy 100,000

ozone molecules. Unfortunately, a typical chlorine molecule can survive for up to 100 years, so a major problem does exist.

Armed with these facts, 24 nations (representing the United Nations Environment Program (UNEP)) met and signed the Montreal Protocol in 1987. They discussed substances that deplete the ozone layer [Ref. 1] and called for a near-term freeze on the production and consumption of these substances. To be more specific, it required production of these chemicals to be cut back to 1986 levels followed by a two-phased reduction culminating in cutbacks of 50% by mid-1998; this came into effect on July 1, 1989. In 1990, a progress meeting was held in London where UNEP delegates agreed to completely phase out all CFCs by the year 2000 [Ref. 2]. This was a needed, but worrisome change for the U.S. Navy as they use a number of different CFCs for various refrigeration and solvent/cleaning needs. One such need is the approximately 1850 shipboard air conditioning (AC) plants presently using CFC-12 (in reciprocating compressor plants) and R-114 (in centrifugal compressor plants). These AC plants not only provide personal comfort, but cool vital electronic components, weapons systems and other auxiliary equipment.

To comply with the Montreal Protocol and U.S. legislation, the Mechanical Systems Branch/(Code 2722) at David Taylor Research Center (DTRC) is pursuing research aimed at eliminating shipboard use of CFCs. As mentioned by Krinsky and Noel [Ref. 3] this research is to be completed in three phases:

1. In the short term, to identify suitable alternative ozone-safe chemicals to directly replace CFC-12 and CFC-114. In order to do this, the heat transfer characteristics must be similar to the existing refrigerants in place and hence the need for a database exists for current refrigerants (i.e. R-114, R-12, R-113) so that they can be compared to the new proposed refrigerants.

2. In the longer term, to research, develop and test substitute chemicals and alternative technologies to replace existing CFC uses.

3. To implement new cooling system technologies into the Fleet which do not depend on CFCs or their replacements. One such technology under investigation at the Naval Postgraduate School is thermoacoustic refrigeration, which uses sound waves to compress and expand harmless gas molecules (such as helium) inside a tube.

The purpose of this thesis is to supplement DTRC's research on alternatives to CFCs by establishing baseline nucleate pool boiling data of R-113 from a small bundle of enhanced tubes representing a section of a flooded evaporator . Emphasis is placed on surface history affecting activation/deactivation of nucleation sites, hysteresis, and the affect of varying evaporator pool height. The data obtained are expected to serve as reference data for comparison with future proposed refrigerants from bundles of both smooth and enhanced tube surfaces. It is felt that what is learned from this thesis about the characteristics of R-113 can be applied to any general refrigerant and can help the Navy design future AC systems using alternative chemicals.

B . OBJECTIVES

The objectives of this thesis are as follows:

1. Understand in greater detail both the convection and nucleate pool boiling phenomena and hysteresis effects within a small enhanced tube bundle.

2. Vary the evaporator pool height above the tube bundle to see how this effects nucleation site activation and general evaporator performance.

3. Investigate the effect of surface history on nucleation site activation/deactivation.

4. Compare data with similar studies (i.e. same fluid or tube) done at the Naval Postgraduate School.

II. LITERATURE SURVEY

A. GENERAL INTRODUCTION

Due to the desirability of operating many engineering devices in the nucleate boiling region, many types of enhanced tubes are being studied. Nishikawa et al. [Ref. 4] noted that there are two primary ways to increase the heat transfer performance of a boiling tube. The first was to decrease the wettability of the fluid in which you are immersed. They suggested using a Teflon coating on the boiling surface. However, this is not very effective for refrigerants as they are very highly wetting on any surface and fill the cavities of the Teflon surface. The second way proposed was to manufacture a tube with many re-entrant cavities, thereby trapping the vapor and keeping the nucleation sites active. These re-entrant cavities are designed such that if one site is activated, neighboring sites will soon follow and cause the entire tube to nucleate almost instantaneously due to the interconnecting passageways. There are now many such tubes with re-entrant cavities on the market.

The two main types of reboilers analyzed today are kettle reboilers and full bundle boilers. The difference is described in detail in Payvar [Ref. 5]. To summarize, in the kettle type reboiler the tube bundle only occupies the middle lower portion of the evaporator leaving large areas on the sides of the bundle for fluid circulation. The full bundle boilers occupy the whole cross section of the lower half of the evaporator shell. As can be reasoned from these definitions, circulation patterns are very different for the two types of boilers.

The following is a brief summary of the work done on the bundle apparatus at the Naval Postgraduate School:

1. T.J. Murphy, September 1987 [Ref. 6]
 - Designed System
 - Conducted Preliminary Operation
2. C.L. Anderson, June 1989 [Ref. 7]
 - Tested Smooth Tubes, R-113
 - Tested Smooth Tubes, R-114/Oil
 - Tested Finned Tubes (19 fpi), R-114/Oil
3. N. Akcasayar, December 1989 [Ref. 8]
 - Tested Finned Tubes (19 fpi), R-114/Oil
 - Tested High Flux Tubes, R-114/Oil
4. H. Eraydin, December 1990 [Ref. 9]
 - Tested High Flux Tubes, R-114/Oil
 - Tested Turbo-B Tubes, R-114/Oil

B. EXPERIMENTAL AND THEORETICAL STUDIES

In the literature survey, no papers were found on the Turbo-B tube operating in a bundle or how surface history affects Turbo-B nucleation site activation/deactivation. In addition, no information was found on varying the pool height above the bundle to see how this affects nucleation site activation and general evaporator performance. These areas could be very important to the U.S. Navy as well as to industry and could cause the startup procedure of refrigeration units to be altered, thus emphasizing the need for the objectives of this thesis.

In the past decade, there have been significant improvements made to tube surfaces and in understanding the natural convection and nucleate boiling regions for a single tube apparatus and several correlations have been adapted. However, the tube bundle opens a new arena of topics.

Yilmaz and Westwater [Ref. 10] studied the effect of velocity past a smooth tube and how it effects the heat transfer performance. They used a 6.5 mm diameter tube in R-113. They found that with an increase in velocity, the heat transfer performance of the tube was better.

Cornwell and Schuller [Ref.11] stated that the increases in heat transfer coefficient found by Yilmaz and Westwater could not entirely be explained by the increase in velocity past the tube. Therefore, they decided to conduct a photographic study of boiling R-113 in a bundle at one atmosphere. Their study used 241 electrically heated tubes, 19.1 mm in diameter and arranged in a square in-line pitch of 25.4 mm, giving a pitch-to-diameter ratio of 1.33. They found that the bubbles leaving the lower tubes in the bundle impacted and caused a sliding motion around the upper tubes. Cornwell and Schuller attribute the increase in the upper tubes heat transfer performance on this impact and sliding motion of bubbles from lower tubes. Cornwell and Schuller also showed that the heat transfer coefficient was the highest for the top tube in the bundle and decreased as one moved down the bundle; the difference was as much as four times. Cornwell [Ref. 12] later found that in the nucleate boiling region, sliding bubbles and liquid forced convection could account for all the heat transfer in the top of the bundle.

Chan and Shoukri [Ref. 13] studied the boiling characteristics of a small enhanced multitube bundle in a pool of R-113. The rectangular bundle had a vertical pitch of 23.8 mm and a horizontal pitch of 31.75 mm. From there studies, they concluded that the convective contribution is highest for tubes near the top of the bundle due to the increased quality and fluid velocity across these tubes. They also noted at lower heat fluxes, the convective effects dominate whilst for higher heat fluxes, the primary mode of heat transfer was nucleate boiling. At high heat fluxes there are numerous active nucleation sites and a high bubble generation rate which decreased the influence of rising bubbles generated from

tubes below. They also found that the convective effect from a boiling tube below an upper tube in a bundle has less of an effect as it gets farther from the tube of interest.

A study by Bergles et al. [Ref. 14] showed that if a tube is on the verge of nucleation, it burst into nucleation if tapped. This test was repeated many times with the same results. Several other experimenters using different tubes, refrigerants, and bundle arrangements, have also shown the influence of tube position on heat transfer performance in the bundle. Wallner [Ref. 15] used a smooth tube bundle with both square and triangular geometric arrangements giving pitch-to-diameter ratios of 1.33 to 1.5 respectively. He found a 50 percent increase in the heat transfer coefficient over a single tube for tubes near the top of the bundle.

Fujita et al. [Ref. 16] used both smooth and enhanced tubes to study the effects of tube position, distribution of heat flux, and system pressure changes (0.1 to 1 MPa) within the bundle. They used a triangular tube arrangement with R-113. In these tests, they reported similar results as above with higher tubes giving improved performance. The enhancement in heat transfer again was believed to be caused by bubbles generated from the tubes below.

Webb et al. [Ref. 17] pointed out that in air conditioning applications, the refrigerant typically enters the bundle with a 15 percent quality. With this entering quality into the bundle, it simulates the effect of lower tubes activated in the bundle and thus will improve the performance of the entire bundle. Furthermore, the boiling mechanism for a flooded evaporator is very different from the kettle type evaporator and therefore it is very hard to formulate and evaluate a theoretical model for a bundle.

Leong and Cornwell [Ref. 18] looked at the same representative slice of a flooded evaporator that Cornwell and Schuller [Ref. 11] and Cornwell [Ref. 12] studied. They

concluded that the heat transfer coefficients were the highest at the top of the bundle and decreased in performance as you went down the bundle.

Based on the above-mentioned studies, all experimenters seem in agreement, independent of the fluid or tube used in the bundle, that the presence of boiling lower tubes causes a convective flow in the evaporator that gives rise to an increase in the heat transfer coefficient on the upper tubes.

III. EXPERIMENTAL APPARATUS

A. TEST APPARATUS OVERVIEW

The whole experimental apparatus including the auxiliary equipment and the evaporator/condenser test apparatus used during this investigation is shown in Figure 1. The following is only a general description of the whole experimental apparatus. A more detailed look at the condenser and evaporator is provided in Section D. Further information about the apparatus is provided by Murphy [Ref. 6] and Anderson [Ref. 7].

Looking at Figure 1, the apparatus uses three closed loops. The first loop consists of an 8 ton refrigeration unit located outside the laboratory which is used to cool an ethylene glycol/water mixture. The second loop is the ethylene glycol/water mixture flowing through the condenser. This flow rate through the condenser was delivered by two pumps which could be operated independently or together; this coolant mixture condenses the refrigerant vapor in the condenser and maintains system pressure. Pump number one provided coolant flow through the four test tubes as well as to one of the auxiliary coils. Pump number two provided coolant through a manifold which distributed the coolant to the remaining four coils in the condenser. The third loop is the evaporator/condenser itself. The vapor generated in the evaporator flowed upward and condensed in the condenser which then returned the condensate to the evaporator via gravity.

B. AUXILIARY EQUIPMENT

1. 8 Ton Refrigeration Unit

This unit was used to cool the ethylene glycol/water mixture (coolant) to the desired temperature needed to condense the refrigerant vapor. For the present pool boiling experiments, the temperature control was set to maintain the sump at 5°C. This

refrigeration unit had a cooling capacity of 28 kW (8 tons) with a 30 gpm pump providing circulation of the coolant to achieve the set temperature. To prevent damage of the unit, several safety features were provided: low temperature cutout, high pressure cutout, low flow cutout, and a hot gas bypass which allowed for continuous operation. For operation procedures, see Appendix E.

2. Ethylene Glycol/Water Mixture

The coolant used was a 54% by weight ethylene glycol/water mixture. This was used to control the system pressure by circulating it through the condenser.

3. Pumps

There were two pumps available to circulate the coolant from the sump through the condenser. Pump number one fed four test tubes and one of the secondary condenser coils. Pump number two was used to feed the other four secondary condenser coils. Pump number one provided enough cooling for tests up to five evaporator tubes. However, during bundle and simulation evaporator operation, both pumps were needed at heat fluxes above approximately 60,000 W/m².

4. Flowmeters

Four calibrated float-type flowmeters, connected to pump number one, were used to measure the flowrate passing through the four test condenser tubes. One additional flowmeter which was connected to pump number two was used to measure the total flow to the secondary condenser coils. In addition, each of the four secondary condenser coils had a globe valve to further regulate (or shut off) flow as desired. In the test tubes, the flow was regulated by a ball valve.

C. DATA ACQUISITION SYSTEM/INSTRUMENTATION

As described by Akcasayar [Ref. 8], a Hewlett Packard HP-3497A Data Acquisition System, HP-9125 computer and HP-701 printer were used for data acquisition, data

reduction and data printing respectively. Although an HP-9826 computer and HP-7470A plotter can be used for final graph printing, a Macintosh Classic computer using CricketGraph 1.3.2 was utilized. HP Basic 3.01 was used for data reduction. At the beginning of every set of runs, the HP-9125 computer had to be initialized by using three system discs if the system was turned off. As described by Anderson [Ref. 7], type-T copper-constantan thermocouple measurements (mvolts) were made on the HP-3497A with the relay multiplexer assembly equipped with thermocouple compensation. A 20 channel relay multiplexer card was used to measure the voltage output from voltage and amperage sensors. Voltage measurements were taken from separate sensors that measured the voltage going to the tube bundle, simulation and auxiliary heaters. The total amperage going through the auxiliary and simulation heaters was measured using an American Aerospace Control (AAC) current sensor. The currents of each instrumented tube heater were measured using five identical current sensors. The voltage supplied to the other active tubes was also measured but the current of each active tube was not (the total current for a pair of active tubes was measured). This was felt to be sufficient since these tubes each had the same power output (1000 W) as the test tube heaters and there was no apparent reason to monitor each active tube heat flux individually.

Computer channel assignments for data acquisition and array assignments are given in Table 1.

D. EVAPORATOR/CONDENSER

An overall view of the evaporator/condenser is shown in Figure 2. The evaporator was designed to simulate a small portion of a refrigerant flooded evaporator. Front and side views of the evaporator are shown in Figures 3 and 4. It was fabricated from stainless steel plate and formed into a short cylinder 610 mm in diameter and 241 mm long. Electrically heated tubes were cantilever-mounted from the back wall of the evaporator to

permit viewing along the axis of the tubes through the lower of two glass/Plexiglass windows mounted in the front. The glass was used on the refrigerant side in order to prevent crazing or cracking of the Plexiglass and the Plexiglass gave the glass added strength. Figure 5 is a schematic sectional view of the evaporator that shows the four kinds of heated tubes used in this study. The four kinds of heater tubes were as follows: Instrumented, Active, Auxiliary, and Simulation. Table 2 gives the power rating for the heaters and the number used in the evaporator.

The electric power can be applied separately to each set of heaters using a STACO 240V, 23.5 KVA rheostat controller shown in Figure 6. Also, the desired number of instrumented tubes, active tubes, auxiliary, or simulation heaters can be turned on by using individual circuit breakers. The four auxiliary heaters, each with a maximum rating of 4 kW, were installed two on each side of the test bundle to maintain the liquid pool at saturated conditions and to provide system pressure control. The five simulation heaters, also capable of 4 kW each, were mounted below the test bundle in order to simulate additional tube rows in a larger bundle and to provide inlet vapor quality into the bottom of the test bundle as suggested by Webb [Ref. 17]. The auxiliary and simulation heaters had to be used with caution to avoid breakdown of the refrigerant.

The tube bundle consists of instrumented, active, and dummy tubes. The location of each tube is represented by the respective letter I, A, and D shown in Figure 5. The test bundle consisted of two types of heated tubes: active tubes (marked "A") which contained 1 kW cartridge heaters, and instrumented tubes (marked "I") which, in addition to the 1 kW cartridge heaters, contained six wall thermocouples. In measuring boiling heat-transfer coefficients, great care must be exercised with the cartridge heater and temperature measuring instrumentation to ensure good accuracy. For example, the type of heater used could have an affect on heat transfer. Bergles [Ref. 19] stated that the method of heating is

immaterial except for the case of a.c. resistance heating which may cause bubble generation in phase with the power supply. However, more recently, Jung and Bergles [Ref. 20] who carried out extensive pool boiling data with R-113, concluded that the heat transfer coefficient of a single tube in pool boiling is not sensitive to variations in the cartridge heater heat flux provided that enough thermocouples are used to measure an average wall temperature. Prior to this investigation, the instrumented test tubes were fabricated in a similar way to those used by Hahne and Muller [Ref. 21] and Wanniarachchi et al. [Ref. 22]. The exact procedure can be found in Eraydin [Ref. 9]. Figure 7 is a cross-sectional sketch of an instrumented tube used during this thesis, showing the construction details and the location of the wall thermocouples. The thermocouples were imbedded in the wall at different circumferential and longitudinal positions along the heated section of the tube. The instrumented tubes were located along the centerline of the tube bundle, forming a vertical in-line column. All the instrumented and active tubes were Turbo-B tubes made by Wolverine. These tubes were 14.15 mm in diameter and were arranged in an equilateral triangular pitch (i.e. centerline-to-centerline spacing) of 19.1 mm, giving a pitch-to-diameter ratio of 1.35. The bundle also contained a number of unheated dummy smooth tubes (marked "D") that were used to guide the two-phase mixture through the bundle. The dummy tubes were made from commercially available 15.9 mm in diameter smooth copper tubing. Two vertical baffle plates were made of aluminum to restrict circulation into and out of the bundle from the sides. A small open space approximately 5 mm in height was left between the bundle and the dummy tube rack. This space allowed some liquid to enter the bundle and replace the vapor being generated in the bundle. However, there was also a space below the dummy rack that provided the majority of the circulation. Thus, liquid/vapor circulation was vertically upward over the five instrumented test tubes with no net horizontal component. The dummy rack (Figure 8) used 12 tubes made of solid

aluminum rods each 15.9 mm in diameter and spaced 19 mm from centerline to centerline. This rack had a triangular pitch arrangement with vapor retaining plates on the side and was used for two purposes. This dummy rack was designed to collect all rising two-phase flow generated by the simulation heaters and direct it to the test section. The other purpose was to simulate the vapor passing through a larger bundle before reaching the instrumented tubes. The liquid-vapor mixture after passing through the bundle was separated when it reached the pool surface. The vapor flowed toward the condenser and the liquid was circulated back toward the bottom of the bundle.

The condenser included four test tubes (each 2 m in length) in a vertical in-line column and five auxiliary copper coils used to regulate the pressure in the system. It was designed to permit independent condensation studies of small in-line tube bundles, using the evaporator as a source of vapor. All these tubes and coils were cooled by a refrigerated mixture of water and ethylene glycol. Each of the test tubes and auxiliary coils could be operated separately using ball or globe valves respectively to regulate the desired flow rate. The vapor that was produced in the evaporator was guided up toward the top of the condenser by a vapor shroud as shown in Figure 9. The vapor was then directed down over the condenser tubes and coils where it condensed. Once condensed, the force of gravity returned the condensate back to the evaporator. Observation windows in both the condenser and the evaporator allowed for easy viewing of condensation and boiling.

E. GEOMETRY OF ENHANCED SURFACE USED

1. Turbo-B Tube

The Turbo-B tube, manufactured by Wolverine Tube Inc., has an enhanced surface geometry. The exterior boiling enhancement is made by raising integral low fins, cutting diagonally across these fins, and then rolling the fins to compress them to form mushroom-like pedestals [Ref. 23]. This process forms numerous re-entrant

passageways. Figure 10 shows the surface of the tube at 25 times its actual size. The tube is currently available in copper, cupro-nickel, and low carbon steel. The relative dimensions of the tube used in the present experiments are:

Tube material - Copper

Outside diameter = 14.15 mm

Inside diameter = 12.7 mm

Enhanced surface length = 203.2 mm

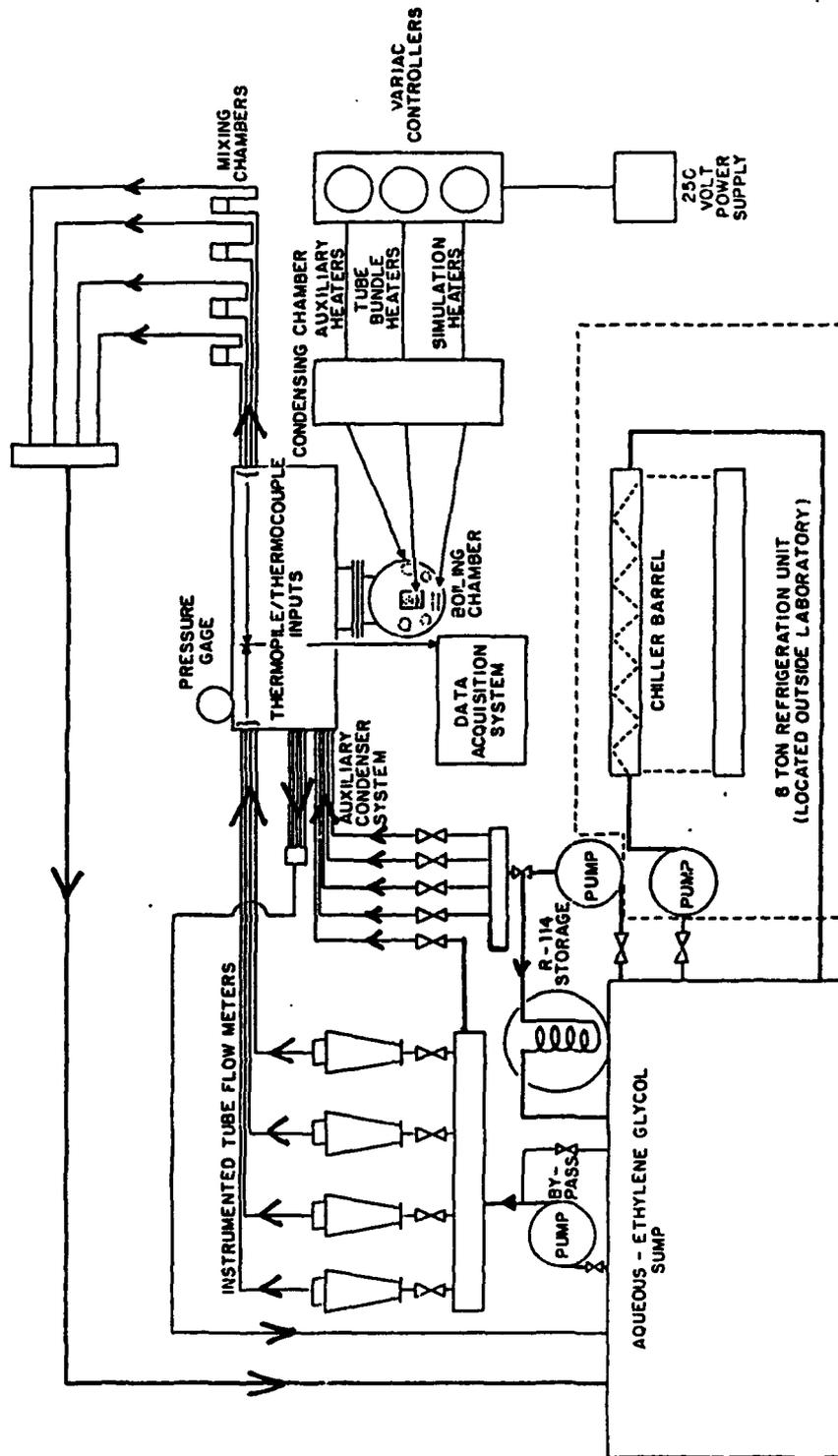


Figure 1. Schematic View of the Apparatus

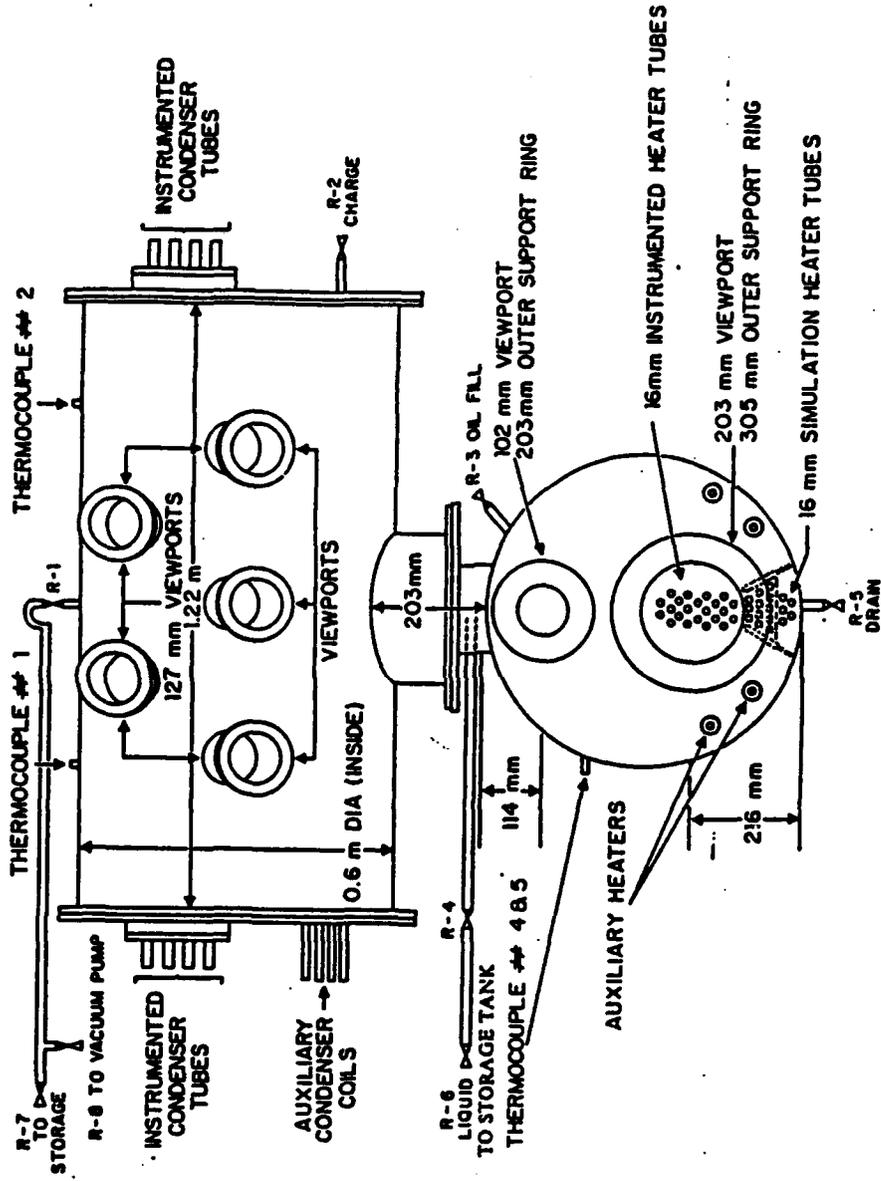


Figure 2. Evaporator/Condenser Schematic

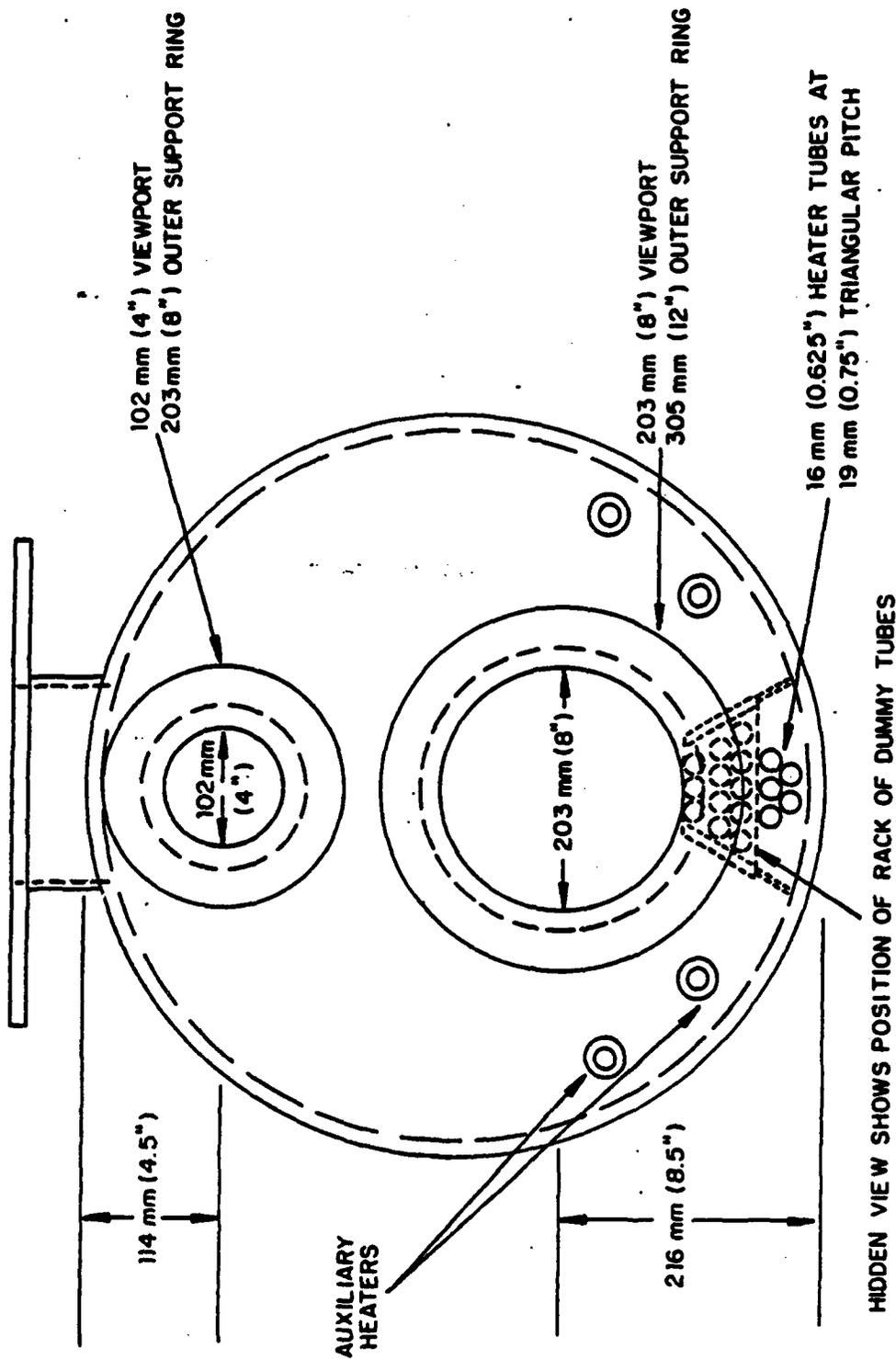


Figure 3. Front View of Evaporator

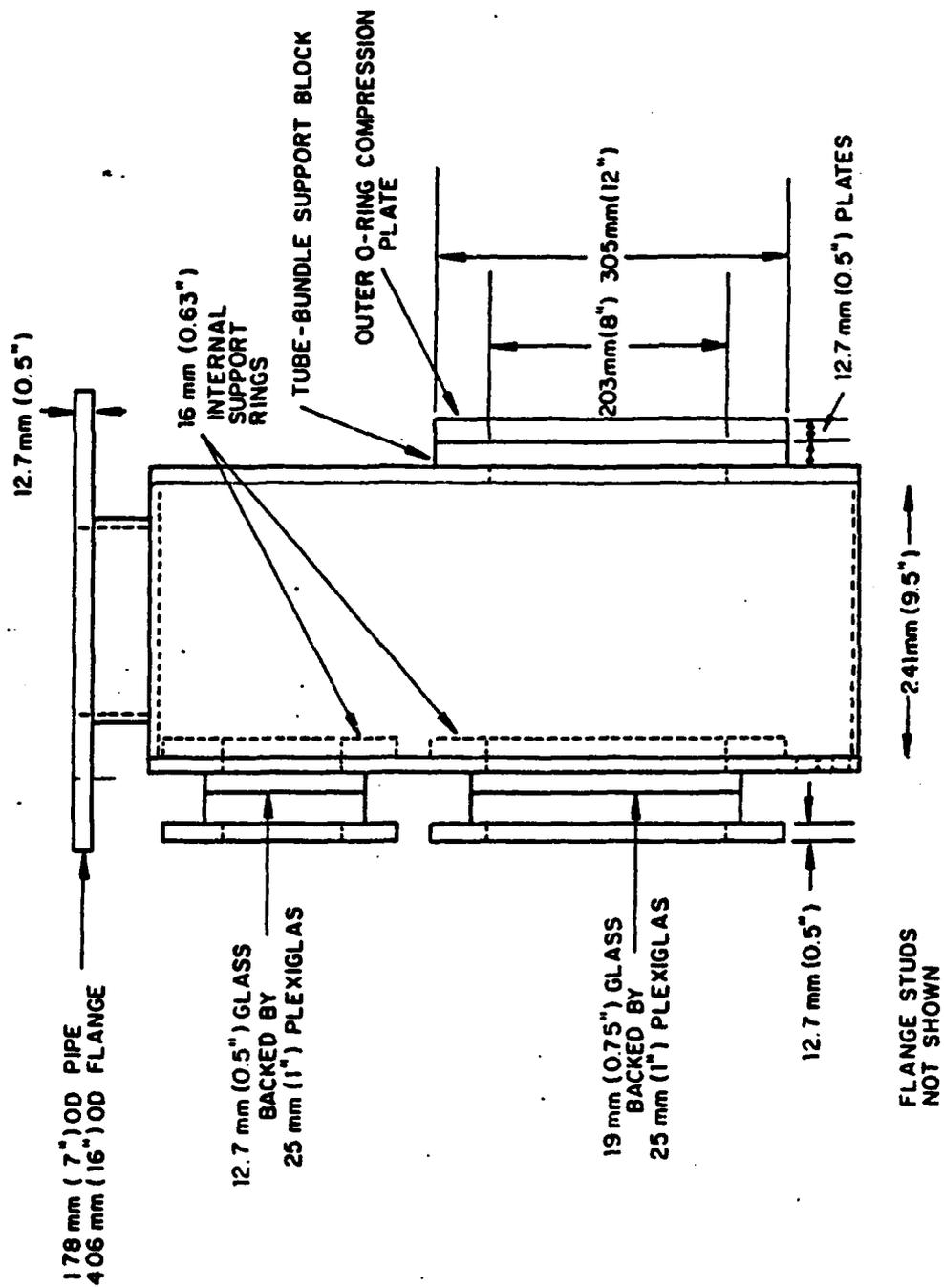


Figure 4. Side View of Evaporator

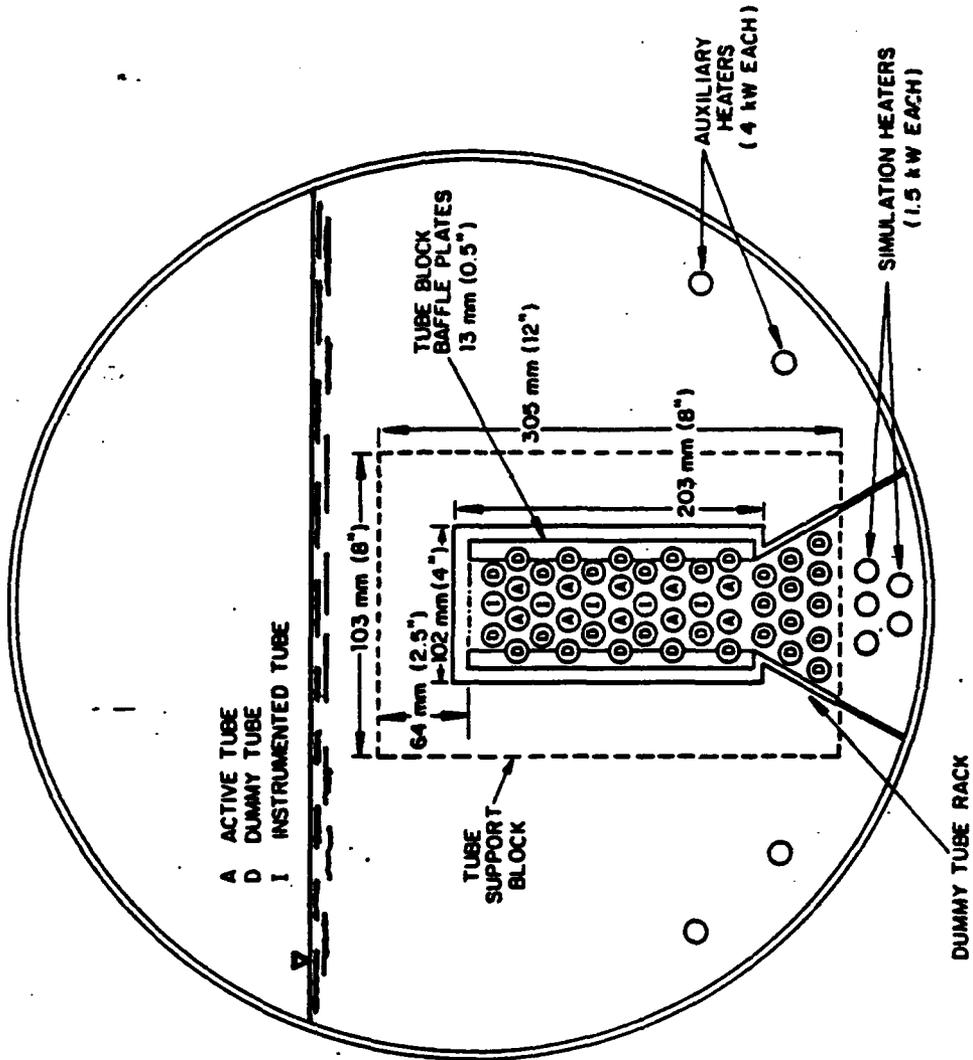


Figure 5. Sectional View of Evaporator Showing Tube Bundle

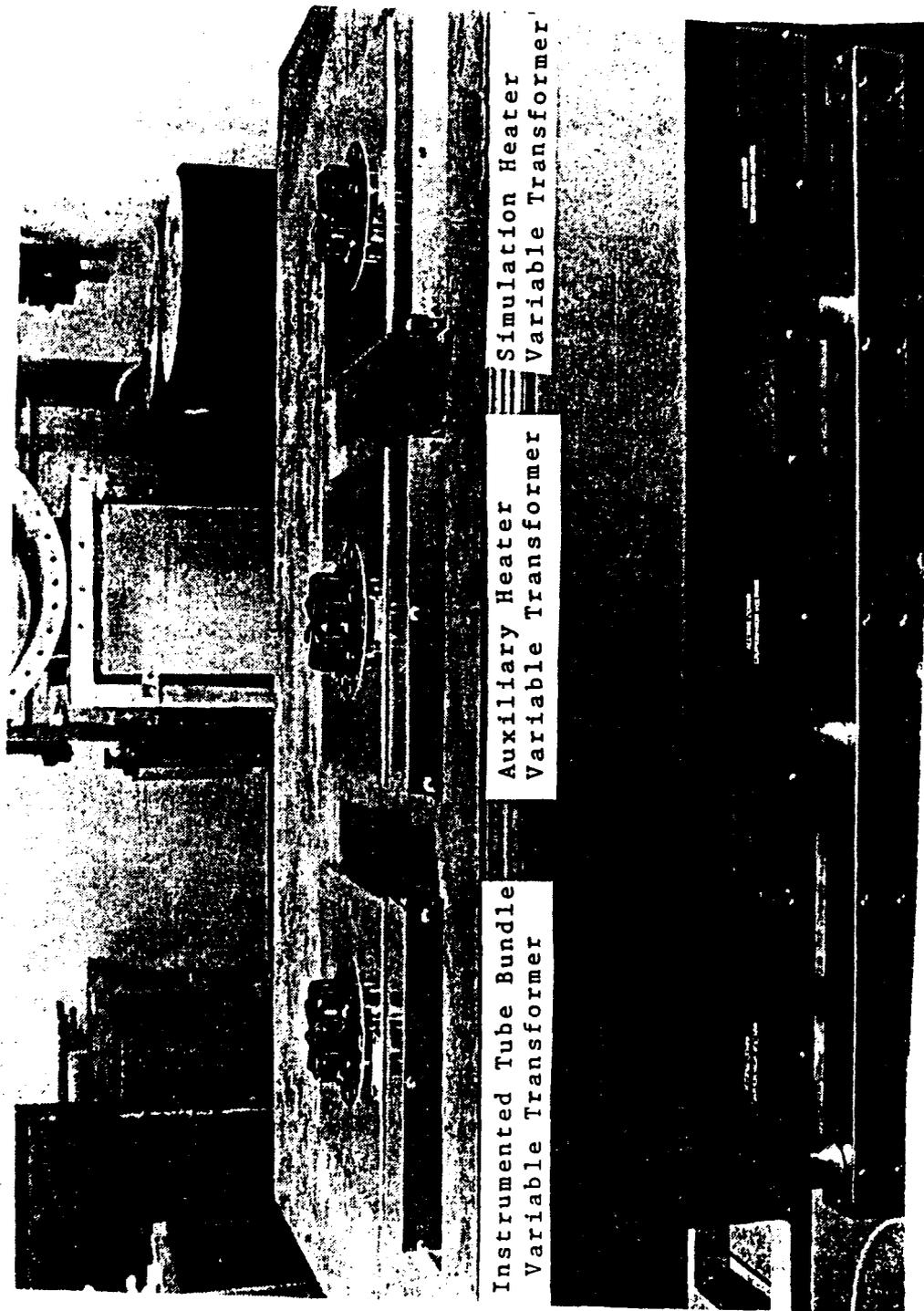


Figure 6. Photograph of 208 V, 75 A, Variable Transformers

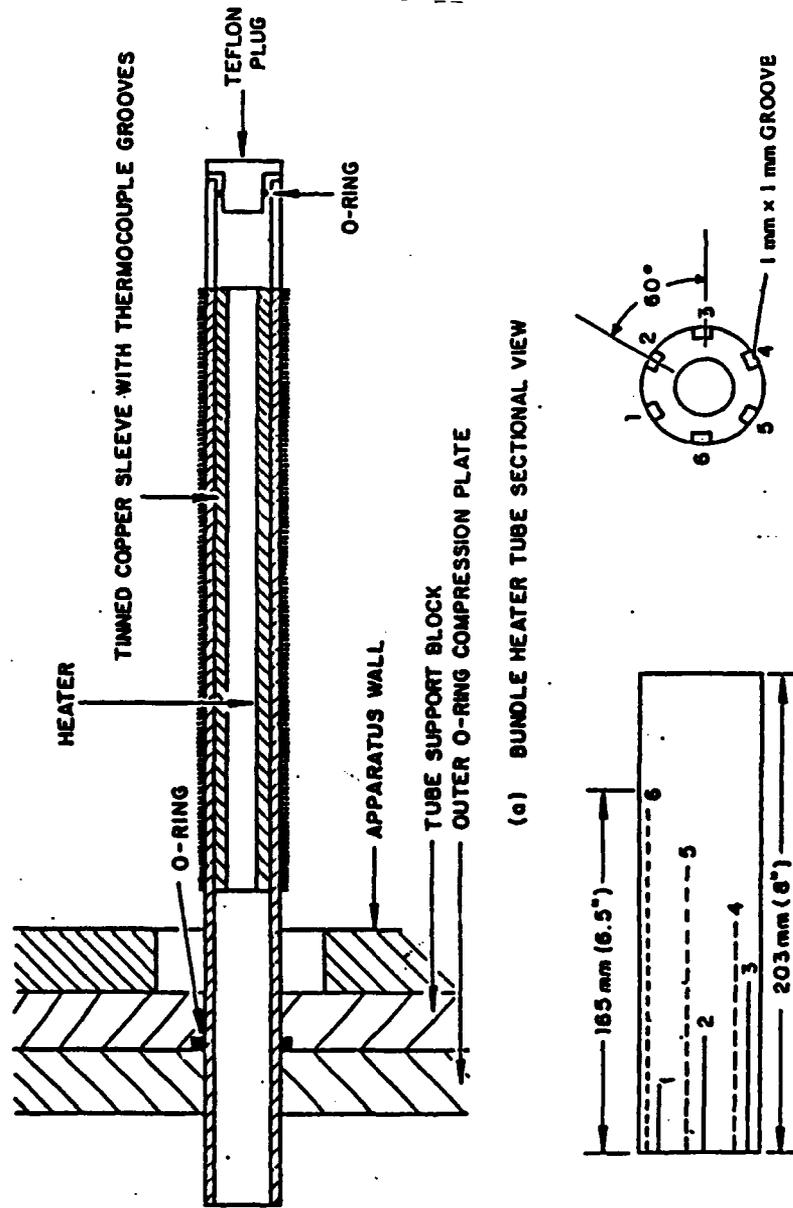


Figure 7. Thermocouple Locations on an Instrumented Boiling Tube and Tube Section View.

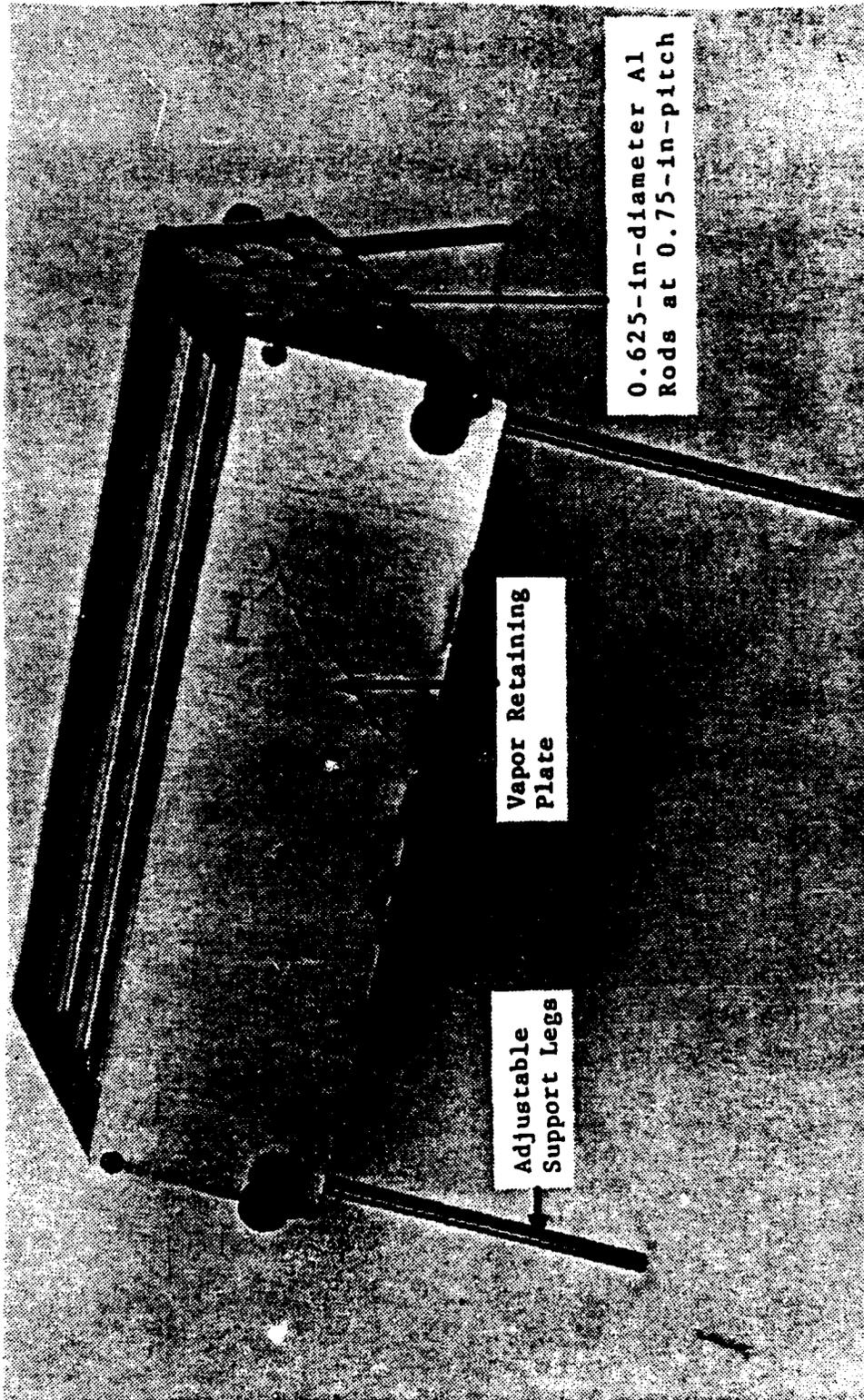


Figure 8. Photograph of Dummy Tube Rack

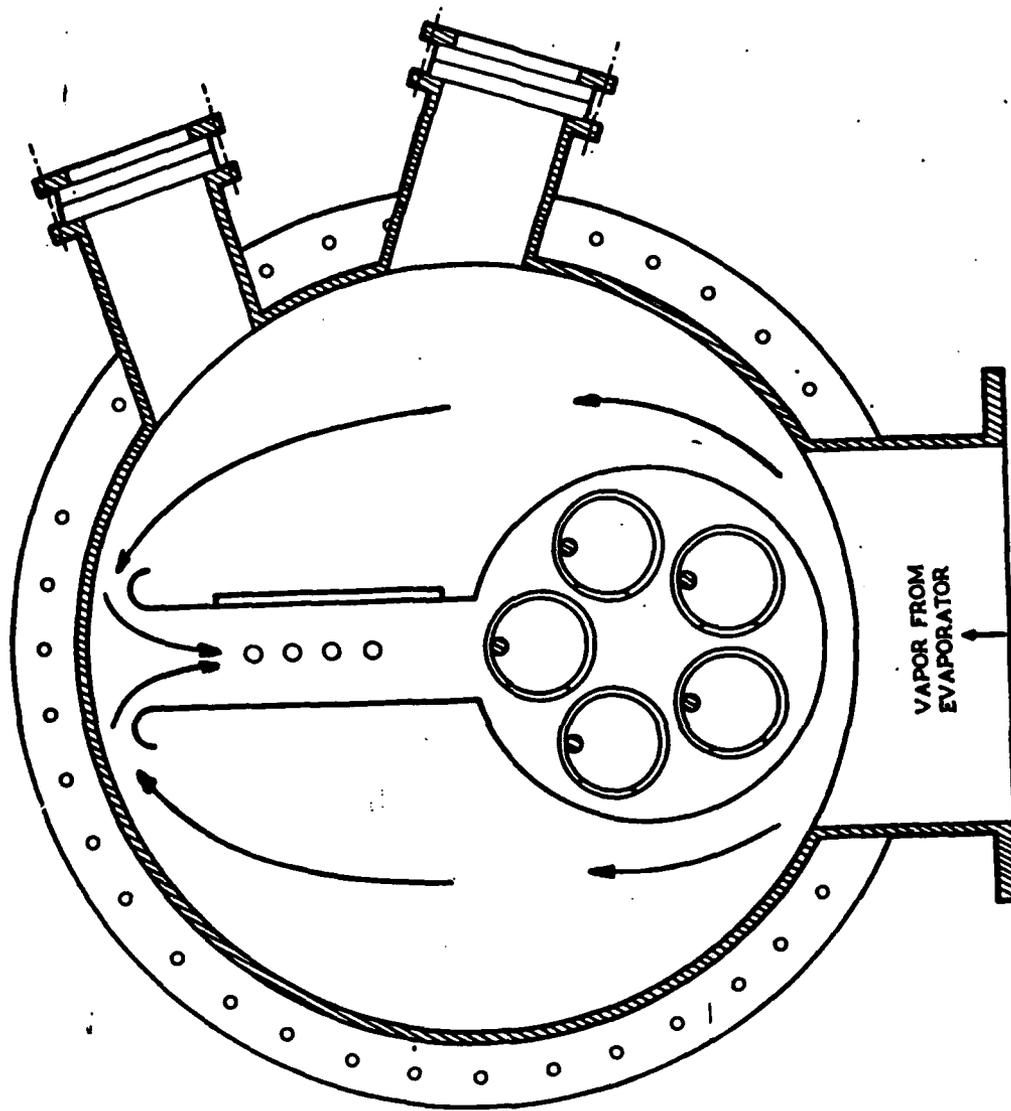


Figure 9. Vapor flow path in Condenser

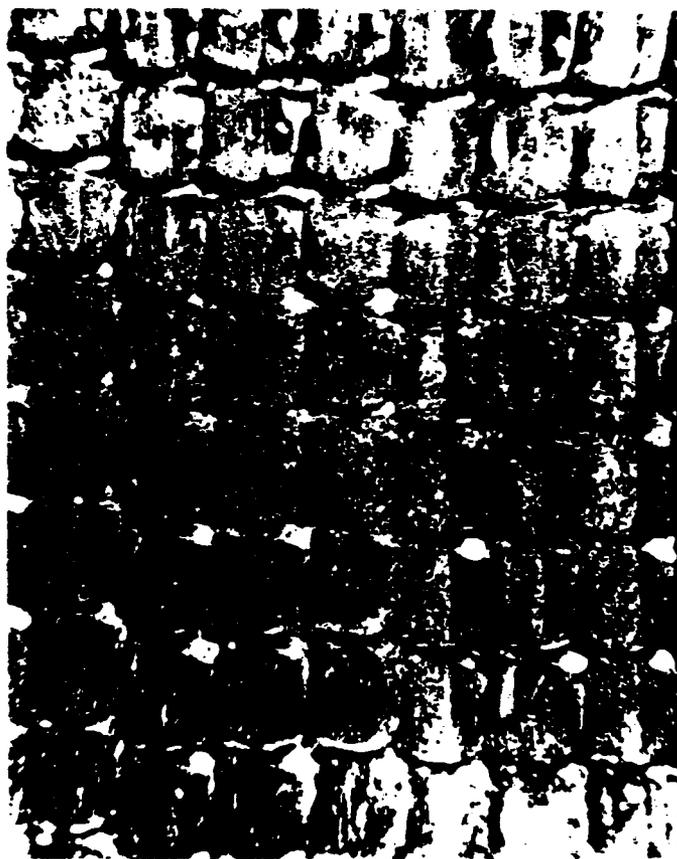


Figure 10. Close-up View of Turbo-B Tube Surface (25 Times)

TABLE 1. COMPUTER/DATA ACQUISITION ASSIGNMENT

Thermocouple Description	Channel	Array in code
Vapor 1-Top of Condenser	00	T(0)
Vapor 2-Top of Condenser	01	T(1)
Vapor 3-Top of Evaporator	02	T(2)
Liquid 1-Top of bundle	03	T(3)
Liquid 2-Top of bundle	04	T(4)
Liquid 3-Bottom of bundle	05	T(5)
Tube 1,No. 1	40	T(6)
Tube 1,No. 2	41	T(7)
Tube 1,No. 3	42	T(8)
Tube 1,No. 4	43	T(9)
Tube 1,No. 5	44	T(10)
Tube 1,No. 6	45	T(11)
Tube 2,No. 1	46	T(12)
Tube 2,No. 2	47	T(13)
Tube 2,No. 3	48	T(14)
Tube 2,No. 4	49	T(15)
Tube 2,No. 5	50	T(16)
Tube 2,No. 6	51	T(17)
Tube 3,No. 1	52	T(18)
Tube 3,No. 2	53	T(19)
Tube 3,No. 3	54	T(20)
Tube 3,No. 4	55	T(21)
Tube 3,No. 5	56	T(22)
Tube 3,No. 6	57	T(23)
Tube 4,No. 1	58	T(24)
Tube 4,No. 2	59	T(25)
Tube 4,No. 3	60	T(26)
Tube 4,No. 4	61	T(27)
Tube 4,No. 5	62	T(28)
Tube 4,No. 6	63	T(29)
Tube 5,No. 1	64	T(30)
Tube 5,No. 2	65	T(31)
Tube 5,No. 3	66	T(32)
Tube 5,No. 4	67	T(33)
Tube 5,No. 5	68	T(34)
Tube 5,No. 6	69	T(35)

TABLE 1. COMPUTER/DATA ACQUISITION ASSIGNMENT (CONT.)

Amperage Sensor Description	Channel	Array
Tube 1	30	Amp(0)
Tube 2	31	Amp(1)
Tube 3	32	Amp(2)
Tube 4	33	Amp(3)
Tube 5	34	Amp(4)
Active Heater Group 1	35	Amp(5)
Active Heater Group 2	36	Amp(6)
Active Heater Group 3	37	Amp(7)
Active Heater Group 4	38	Amp(8)
Active Heater Group 5	39	Amp(9)
Auxiliary Heaters	25	Amp(10)
Simulation Heaters	26	Amp(11)

Voltage Sensor Description	Channel	Array
Instrumented/Active	27	Volt(0)
Simulation Heaters	28	Volt(1)
Auxiliary Heaters	29	Volt(2)

TABLE 2. EVAPORATOR HEATERS

Heater Type	Number	Power Rating per Heater
Instrumented Tube Heaters	5	1000W
Active Tube Heaters	12	1000W
Auxiliary Heaters	4	4000W
Simulation Heaters	5	4000W

IV. EXPERIMENTAL PROCEDURES

A. REMOVAL OF TUBE BUNDLE FROM EVAPORATOR

Before removing the tube bundle from the evaporator, it was ensured that the evaporator was free of any refrigerant and was at atmospheric pressure. The tube bundle support block bolts were then loosened and removed. The tube bundle was then removed from the back of the boiler. Care was taken when removing the tube bundle as to not damage the thermocouple or heater wires. It was easier to disconnect the thermocouple wires from the data acquisition board and the heater wires from the power panel instead of leaving them connected to the tubes when it was necessary to work on or clean the tubes in the bundle. The tube bundle consisted of five instrumented heated Turbo-B tubes, 10 active heated Turbo-B tubes, 18 dummy smooth tubes and two dummy Turbo-B tubes. These two dummy Turbo-B tubes were equipped with heaters and could be connected if desired to study various other bundle configurations (see Anderson [Ref. 7]).

B. BUNDLE DISASSEMBLY

When the bundle needed to be disassembled, it was ensured that there was a clean working space and a container to put small parts in during the procedure. The first process was to remove the perspex plate attached to the aluminum baffle plate by four screws. This plate was modified such that the eight dummy smooth tubes surrounding the instrumented tubes extended through the plate (with ptfе plugs which held the tubes in the proper pitch-to-diameter alignment). This alteration became necessary since at high heat fluxes, the smooth tubes (which were screwed into the tube support block) loosened from the wall and rattled around. The ten screws on each aluminum baffle plate were then removed. The plates were then pulled off the bundle. The two outside smooth dummy tubes remained on

the tube bundle support block as they were countersunk into the block. The three inner smooth tubes could be removed from the aluminum block as they were attached only by the screws already removed. The 12 smooth tubes were then unscrewed from the tube bundle support block as seen in Figure 11. Care was taken in noting the order in which all the tubes were removed as it saved time in reassembly. The bundle was engraved to help in this process. With these tubes and baffle plates removed, only the instrumented and active heater tubes remained. These tubes were removed by loosening the outer O-ring compression plate; this allowed the tubes to be pulled from the tube support block. Care was taken when pulling the tube from the tube support block so as to not break the thermocouple or heater wires.

C. SYSTEM CLEAN-UP

If the system was contaminated it had to be thoroughly cleaned. In order to do this, the entire apparatus had to be taken completely apart and cleaned in the following manner.

After removal of the R-113 from the evaporator and system at atmospheric pressure, all electrical connections to the bundle were disconnected and the front-viewing glass windows were removed. The tube bundle was then be removed as described above. The dummy tube rack was then taken out; at all times, the system was ventilated with a fan.

Having removed the tubes from the tube bundle, they were individually washed with warm water, rinsed and then wiped down with acetone. The smooth tubes were cleaned with Copper Brite to remove any tarnish. They were wiped down with warm water and acetone. The same procedure was followed for the Turbo-B tubes except they were not cleaned with Copper Brite. During the cleaning process, a soft bristled toothbrush was used to ensure the enhanced surface was cleaned properly, exercising care not to interfere with the tube surface. The storage tank, if thought to be contaminated also was drained, vented, opened and cleaned using the same procedure.

D. SYSTEM REFIT

1. Installation of tube bundle in evaporator

Prior to installing the evaporator tubes and support block, the bundle and evaporator was thoroughly wiped down with acetone. Once the evaporator tubes were installed in the support block, and prior to tightening the tube bundle support block nuts, the bundle was guided into the evaporator section. After the bundle was in position, it was then checked that the dummy rack was still properly positioned below the bundle and that the vapor thermocouple positions were still 1.75 cm above the bundle. The support block nuts were then tightened equally on opposite sides to give equal compression of the gasket. If the front window was removed during maintenance, the window was put back on very carefully with small equal torques applied to each nut, in turn, in a clockwise direction around the outer ring support. After the window was in place, each tube (which extended through the outer O-ring compression plate) was tapped forward so as to touch the front-viewing-window. Once completed, the O-ring compression plate was tightened. This compressed the O-rings (which were slightly undersized because the tubes were so close together) providing a seal between the tube support block and the stainless-steel backing plate. Also, the compression plate had grooves for the O-rings to fit into to ensure proper alignment and seal.

2. System Leakage Check

After the system was isolated from the atmosphere and system integrity restored, a Seargent Welch 10 SCFM vacuum pump was turned on and the pressure in the system was reduced to 25 in-Hg vacuum. The system was then secured and left untouched for at least 10 hours to see if there was any leakage. If there was significant leakage(>1 inHg), then the system vacuum was broken by cracking valve R-2 (Figure 2) slowly (to ensure minimum moisture was allowed to enter the system). This valve was left open until

the system was at atmospheric conditions. The system was then pressurized with air to approximately 5 psig through valve R-2. Large leaks were then detected by simply listening to the air issuing from the system. If the leaks were small, they could be found by applying a small amount of soap/water solution to all joints in the system. One leak that was found was where the sleeve had been soldered onto the Turbo-B tube. Since this was found to be the source of a leak, all the Turbo-B tube joints were carefully resoldered. After all leaks had been corrected, the system was again subjected to a vacuum for a minimum of 10 hours. If the increase was less than 1/2 to 1 inHg rise in a 10 hour period, then the system was filled with refrigerant.

E. REFRIGERANT

1. Fill

a. From System Storage Tank

A refrigerant storage tank was used to store excess R-113 during experiments. The storage tank prevented discharge of the R-113 into the atmosphere and made experimentation less costly. To fill the evaporator with R-113 from the storage tank, the system pressure was equalized to the storage container pressure by opening valves R-1 and R-7 (Figure 2). Once the pressure was equal, then valves R-6 and R-4 were opened. Due to the pressure difference caused by the hydrostatic head of the liquid in the storage container, R-113 flowed from the storage tank into the evaporator. The amount of refrigerant that was transferred was controlled by throttling valve R-4 to obtain the desired level. Once the desired amount of refrigerant had been transferred, valves R-4, R-6, R-7, R-8 were closed. If required, additional R-113 was later added from a storage drum at atmospheric pressure to the system using valve R-2 (see next section).

b. From Refrigerant Storage Canister

To fill the apparatus from the refrigerant drum, the ethylene glycol/water mixture was first cooled to a temperature of 5°C. Both condenser pumps were put into operation thus allowing coolant to flow through the condenser section. This allowed for a differential pressure to exist between the evaporator and ambient. A clean plastic hose was connected to valve R-2 (Figure 2) and the other end was end put in the refrigerant drum. Once this differential pressure and hose hookup was completed, refrigerant transfer between ambient and the evaporator was possible by slowly opening valve R-2.

2. Removal

a. To System Storage Tank

For tube replacement, system maintenance or clean-up purposes, the R-113 was transferred to the storage tank. The ethylene glycol/water mixture temperature flowing through the storage tank was cooled to less than 5°C; valves R-7 and R-8 (Figure 2) were opened and the vacuum pump was turned on to put the storage tank under vacuum. Once the storage tank was under a vacuum, R-113 flowed from the evaporator to the storage tank because of the pressure difference. This pressure difference was maintained by keeping the heaters on in the evaporator and the coolant flow through the storage tank. As the level in the evaporator came down, power to the heaters was secured to avoid overheating. Any remaining R-113 that could not be transferred into the storage tank was drained through valve R-5 and put into a drum to be used later.

b. To Refrigerant Storage Canister

This procedure is primarily used to change refrigerants. The system vacuum can be broken by slowly cracking open R-2 (Figure 2) to ensure that moisture was not allowed to enter the system. Once the system was at atmospheric pressure, valve R-2

was opened wide to allow air to enter when the refrigerant was removed. The refrigerant could then be drained through valve R-5 and put into a drum to be used later.

F. OPERATION

1. System Lightoff, Securing and Emergency Procedures

See Appendix E

2. Normal Operation

The evaporator was filled with R-113 to a level of approximately 10 cm above the top tubes in the bundle. Prior to operating the system, the 8-ton refrigeration unit was run for approximately an hour to reduce the ethylene-glycol/water mixture in the sump to a temperature of 5°C. The pressure in the evaporator was usually 14 to 16 inHg vacuum if the system was left secured overnight. As the sump was brought to temperature, the data acquisition system and computer were turned on. This allowed the temperature in the system to be monitored during warm-up to saturation conditions. With this and pump number one running, the auxiliary heaters were then used to bring the pool up to saturation temperature. The auxiliary heaters were set to 1 kW nominal after pool temperature had been reached. The system pressure was slowly raised by allowing minimal coolant to flow at a low rate through the condenser tubes while heating the system with the auxiliary heaters. Once the required saturation temperature of 47.5°C was reached, the instrumented tubes were switched on and set to the desired value. This was done to prevent the tubes from nucleating prematurely. The heat flux of the instrumented tubes was then slowly increased by adjusting the rheostat. For increasing heat flux, the data were taken with very small heat flux increments, waiting at least 5 minutes to attain steady state conditions at each heat flux. At all regions of the boiling curve (and especially near the onset of nucleate boiling), two readings were taken for each heat flux. The bundle was continuously monitored through the observation windows.

Figure 12 shows the tube bundle arrangements used during experimentation. Test One was with only instrumented tube number one on in the bundle. Test two was with instrumented tubes one and two on in the bundle. Test three was with instrumented tubes one, two and three on in the bundle. Test four was with instrumented tubes one through four on in the bundle. Test five was with all five instrumented tubes on in the bundle. Test six was all five instrumented tubes plus all five pairs of active heater tubes on in the bundle. Test seven was the same as test six but with the simulation heaters on.

G. DATA REDUCTION PROCEDURES

The data reduction program "DRP4A" was used during the experiments for processing the data collected. The program was written in HP Basic 3.01 and run on an HP-9000 series computer. The characteristics and capabilities of this software and the entire listing of the program is similar to that provided by Anderson [Ref. 7]. The following modifications were made:

1. Correction for pool height
2. Installation of new thermocouple at bottom of liquid pool (bundle inlet temperature)

The entire program is included in Appendix F to provide continuity for future thesis work.

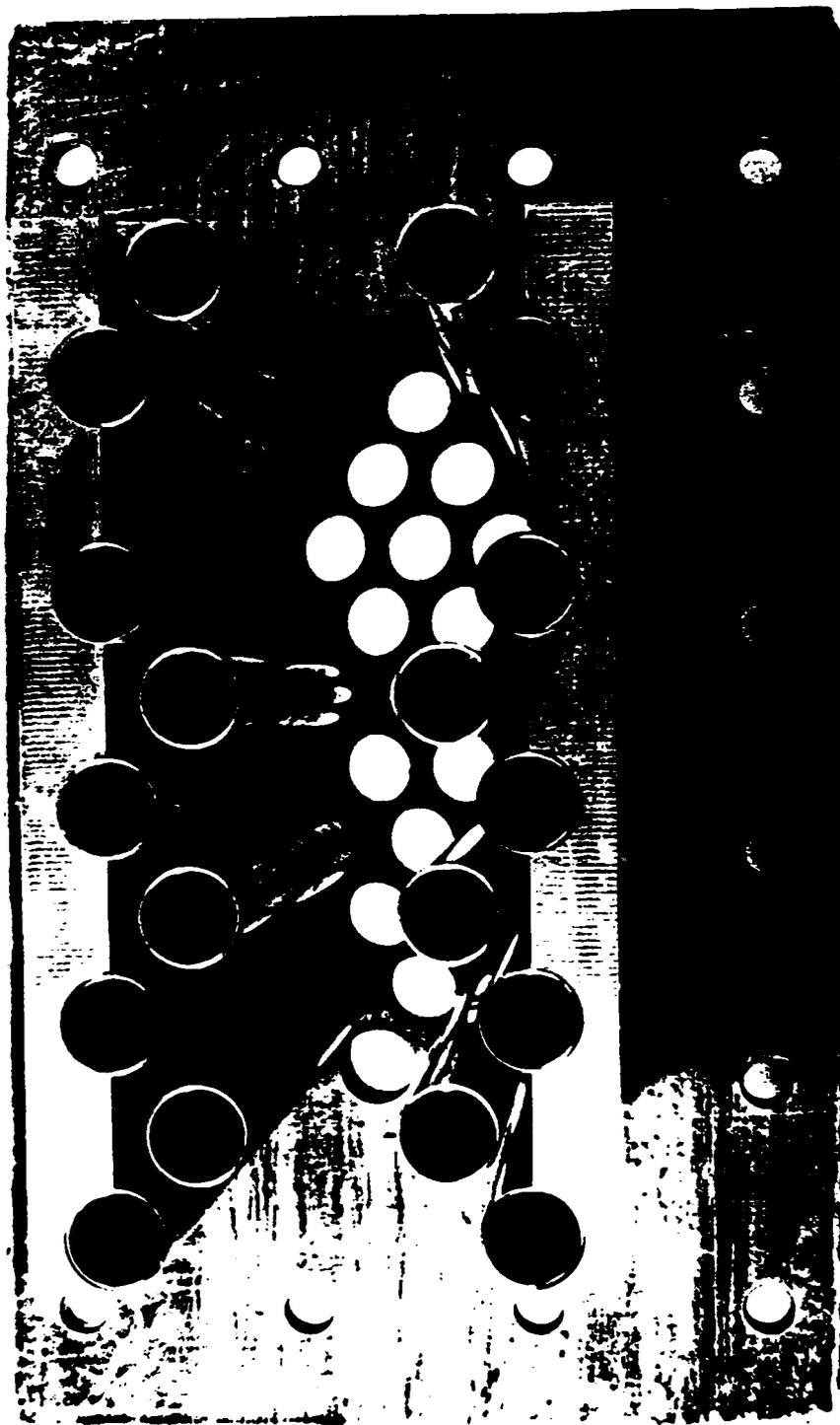


Figure 11. Photograph of Tube Bundle Support Block

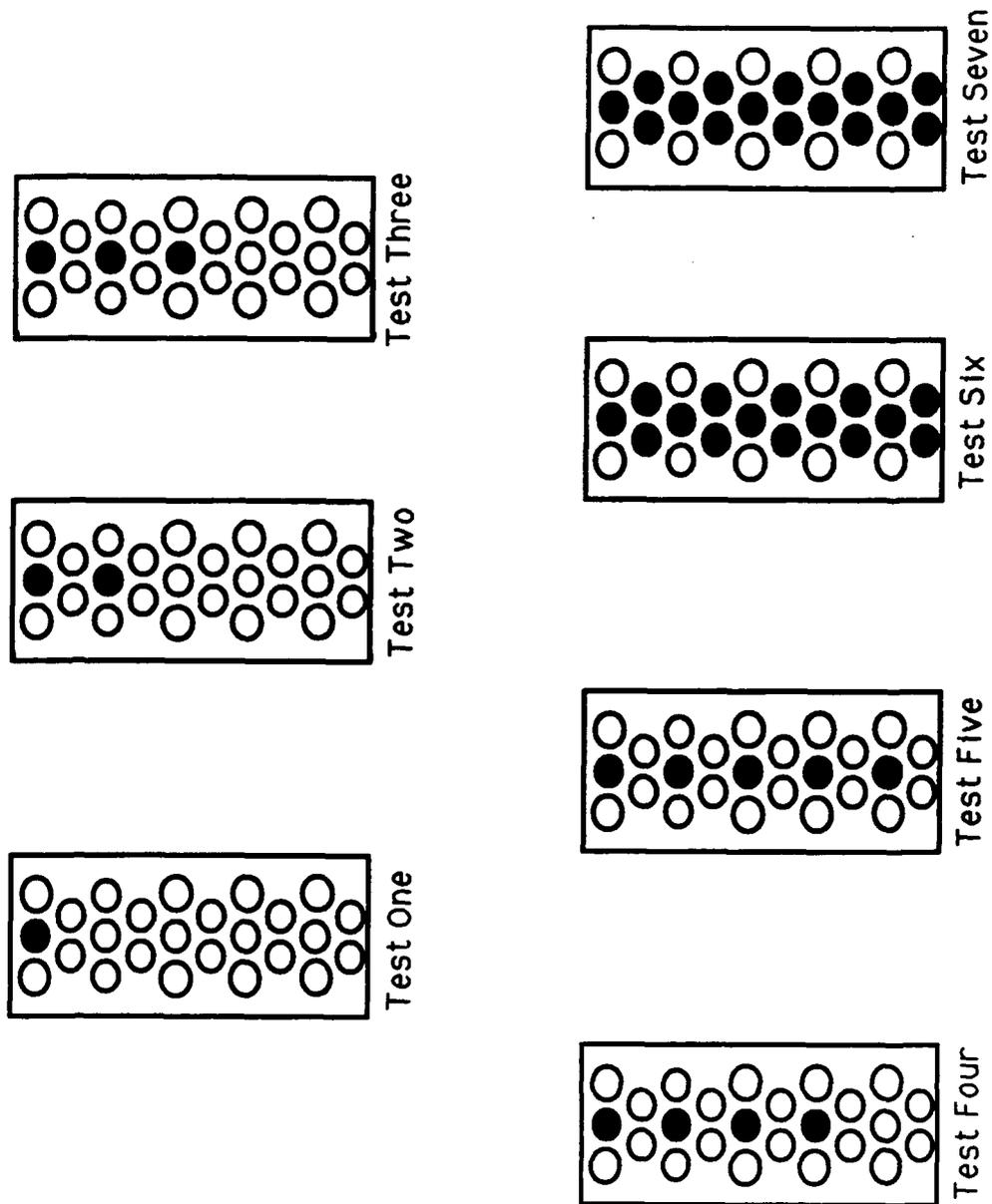


Figure 12. Tube Bundle Arrangements used During Experimentation

V. RESULTS AND DISCUSSION

A. GENERAL COMMENTS

The results are presented in five sections with sub-sections as appropriate. The first section discusses the natural convection, nucleate pool boiling phenomena and hysteresis effects within a small enhanced tube bundle. The second section discusses how evaporator pool height above the tube bundle affects the nucleation site activation and general evaporator performance. The third section looks at the effects of auxiliary heaters. The fourth section discusses the effect of surface history on nucleation site activation/deactivation. The final section shows comparisons of data taken during this thesis with previously obtained data at the Naval Postgraduate School.

A list of data runs conducted during this investigation may be found in Appendix A. All data files used in this thesis use the following filename sequence. Each file is composed of five sets of alpha-numeric characters used to describe the experiment.

First set (1 char.)	Heat flux	I(Increasing heat flux) D(Decreasing heat flux)
Second set (2 char.)	Type of tube used	TB (Turbo-B)
Third set (2 char.)	Number of Experiment for accounting purposes	

To give an example, the file name ITB12 means "increasing heat flux, using a Turbo-B tube and the 12th data run. If more detail is desired about a data run, see Appendix A. All plot files are similar to data files except they start with the letter "P". All tests were done with the auxiliary heaters at either 0, 1, or 3 kW nominal power setting (for details see Appendix A).

All the graphs show heat flux (W/m^2) along the ordinate (y axis) and wall superheat (K) along the abscissa (x axis). The heat flux was changed through the use of a variac from 600 to 100,000 W/m^2 for increasing or 100,000 to 600 W/m^2 for decreasing runs. Approximately 25-30 points were taken on the increasing heat flux and about 20 points were taken for the decreasing heat flux. The wall superheat is the difference between the corrected average tube wall temperature and the liquid saturation temperature.

To clarify the operation of the evaporator during the above tests, we used seven basic bundle arrangements during the test procedures as discussed and shown in Chapter IV.

Anderson [Ref. 7] used four types of surface preparation techniques.

1. Surface preparation A maintains the evaporator tube(s) at a heat flux of 30 kW/m^2 for one hour, slowly reducing heat flux to a minimum value of around 1 kW/m^2 , and beginning data collection immediately at successively increasing heat fluxes. The motivation for this surface preparation is a widely varying dynamic load often encountered in an air-conditioning machine.

2. Surface preparation B simulates an operating refrigeration system undergoing frequent off-cycles. A heat flux of 30 kW/m^2 at saturation conditions is maintained for one hour. Power is then secured for 30 minutes and then data are taken at successively increasing heat flux steps.

3. Surface preparation C represents the initial start-up of a refrigeration system. During this process, the evaporator was brought up to temperature and pressure with the auxiliary heaters alone to ensure the tubes did not have any active nucleation sites. Once at saturation pressure, the tube was turned on and the heat flux varied from 600 to 100,000 W/m^2 to develop a heat flux versus wall superheat plot. This process is very interesting as it introduces many complexities such as boiling hysteresis.

4. Surface preparation D represents a continuous operating air-conditioning system. It is closely modelled by a continuously decreasing heat flux starting from maximum power of 100 kW/m^2 after it has been boiled at this power for one-half hour. Considering that the return flow to the boiler is normally two-phase, nucleation sites are maintained active throughout the evaporator tube bundle. The decreasing heat flux data runs are normally the most readily reproducible and are used most often in measurements of tube-bundle performance. This surface preparation is the most widely used for reporting the performance of evaporator-tube surfaces.

Three of these surface preparation techniques were used during the course of the present work. Surface preparation technique C and D were used exactly as stated above and surface preparation technique B was the same but with a modification. Surface preparation technique B was modified such that power to the tube heaters could be secured for any amount of time but the pool temperature had to be maintained at saturation temperature.

1. Repeatability of data

Figure 13 presents similar data taken on two different days for the top tube operating alone in the bundle; the repeatability is seen to be very good. The arrows on the figure indicate the familiar hysteresis loop. The two tests show very similar temperature overshoot values (indicated by the horizontal line). The point of incipience (point where nucleate boiling first occurs) is also very similar for both tests.

The heat-transfer coefficient, h , is often used as a measure of tube performance: it is found by dividing the heat flux by the wall superheat. From Figure 13, values of h in the nucleate boiling region range from $1540 \text{ W/m}^2\text{K}$ at low heat flux to $13,750 \text{ W/m}^2\text{K}$ at high heat flux. Corresponding values of h in the convection region range from $480 \text{ W/m}^2\text{K}$ at low heat flux to $700 \text{ W/m}^2\text{K}$ at medium heat flux. It can be seen from Figure

13 that the tube performance typically improves by a factor of five once the tube starts to nucleate. This explains the importance of ensuring a flooded evaporator operates in the nucleate boiling rather than the natural convection region.

Also shown on Figure 13 are typical uncertainty bands for the data at both high and low heat flux and wall superheat. It can be seen that the greatest uncertainty occurs at low wall superheat and heat flux; this was as expected since the values of wall superheat are of the order accuracy for the thermocouples.

Figure 14 shows the limited predictions that are available for both natural convection and nucleate pool boiling data. These correlations were formulated for single smooth tubes, but represents all that is available for enhanced surfaces and tube bundles. This indicates the urgent need for further work in this area. For the natural convection region, two correlations are shown: Churchill and Chu [Ref. 24] and Churchill and Usagi [Ref. 25]. The experimental data for a single tube within the bundle show an appreciable *higher heat-transfer performance than prediction*. This might be expected as the tube is an enhanced surface. However, in the convection region, one should not expect a large difference in performance between different tube surfaces as they are designed primarily for the nucleate region. Indeed, experiments by Murphy [Ref. 6] have shown that the data for enhanced surfaces falls on top of smooth tube data in the convection region. Consequently, the discrepancy seen is more likely to be due to circulation effects within the bundle.

In the nucleate boiling region, there is also a large enhancement seen in the experimental data when compared with the correlation of Stephan and Abdelsalam [Ref. 26]. However, in this region, the discrepancy can be explained due to the enhanced nature of the surface. Circulation effects are still likely to be present, but small for a single tube when compared to the large number of active nucleation sites.

B. BUNDLE TRENDS FOR A POOL HEIGHT OF 10 CM

Figure 15 shows the influence of tube two on tube one. One may expect the thermal currents from the lower tube to further enhance the upper tube. However, with this lower tube heated, the performance of tube one in the convection region did not change. More striking is the significantly poorer performance of tube two in this region for which no explanation can be found. It is interesting to note that tube two (which should behave as an isolated single tube in the convection region, i.e. feeling no effect from the tube above) is now in much better agreement with the natural convection correlations.

Also seen is that the top tube nucleates at a lower heat flux. However, once both tubes are nucleating, the agreement is very close, with the top tube having the slightly better performance. Although this slight discrepancy could be due to uncertainty in the data, it is more likely to be due to the influence of the bubbles coming from the tube below, especially when one compares it with the top tube acting alone (Figure 13).

Figure 16 shows decreasing heat flux for two tubes. Agreement is very close, with the top tube performing slightly better at high heat flux, but the opposite at low heat flux. However, as heat flux is reduced, the uncertainty in the data increases.

With three tubes in operation (Figure 17), the trends are much the same. One point of interest is the effect on lower tubes as upper tubes start to nucleate. As tube one starts to nucleate, tubes two and three shift significantly to the left, indicating an increase in heat-transfer coefficient. However, tubes two and three remain in the convection region. Any further movement to the left by the upper tubes causes a corresponding shift to the left for the tubes below. This is probably due to increased circulation effects (i.e. as the bubbles from the upper tubes move around the evaporator, they help to agitate the thermal boundary layer around the tubes below). The shift to nucleation is strictly in order as one moves down the bundle.

For decreasing heat flux (Figure 18), there is a significant drop-off in performance for tube three, especially at a low heat flux. It may be that as one moves down the bundle, the greater pressure deactivates the nucleation sites at a faster rate.

Figures 19 to 22 show four and five tubes activated for increasing and decreasing heat flux. Similar trends to those already reported are seen; tube one nucleates first followed by two, three, etc. As each successive tube nucleates, the performance of the remaining lower tubes is improved slightly. In the nucleate region at high heat flux, tube one exhibits the best performance followed by tubes two, four, five and three. This somewhat strange order maybe due to uncertainty or the fact that tube three is only partially nucleating. At the very highest heat flux, all five tubes seem to coincide. At low heat fluxes, tube two gives the best heat transfer; it is unclear as to why this should be.

Because of the unexpected behavior of tube three at high heat flux, the positions of tubes three and five were switched to see if this behavior was a "bundle" effect or simply due to the particular tube itself. Figure 23 shows the results after switching for decreasing heat flux. New tube five (formerly tube three) now has the poorest performance, indicating that it is the tube rather than the bundle causing the earlier effect. It may be that air pockets surround the thermocouple junctions of tube five. Consequently, the tubes were kept in this position for the remainder of the tests, with the "bad" tube in the lowest position.

Figures 24 and 25 show the entire bundle activated for both increasing and decreasing heat flux while Figures 26 and 27 show the entire bundle plus simulation heaters activated for increasing and decreasing heat flux. These simulation heaters give the bottom of the bundle an inlet quality of about 20 percent, thereby simulating a real evaporator. Similar trends to those seen before are evident. The heat flux at which incipience occurs continues to decrease for all tubes, indicating the extra quality moving through the bundle helps to trigger "early" nucleation. As this simulates part of a real evaporator, this trend is

encouraging, as it is more likely to be operating in the nucleate region rather than the convection region. For the decreasing heat flux run, the heat transfer from the lower tubes has also been improved due to the increased vapor passing over them.

As already mentioned, it is difficult to make too many direct comparisons when all five tubes are independently instrumented. One of the tubes may have certain induced errors due to manufacture that another tube does not. Consequently, of perhaps more use is to look at what happens to the top tube only as successive tubes are activated below. Figure 28 does this for all seven tests (see Chapter IV: normal operation, for description of tests) for an increasing heat flux. In the natural convection region, the point of incipience occurs at increasingly lower heat fluxes as more tubes are activated. In the nucleate boiling region, the heat-transfer coefficient increases as more tubes are activated. Both the natural convection and nucleate boiling regions are well defined indicating good reliability of the data. For decreasing heat flux (Figure 29), the heat-transfer coefficient is again clearly increased as more tubes are activated below. This is more evident at low heat flux than at high heat flux.

C. BUNDLE PERFORMANCE WITH VARYING POOL HEIGHT

One of the objectives of this thesis was to see the effect of pool height on heat-transfer performance. Pool height here is defined as the height from the free liquid surface down to the top of the bundle (tube one). All experiments to date had been carried out at a pool height of 10 cm. Two additional heights of 0 cm and 20 cm were also studied with the same vapor pressure within the evaporator (i.e. to see the effect of pressure head on the tubes in the bundle). It is understood that a true flooded evaporator has zero pool height (indeed the top tubes operate in the bubbly froth).

Figures 30 to 42 show the same seven tests for a pool height of 20 cm as previously shown for 10 cm. The trends of all these graphs are exactly the same as for 10 cm. The

effect of the greater pool height is generally to delay the point of incipience. Figures 43 and 44 show tube one only for all seven tests (i.e. to see the effect of successive activated tubes below) for increasing and decreasing heat flux respectively. This to shows similar trends to before, with the effect of successive tubes triggering earlier nucleation on the top tube as well as enhancing the nucleate boiling heat-transfer coefficient.

Figures 45 to 57 show the same seven tests for a 0 cm pool height and again the trends are very similar. However, this time, the point of incipience occurs at the lowest value of heat flux. Figures 58 and 59 show tube one only for all seven tests for increasing and decreasing heat flux respectively. The conclusions drawn from these figures are the same as before.

To summarize the effect of pool height, Figures 60 and 61 show tube one (i.e. Test One) at the three pool heights for increasing and decreasing heat flux. It can be seen that the zero pool height data nucleates first followed by 10 cm and then 20 cm. Similar trends were seen regardless of what test was chosen i.e. for test seven with whole bundle plus simulation heaters activated, all three points of incipience (for the 3 pool heights) move to a lower heat flux but the zero pool height data still nucleate first. Obviously, the greater pressure heads felt by the tubes at larger pool heights inhibit the transition to nucleate boiling i.e. larger wall superheats are required to overcome the increased pressure. Further experiments should be conducted in the future whereby the vapor pressure above the bundle is varied with the pool height such that the pressure that each tube "feels" at a given location is the same.

D. EFFECT OF AUXILIARY HEATERS

For all tests reported so far, the auxiliary heaters were set to 1kW nominal. The auxiliary heaters were needed to maintain pool temperature throughout the test. They were only really needed at low heat fluxes or if only a few tubes in the bundle were activated.

For these tests, if they were not used, the evaporator could not produce enough vapor to keep the pressure constant even with the condenser shut down (i.e. the walls of the test section acted as the condenser). As a consequence, the pool temperature would drop. However, the necessary operation of the auxiliary heaters has an effect on the circulation patterns within the bundle (this has been demonstrated in the single tube facility). Therefore, by having these auxiliary heaters set to the same value for each test, any effect they may have should be a constant factor. To see the effect that the auxiliary heaters have, Figure 62 shows data for three tubes on during a decreasing heat flux with the auxiliary heaters off compared to Figure 18 with them set at 1 kW for a 10 cm pool height. Essentially the effect is minimal in the nucleate region at high heat fluxes. At lower heat fluxes, no data could be taken with the auxiliary heaters off. In the convection region (again at low heat flux so there is no data with the auxiliary heaters off), the effects of increasing the auxiliary heater power is to increase the heat-transfer coefficient (i.e. reducing the wall superheat). The same effect was seen for four tubes with the auxiliary heaters off and set to 1 kW for a 10 cm pool height; shown in Figures 63 and 20 respectively. Figures 64 and 30 show the same trend for tube one with the auxiliary heaters set at 3 kW compared to 1 kW for a pool height of 20 cm. These trends are probably seen due to the increased circulation within the bundle at the higher auxiliary heater setting. Obviously, it would be preferable to do away with the auxiliary heaters altogether. With R-114, due to the lower normal boiling point, this should be possible.

E. NUCLEATION SITE ACTIVATION/DEACTIVATION

Nucleation site activation/deactivation is not well understood. Once a tube is nucleating, there are a couple of ways that the nucleation sites can die out:

1. Reducing the heat to the tube surface thereby allowing the fluid to collapse the vapor bubble and re-wet the surface due to pressure effects.

2. Increasing the subcooling of the liquid around the tube (i.e. causing the vapor bubble to condense into the fluid).

The following tests were conducted to see how quickly the nucleation sites, once activated, died away if the power to the tube was cut off (i.e. to see how quickly the liquid re-wets the surface as discussed in mechanism one above). The pool temperature was maintained at saturation conditions throughout the test (i.e. there was no subcooling). All the tests were conducted on the top tube only. The test procedure used was the modified surface preparation B. The power to the heater was then turned off for a known finite time and then reactivated. An increasing run was then carried out. This was repeated for a number of different times and pool heights. The auxiliary power setting was 1 kW for all tests.

Figures 65 and 66 show the data for a pool height of 20 cm. The turn-off time for the heater varied between five seconds and one hour. It can be seen that after only 15 s, the nucleation sites have all died out and the tube behaves as if it had been secured overnight (these are the data sets listed as 14 and 15 hours). Of course, by securing overnight, subcooling also plays a part in deactivating the sites.

Figure 67 shows the data for a pool height of 10 cm. The turn-off time for the heater varied between five seconds and one minute. It can be seen that after one minute, the nucleation sites have all died out and the tube behaves as if it had been secured overnight. Hence, it would seem that due to the reduced pressure head trying to push the liquid into the sites, the time needed to deactivate all the sites is significantly longer.

Figures 68 and 69 show the data for a pool height of 0 cm. The turn-off time for the heater varied between 40 seconds and 8 hours (keeping pool temperature constant throughout). It can be seen that even for a shut-off time of 8 hours, none of the nucleation sites are deactivated. The pressure head is negligible here and it is mechanism two that

deactivates the sites. As the pool temperature was not subcooled during this particular test, none of the sites are therefore deactivated. Figure 70 shows a test where the apparatus was secured for 2.75 hours (i.e. allowed to subcool). The deactivation seen is due to the subcooling that has occurred.

Similar trends for all three pool heights have been obtained for an auxiliary heater power setting of 3 kW. Slight differences in the times needed for total deactivation were noted to be 20 seconds for 10 cm vice one minute. These data are shown in Figures 71 to 75.

F. COMPARISONS WITH PREVIOUS NPS DATA

Figure 76 shows a comparison between the present data for a Turbo-B bundle in R-113 and the data of Anderson [Ref. 7] for a smooth tube bundle in R-113. For clarity, only the top tube has been shown for a decreasing heat flux. It can be seen that the heat transfer enhancement given by the enhanced tube is three to five times for high and low heat fluxes respectively.

This is also true for the overall bundle heat transfer coefficient, giving a factor of 4 enhancement at a typical operating heat flux of $20,000 \text{ W/m}^2$. Also shown on the figure is the correlation of Stephan and Abdelsalam [Ref. 26] showing a fairly good agreement with the smooth tube data.

Figure 77 shows a comparison between the present data and that of Eraydin [Ref. 9] who used a Turbo-B bundle in R-114. It can be seen that there is very little difference between the two sets of data. The R-114 data giving the slightly better performance. This could be due to the slightly better thermal conductivity of R-114 at its saturation temperature compared to R-113 at its saturation temperature.

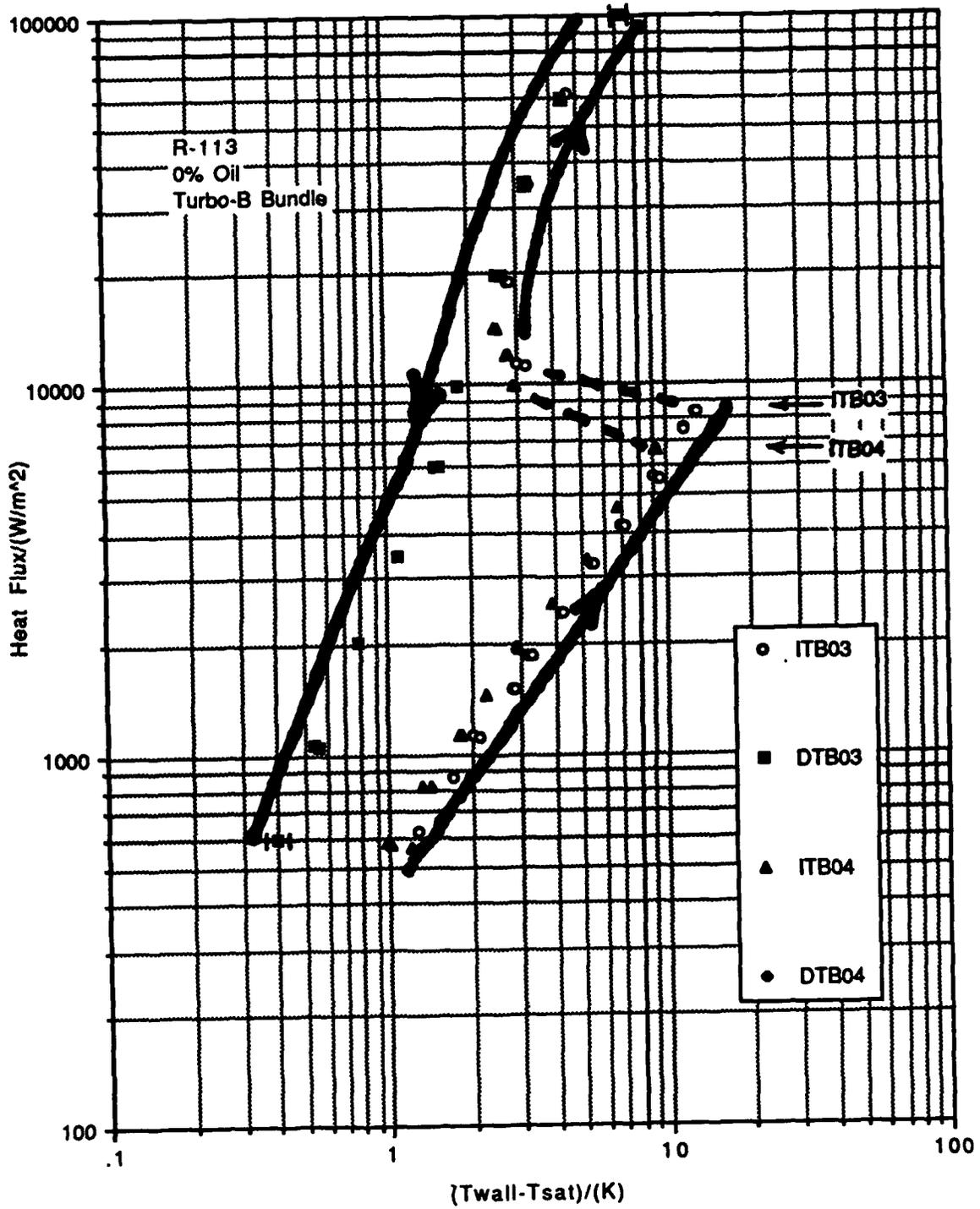


Figure 13. Performance of Tube 1 at a 10 cm Pool Height for Similar Data Taken on Different Days to Show Repeatability

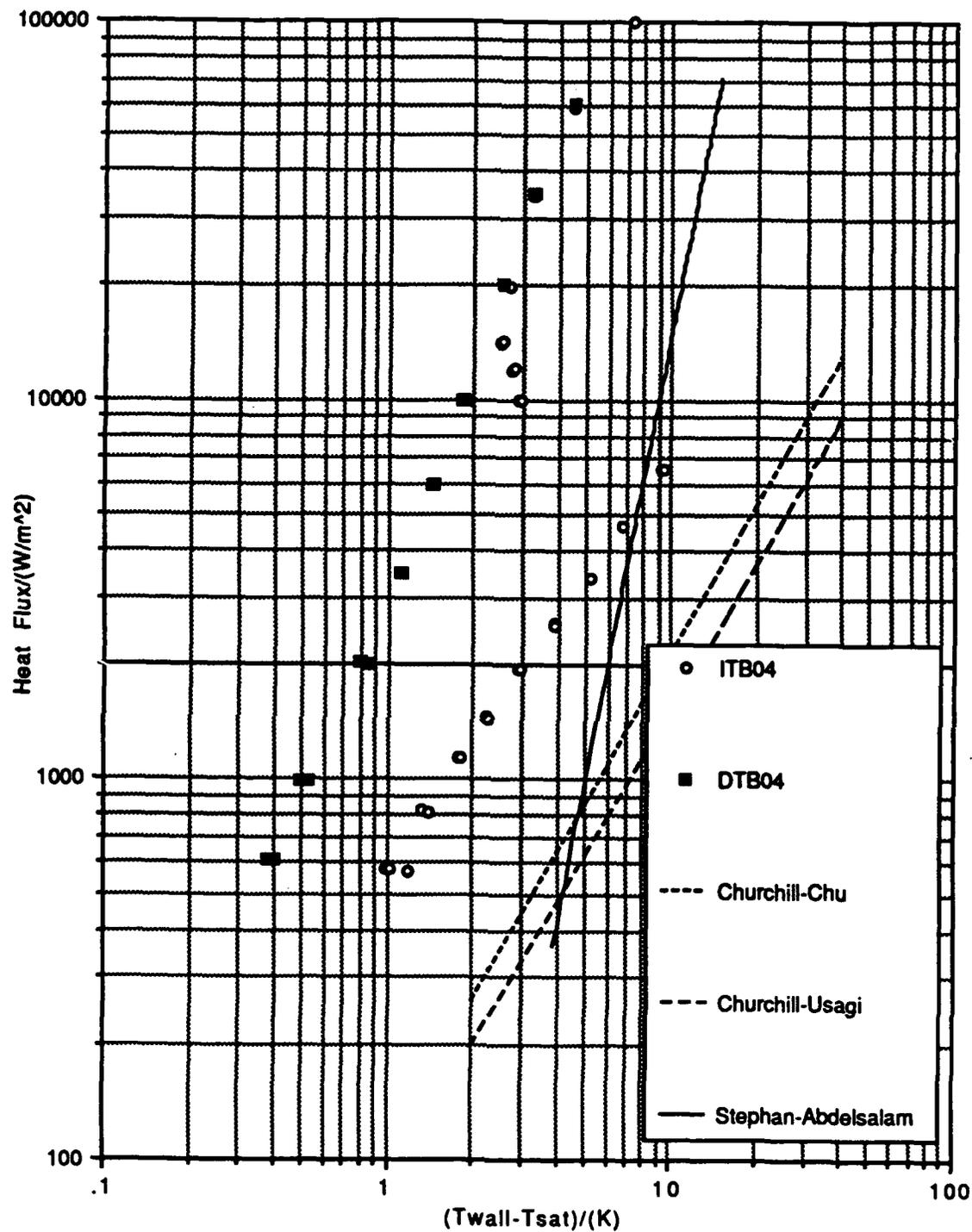


Figure 14. Performance of Tube 1 at a 10 cm Pool Height Along With Correlations for Natural Convection and Nucleate Pool Boiling Regions

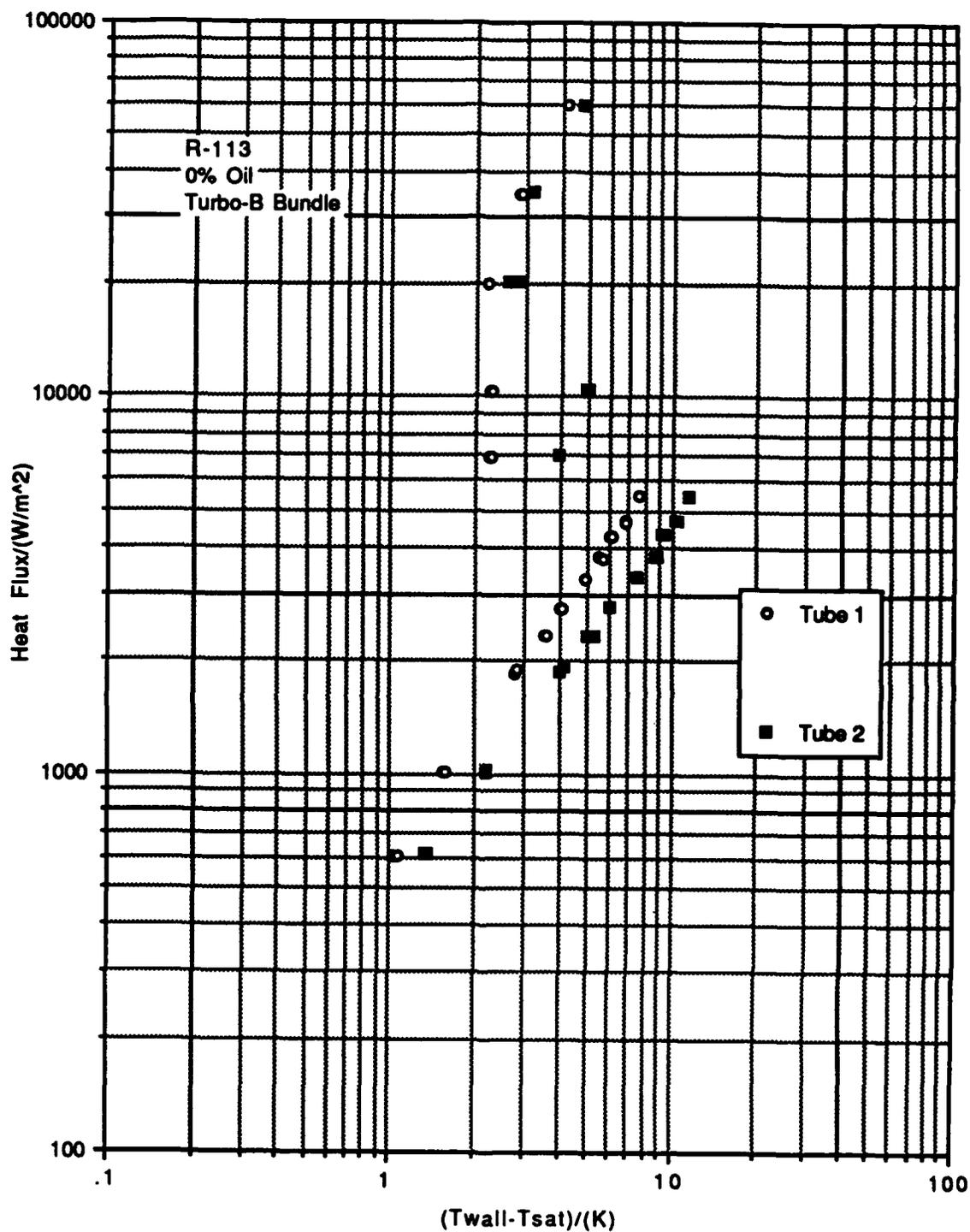


Figure 15. Performance Variation of Tubes 1&2 at a 10 cm Pool Height During a Increasing Heat Flux (ITB05)

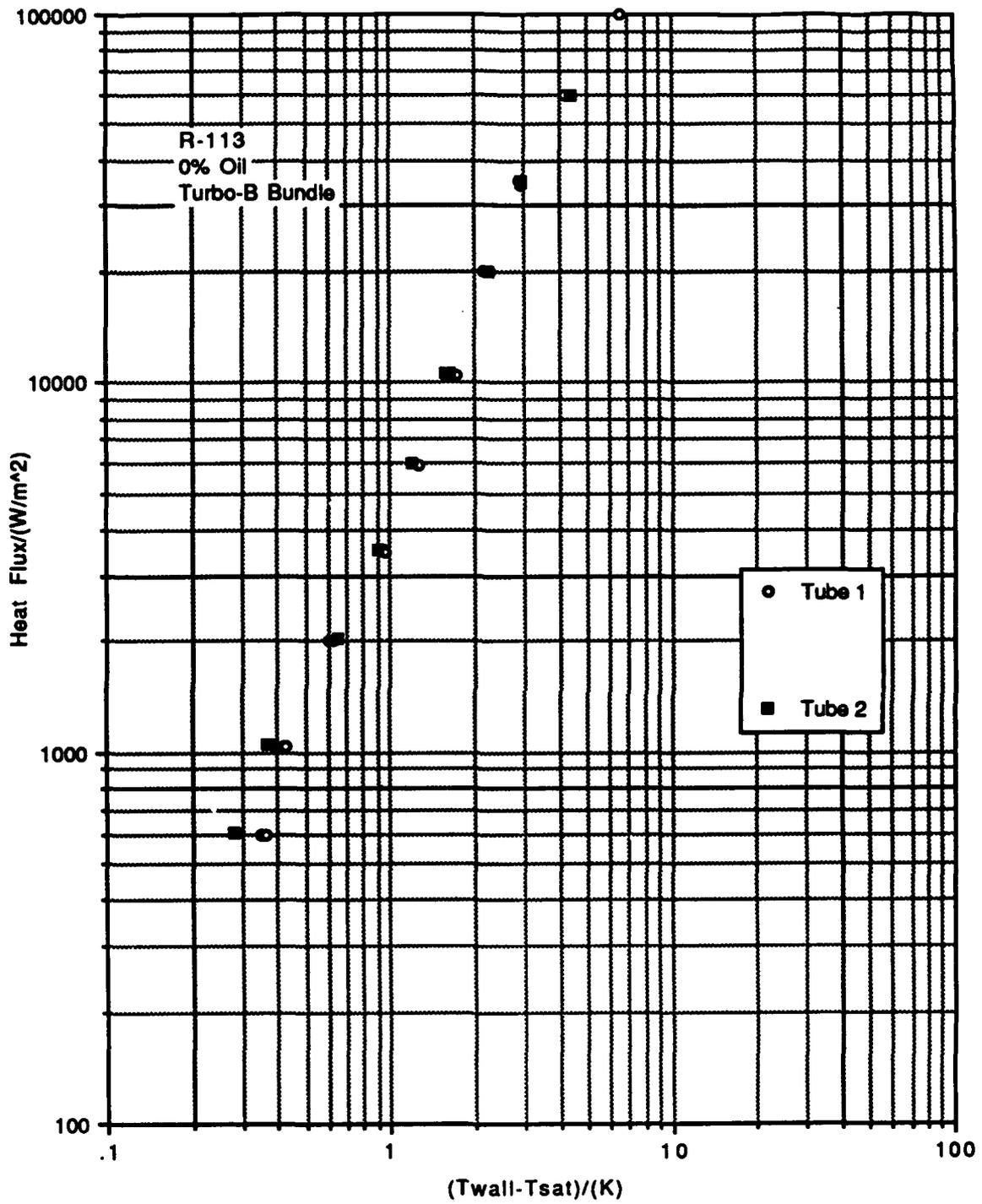


Figure 16. Performance Variation of Tubes 1&2 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB05)

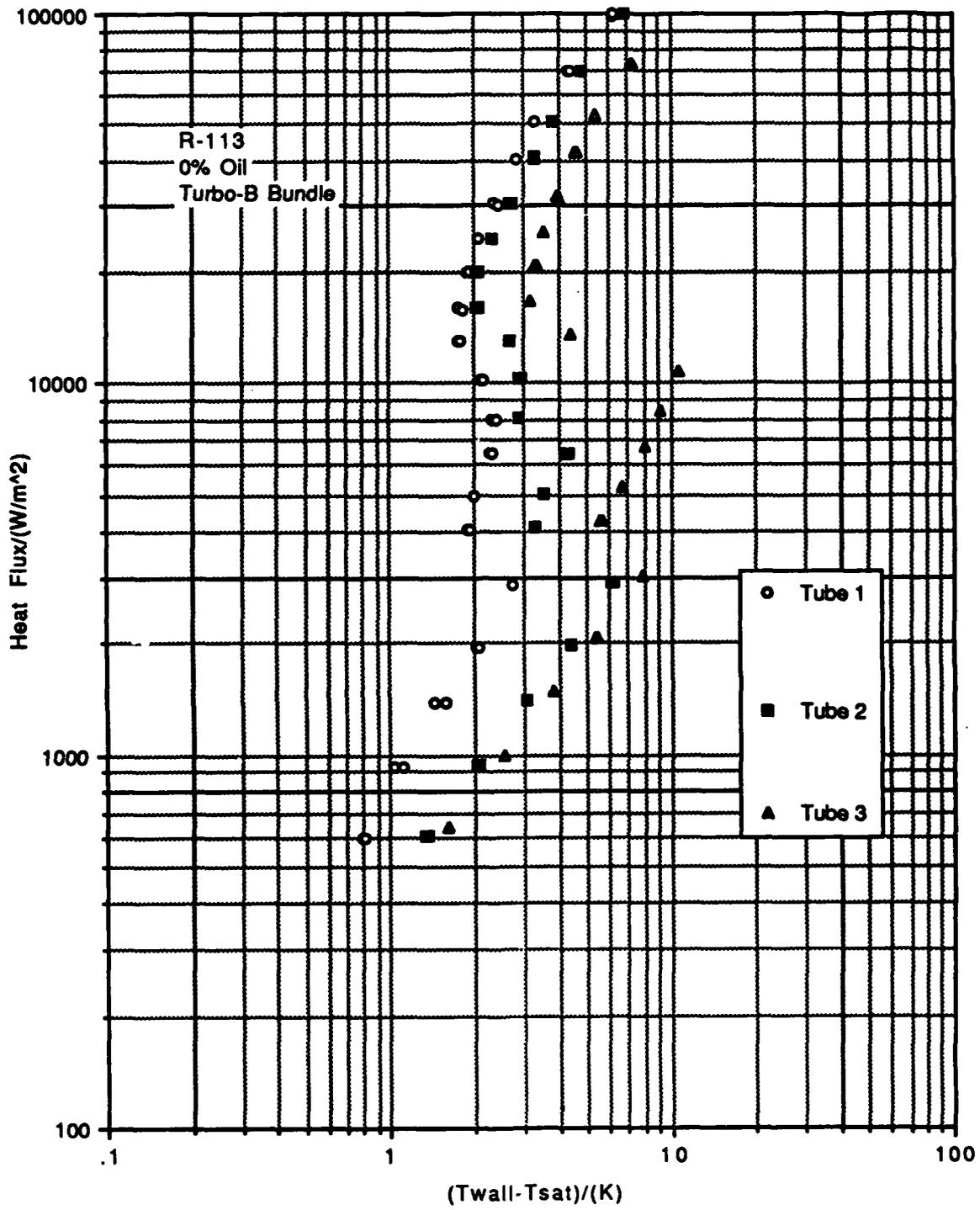


Figure 17. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Increasing Heat Flux (ITB06)

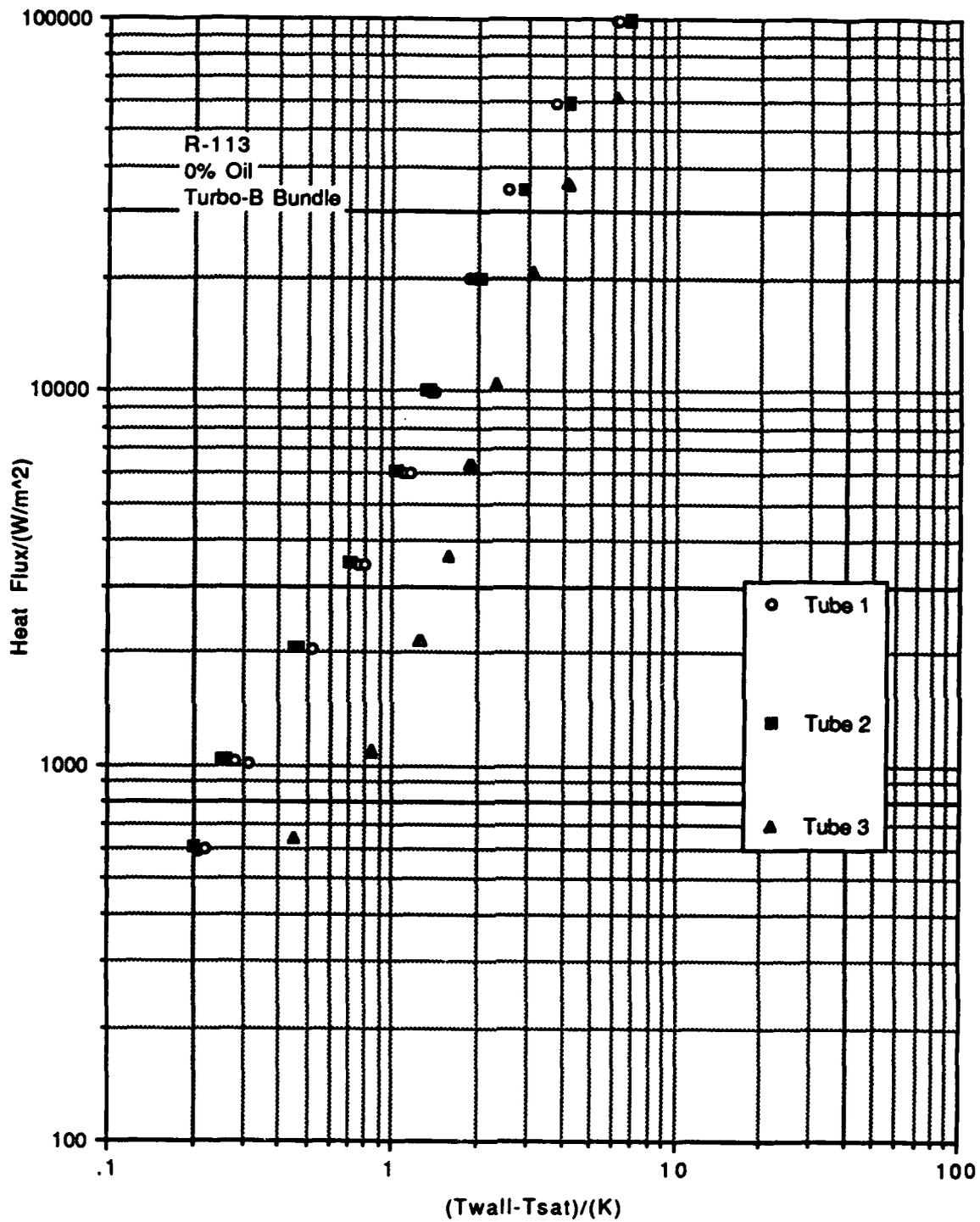


Figure 18. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB06)

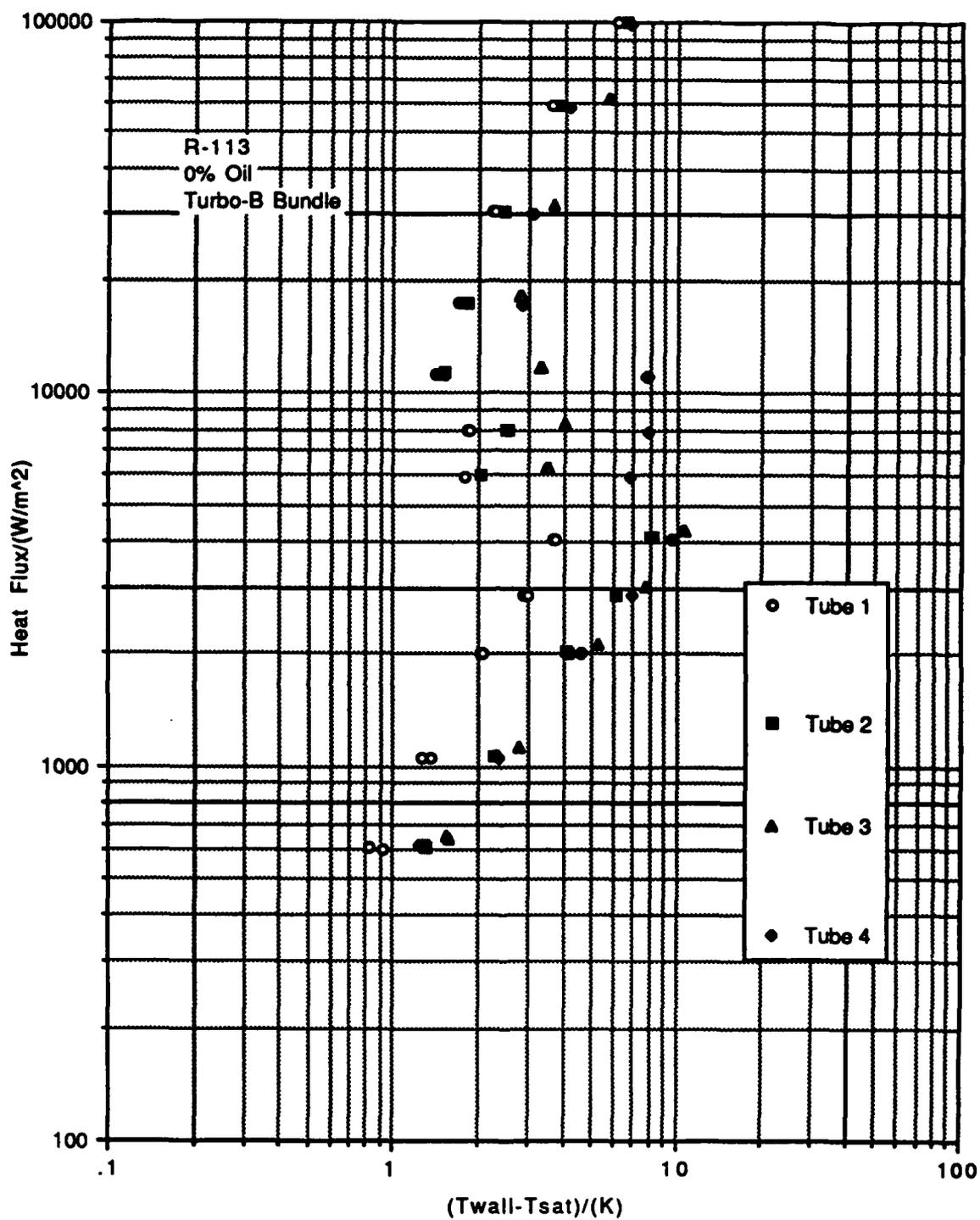


Figure 19. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Increasing Heat Flux (ITB07)

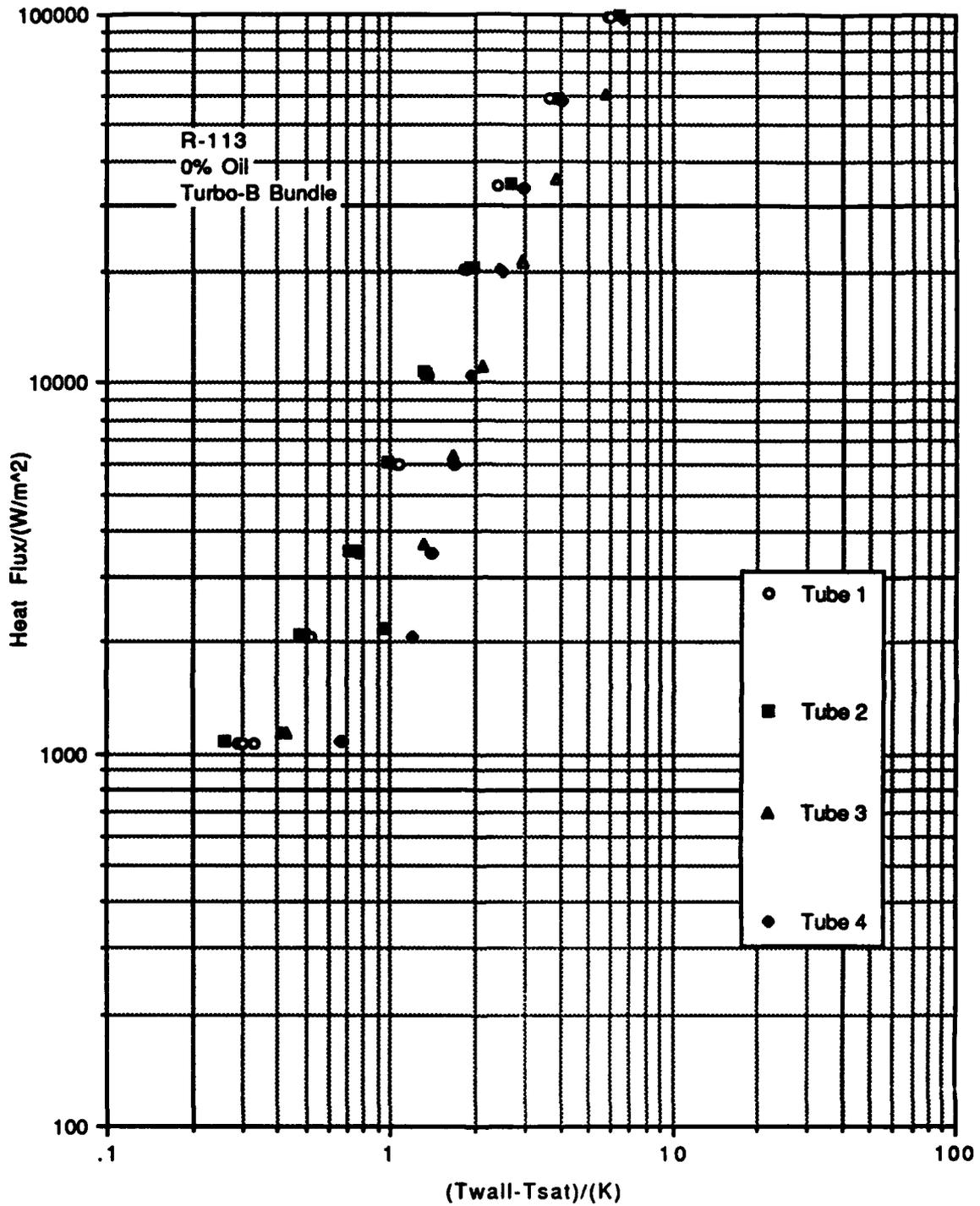


Figure 20. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB07)

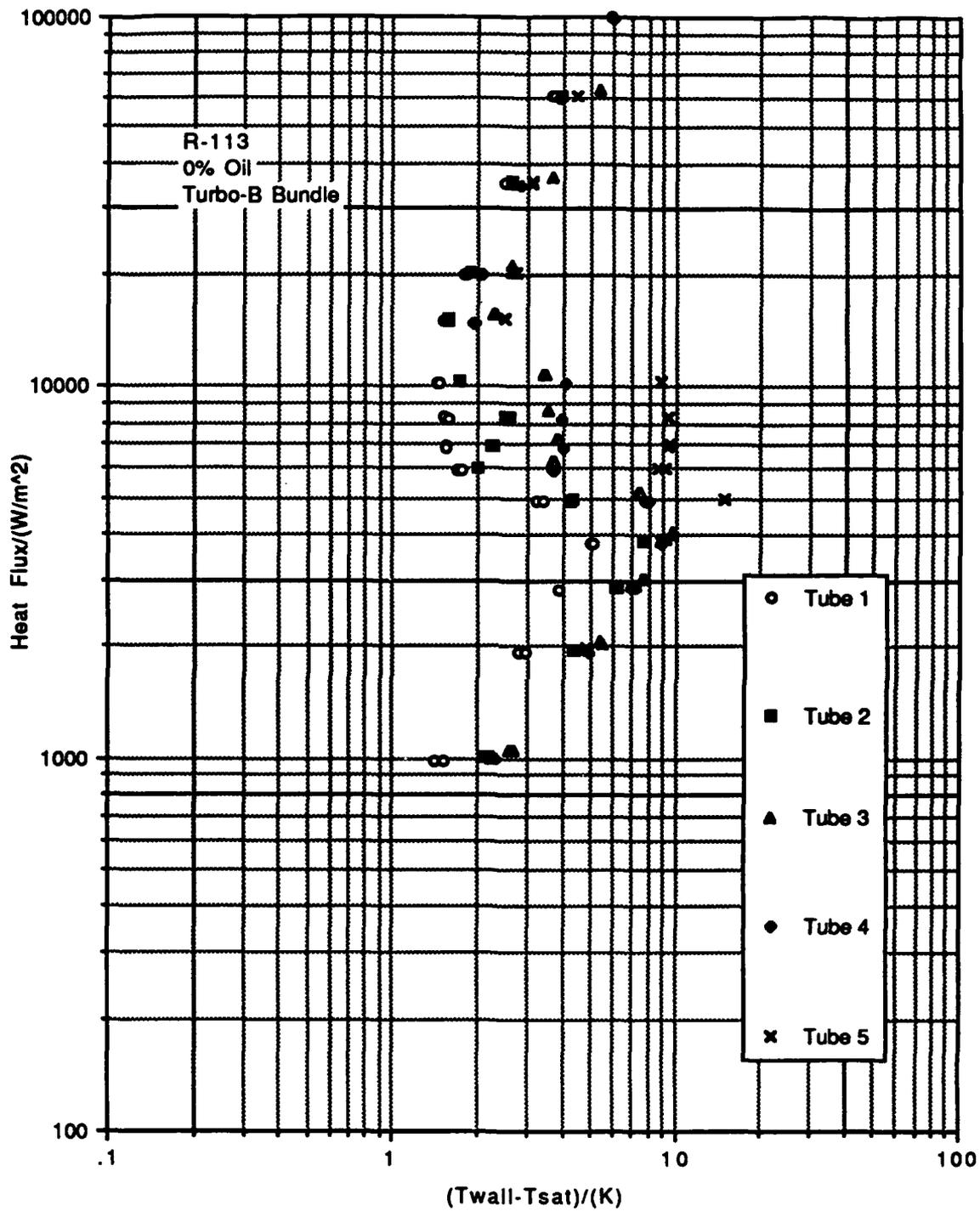


Figure 21. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Increasing Heat Flux (ITB27)

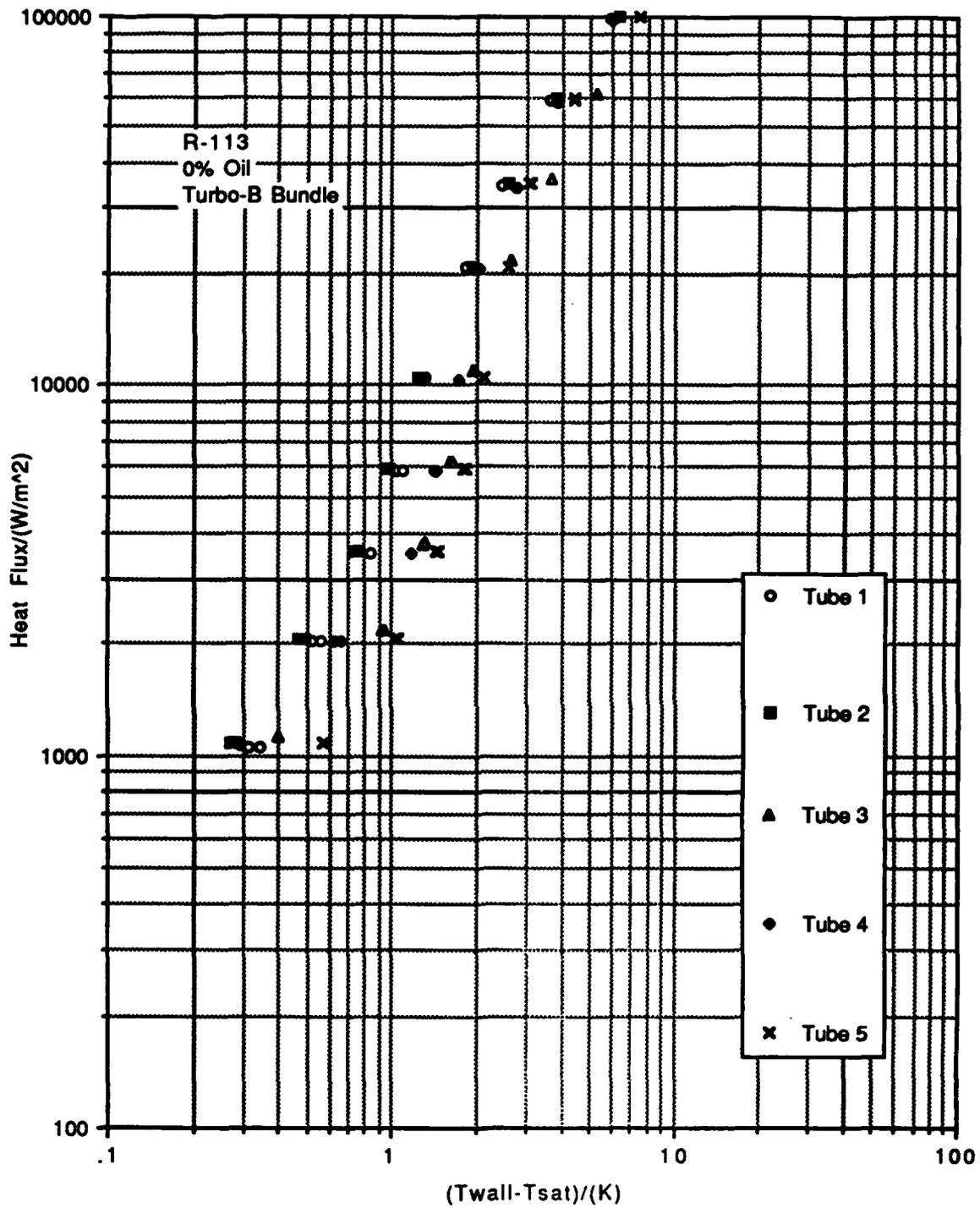


Figure 22. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Decreasing Heat Flux (DTB27)

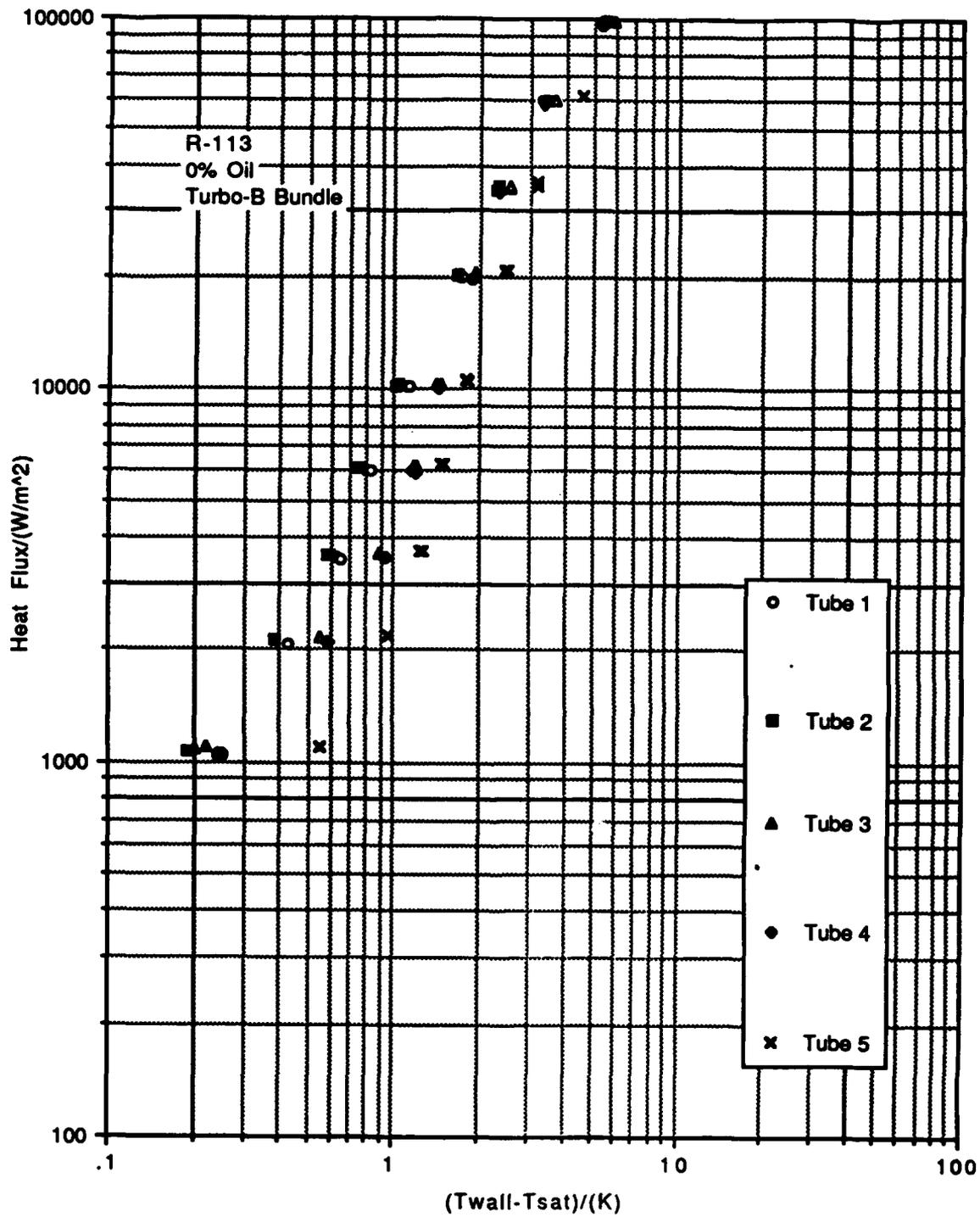


Figure 23. Performance Variation of Tubes 1 to 5 at a 10 cm Pool Height During a Decreasing Heat Flux with Tubes 3&5 Switched (DTB30)

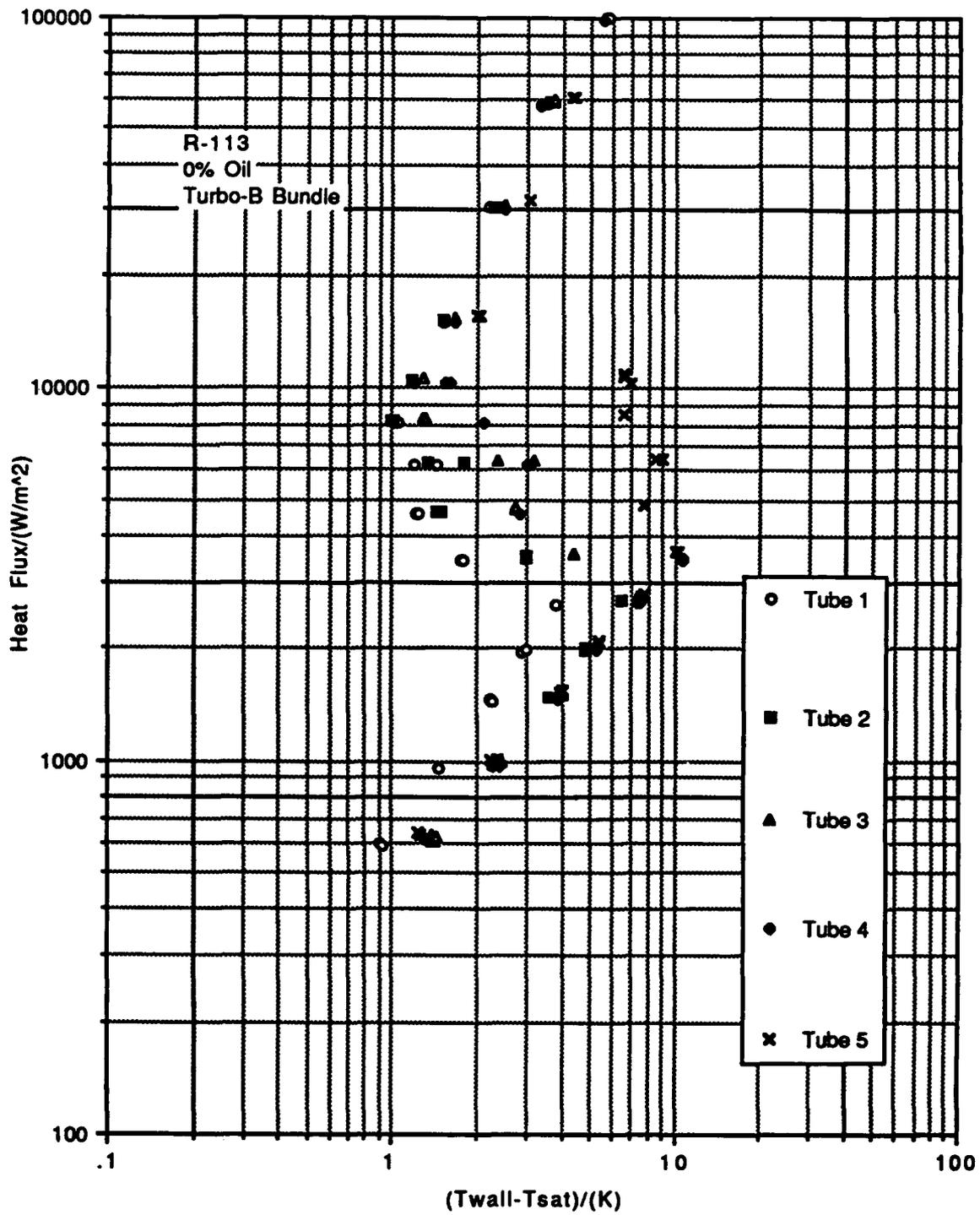


Figure 24. Performance Variation of the Bundle at a 10 cm Pool Height During a Increasing Heat Flux (ITB48)

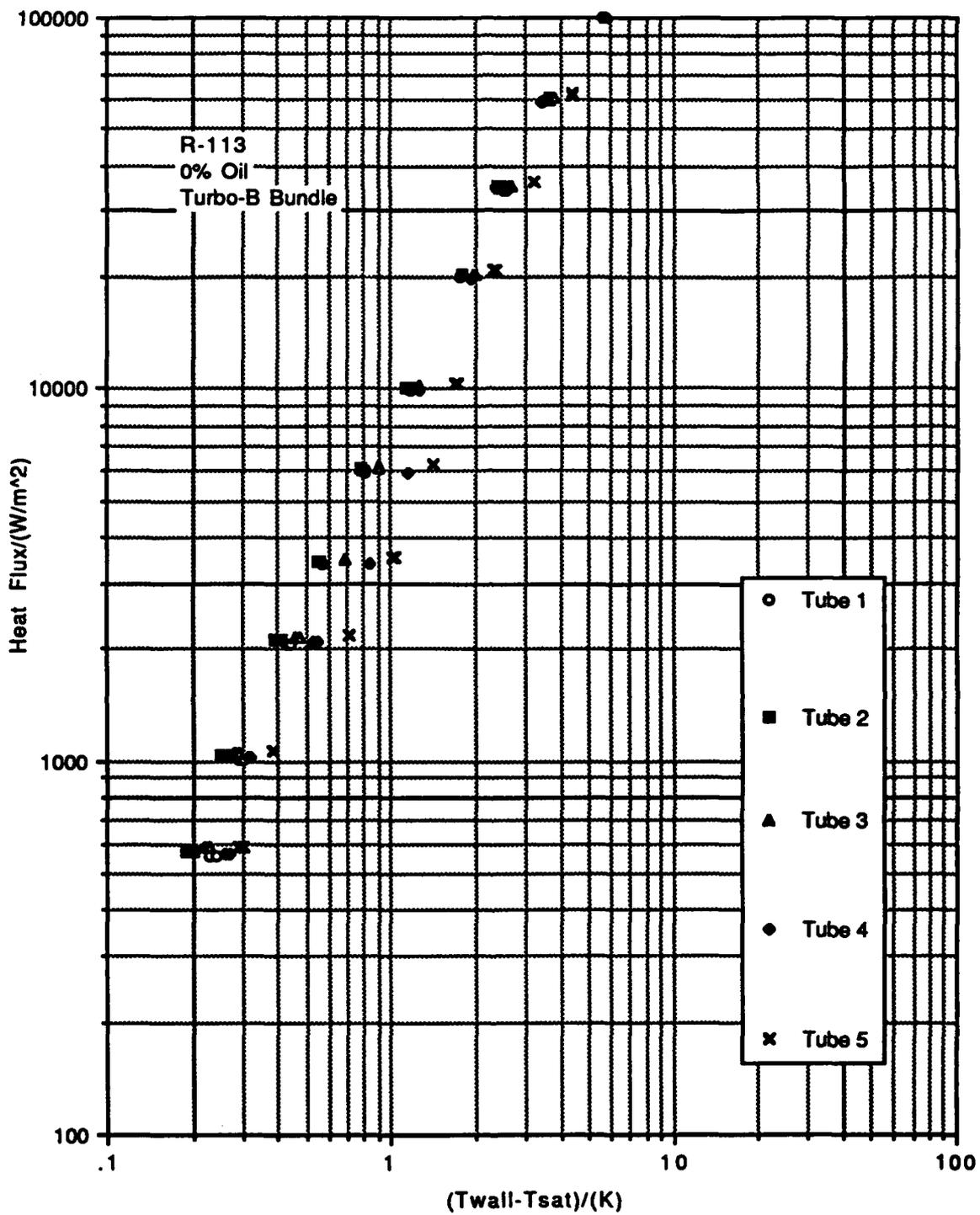


Figure 25. Performance Variation of the Bundle at a 10 cm Pool Height During a Decreasing Heat Flux (DTB48)

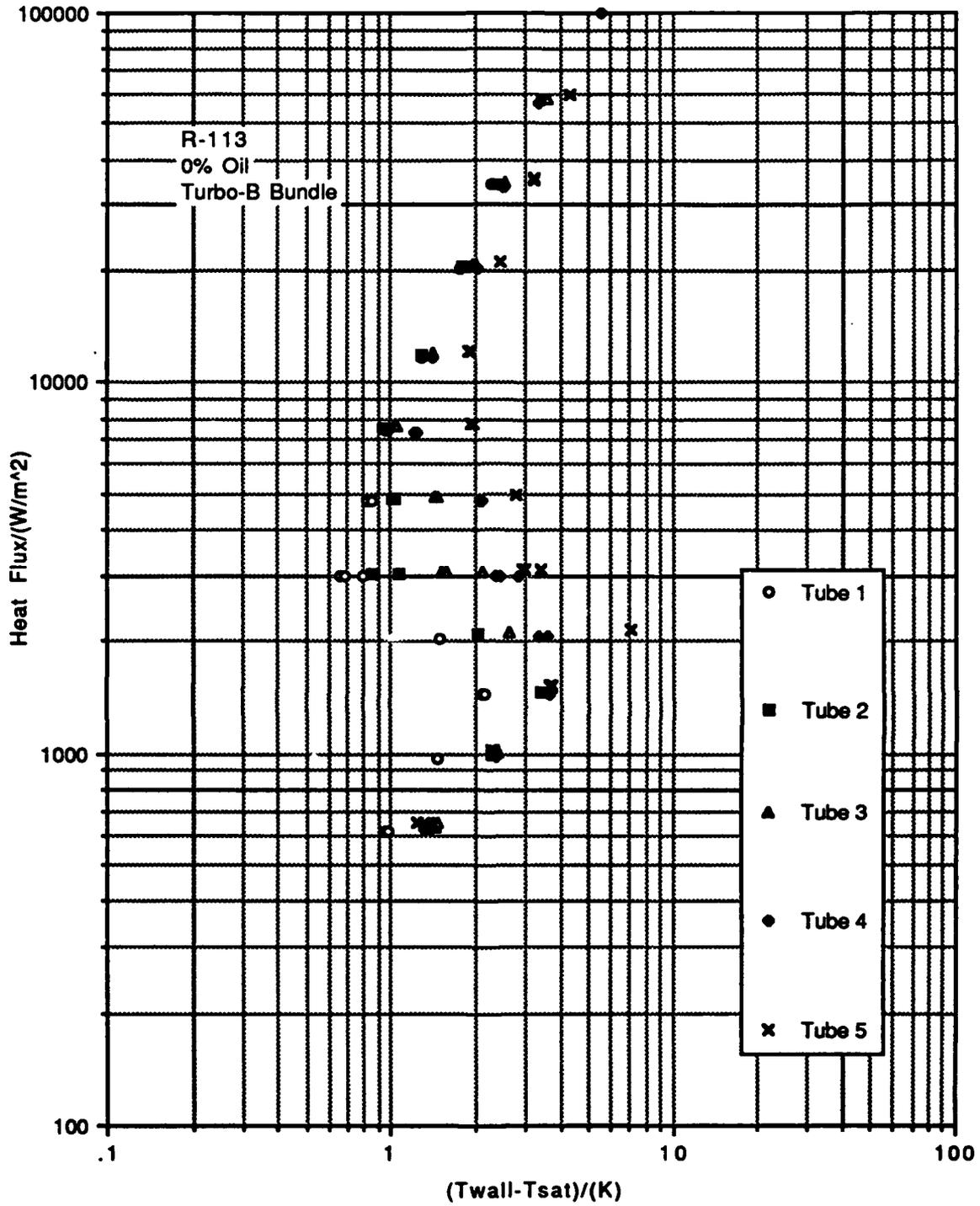


Figure 26. Performance Variation of the Bundle plus Simulation Heaters at a 10 cm Pool Height During a Increasing Heat Flux (ITB49)

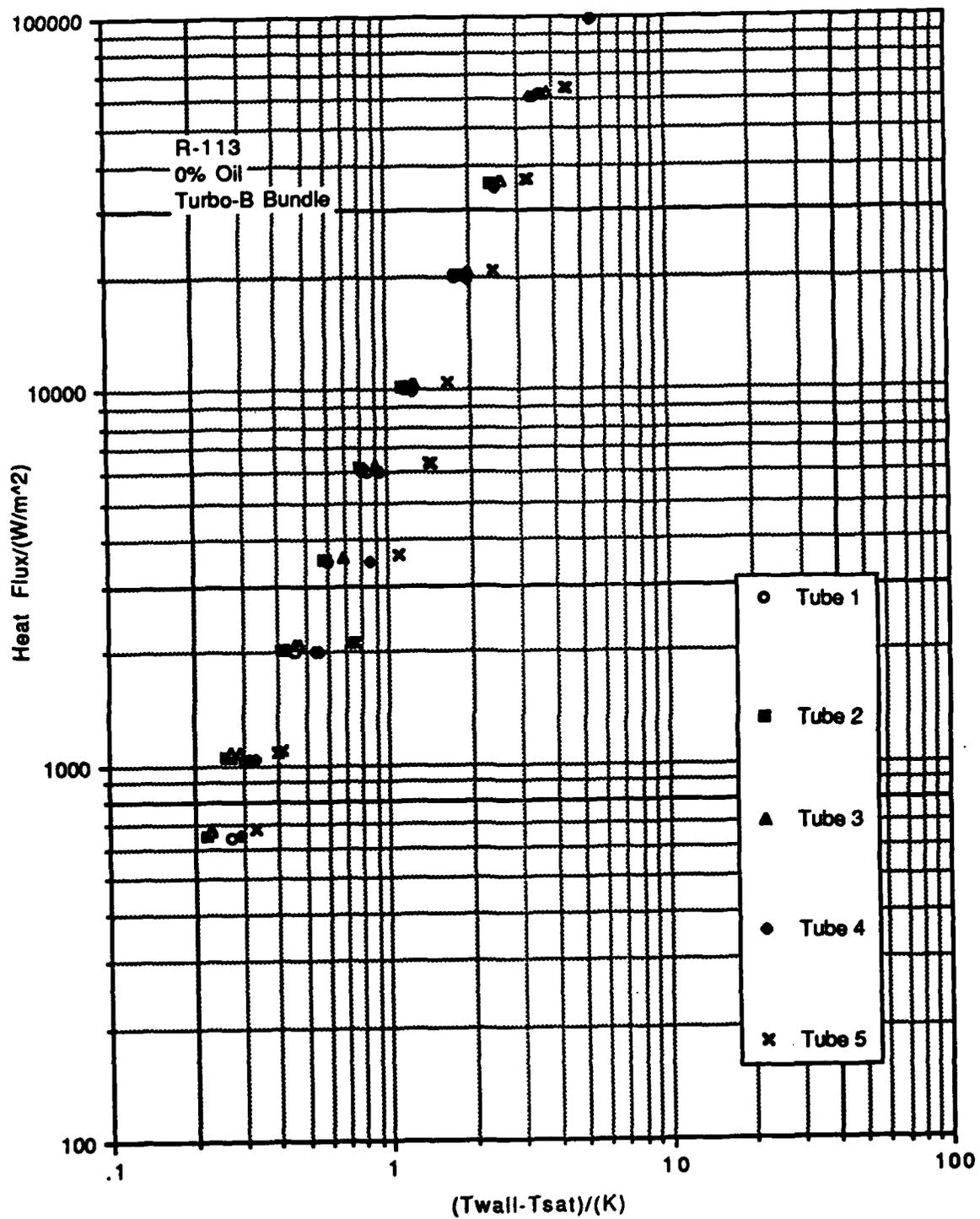


Figure 27. Performance Variation of the Bundle plus Simulation Heaters at a 10 cm Pool Height During a Decreasing Heat Flux (DTB49)

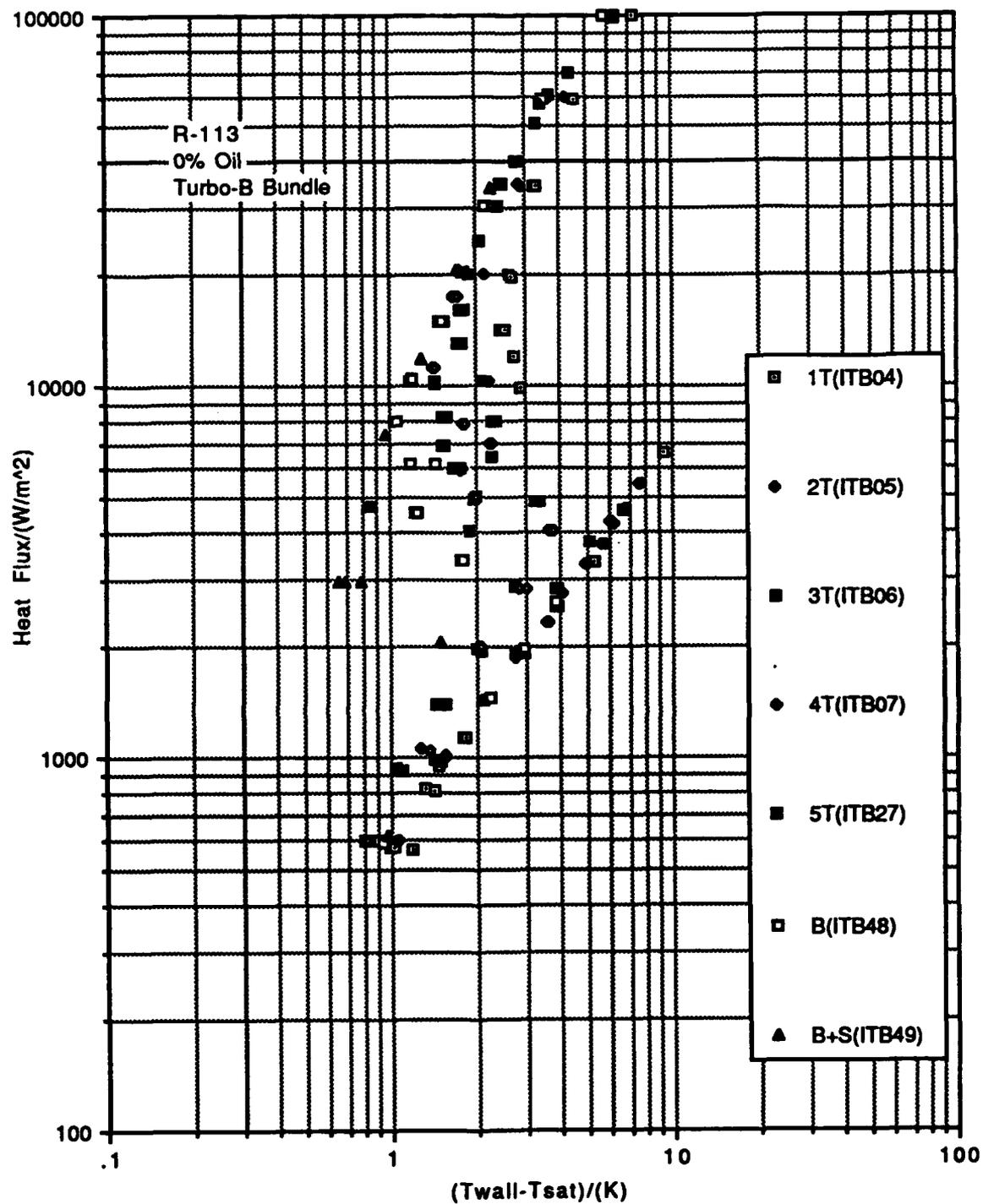


Figure 28. 10 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by a Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

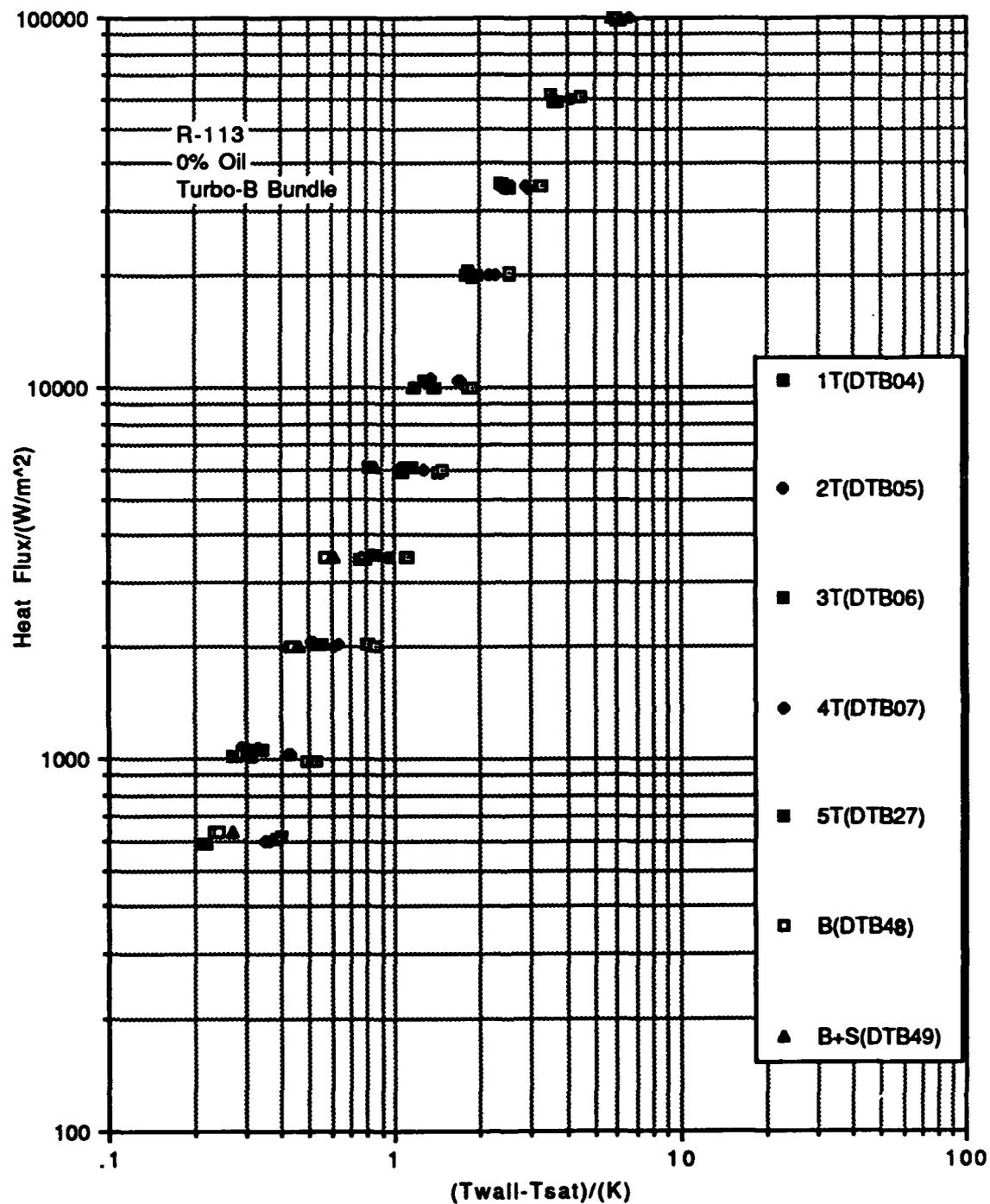


Figure 29. 10 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influence by a Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux

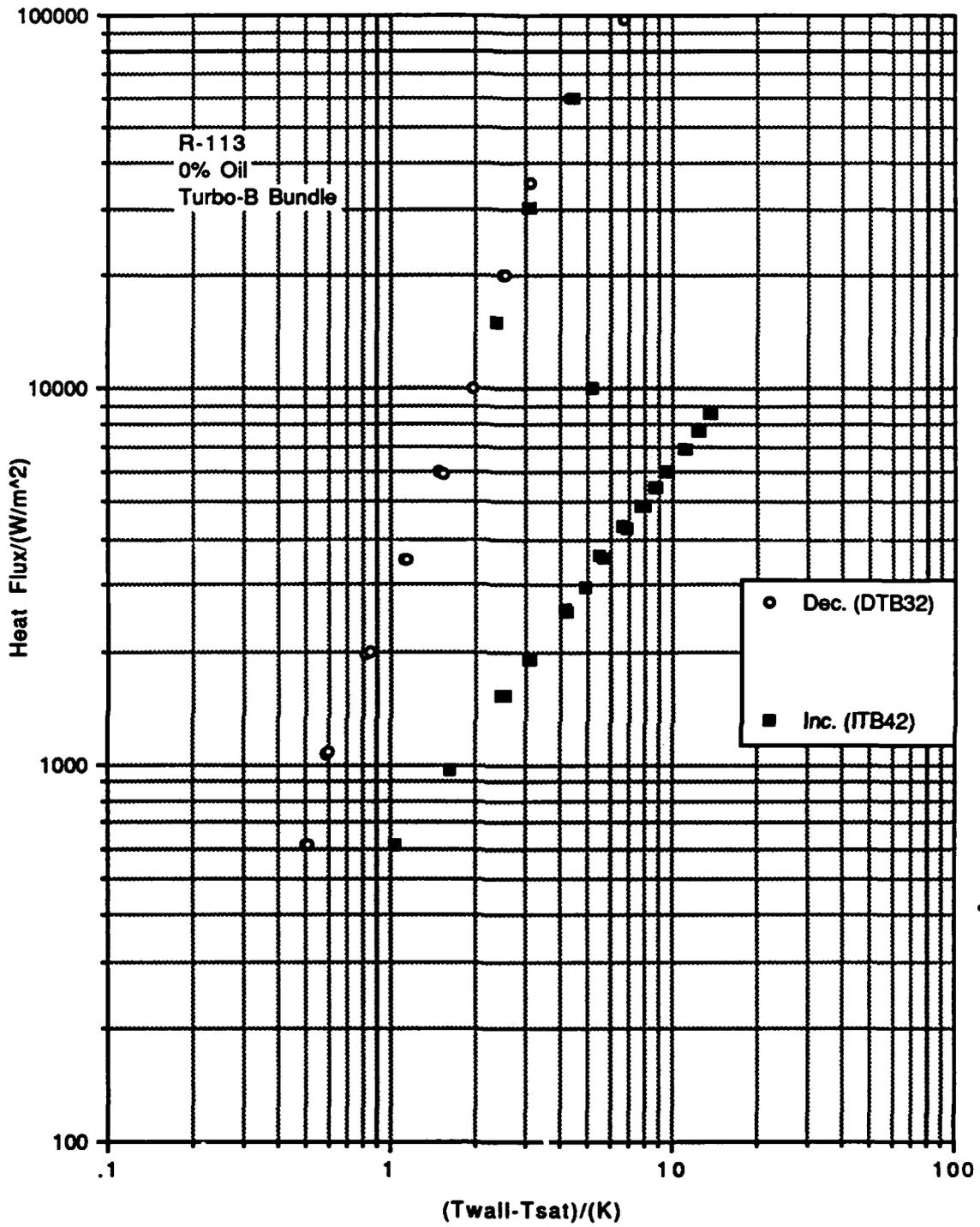


Figure 30. Performance of Tube 1 at a 20 cm Pool Height

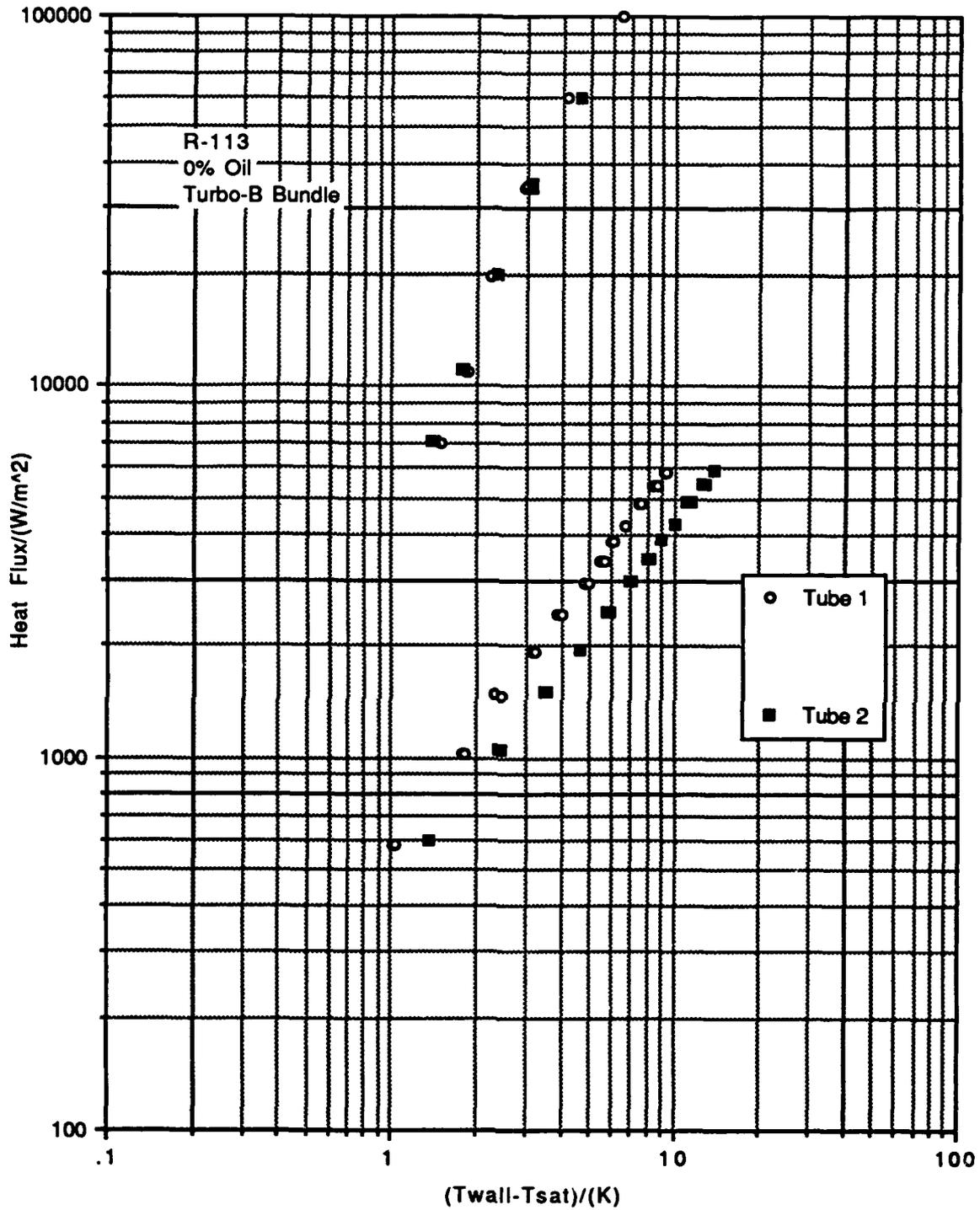


Figure 31. Performance Variation of Tubes 1&2 at a 20 cm Pool Height During a Increasing Heat Flux (ITB34)

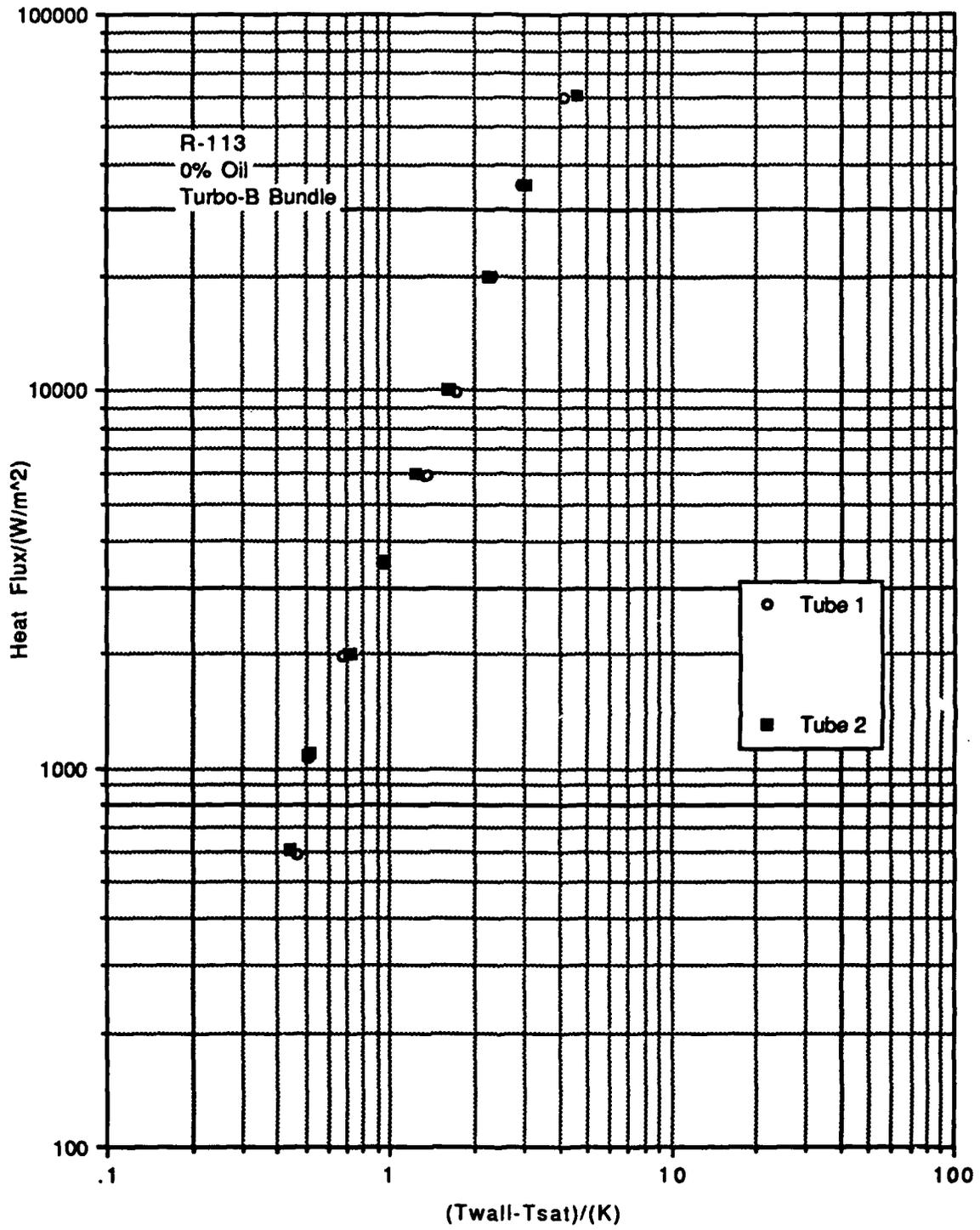


Figure 32. Performance Variation of Tubes 1&2 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB34)

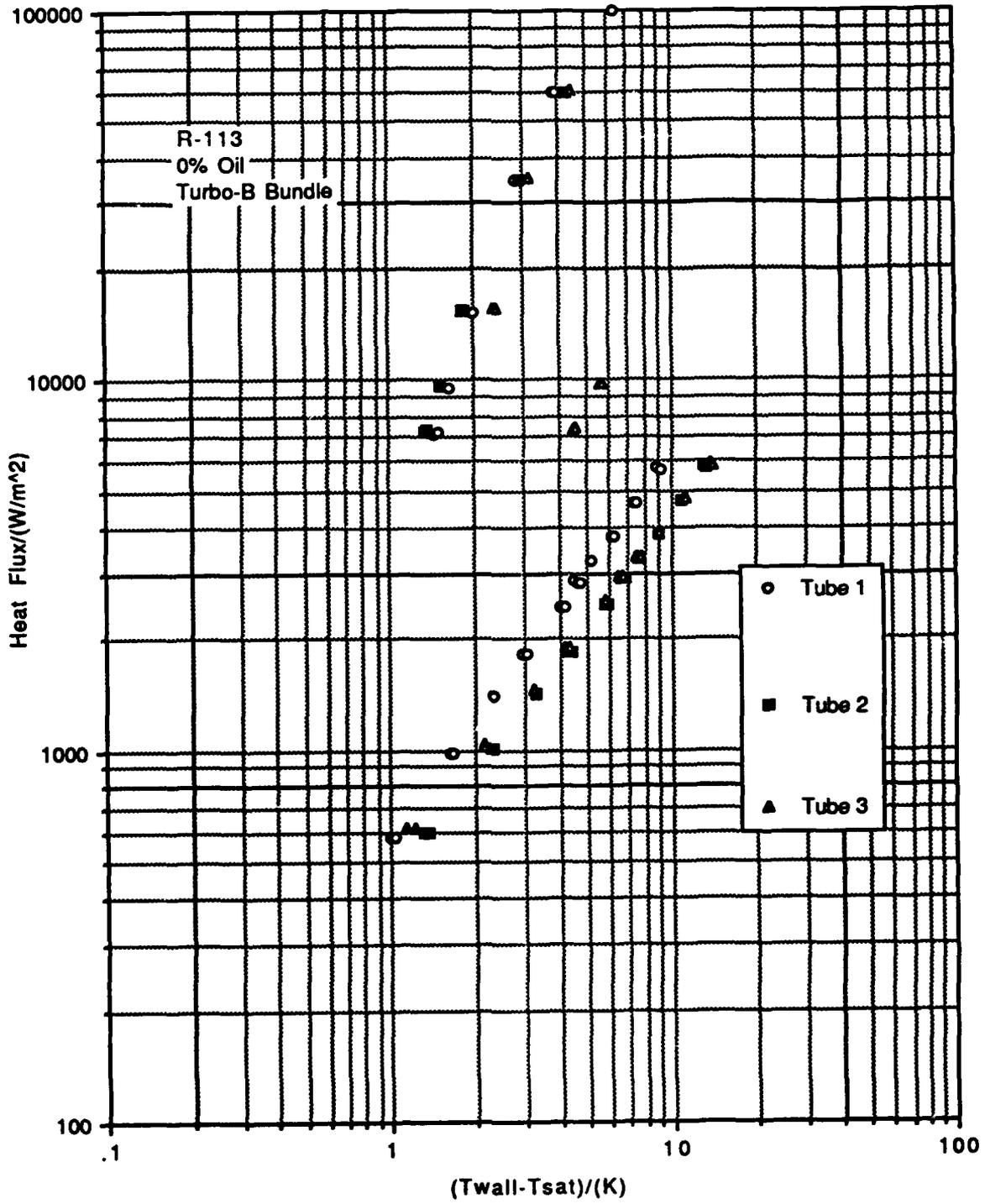


Figure 33. Performance Variation of Tubes 1 to 3 at a 20 cm Pool Height During a Increasing Heat Flux (ITB35)

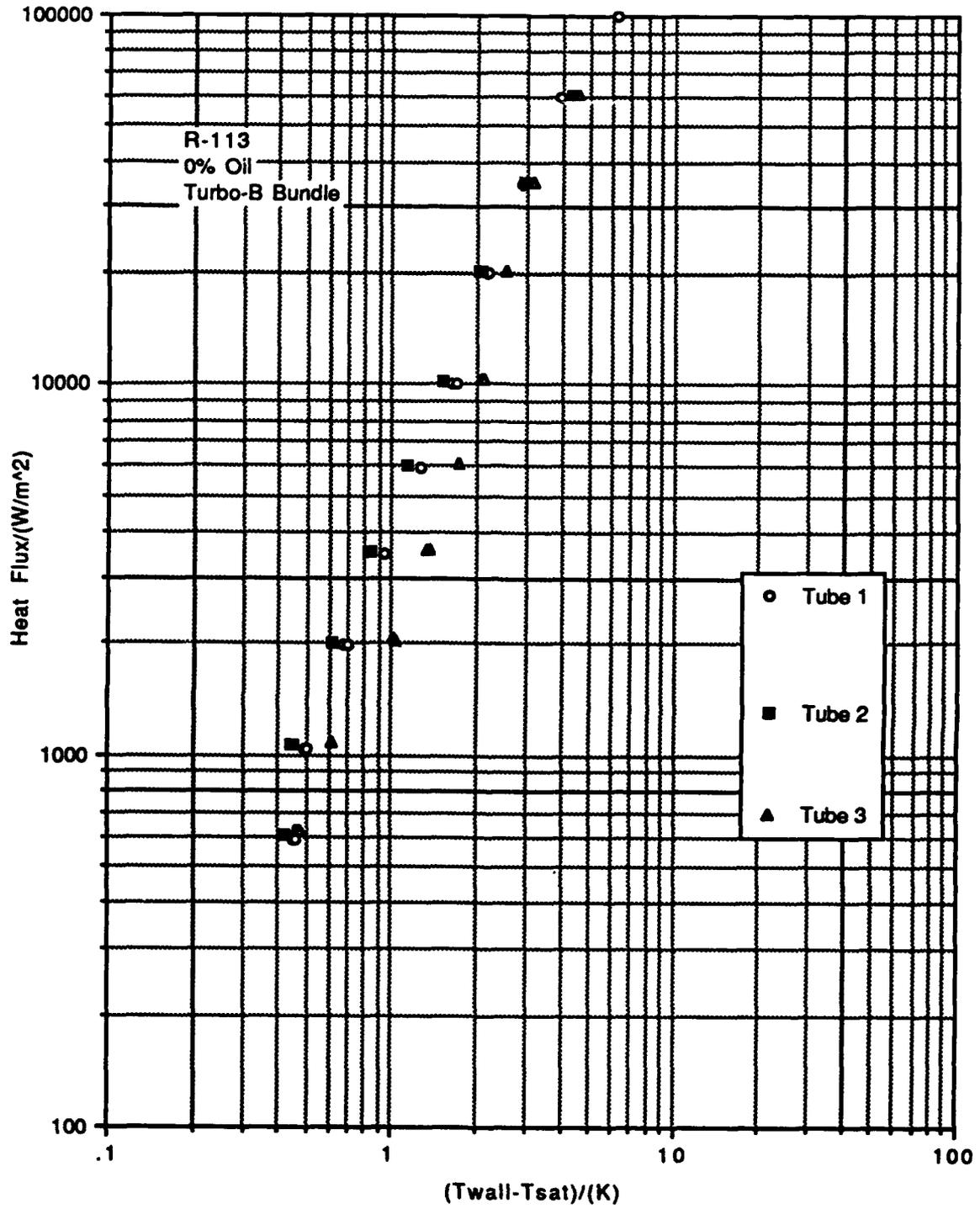


Figure 34. Performance Variation of Tubes 1 to 3 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB35)

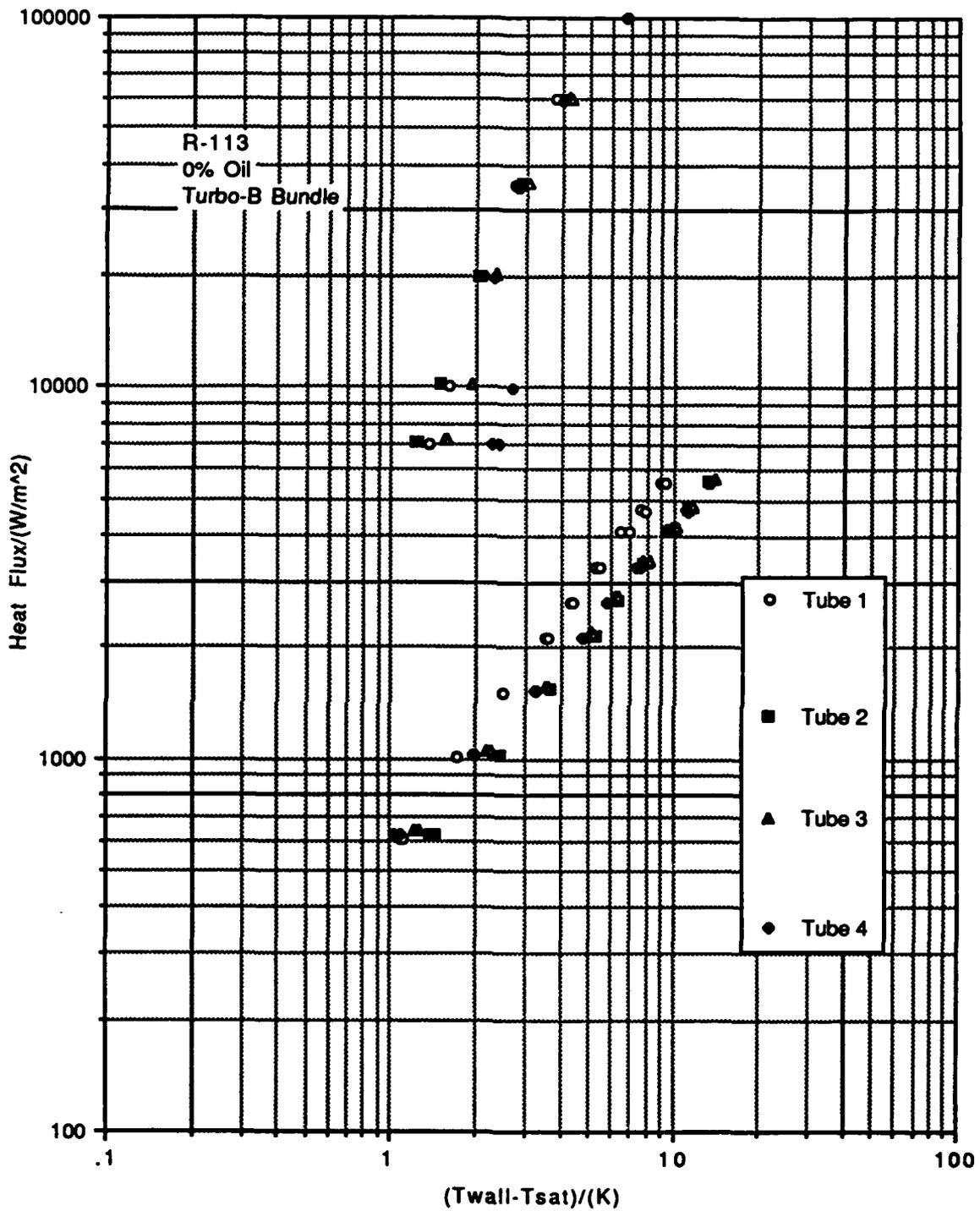


Figure 35. Performance Variation of Tubes 1 to 4 at a 20 cm Pool Height During a Increasing Heat Flux (ITB36)

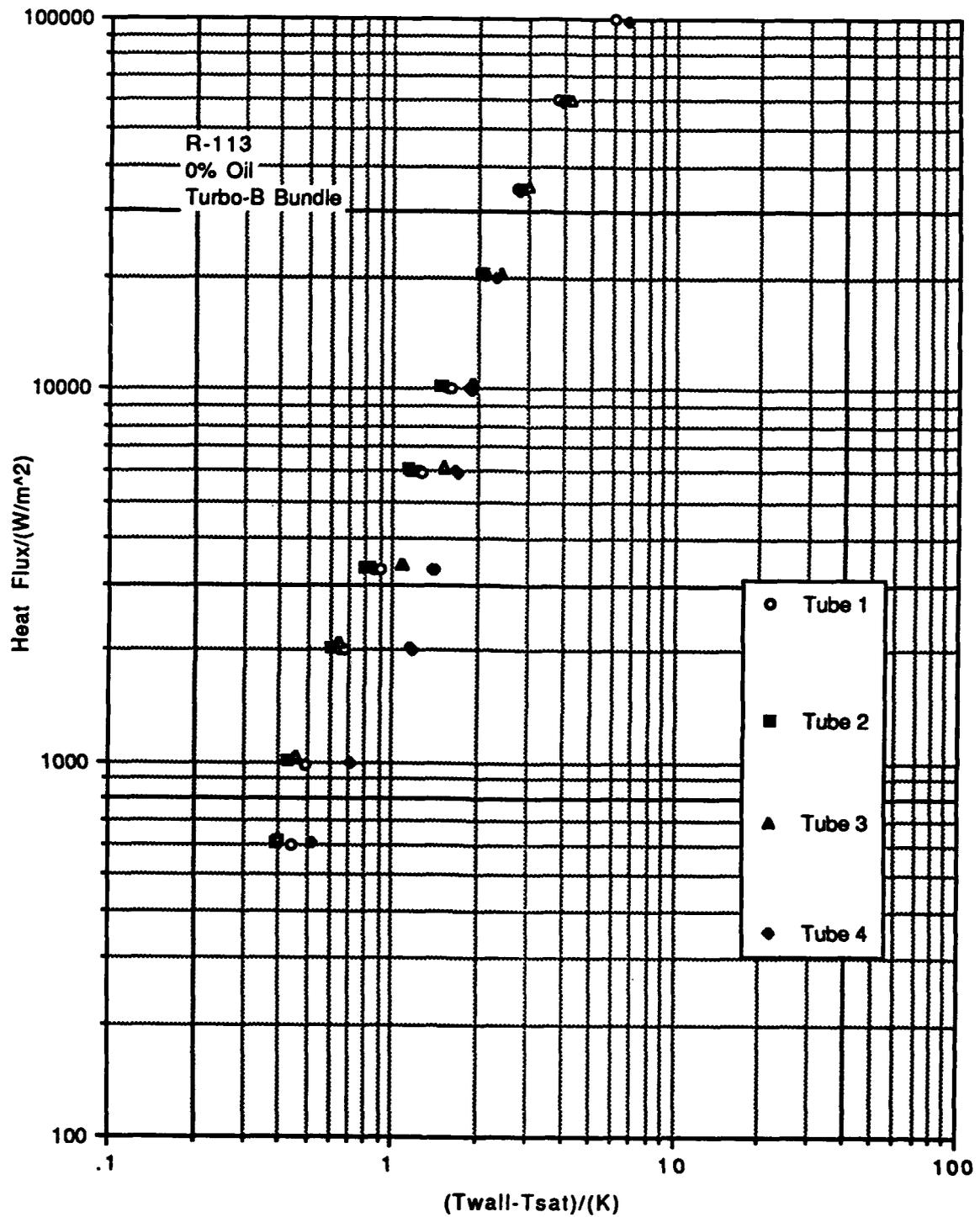


Figure 36. Performance Variation of Tubes 1 to 4 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB36)

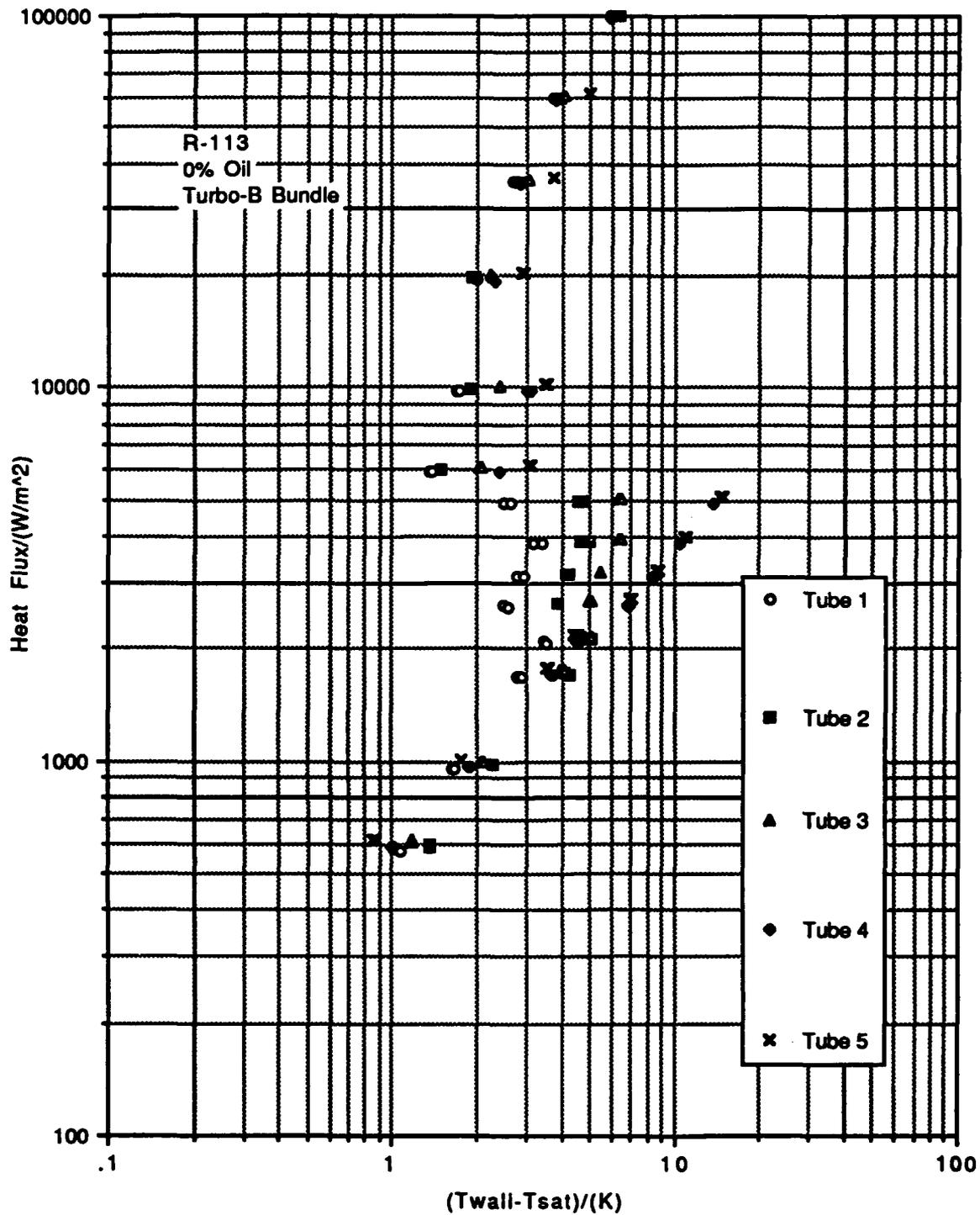


Figure 37. Performance Variation of Tubes 1 to 5 at a 20 cm Pool Height During a Increasing Heat Flux (ITB37)

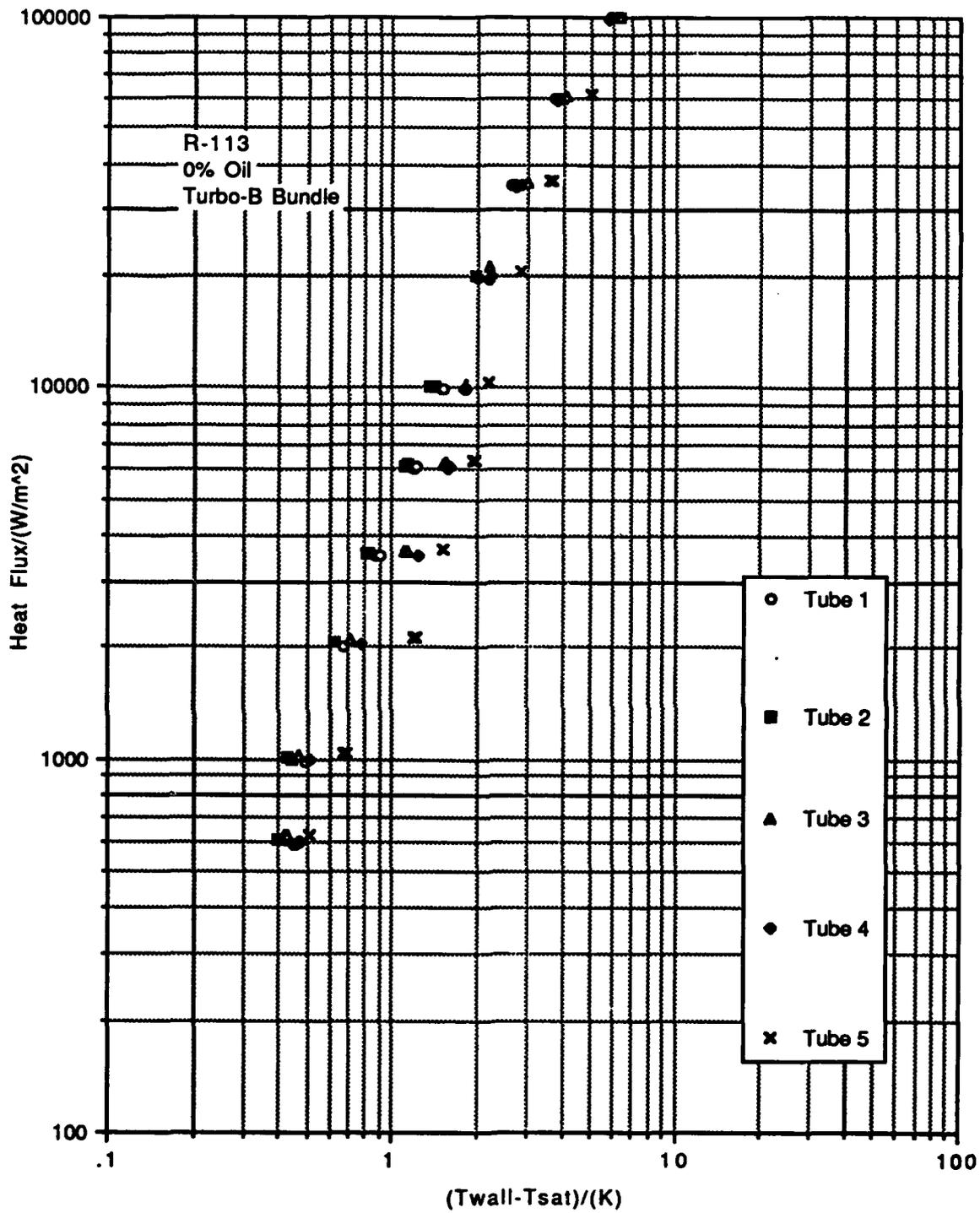


Figure 38. Performance Variation of Tubes 1 to 5 at a 20 cm Pool Height During a Decreasing Heat Flux (DTB37)

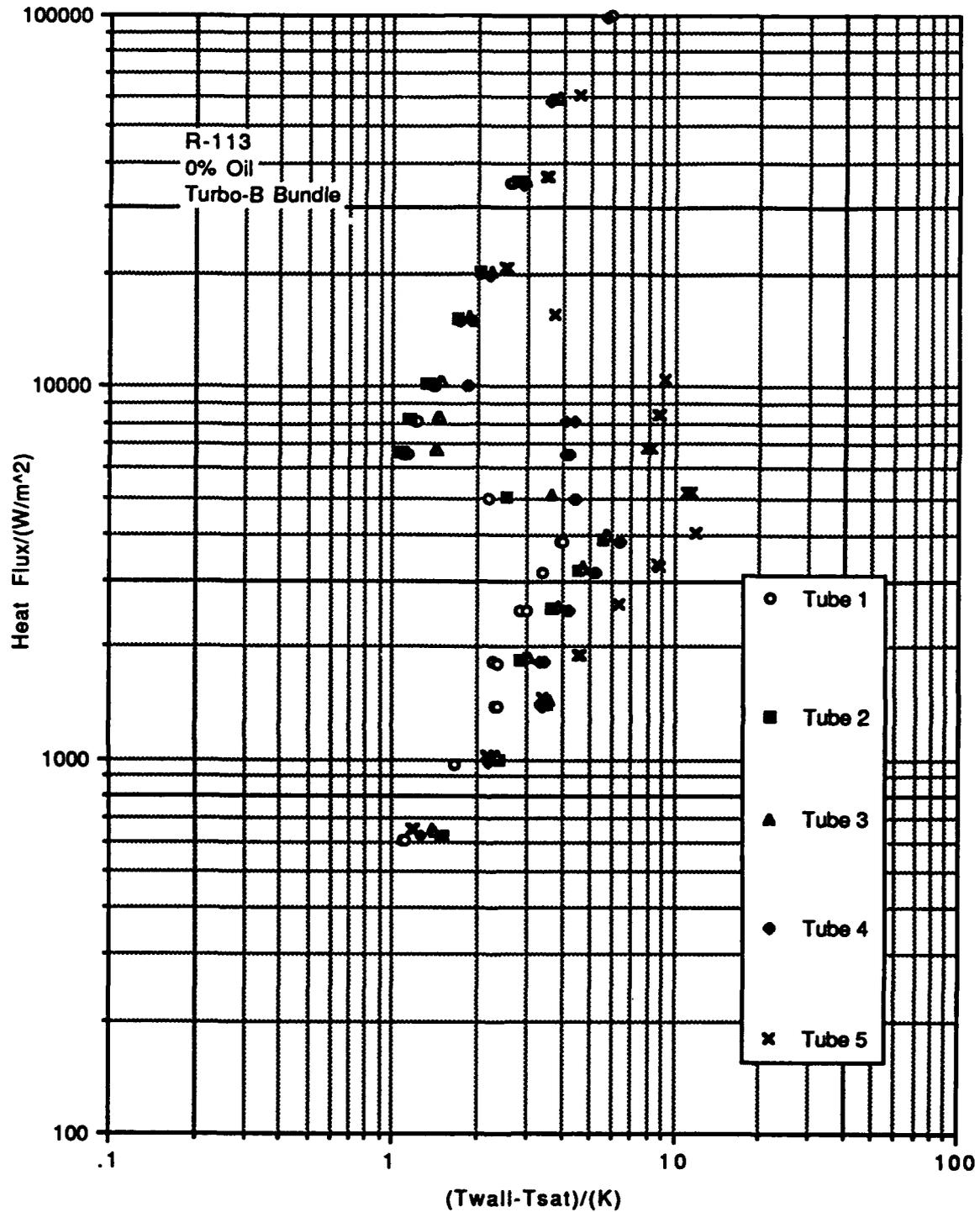


Figure 39. Performance Variation of the Bundle at a 20 cm Pool Height During a Increasing Heat Flux (ITB38)

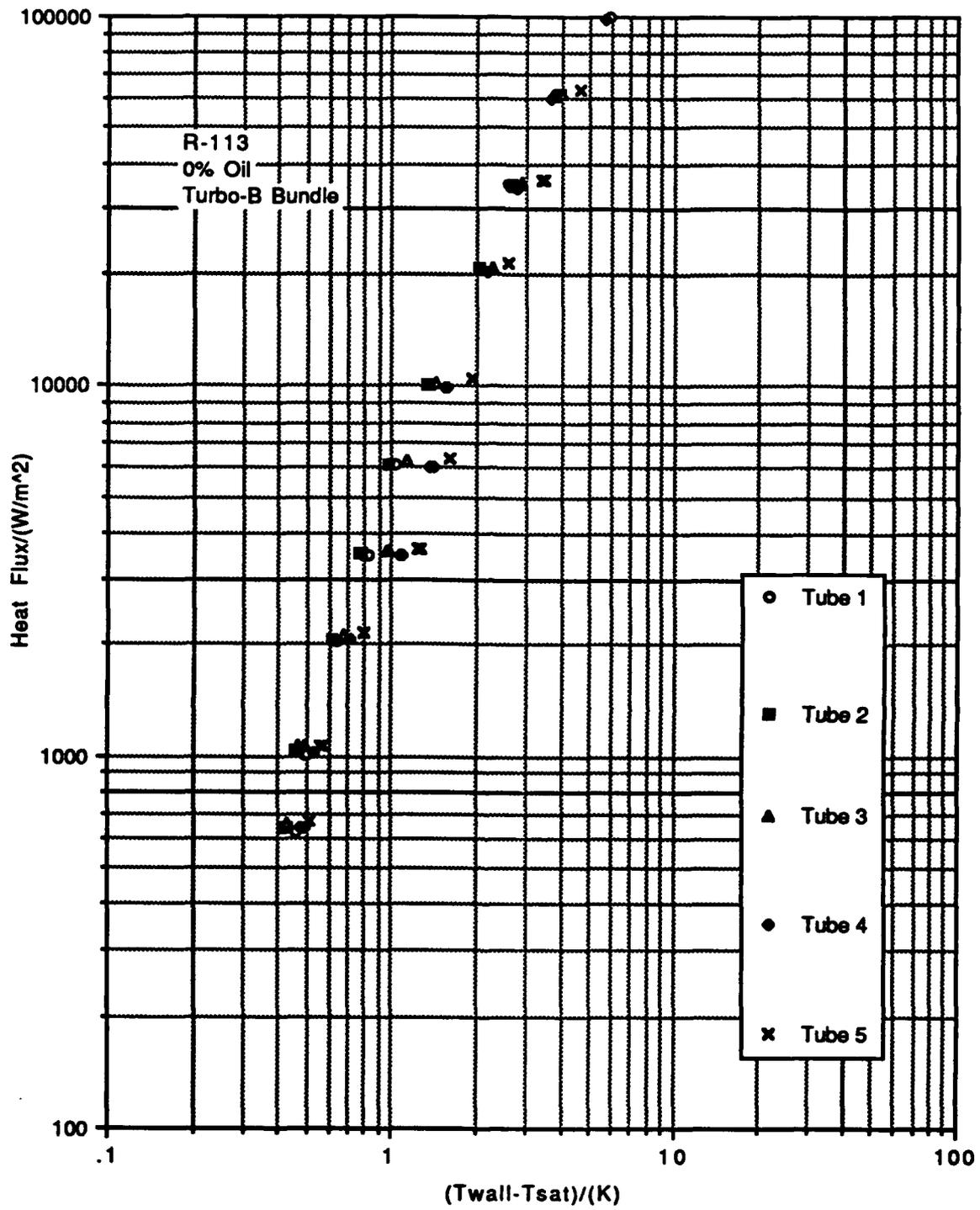


Figure 40. Performance Variation of the Bundle at a 20 cm Pool Height During a Decreasing Heat Flux (DTB38)

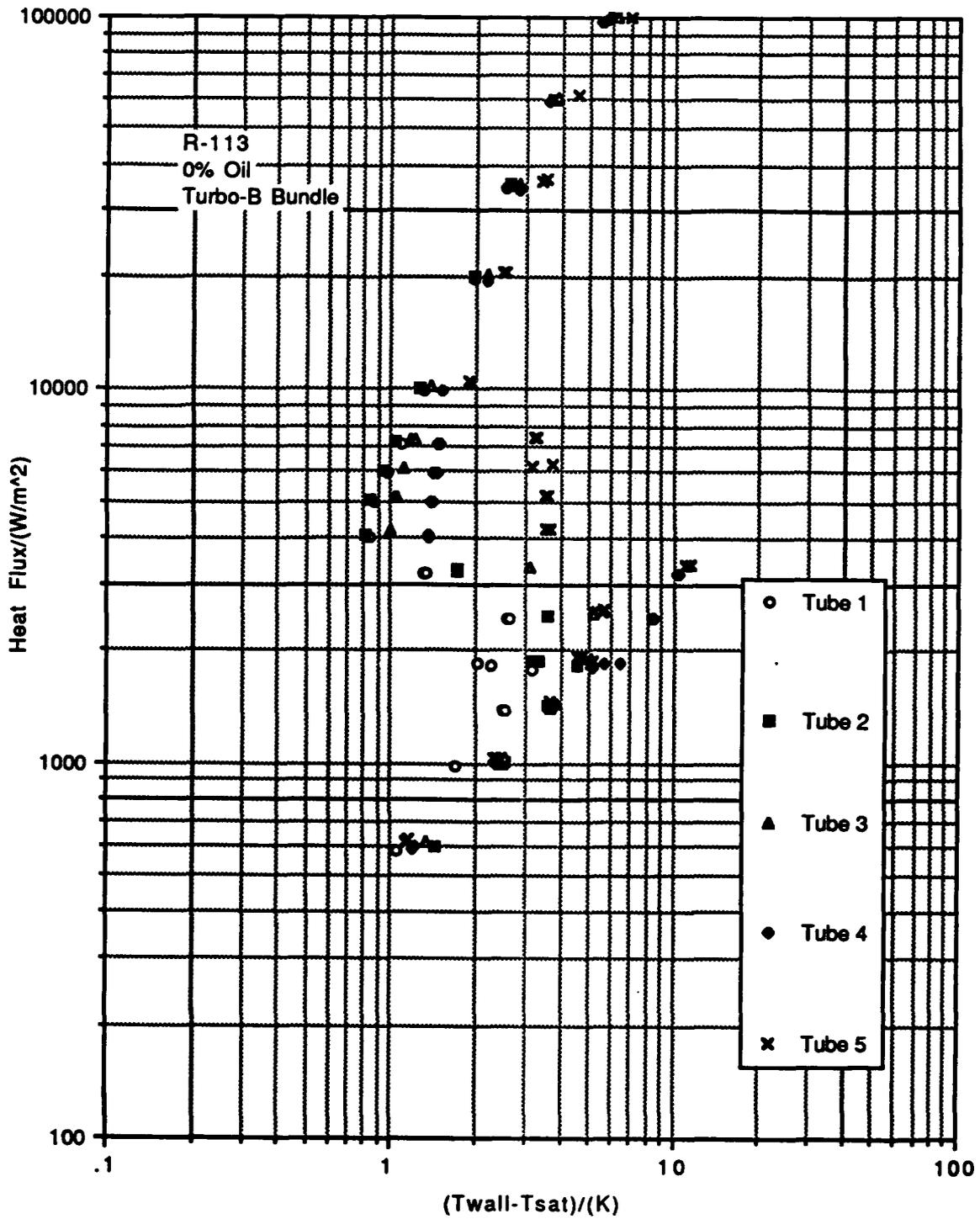


Figure 41. Performance Variation of the Bundle plus Simulation Heaters at a 20 cm Pool Height During a Increasing Heat Flux (ITB40)

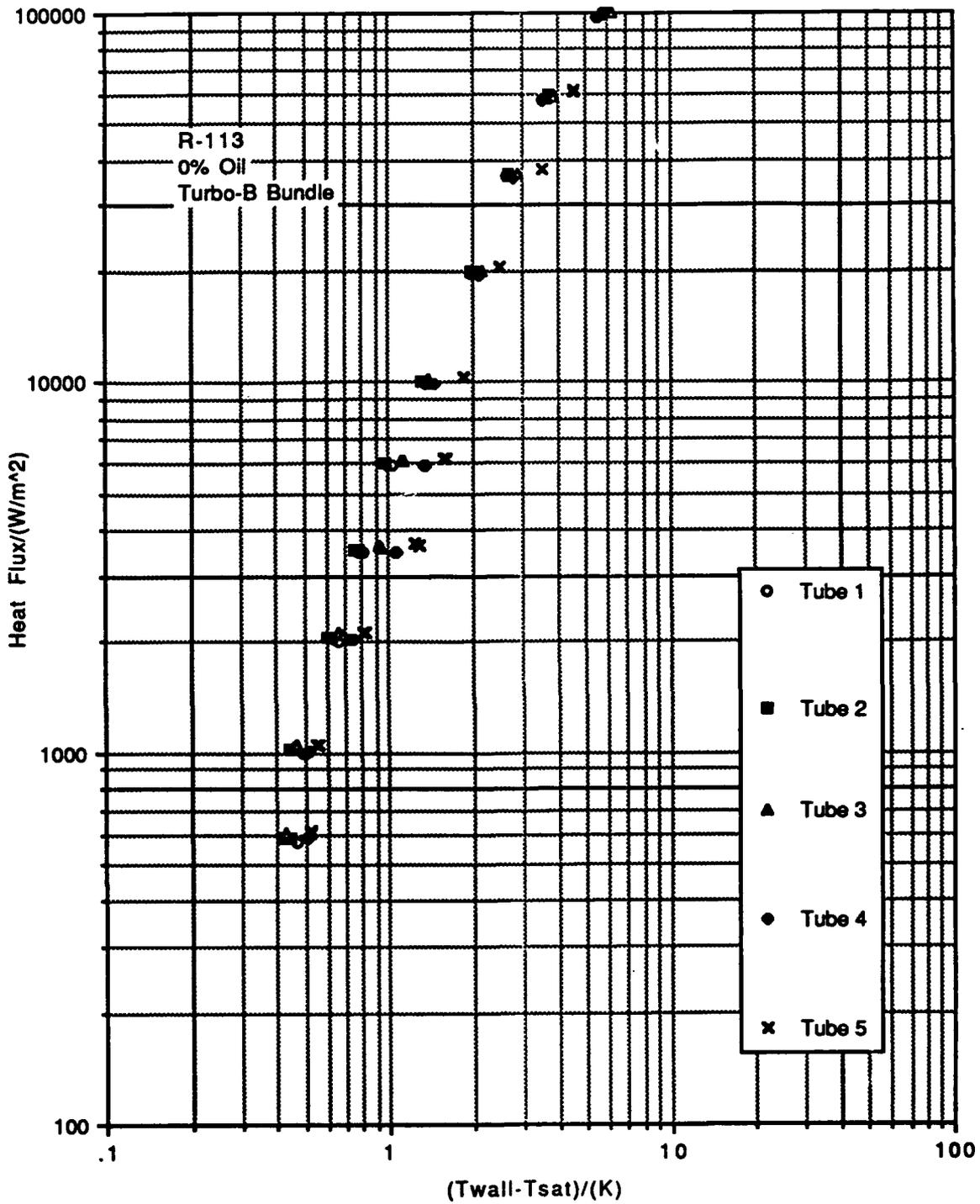


Figure 42. Performance Variation of the Bundle plus Simulation Heaters at a 20 cm Pool Height During a Decreasing Heat Flux (DTB40)

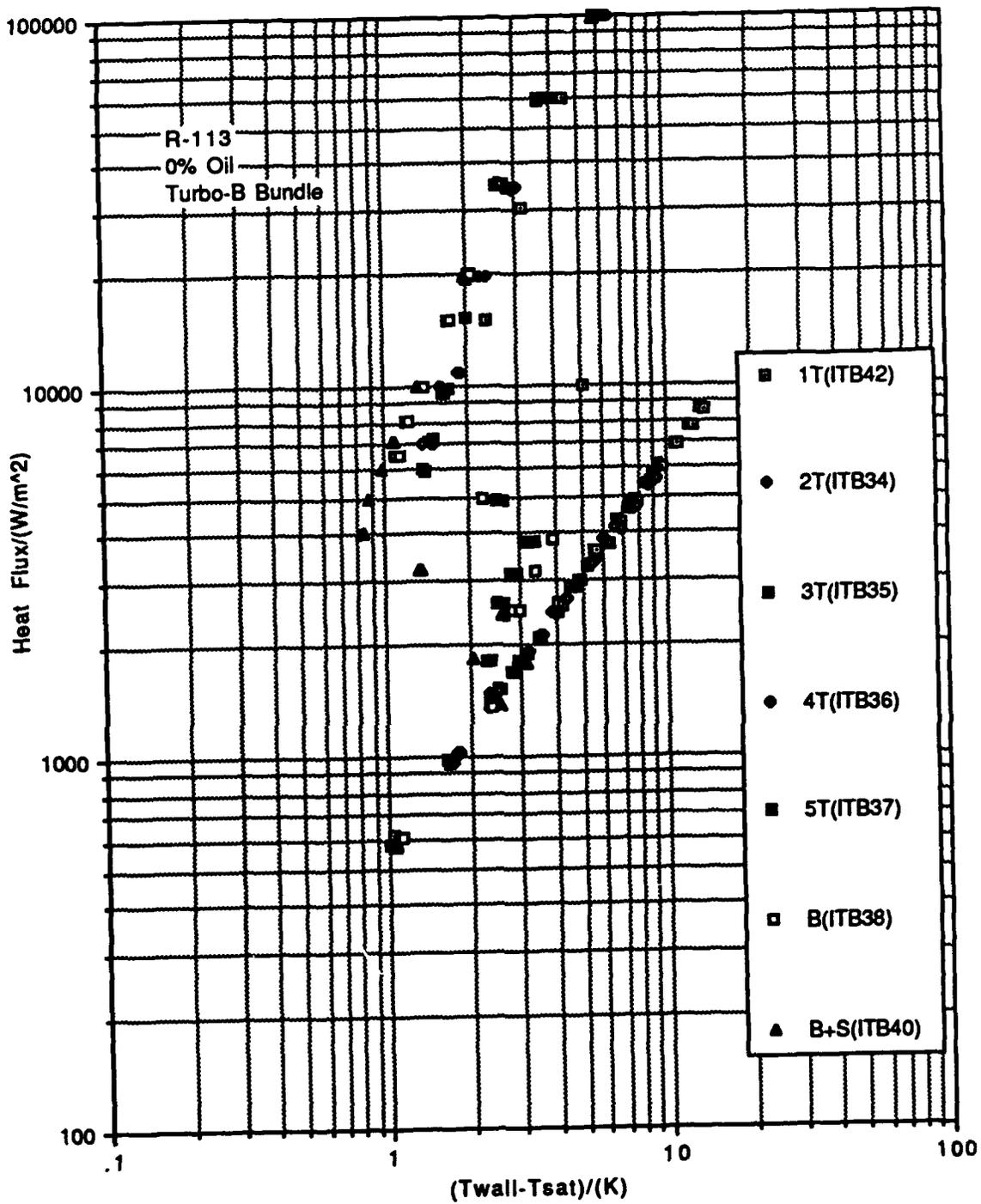


Figure 43. 20 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

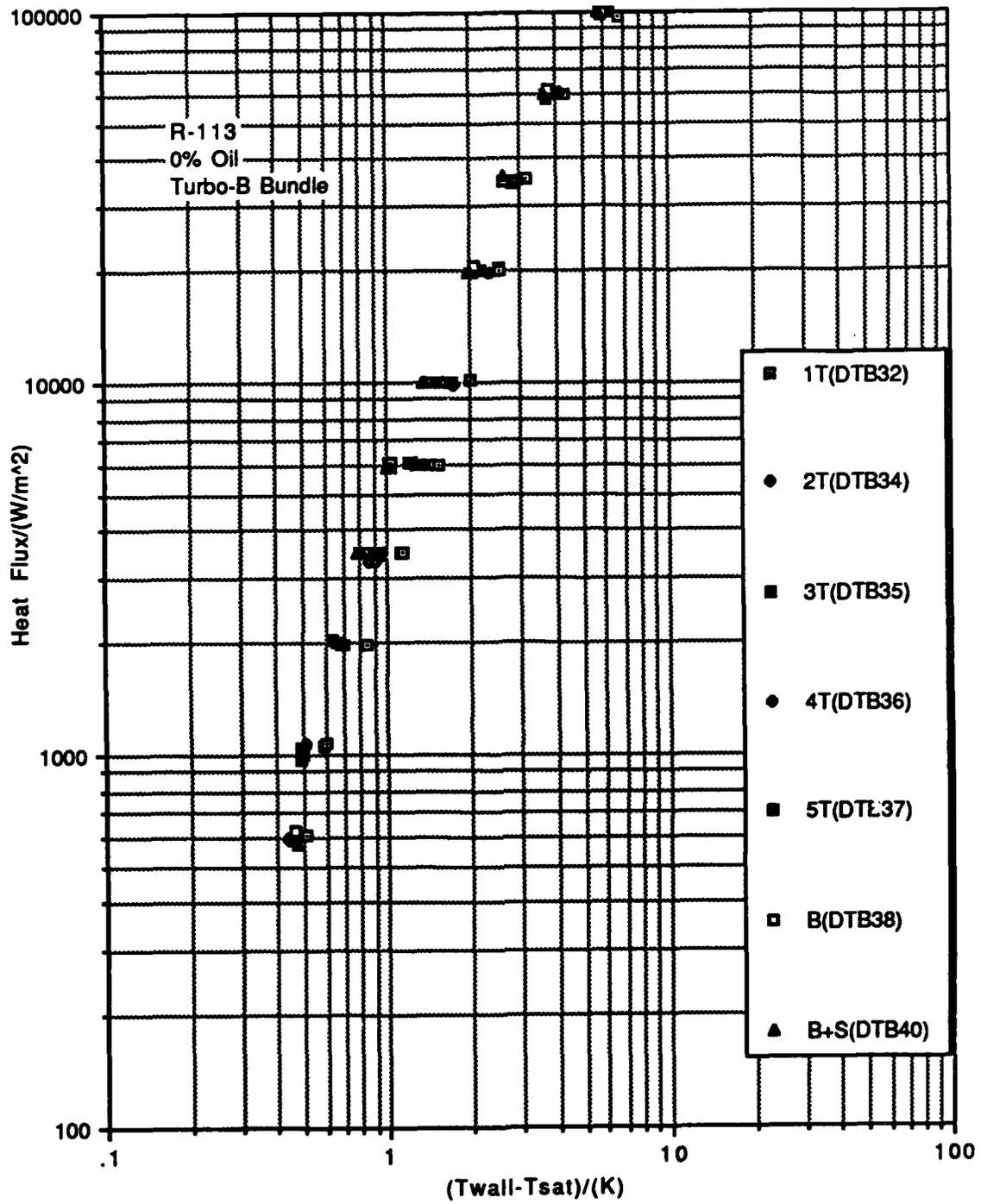


Figure 44. 20 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux.

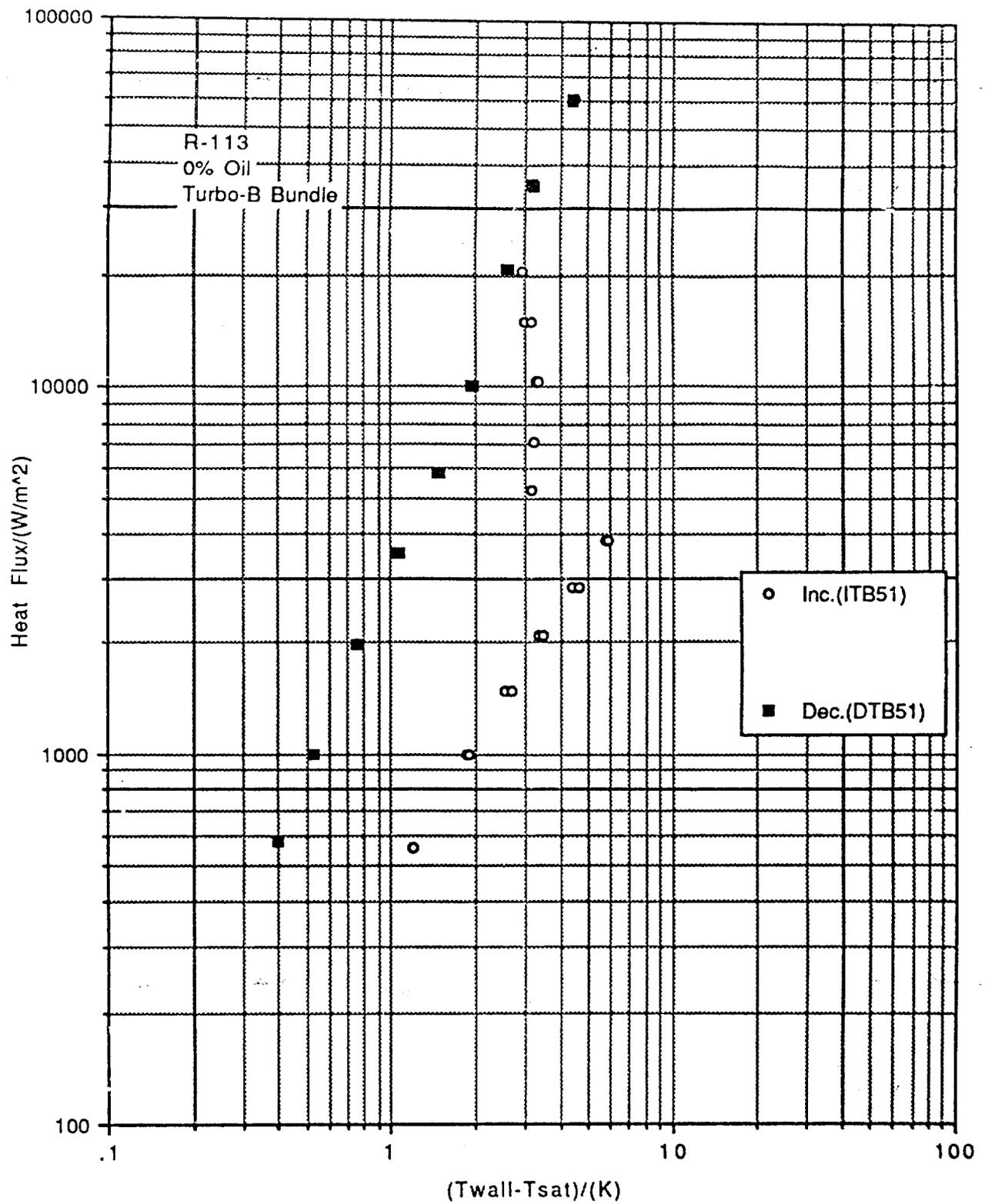


Figure 45. Performance of Tube 1 at a 0 cm Pool Height

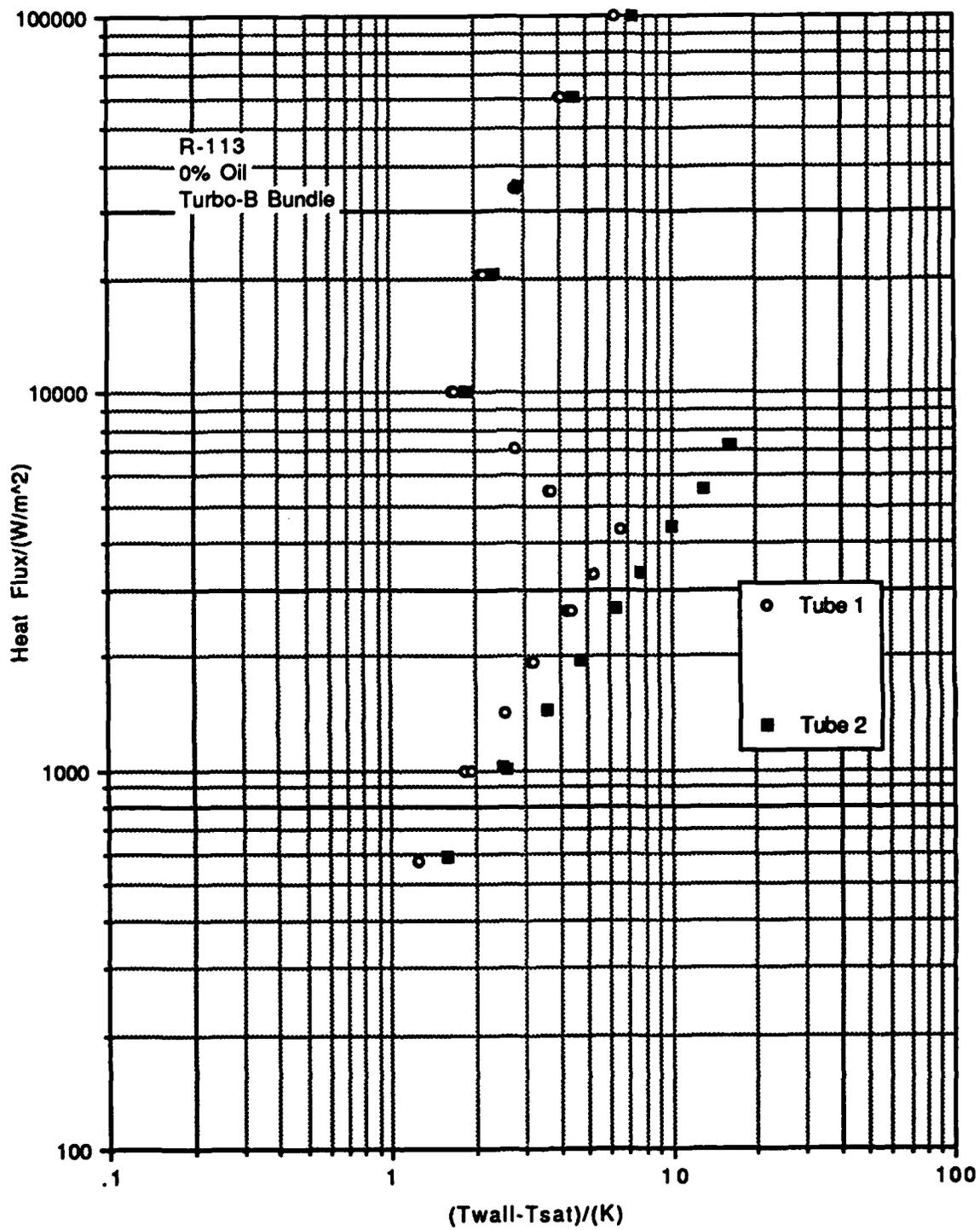


Figure 46. Performance Variation of Tubes 1&2 at a 0 cm Pool Height During a Increasing Heat Flux (ITB52)

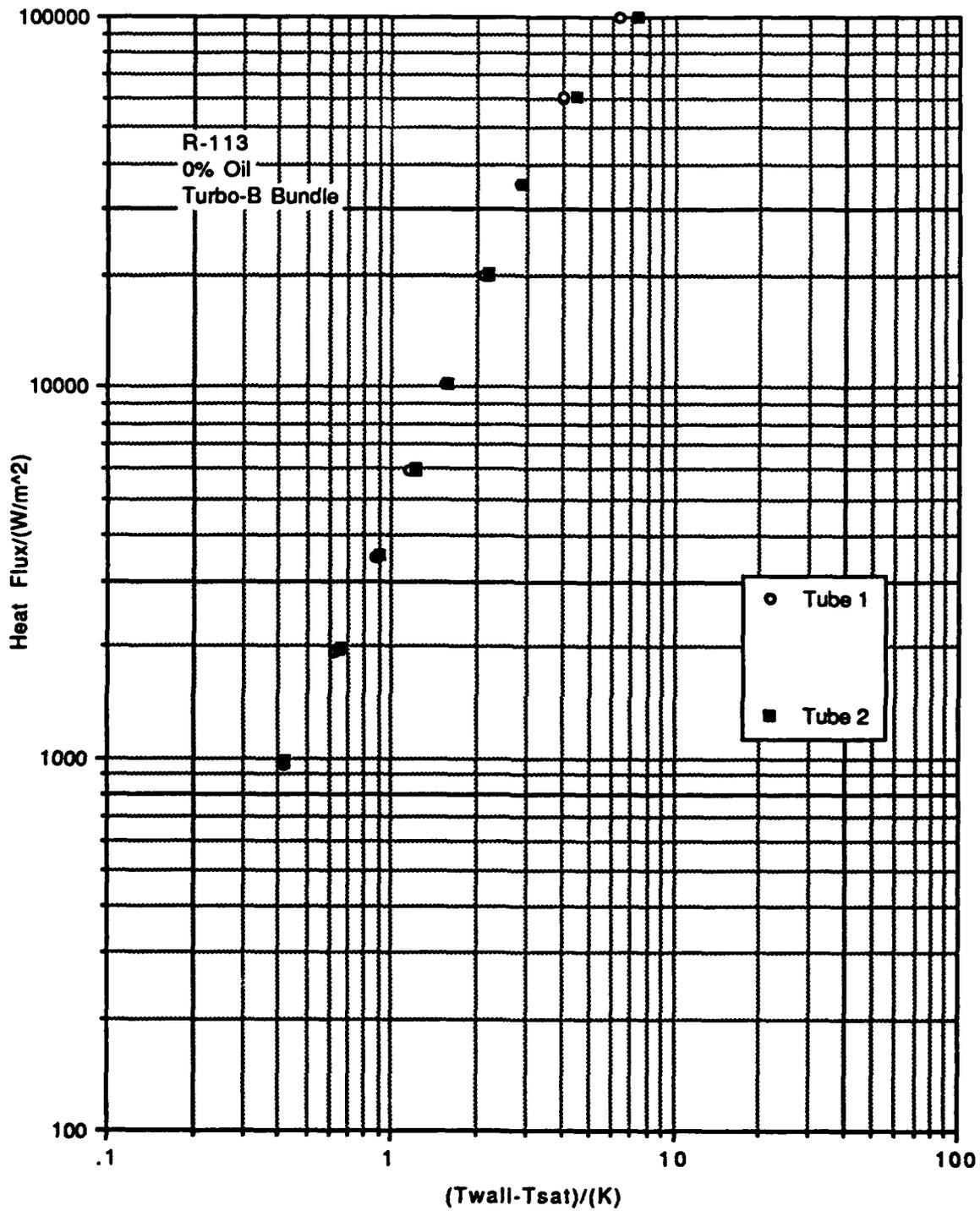


Figure 47. Performance Variation of Tubes 1&2 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB52)

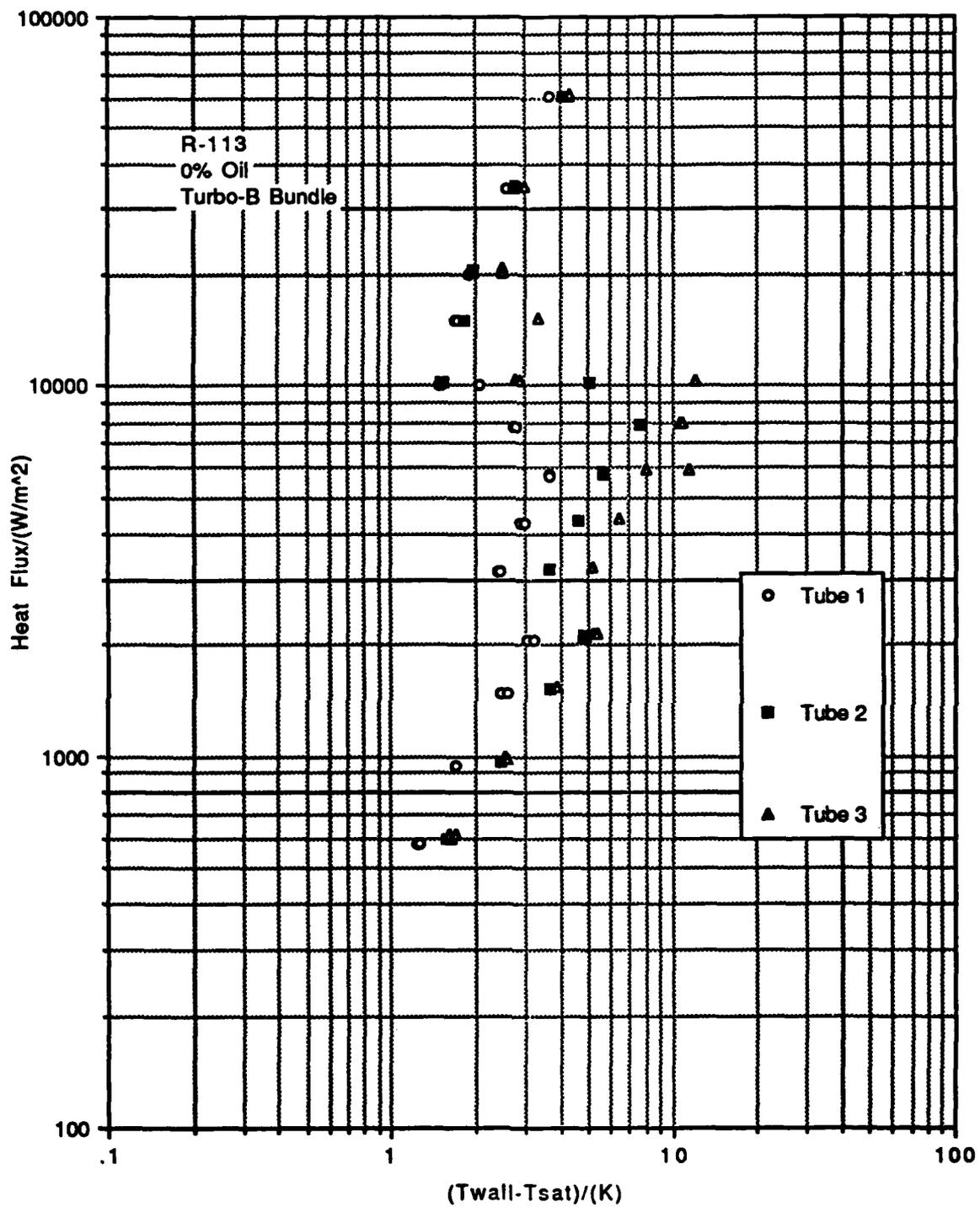


Figure 48. Performance Variation of Tubes 1 to 3 at a 0 cm Pool Height During a Increasing Heat Flux (ITB53)

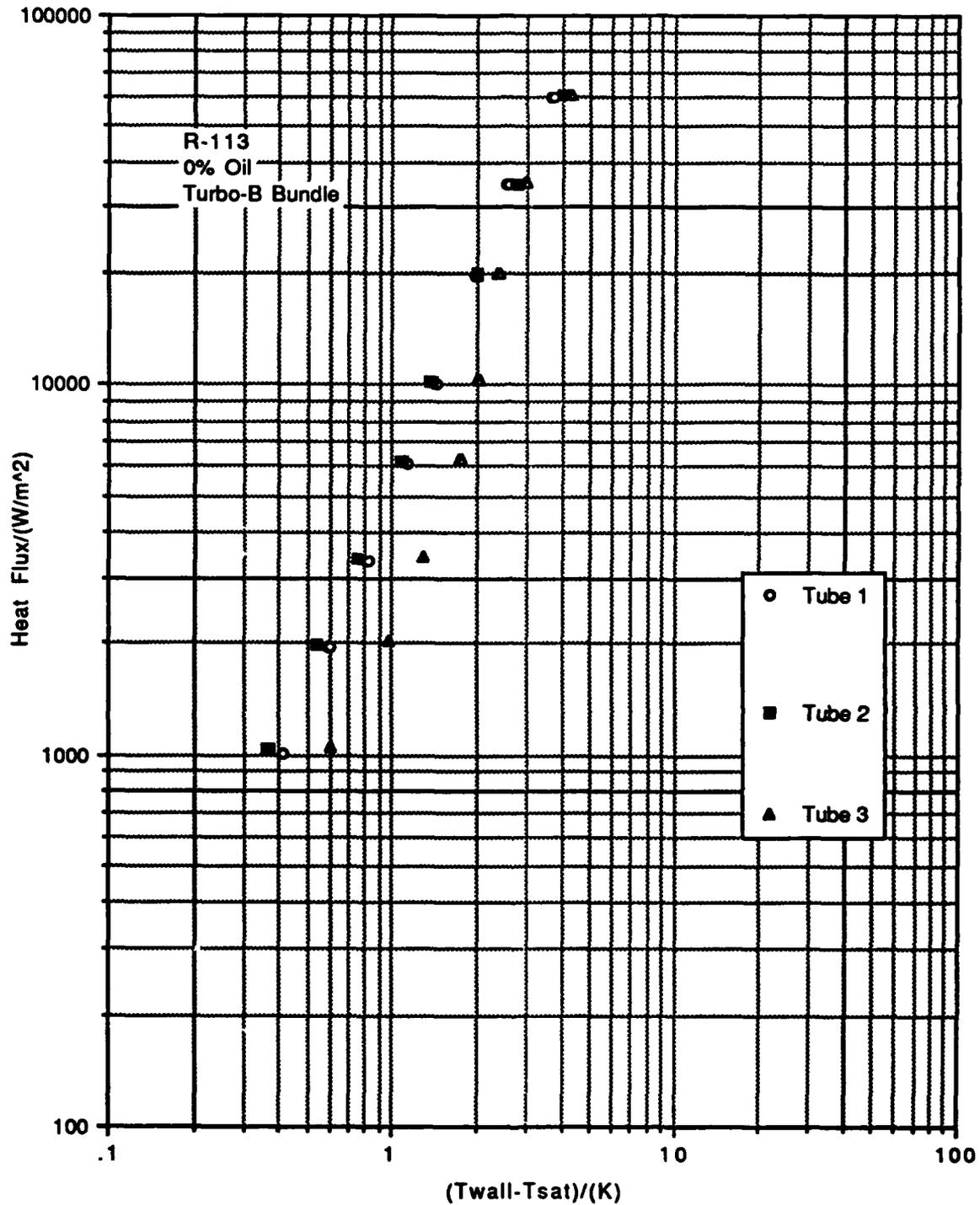


Figure 49. Performance Variation of Tubes 1 to 3 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB53)

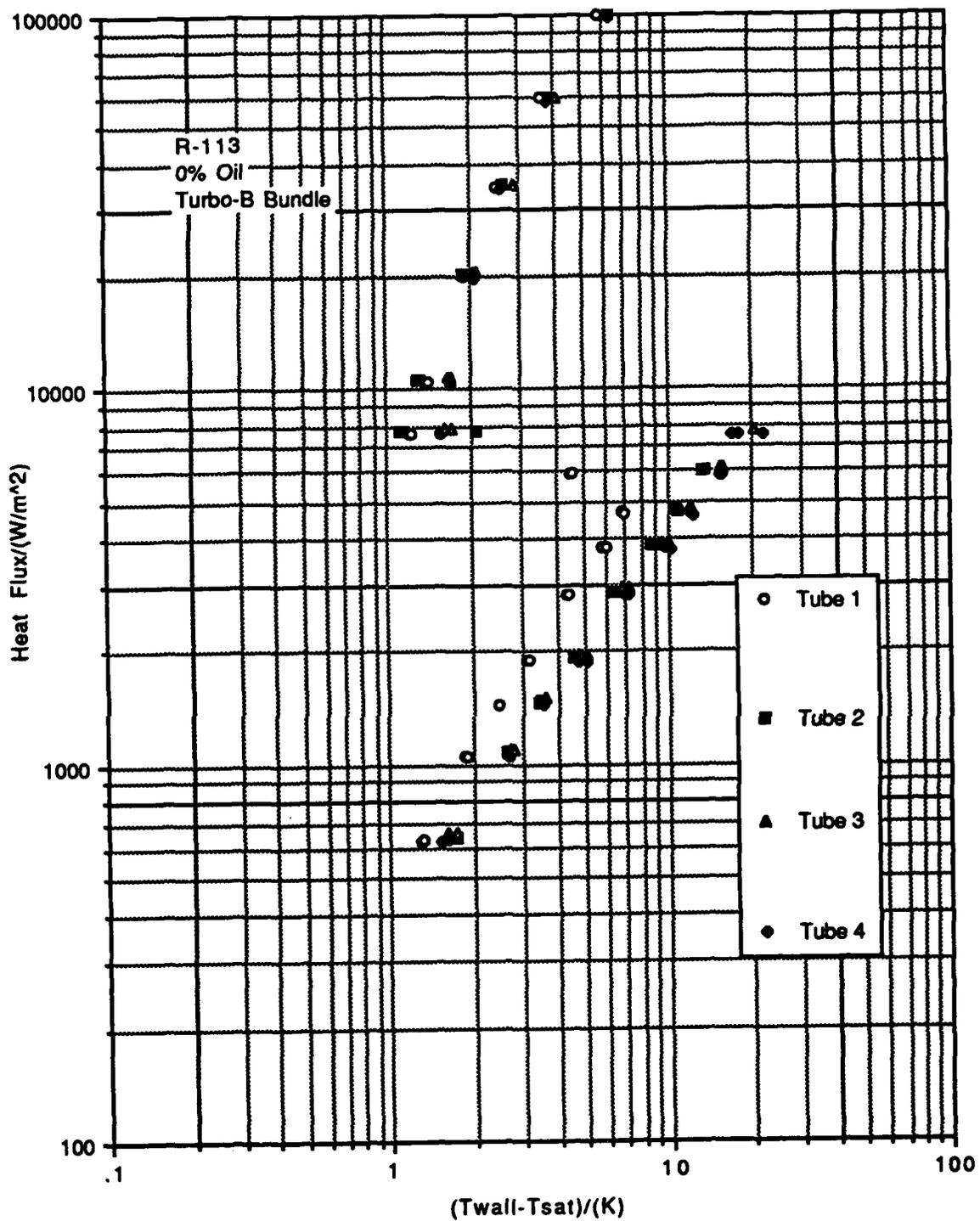


Figure 50. Performance Variation of Tubes 1 to 4 at a 0 cm Pool Height During a Increasing Heat Flux (ITB55)

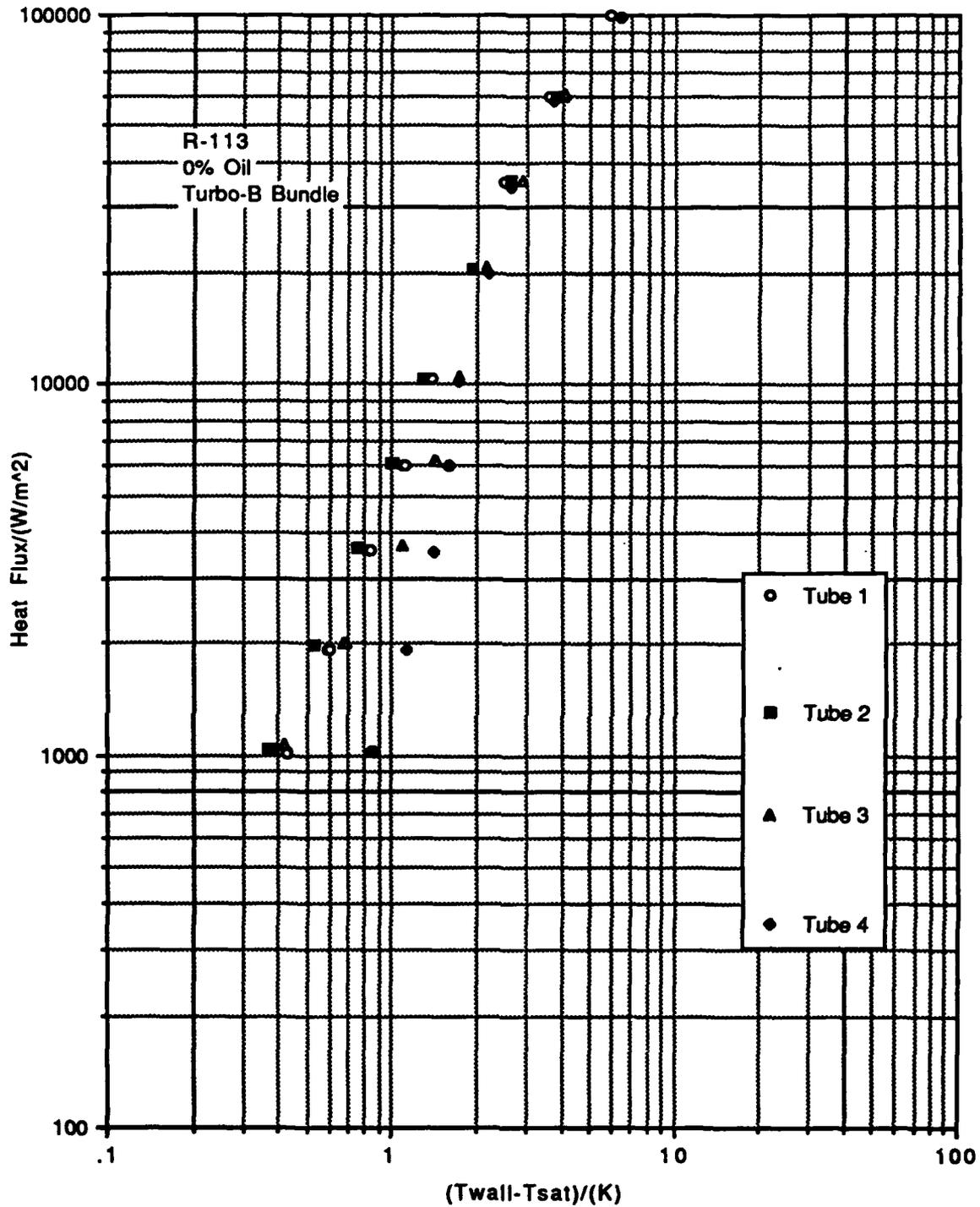


Figure 51. Performance Variation of Tubes 1 to 4 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB55)

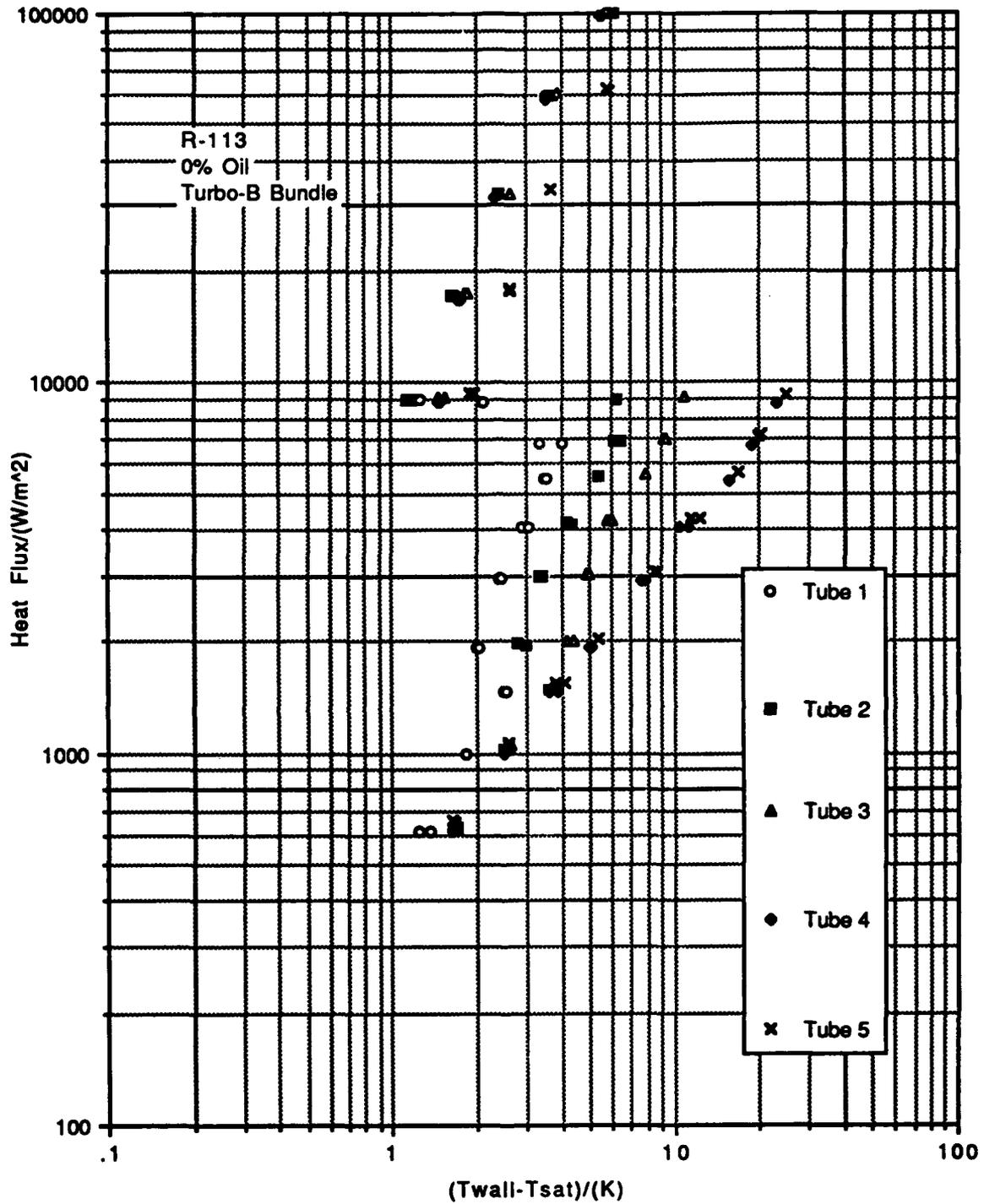


Figure 52. Performance Variation of Tubes 1 to 5 at a 0 cm Pool Height During a Increasing Heat Flux (ITB56)

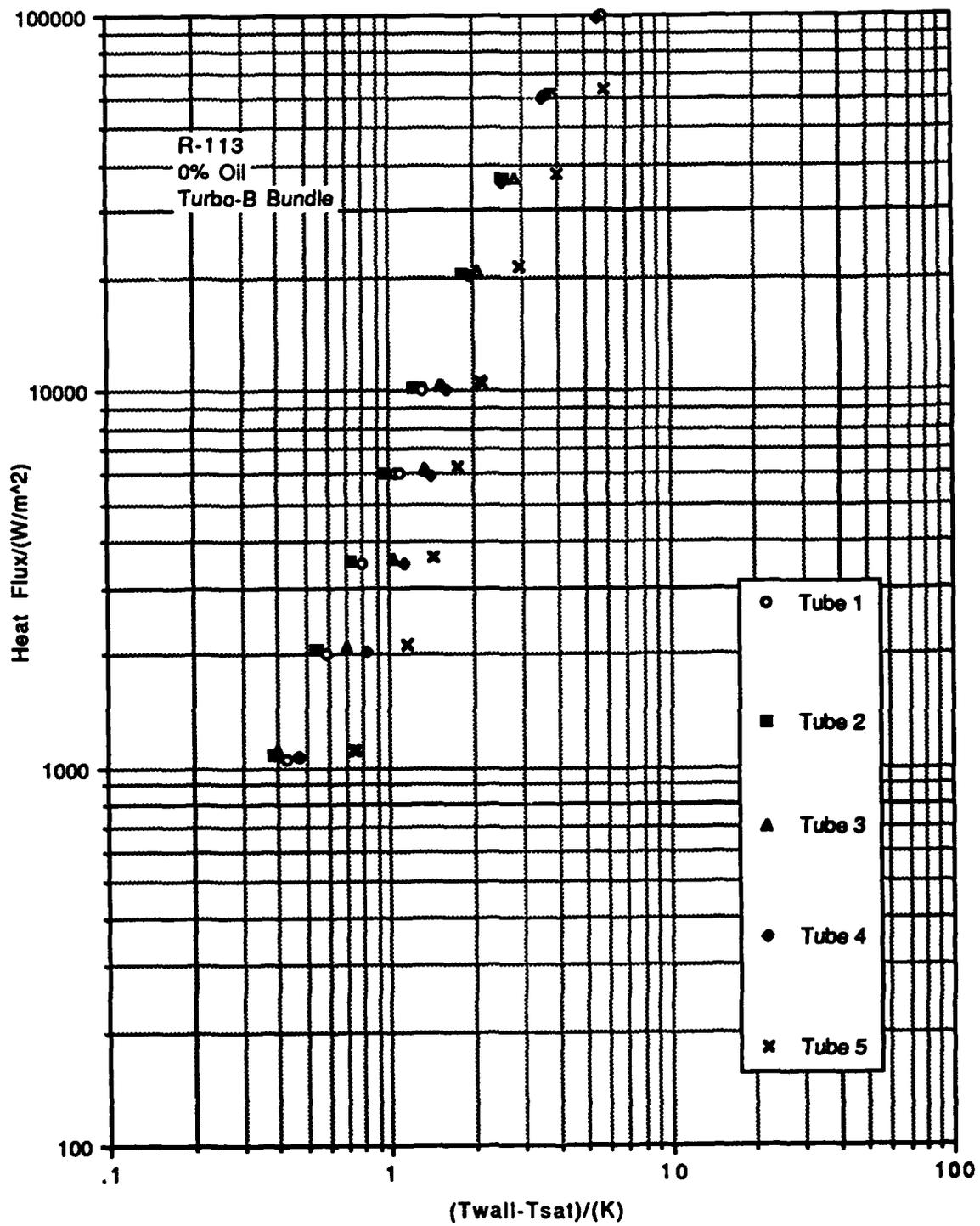


Figure 53. Performance Variation of Tubes 1 to 5 at a 0 cm Pool Height During a Decreasing Heat Flux (DTB56)

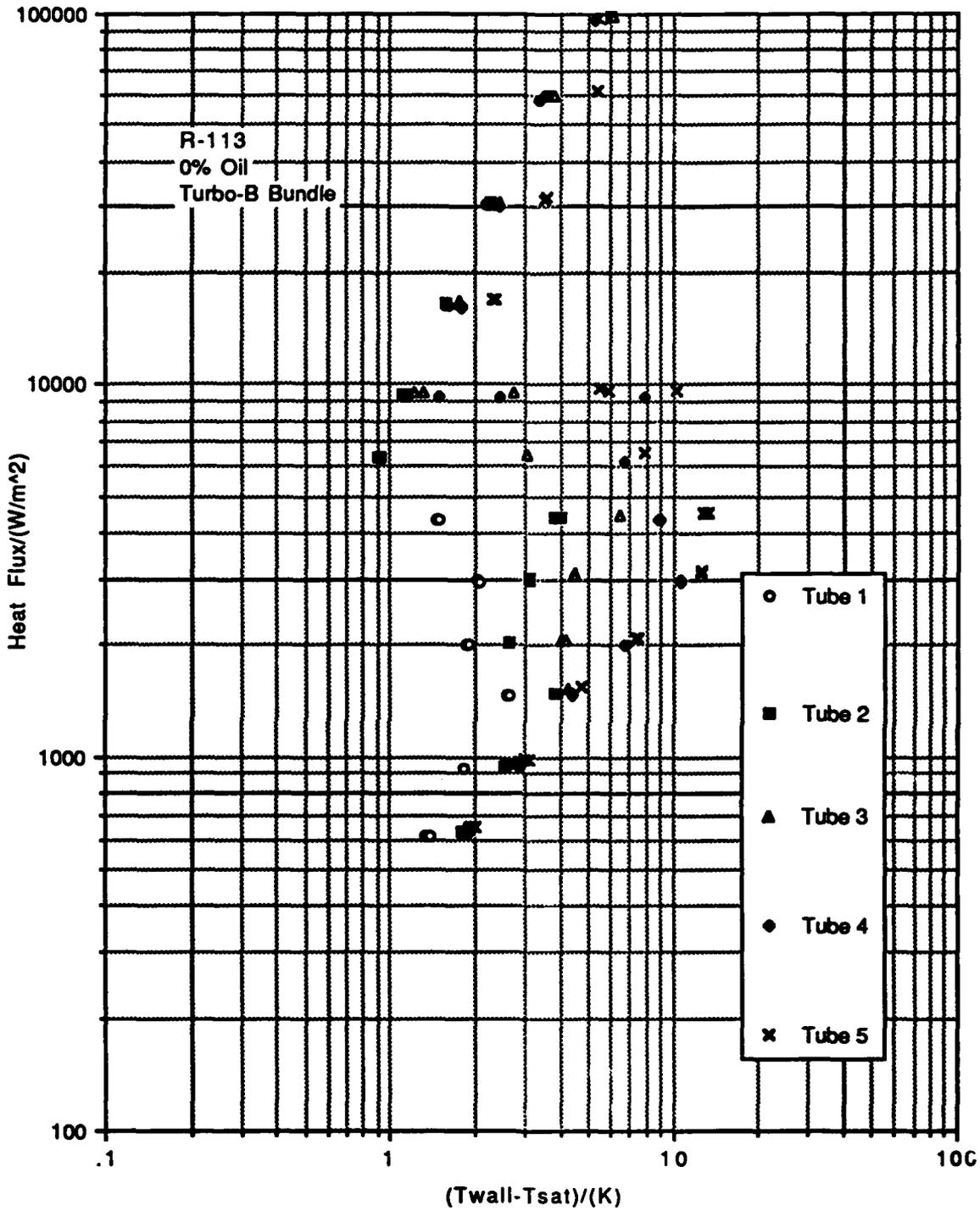


Figure 54. Performance Variation of the Bundle at a 0 cm Pool Height During a Increasing Heat Flux (ITB57)

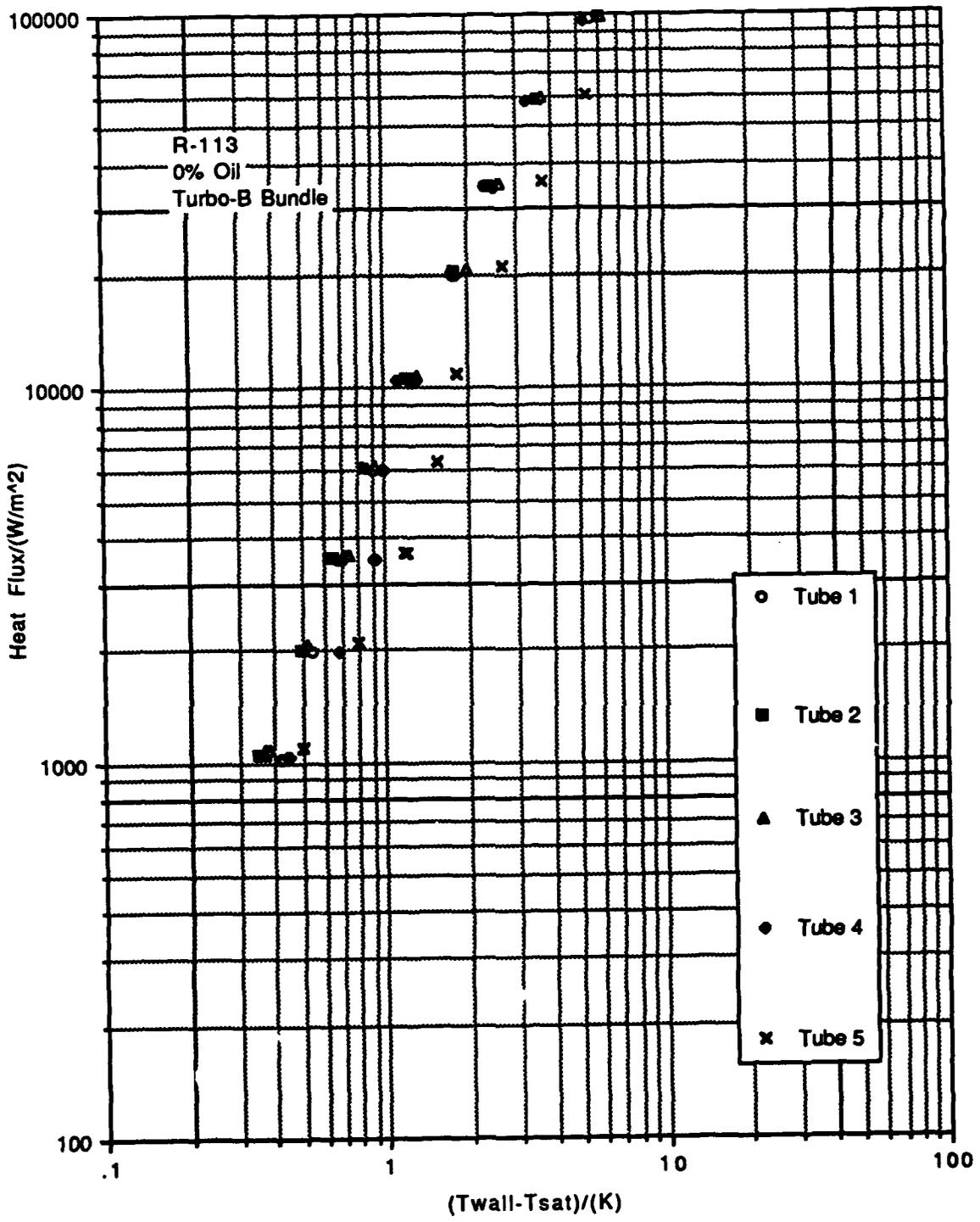


Figure 55. Performance Variation of the Bundle at a 0 cm Pool Height During a Decreasing Heat Flux (DTB57)

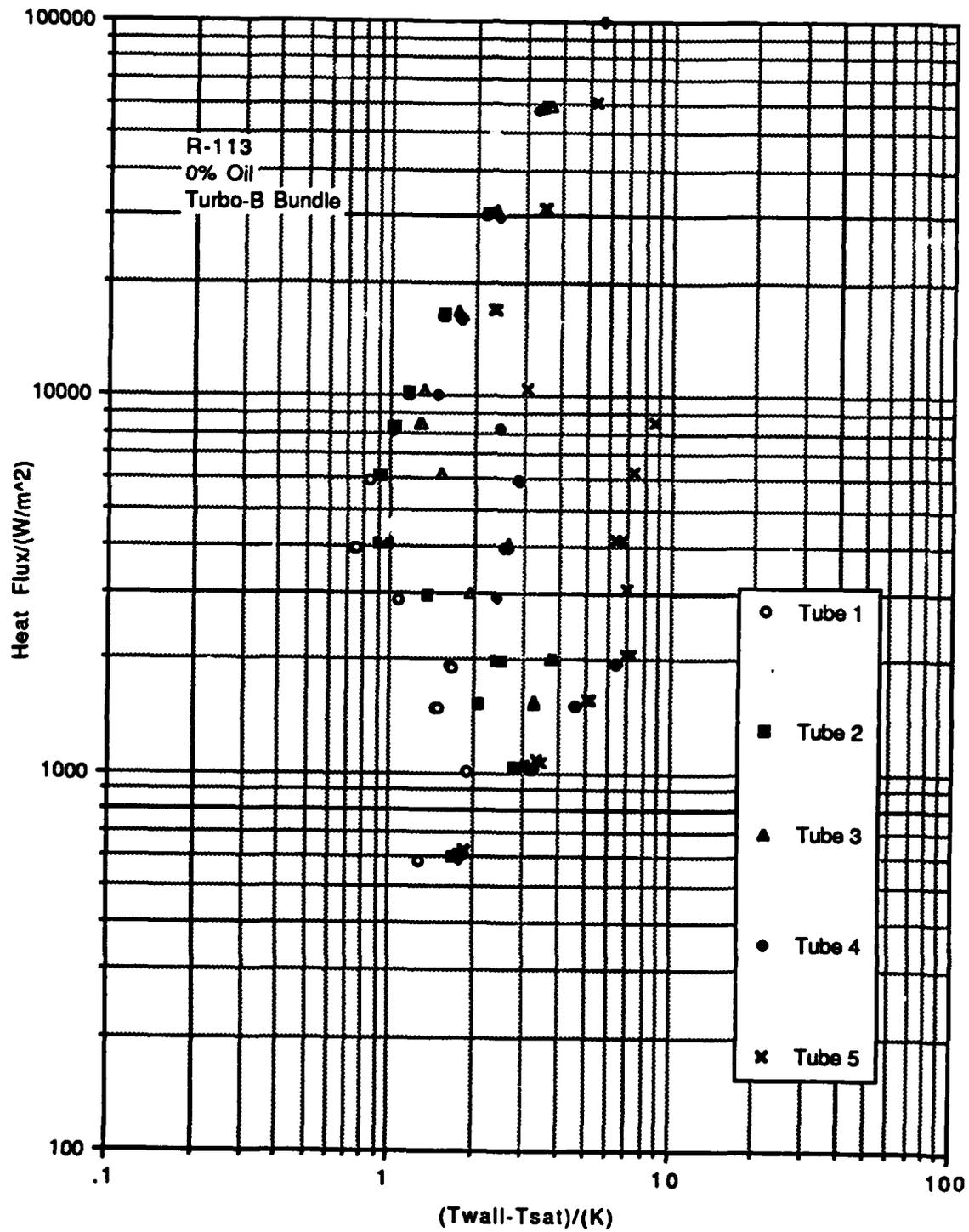


Figure 56. Performance Variation of the Bundle plus Simulation Heaters at a 0 cm Pool Height During a Increasing Heat Flux (ITB58)

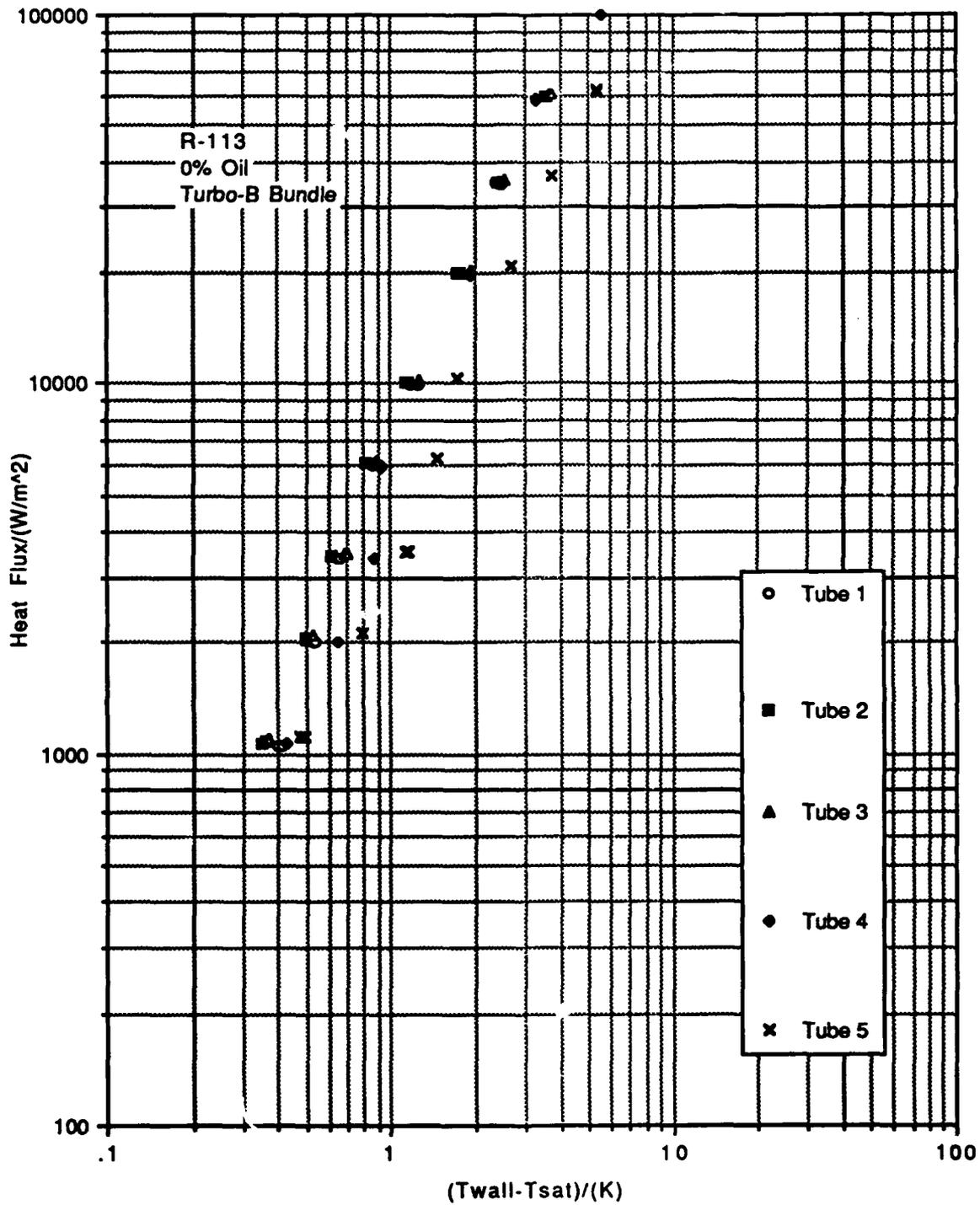


Figure 57. Performance Variation of the Bundle plus Simulation Heaters at a 0 cm Pool Height During a Decreasing Heat Flux (DTB58)

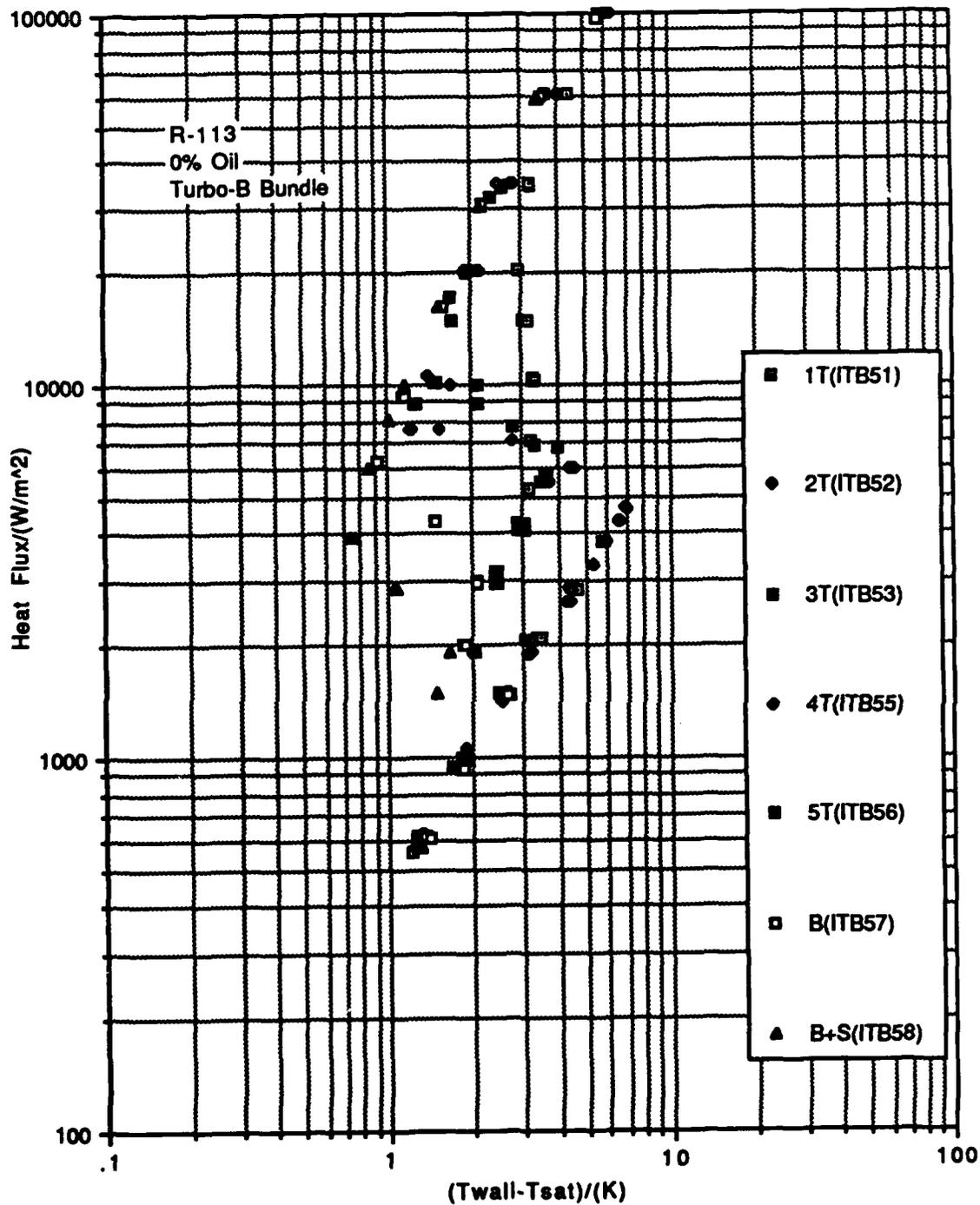


Figure 58. 0 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Increasing Heat Flux

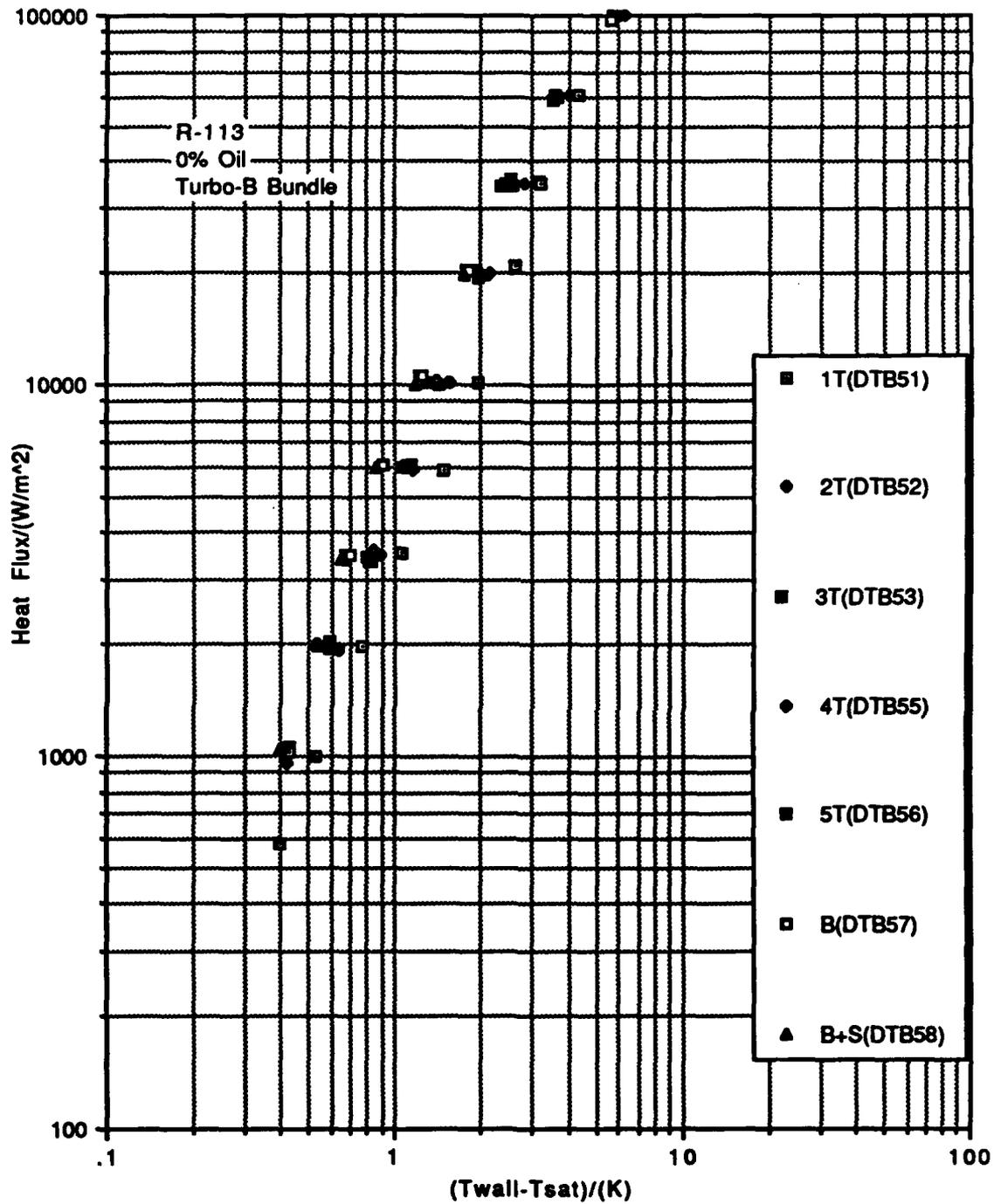


Figure 59. 0 cm. Performance Variation of Tube 1 in a Pool of R-113 When Influenced by an Increasing Number of Heated Tubes in a Turbo-B Bundle During a Decreasing Heat Flux

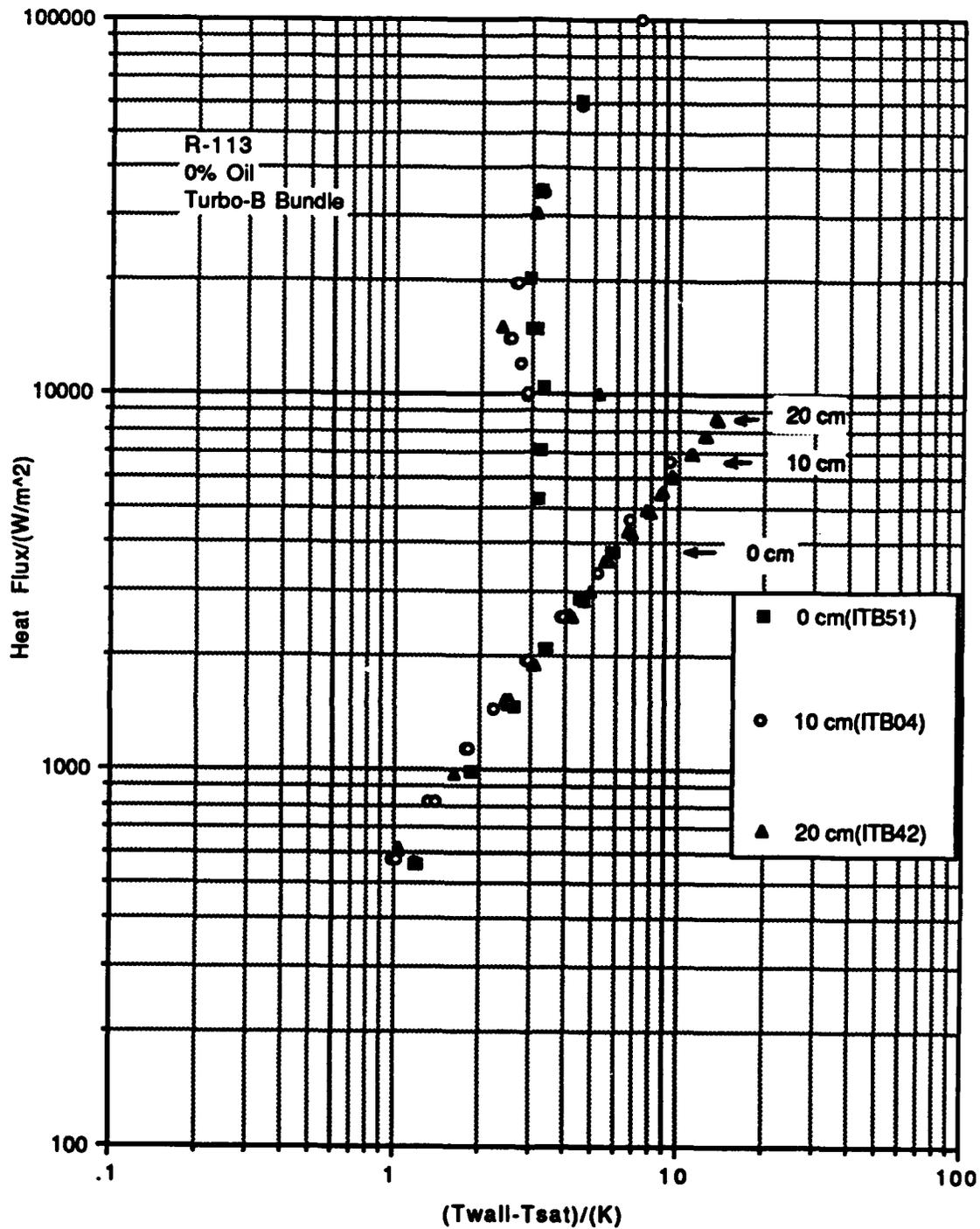


Figure 60. Comparison of Tube 1 in a Pool of R-113 for Three Different Pool Heights During a Increasing Heat Flux

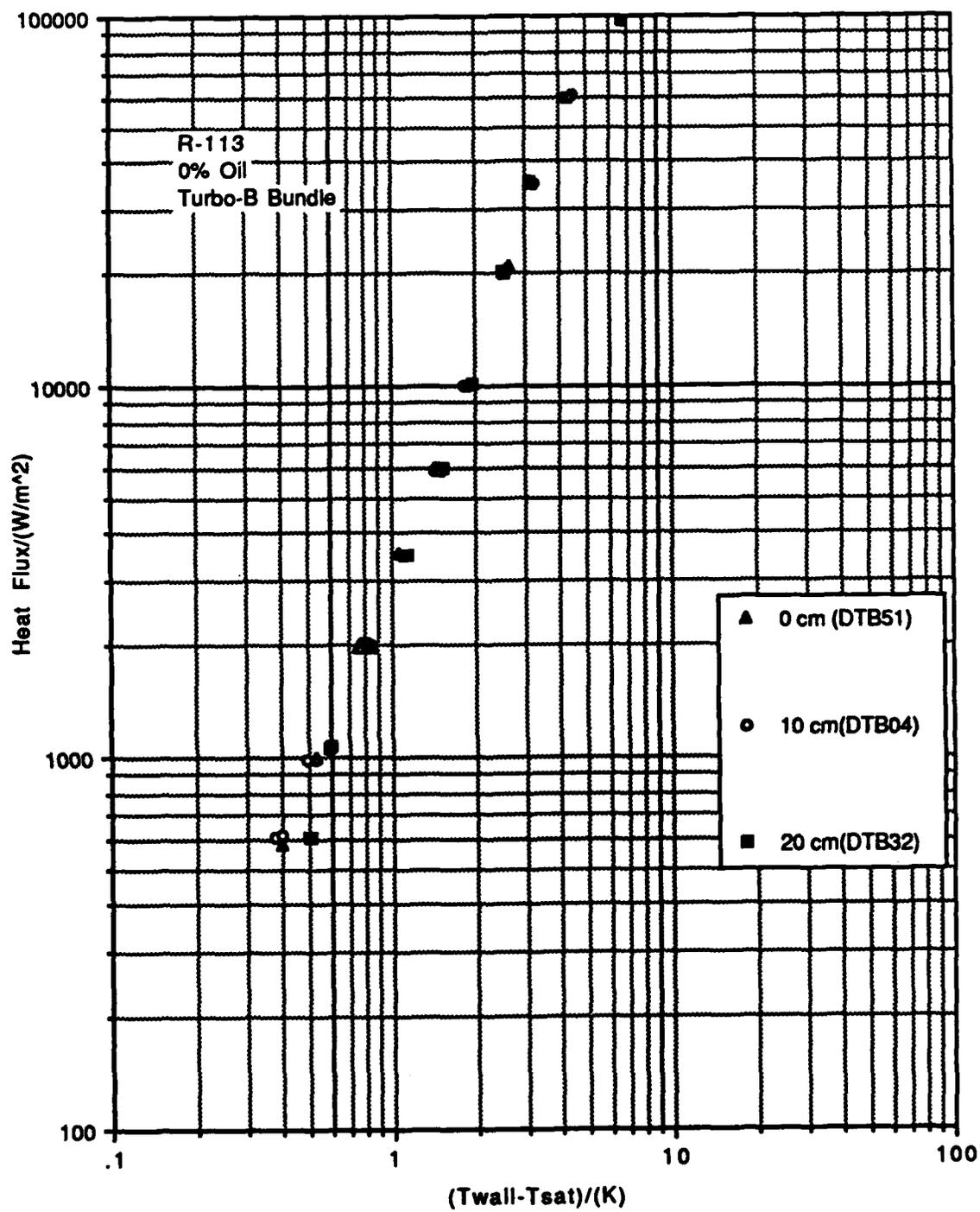


Figure 61. Comparison of Tube 1 in a Pool of R-113 for Three Different Pool Heights During a Decreasing Heat Flux

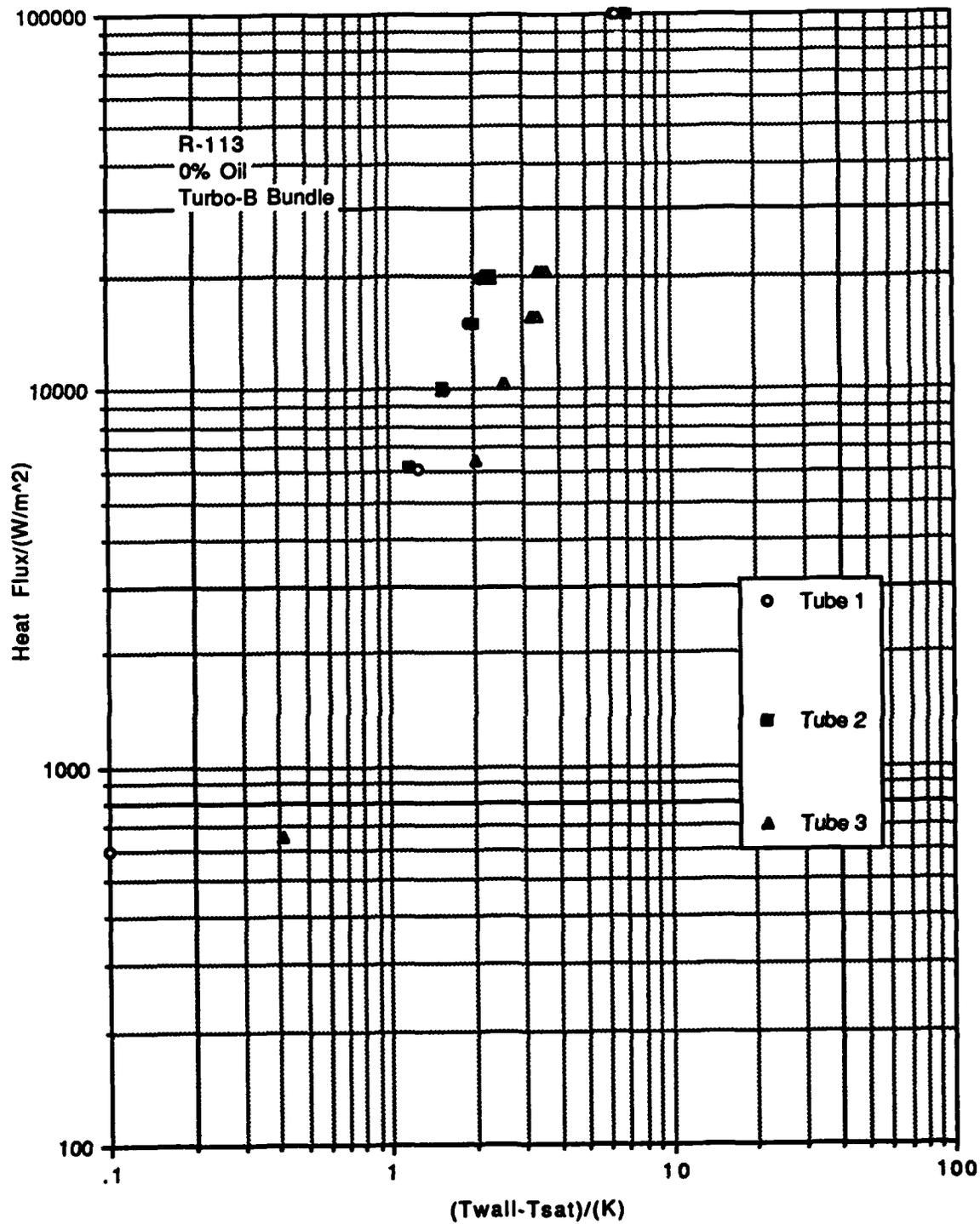


Figure 62. Performance Variation of Tubes 1 to 3 at a 10 cm Pool Height During a Decreasing Heat Flux with Auxiliary Heaters off (DTB06T)

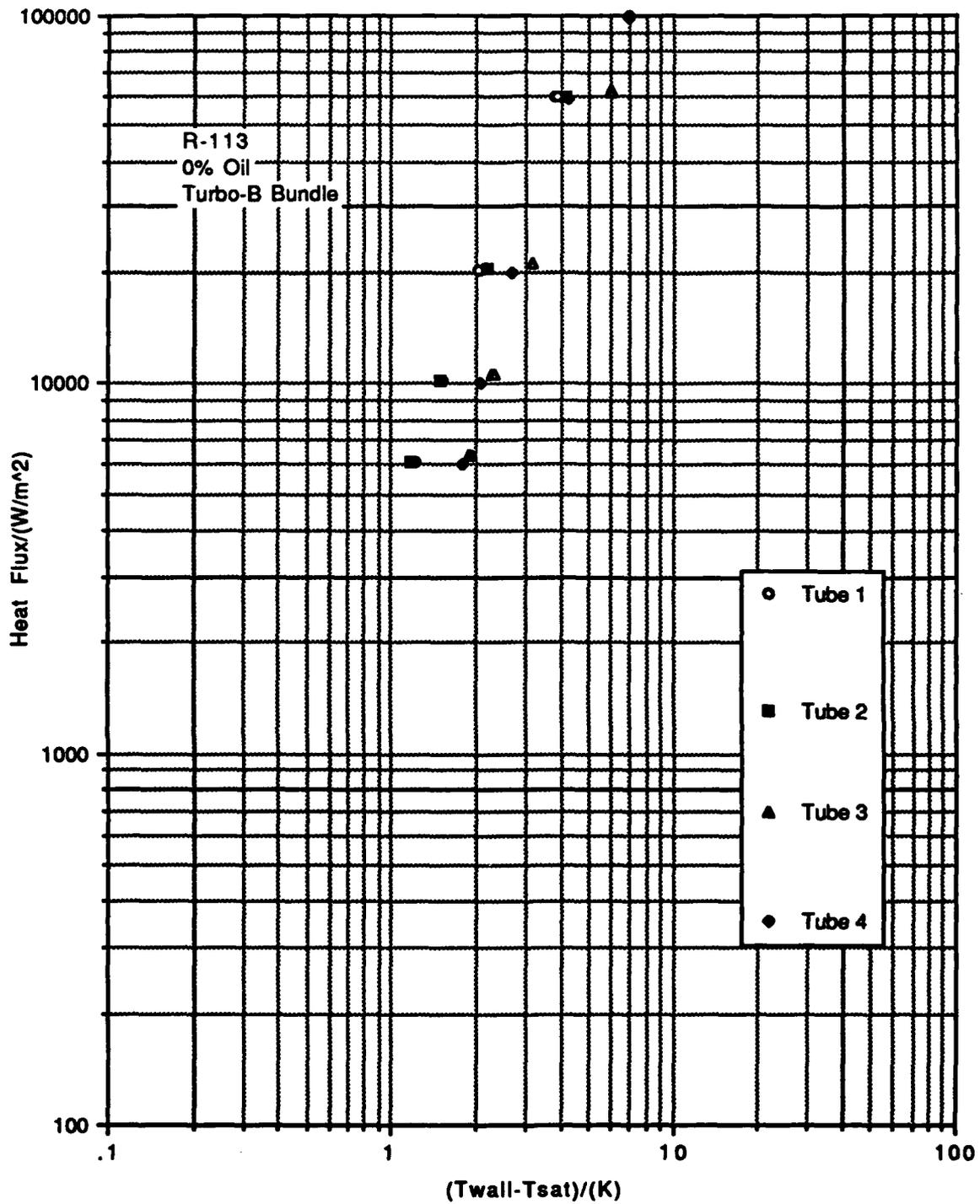


Figure 63. Performance Variation of Tubes 1 to 4 at a 10 cm Pool Height During a Decreasing Heat Flux with Auxiliary Heaters off (DTB07T)

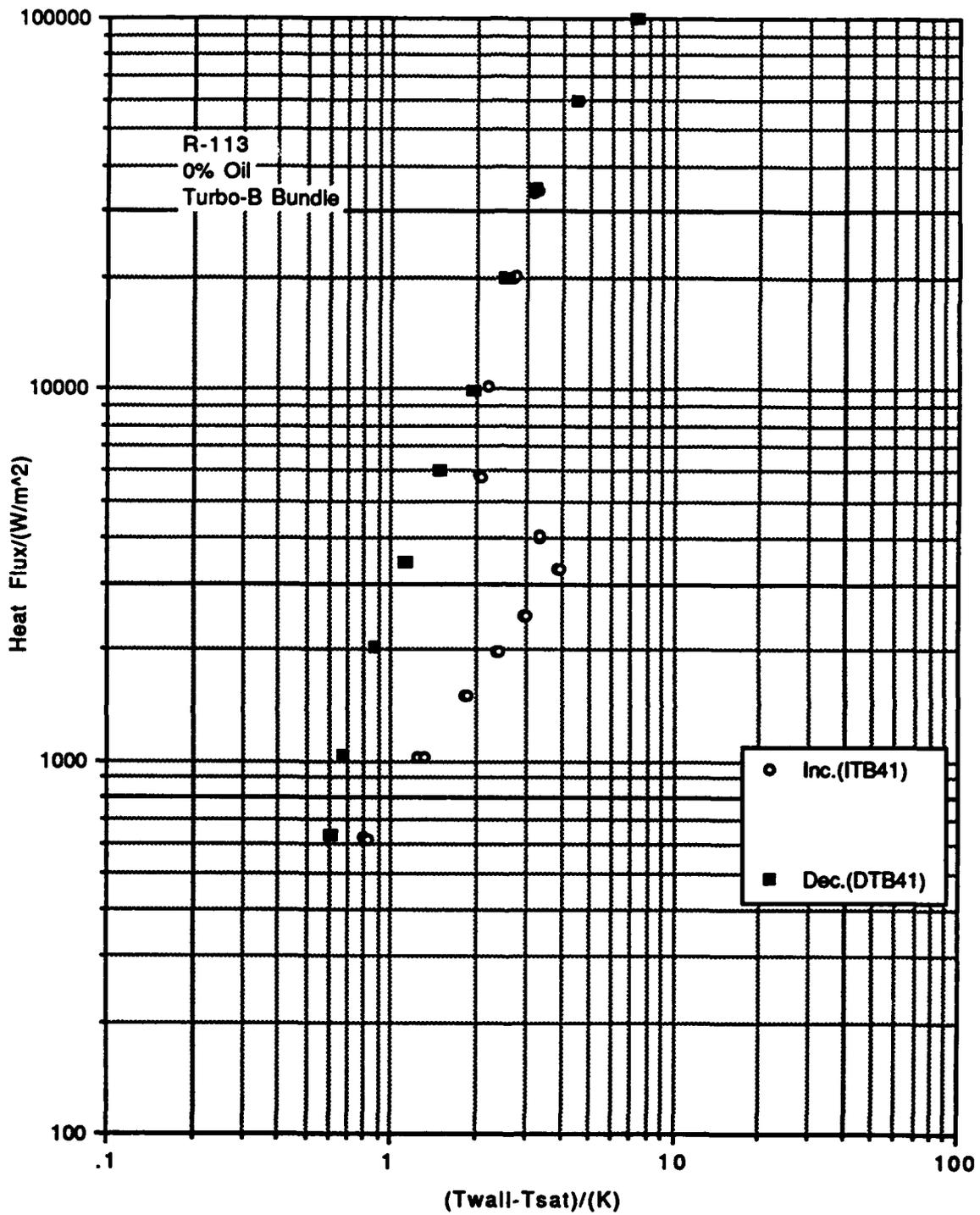


Figure 64. Performance of Tube 1 at a 20 cm Pool Height with the Auxiliary Heater Setting at 3kW

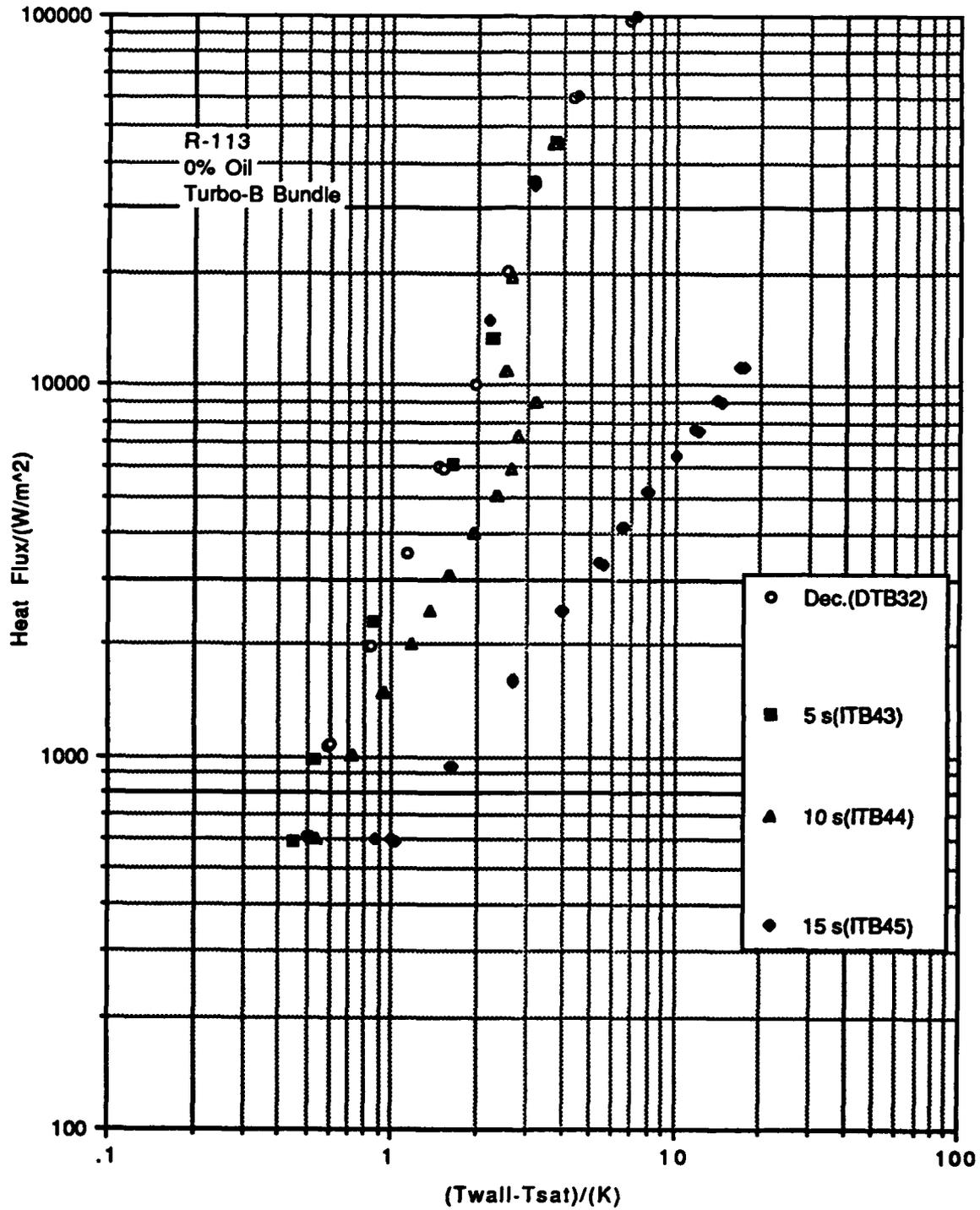


Figure 65. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 20 cm Pool Height

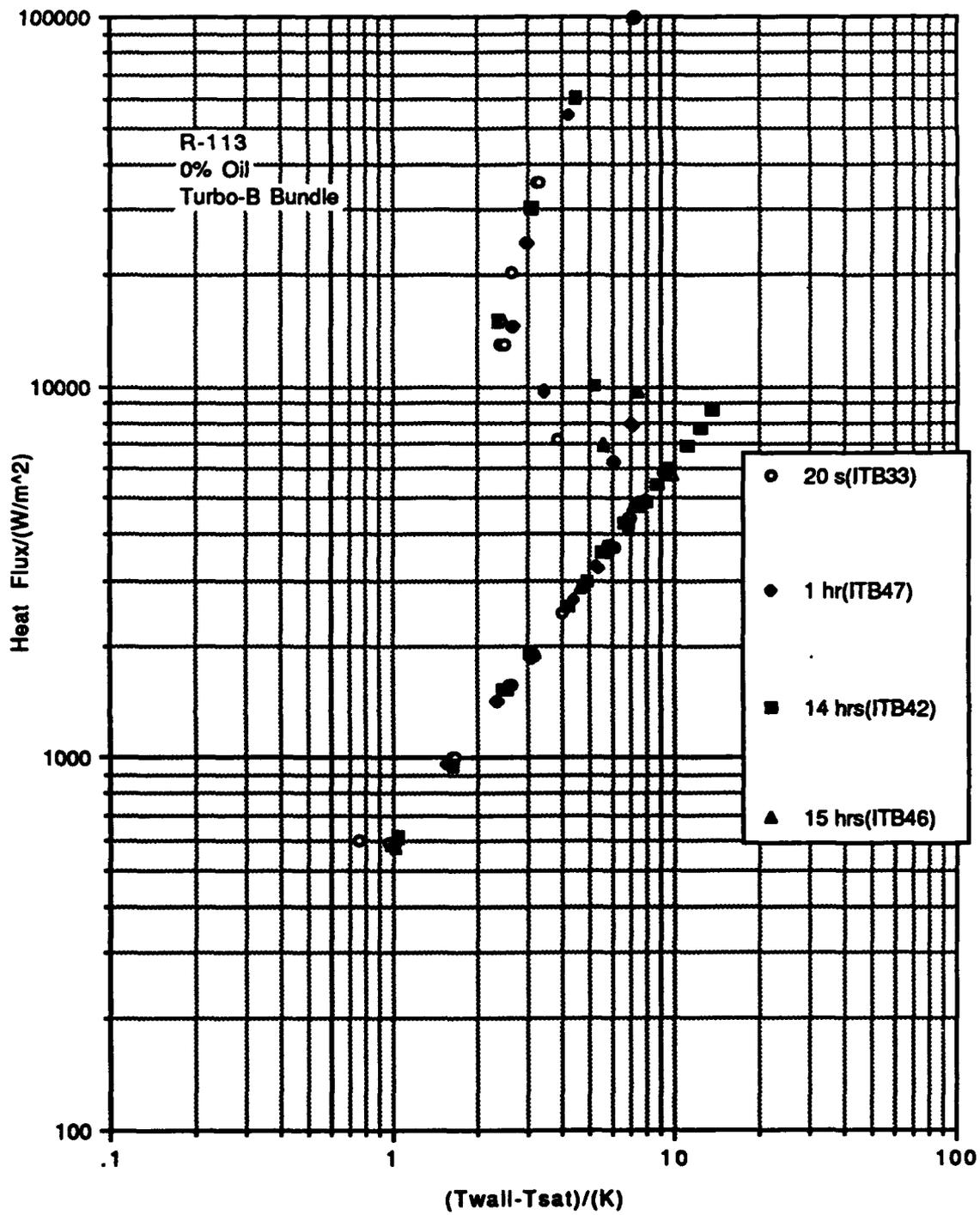


Figure 66. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 20 cm Pool Height

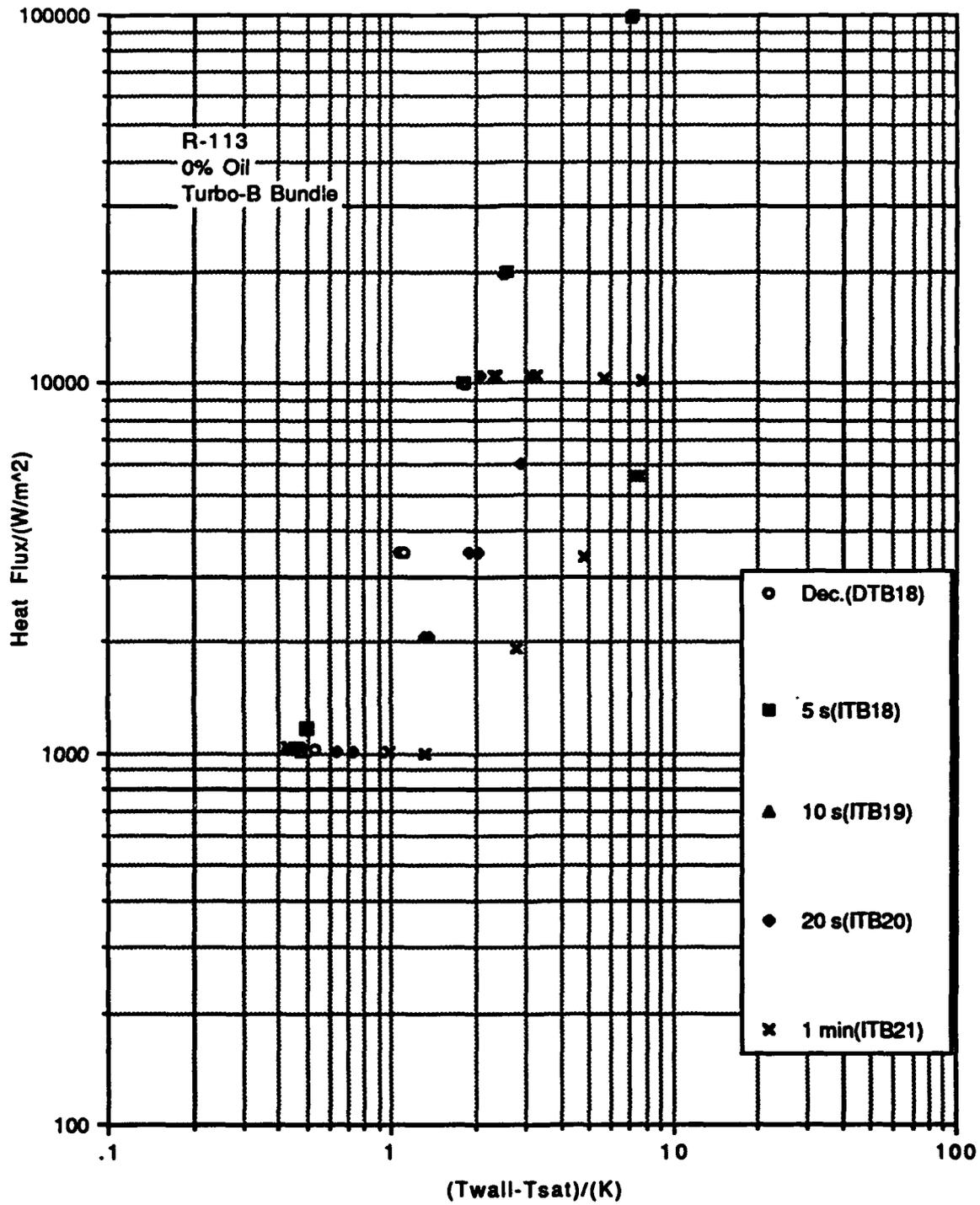


Figure 67. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 10 cm Pool Height

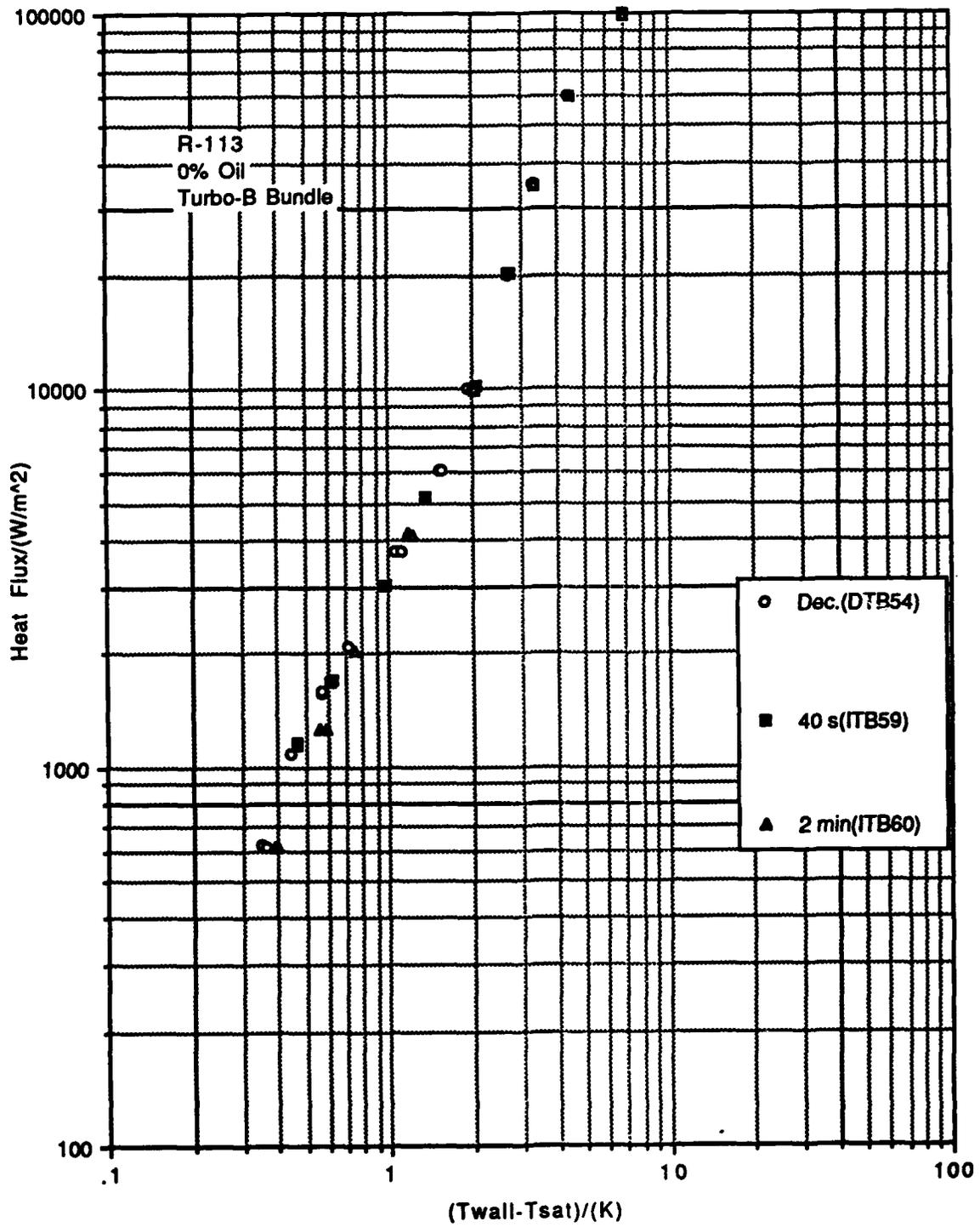


Figure 68. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

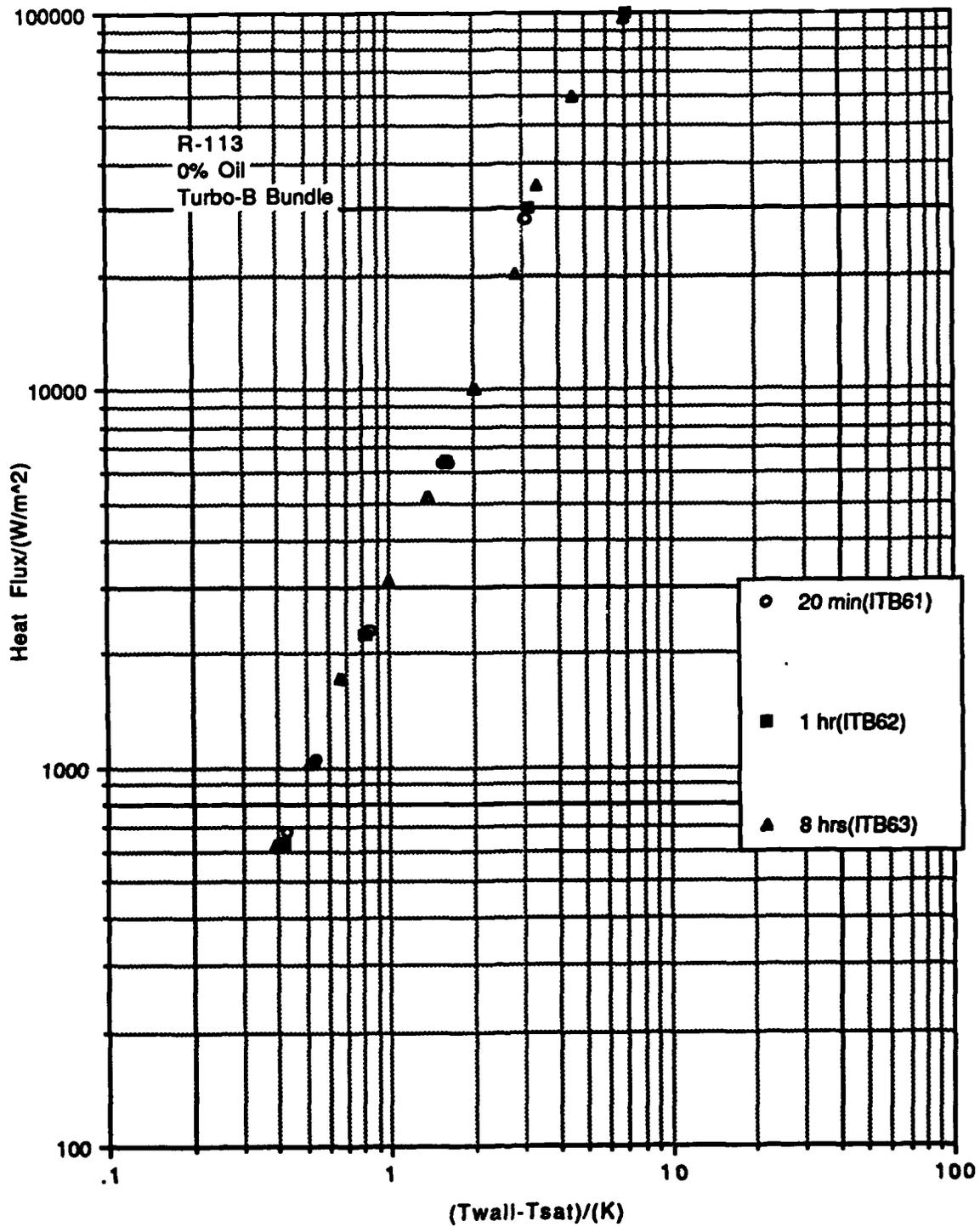


Figure 69. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

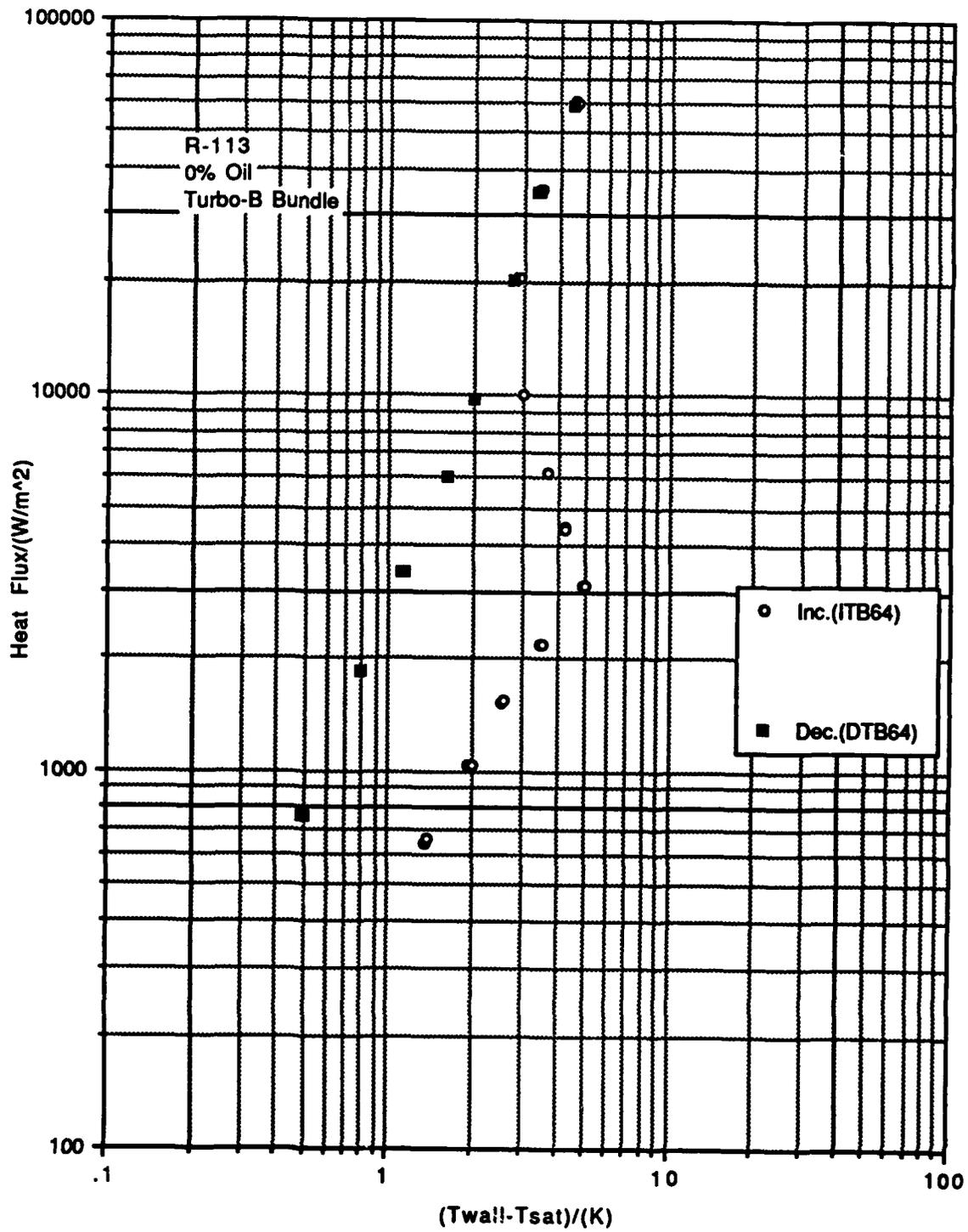


Figure 70. Nucleation Site Deactivation with a 1 kW Auxiliary Heater Setting and a 0 cm Pool Height

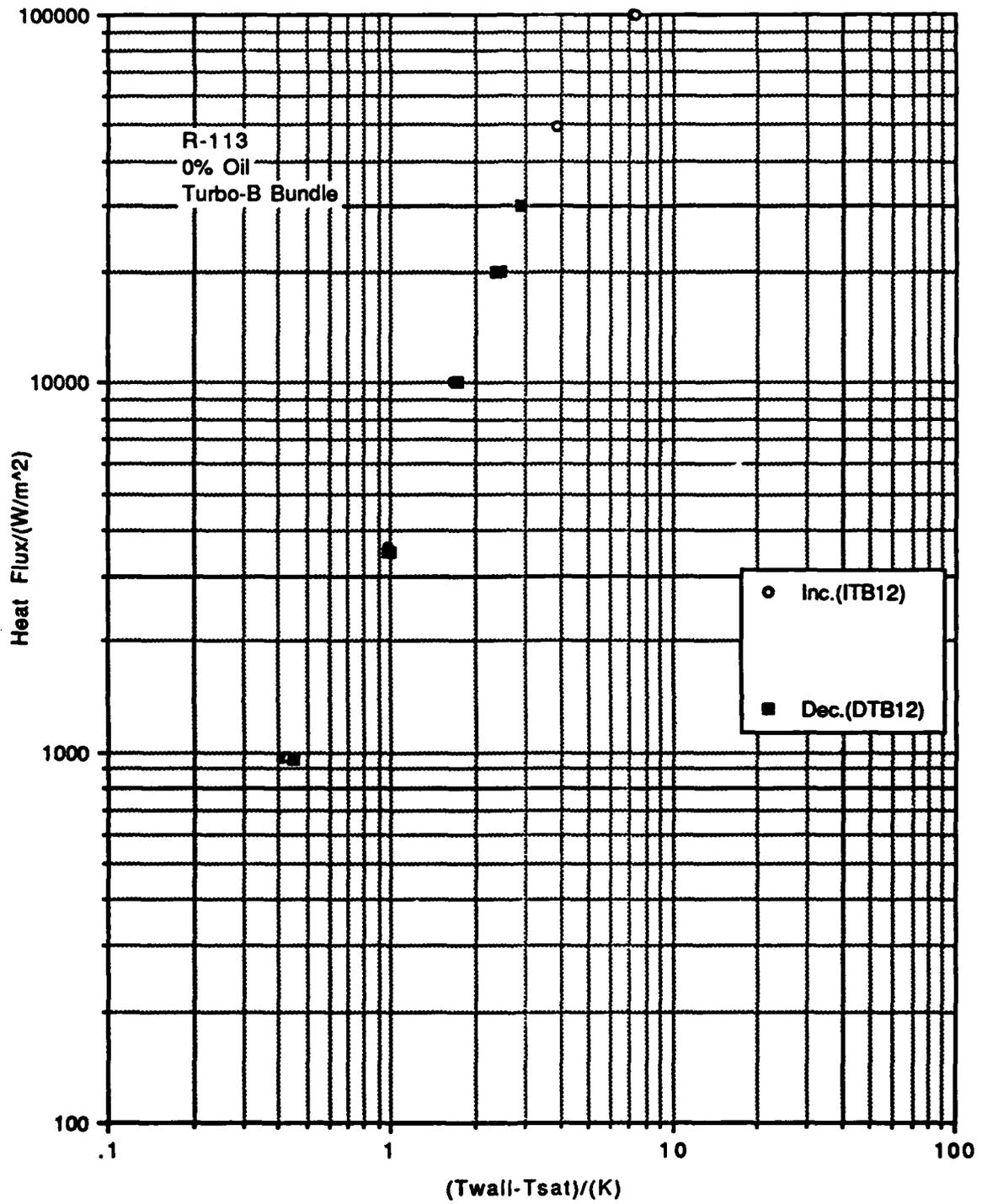


Figure 71. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

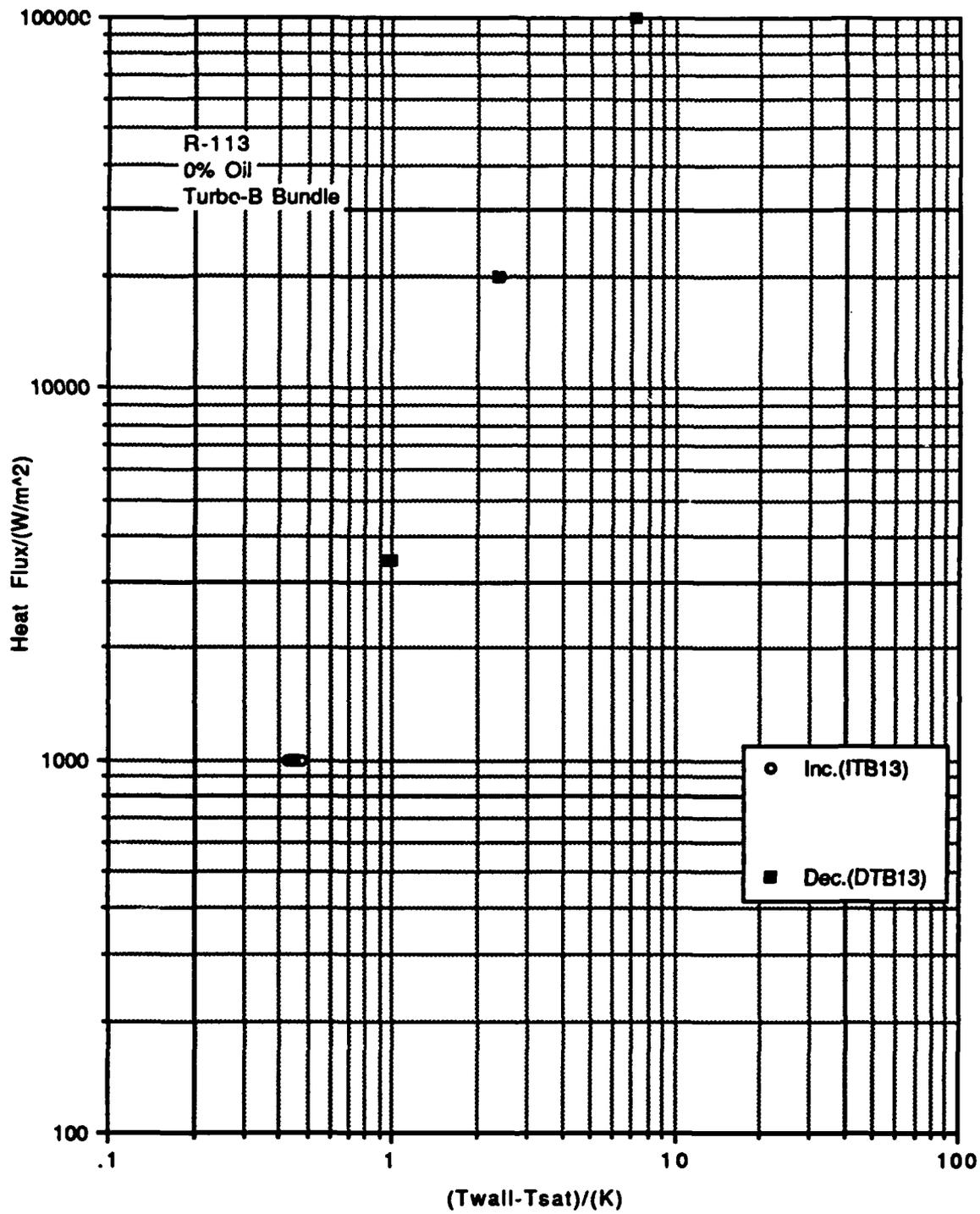


Figure 72. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

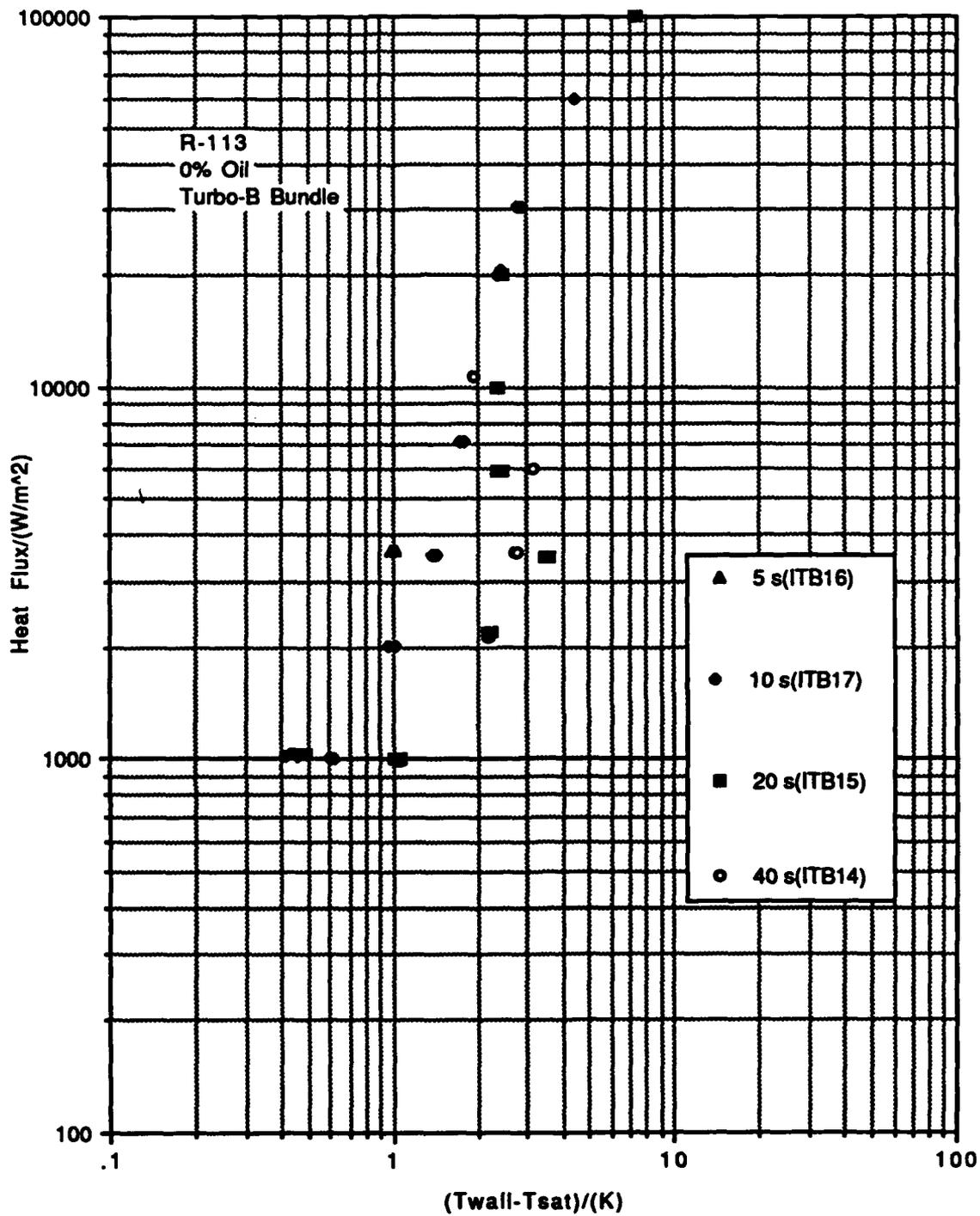


Figure 73. Nucleation Site Deactivation with a 3 kW Auxiliary Heater setting and a 10 cm Pool Height

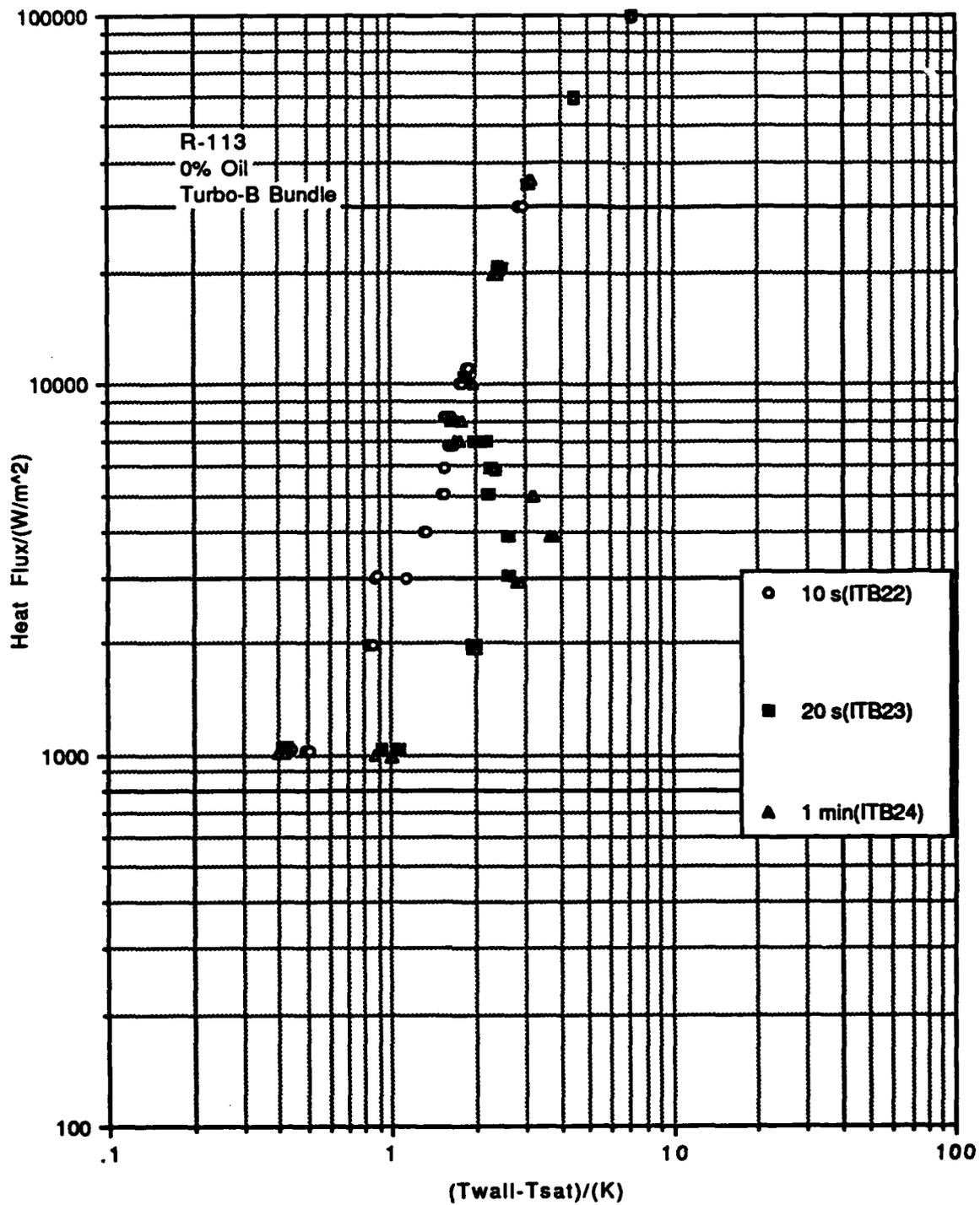


Figure 74. Nucleation Site Deactivation with a 3 kW Auxiliary Heater Setting and a 10 cm Pool Height

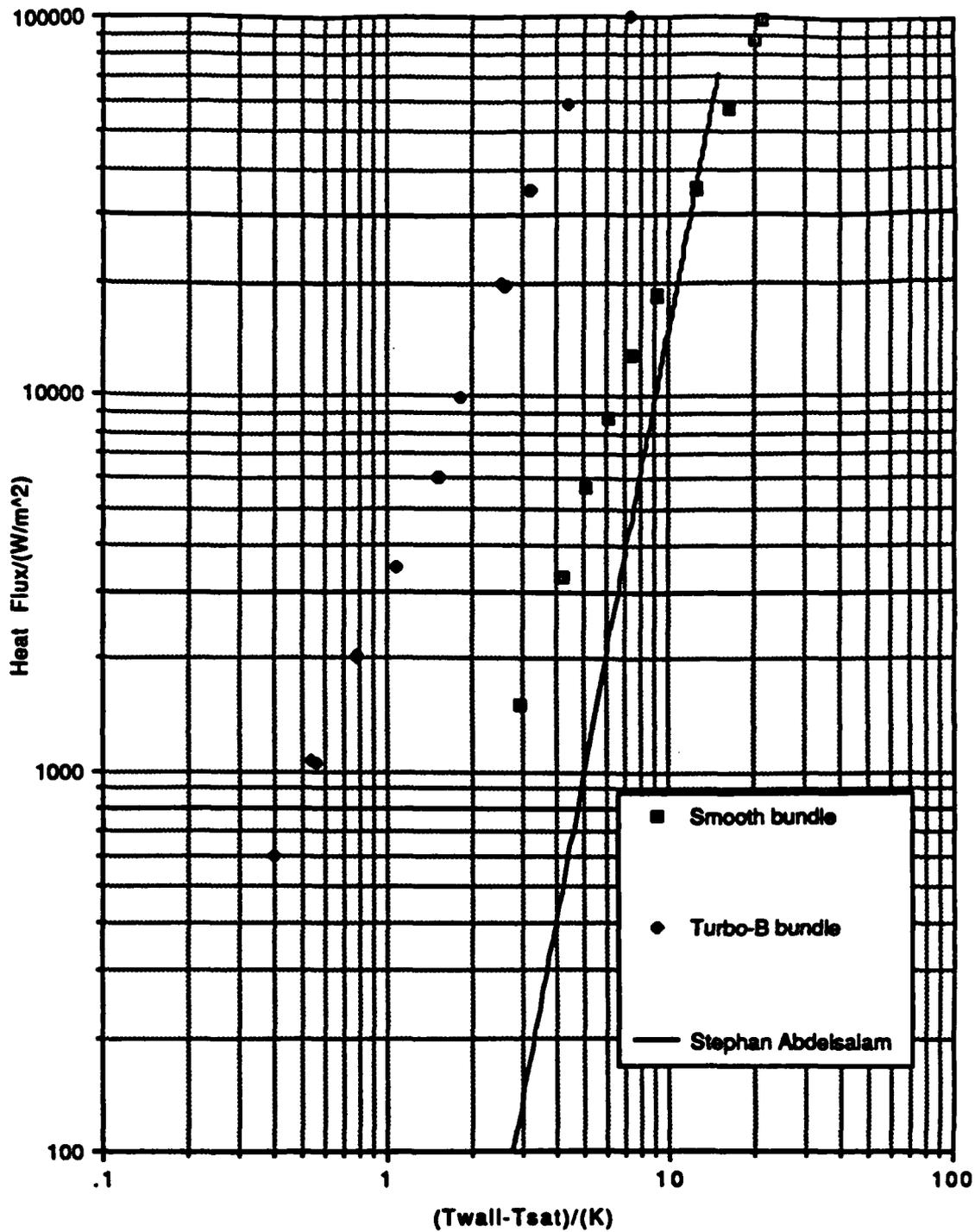


Figure 76. Comparison of Tube 1 During a Decreasing Heat Flux for Smooth vs Turbo-B Bundles in R-113

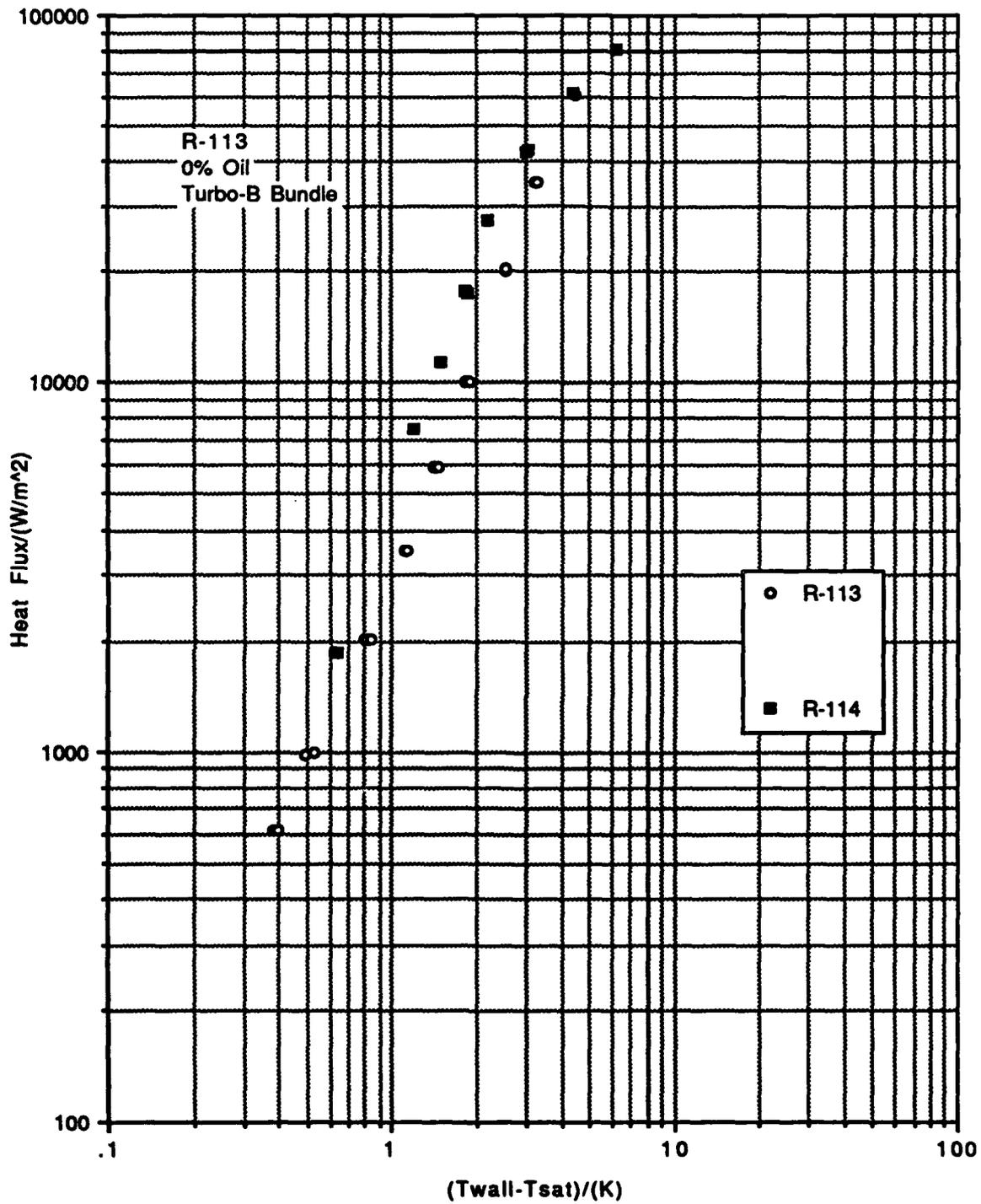


Figure 77. Comparison of Tube 1 During a Decreasing Heat Flux for Turbo-B Tubes in a Bundle with R-113 vs a Bundle for R-114

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. When secured overnight, the bundle exhibited significant temperature overshoot for increasing heat flux (approx. 10°C). The hysteresis loop formed by increasing followed by decreasing heat flux was very repeatable.

2. In the natural convection region, activating lower tubes within the bundle did not affect the upper tubes. However, the heat-transfer coefficient decreased as one moved down the bundle.

3. Activation of the lower tubes caused the upper tubes to nucleate earlier (i.e. at a lower heat flux). As each tube successively nucleated, the heat-transfer performance of the remaining lower tubes improved.

4. In the nucleate boiling region, the performance of the top tube was the best. This performance dropped off steadily as one moved down the bundle.

5. Variation in liquid height above the bundle (from 0 to 20 cm) significantly delayed the point of incipience.

6. For zero pool subcooling, nucleation site deactivation was greatly dependent on both pool height (i.e. pressure head) and tube turn off time. At zero pool height, deactivation was negligible for all time whereas for 10 and 20 cm, there was complete deactivation in 60 and 15 seconds respectively (i.e. decreasing with increasing pool height).

7. At a typical heat flux of 20 kW/m^2 , the Turbo-B tube bundle heat-transfer coefficient was approximately four times that of a smooth tube bundle.

8. The uncertainty of the data was greatest at low heat flux and low wall superheat due to the measurement being of the order of accuracy of the thermocouples.

B. RECOMMENDATIONS FOR FUTURE WORK

1. Due to the way a real flooded evaporator operates, it would be preferable to heat the tubes within the bundle with hot water.

2. The pool height tests should be repeated, but by varying the vapor pressure above the liquid, the local pressure at the tube surface should be maintained at a constant value.

3. A pressure test should be conducted and a pressure relief valve fitted to enable the testing of alternative refrigerants such as R-124 which has a higher vapor pressure.

4. Attention needs to be given to the question of refrigerant disposal. There are reclamation projects undertaken by most manufacturers; however, a method still needs to be found to remove the refrigerant from the apparatus into a container for reclamation.

5. Neutrally buoyant particles should be placed in the pool to facilitate study of the circulation patterns within the bundle in more detail.

6. A high speed camera should be used to study the nucleation process and circulation patterns in more detail (the mechanical engineering department is hoping to purchase such a camera in the near future).

7. A sight glass should be fitted to the refrigerant storage tank.

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APPENDIX A: LISTING OF DATA FILES

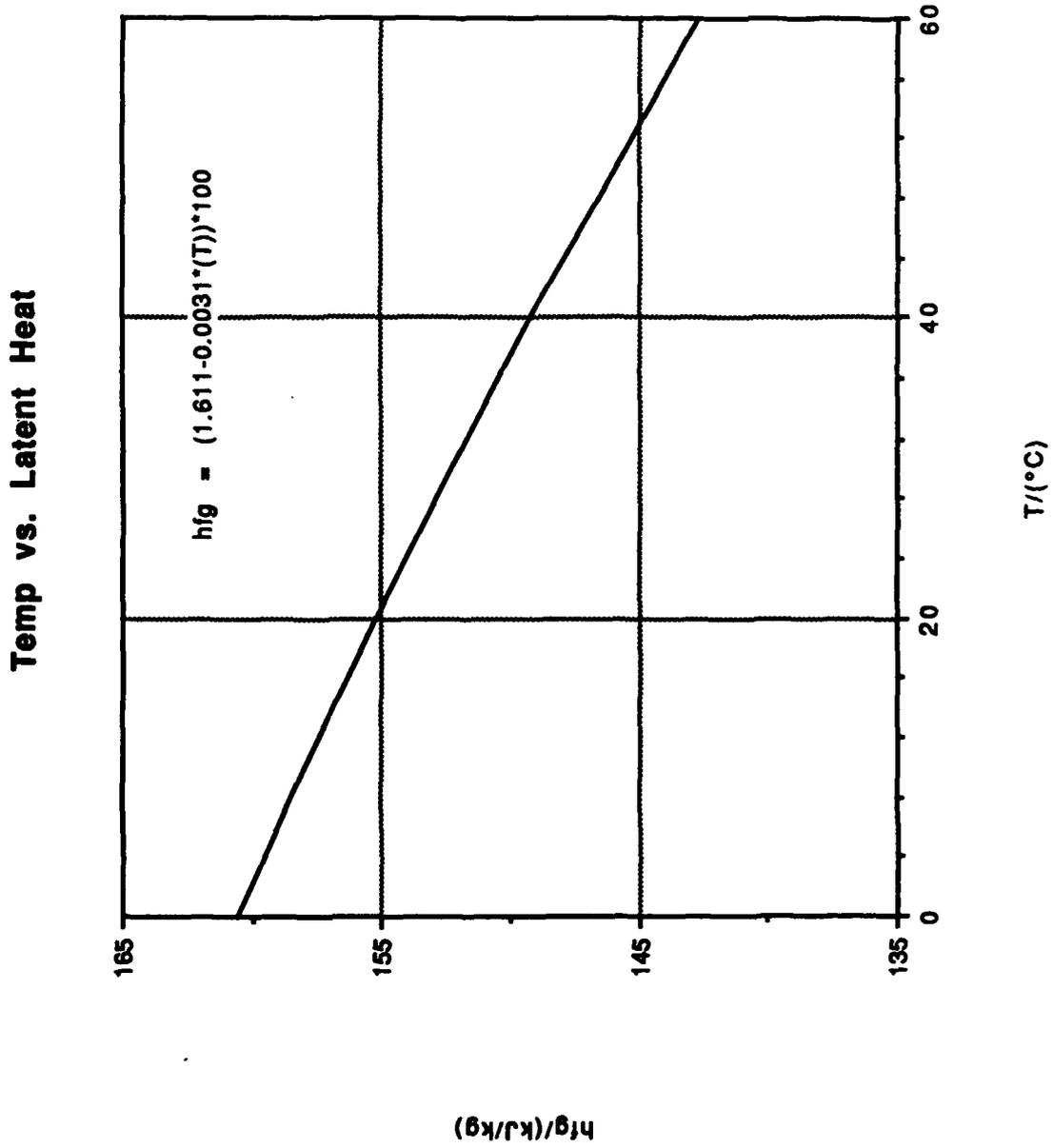
File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB01	17	1	0	0	1kW	10	56 hrs
DTB01	18	1	0	0	1kW	10	
ITB02	51	1	0	0	1kW	10	98 hrs
DTB02	20	1	0	0	1kW	10	
ITB03	32	1	0	0	1kW	10	30 min
DTB03	21	1	0	0	1kW	10	
ITB04	33	1	0	0	1kW	10	48 hrs
DTB04	22	1	0	0	1kW	10	
ITB05	33	2	0	0	1kW	10	68 hrs
DTB05	21	2	0	0	1kW	10	
ITB06	37	3	0	0	1kW	10	14.5 hrs
DTB06	21	3	0	0	1kW	10	
DTB06T	11	3	0	0	1kW	10	
ITB07	24	4	0	0	1kW	10	24 hrs
DTB07	19	4	0	0	1kW	10	
DTB07T	10	4	0	0	1kW	10	
ITB08	4	1	0	0	1kW	10	20 hrs
ITB09	3	1	0	0	1kW	10	20 hrs
DTB10	14	1	0	0	1kW	10	
ITB12	12	1	0	0	3kW	10	Instan. on-off
DTB12	10	1	0	0	3kW	10	
ITB13	9	1	0	0	3kW	10	Instan. on-off
DTB13	8	1	0	0	3kW	10	

File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB14	14	1	0	0	3kW	10	40s
ITB15	16	1	0	0	3kW	10	20s
ITB16	10	1	0	0	3kW	10	5s
ITB17	18	1	0	0	3kW	10	10s
ITB18	16	1	0	0	1kW	10	5s
DTB18	18	1	0	0	1kW	10	
ITB19	8	1	0	0	1kW	10	10s
ITB20	16	1	0	0	1kW	10	20s
ITB21	20	1	0	0	1kW	10	1 min
ITB22	35	1	0	0	3kW	10	10s
ITB23	31	1	0	0	3kW	10	20s
ITB24	30	1	0	0	3kW	10	1 min
ITB25	22	1	0	0	3kW	10	116 hrs
DTB25	18	1	0	0	3kW	10	
ITB26	20	1	0	0	3kW	10	30s
ITB27	28	5	0	0	1kW	10	21 hrs
DTB27	18	5	0	0	1kW	10	
ITB28	18	1	0	0	1kW	10	88 hrs
ITB29	26	1	0	0	1kW	10	30 min
DTB30	18	5	0	0	1kW	10	
ITB31	28	1	0	0	1kW	10	16 hrs
DTB31	20	1	0	0	1kW	10	
ITB34	38	2	0	0	1kW	20	16 hrs

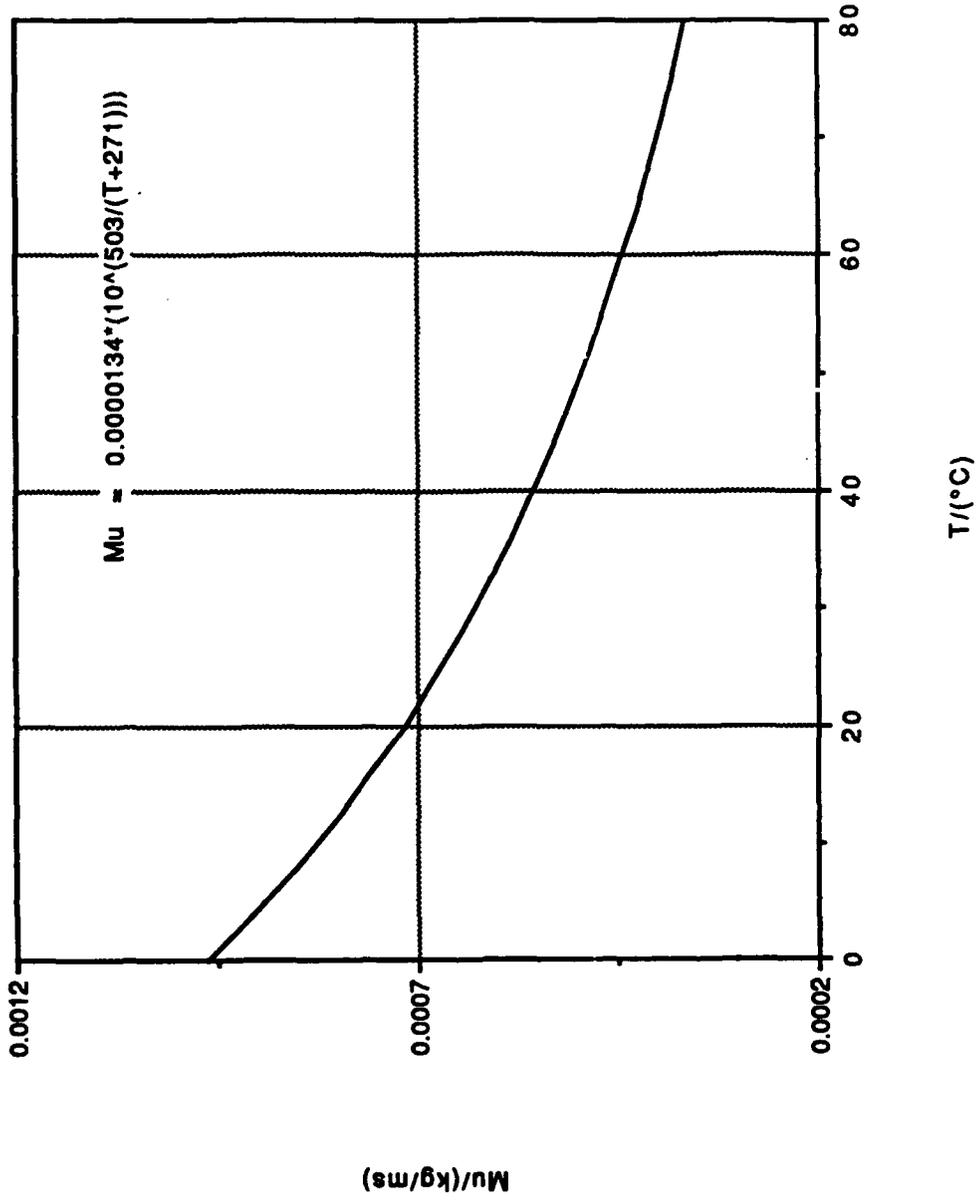
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ITB35	33	3	0	0	1kW	20	1 hr
DTB35	21	3	0	0	1kW	20	
ITB36	30	4	0	0	1kW	20	2.5 hrs
DTB36	20	4	0	0	1kW	20	
ITB37	28	5	0	0	1kW	20	7 hrs
DTB37	20	5	0	0	1kW	20	
ITB38	32	5	5	0	1kW	20	5 hrs
DTB38	20	5	5	0	1kW	20	
ITB40	31	5	5	5	1kW	20	10 hrs
DTB40	20	5	5	5	1kW	20	
ITB41	27	1	0	0	3kW	20	7.5 hrs
DTB41	20	1	0	0	3kW	20	
DTB32	20	1	0	0	1kW	20	
ITB33	33	1	0	0	1kW	20	20 s
ITB43	15	1	0	0	1kW	20	5 s
ITB44	30	1	0	0	1kW	20	10 s
ITB42	38	1	0	0	1kW	20	14 hrs
ITB45	31	1	0	0	1kW	20	15 s
ITB46	26	1	0	0	1kW	20	15 hrs
ITB47	30	1	0	0	1kW	20	1 hr
ITB48	28	5	5	0	1kW	10	15 hrs
DTB48	20	5	5	0	1kW	10	

File Name	Data Points	Number of Instrumented Tube Heaters	Pairs of Active Tube Heaters	Number of Simulation Heaters	Auxiliary Heater Setting (nominal)	Pool Height in centimeters (nominal)	Time Tube Heaters were Deactivated
ITB49	26	5	5	5	1KW	10	24 hrs
DTB49	20	5	5	5	1KW	10	
ITB51	28	1	0	0	1KW	0	12 hrs
DTB51	20	1	0	0	1KW	0	
ITB52	28	2	0	0	1KW	0	1 hr
DTB52	18	2	0	0	1KW	0	
ITB53	30	3	0	0	1KW	0	15 hrs
DTB53	18	3	0	0	1KW	0	
ITB54	22	1	0	0	1KW	0	10 s
ITB55	29	4	0	0	1KW	0	2 hrs
DTB55	19	4	0	0	1KW	0	
ITB56	27	5	0	0	1KW	0	14.5 hrs
DTB56	18	5	0	0	1KW	0	
ITB57	25	5	5	0	1KW	0	3 hrs
DTB57	18	5	5	0	1KW	0	
ITB58	26	5	5	5	1KW	0	12 hrs
DTB58	18	5	5	5	1KW	0	
ITB59	18	1	0	0	1KW	0	40 s
ITB60	14	1	0	0	1KW	0	2 min
ITB61	12	1	0	0	1KW	0	20 min
ITB62	12	1	0	0	1KW	0	1 hr
ITB63	20	1	0	0	1KW	0	8 hrs
ITB64	24	1	0	0	1KW	0	2.75 hrs
DTB64	18	1	0	0	1KW	0	

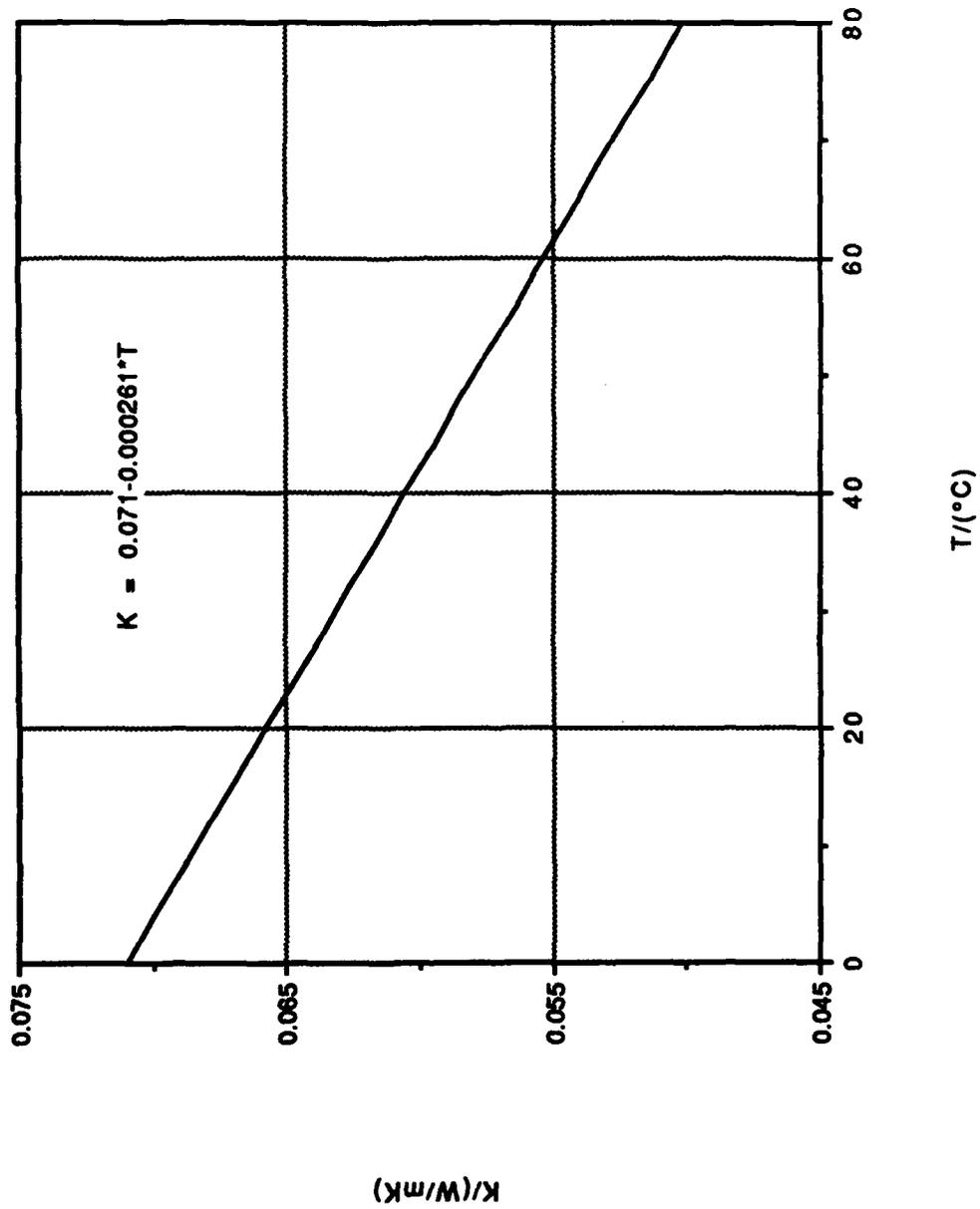
APPENDIX B: PROPERTIES OF R-113



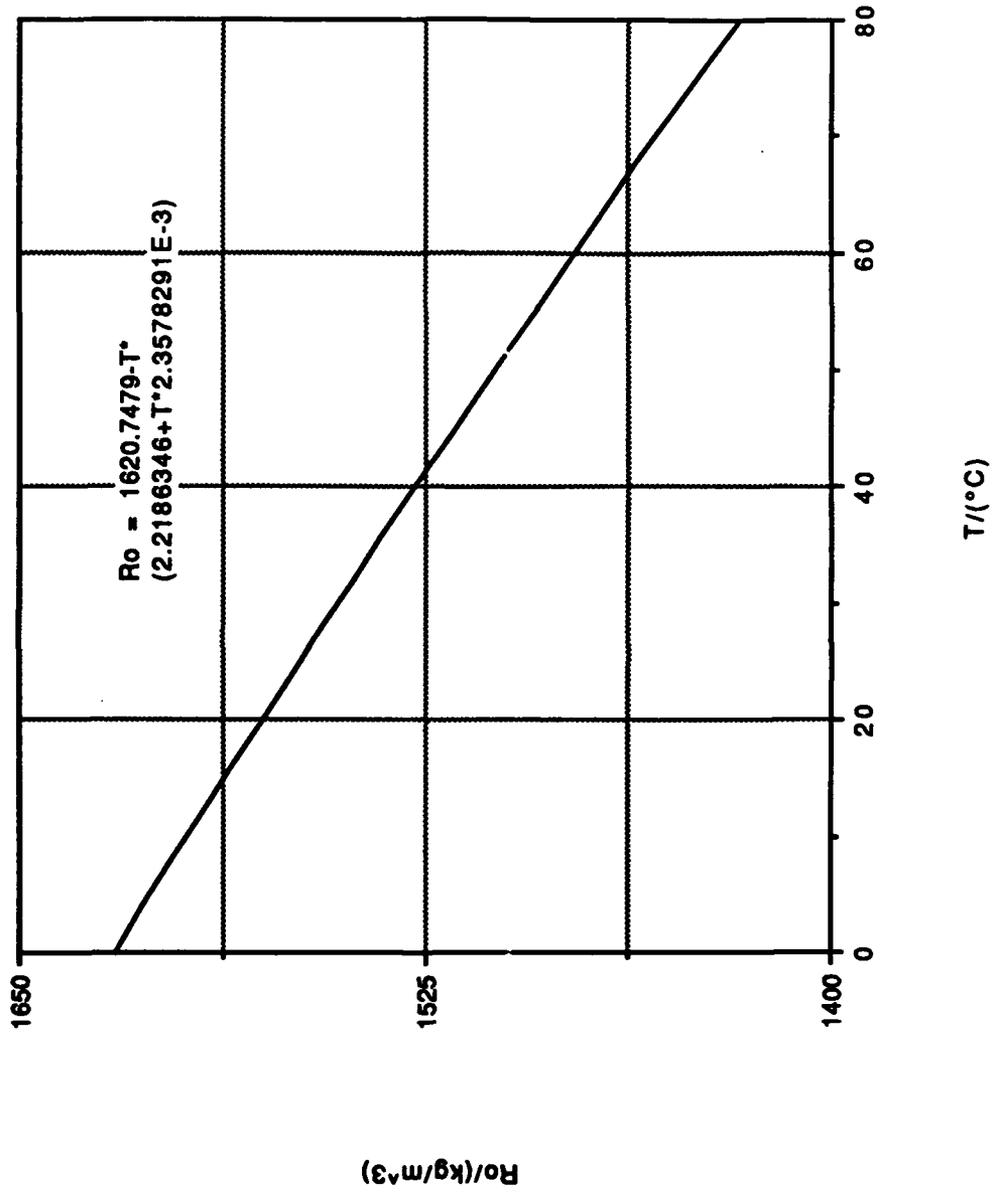
Temp vs. Dynamic Viscosity



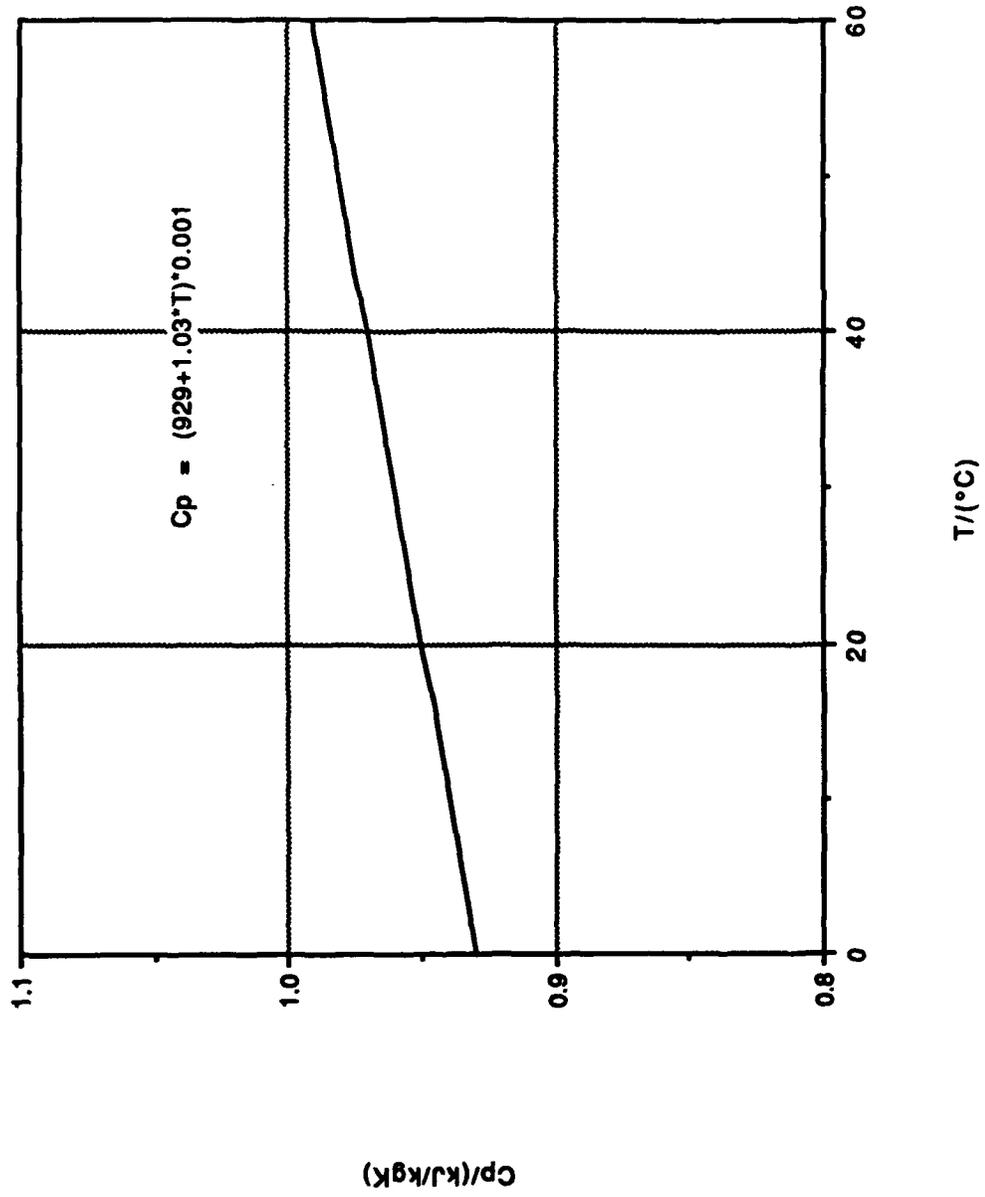
Temp vs. Conductivity(R-113)



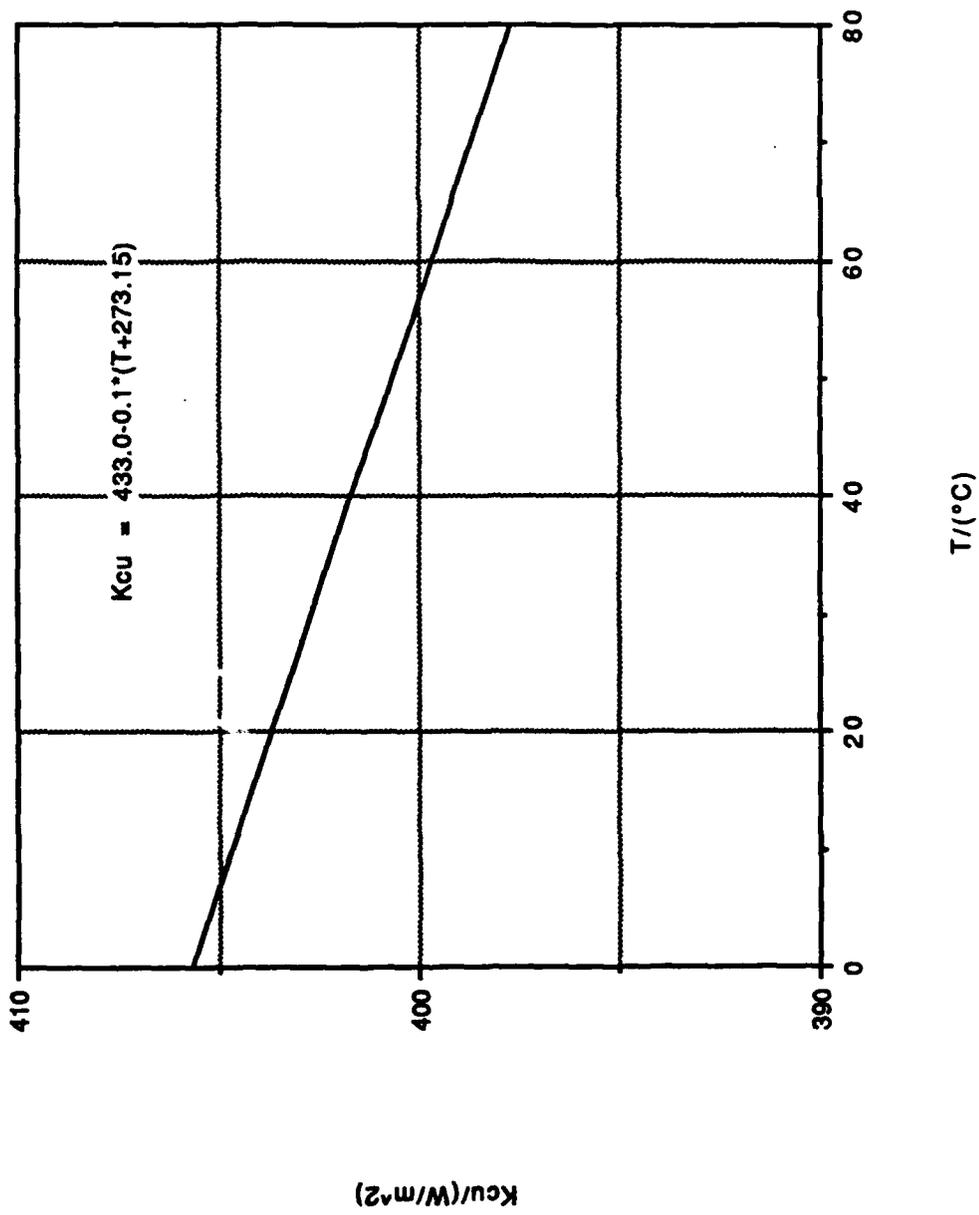
Temp vs. Density



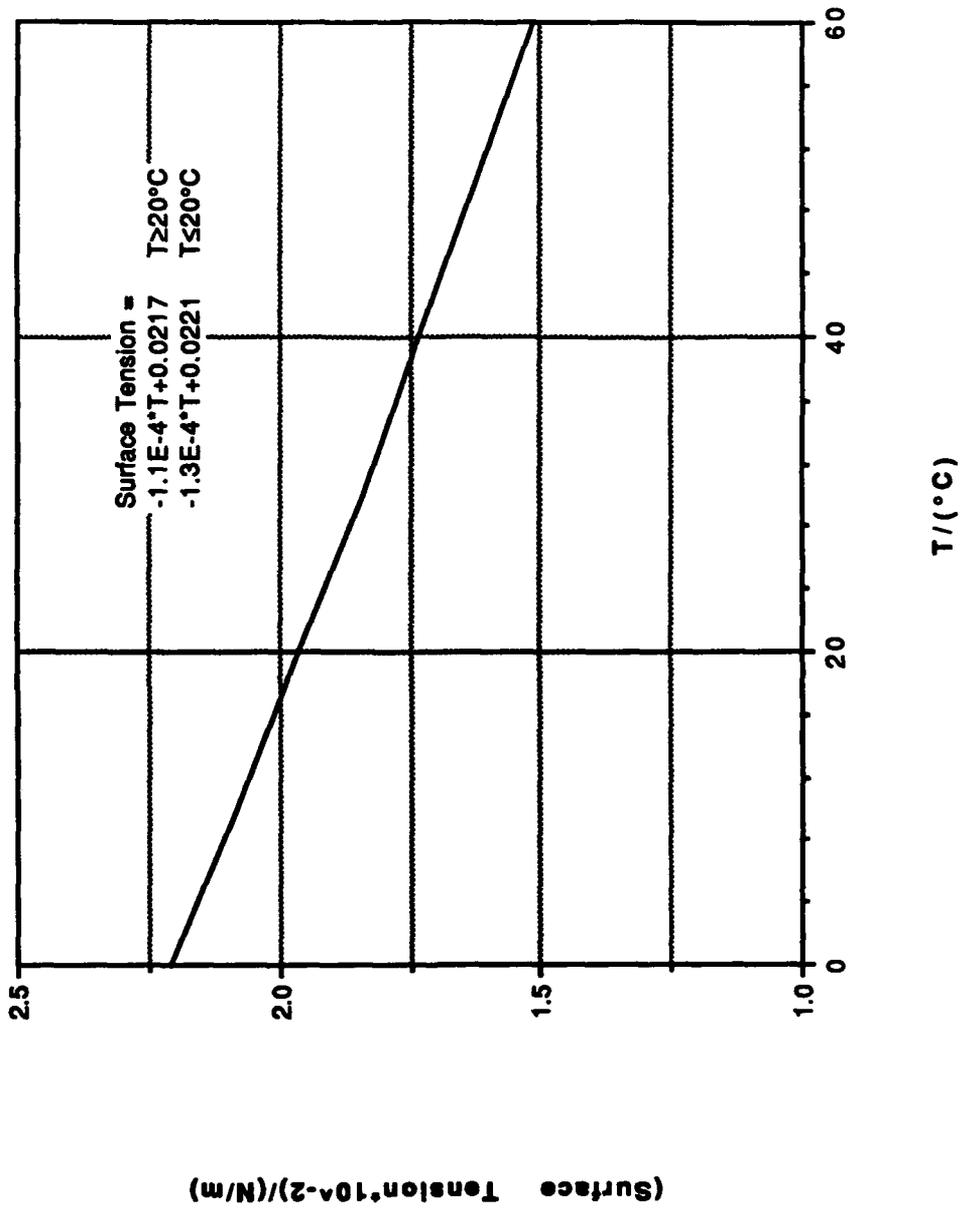
Temp vs Specific Heat



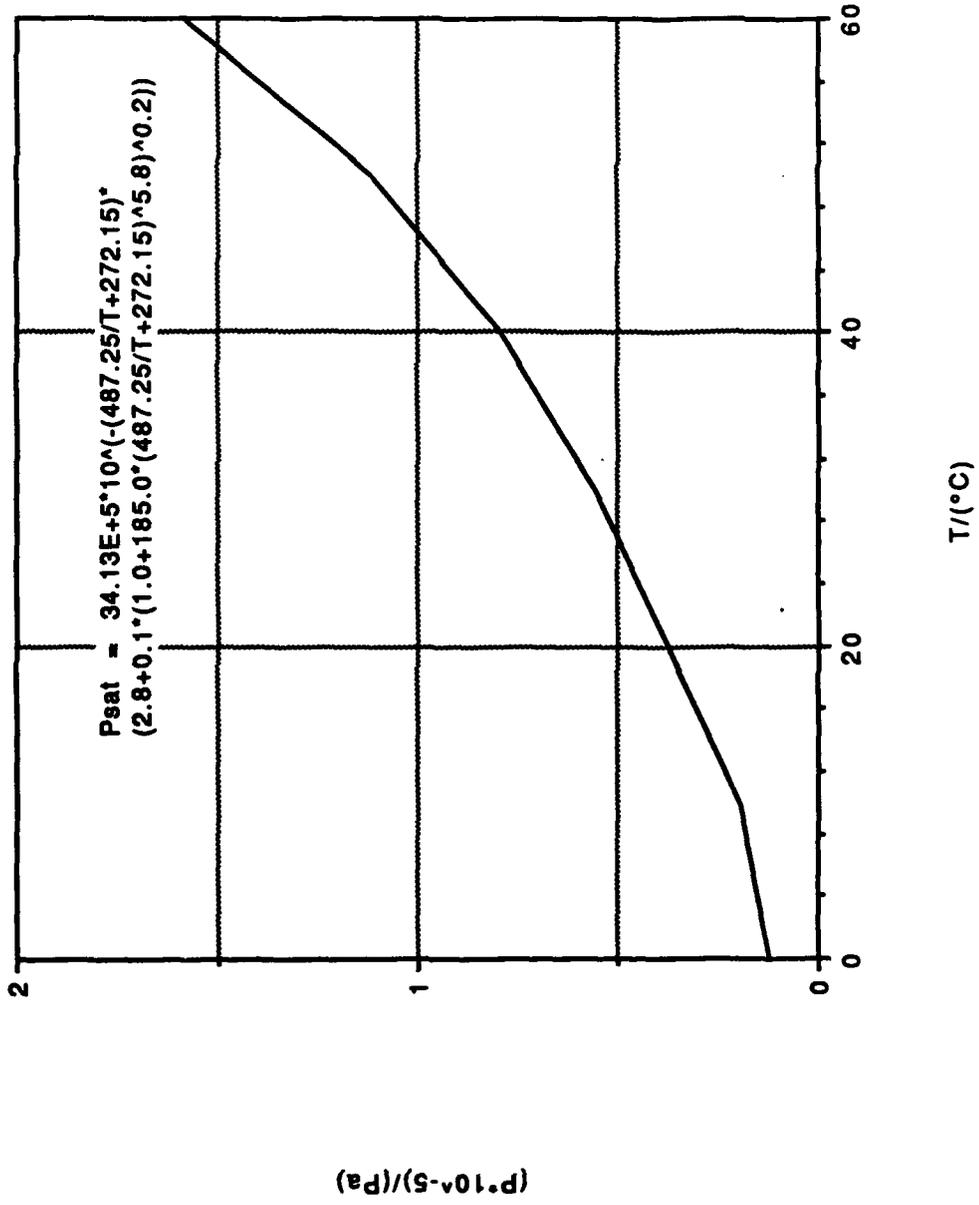
Temp vs. Conductivity(Copper)



Temp vs. Surface Tension



Temp vs. Pressure



APPENDIX C: SAMPLE CALCULATIONS

Data set number 1 of run DTB03 (Decreasing heat flux, Turbo-B tube, Surface preparation D) was used for the sample calculations in order to validate the program used for data acquisition DRP4A. The working fluid was R-113.

1. Test tube dimensions

$$D_{tc} = 11.60 \text{ mm}$$

$$D_o = 14.15 \text{ mm}$$

$$D_i = 12.70 \text{ mm}$$

$$L = 203.2 \text{ mm}$$

$$L_u = 25.4 \text{ mm}$$

2. Measured Parameters

$$T_1 = 54.41 \text{ }^\circ\text{C}$$

$$T_2 = 55.25 \text{ }^\circ\text{C}$$

$$T_3 = 55.80 \text{ }^\circ\text{C}$$

$$T_4 = 55.15 \text{ }^\circ\text{C}$$

$$T_5 = 55.04 \text{ }^\circ\text{C}$$

$$T_6 = 55.38 \text{ }^\circ\text{C}$$

$$T_{td1} = 47.46 \text{ }^\circ\text{C}$$

$$T_{td2} = 47.48 \text{ }^\circ\text{C}$$

$$A_{as} = 3.838 \text{ V}$$

$$V_{as} = 3.958 \text{ V}$$

3. Calculations

The heater power is first calculated from

$$q = V_{as}(V) \times A_{as}(V) \times 60(V/V) \times 1(A/V)$$

Note: The multiplication factors of volt and amp sensors are 60 and 1, respectively.

Therefore:

$$\begin{aligned} q &= 3.958V(3.838V)(60V/V)(1A/V) \\ &= 911.45W \end{aligned}$$

The tube inside wall temperature is obtained from the average of all six thermocouple readings.

$$\begin{aligned} \bar{T}_{wi} &= \frac{1}{6} \sum_{n=1}^6 T_n \\ &= 1/6 (54.41 + 55.25 + 55.80 + 55.15 + 55.04 + 55.38) \\ &= 55.17^{\circ}\text{C} \end{aligned}$$

The tube outside temperature is calculated by knowing the inside wall temperature and using Fourier's Conduction law. Uniform radial conduction is assumed.

$$\bar{T}_{wo} = \bar{T}_{wi} - \frac{q \left[\ln\left(\frac{D_o}{D_i}\right) \right]}{2\pi(k_{cu})(L)}$$

where the second term on the right hand side is the Fourier conduction term. If we define this term as

$$\Phi = \frac{q \left[\ln\left(\frac{D_o}{D_{te}}\right) \right]}{2\pi(k_{cu})(L)}$$

and

$$\theta_b = \bar{T}_{wo} - T_{sat_c}$$

where k_{cu} is the thermal conductivity and is calculated as follow

$$\begin{aligned} k_{cu} &= 434.0 - [0.1(\bar{T}_{wi}-K)] \\ &= 434.0 - [0.1(328.32)] \\ &= 401.17 \text{ W/mK} \end{aligned}$$

Now,

$$\begin{aligned} \bar{T}_{wo} &= \bar{T}_{wi} - \frac{911.45 \left[\ln\left(\frac{14.15}{11.60}\right) \right]}{2\pi(401.17)(0.2032)} \\ &= (55.17 - 0.3567)^\circ\text{C} \\ &= 54.82^\circ\text{C} \end{aligned}$$

The liquid saturation temperature at the top of the tube bundle is

$$\begin{aligned} T_{sat} &= \frac{T_{ld1} + T_{ld2}}{2} \\ &= \frac{47.46 + 47.48}{2} \\ &= 47.47^\circ\text{C} \end{aligned}$$

In order to calculate the local saturation temperature for each tube, correction factors are needed to account for hydrostatic pressure differences between the tube locations and the liquid free surface. This difference is calculated by:

$$\Delta P = \rho (g)(ht)$$

where the density is calculated by

$$\rho = 1620.7479 - T_{sat}(2.2186346 + T_{sat}(2.3578291E-3))$$

Therefore, for $T_{sat} = 47.47^{\circ}\text{C}$

$$\rho = 1510.1 \text{ kg/m}^3$$

So, for the top tube in the bundle which is 0.0124 m below the thermocouples measuring the pool temperature,

$$\Delta P = 1510.1 (9.81)(0.0124)$$

$$\Delta P = 183.69 \text{ Pa}$$

For a 183.69 Pa pressure difference, the corrected saturation temperature is obtained by adding 0.054°C (obtained from standard tables for R-113 or by equations shown in Appendix F.) to T_{sat} . The corrected T_{sat} is:

$$T_{sat_c} = (T_{sat} + 0.054)^{\circ}\text{C}$$

$$= (47.47 + 0.054)^{\circ}\text{C}$$

$$T_{sat_c} = 47.52^{\circ}\text{C}$$

Therefore, the wall superheat can be obtained by the following

$$\begin{aligned}\theta_b &= \bar{T}_{wo} - T_{sat_c} \\ &= (54.82 - 47.52)^\circ\text{C} \\ &= 7.30^\circ\text{C}\end{aligned}$$

Now that the wall superheat is known, we need to calculate the heat flux and the heat transfer coefficient. To do this, we know that the tube is 12 inches long and is heated in a eight inch center portion of the tube. The unheated lengths of the tube are a one inch and a three inch section on opposite ends of the tube. These unheated lengths have a fin effect during the heat transfer process to the evaporating refrigerant. In order to account for this, the following procedure was adopted for both the one and three inch sections. Calculations are shown below for the one inch section .

Heat transfer from the unheated end is calculated as heat from the base of a fin:

$$q_f = (h_b \times p \times k_{cu} \times A_c)^{0.5} \times \theta_b \times \tanh(n \times L_c)$$

where

$$\begin{aligned}p &= \pi \times D_o \\ &= \pi \times 14.15\text{E-}3 \text{ m} \\ &= 44.45\text{E-}3 \text{ m}\end{aligned}$$

now

$$\begin{aligned}A_c &= \frac{\pi}{4} (D_o^2 - D_i^2) \\ &= \frac{\pi}{4} (0.01415^2 - 0.01270^2) \\ A_c &= 3.0578\text{E-}5 \text{ m}^2\end{aligned}$$

The corrected length of unenhanced surface at the end was calculated as follows

$$L_c = L_u + \frac{1}{2}$$

$$L_c = 0.0254 + \frac{(0.01415-0.0127)}{2}$$

$$L_c = 0.0258 \text{ m}$$

h_b is the natural convection heat transfer coefficient of the fin like ends and was calculated by using the Churchill-Chu [Ref. 24] correlation for natural convection from a smooth horizontal cylinder, as modified by Pulido [Ref. 27].

$$h_b = \frac{k}{D_o} \left[0.6 + 0.387 \times \frac{\left[\frac{g \times \beta \times D_o^3 \times \theta_b \times \tanh(n \times L_c)}{v \times \alpha \times L_c \times n} \right]^{\frac{1}{6}}}{\left[1 + \left[\frac{0.559}{Pr} \right]^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

where

$$n = \left[\frac{h_b \times p}{k_{cu} \times A_c} \right]^{0.5}$$

Therefore an iterative technique was necessary to calculate h_b . The iterative technique used was to assume h_b was $190 \frac{W}{m^2K}$ and to continue the iteration until successive values are within 0.001 of each other. The fluid physical properties are calculated at the vapor mean film temperature, given by the following equation.

$$T_{\text{film}} = \frac{T_{\text{sat}_c} + \bar{T}_{\text{wo}}}{2}$$

$$T_{\text{film}} = \frac{47.52 + 54.82}{2}$$

$$T_{\text{film}} = 51.17^\circ\text{C} = 324.32^\circ\text{K}$$

For R-113, the physical properties are given in the program by

Dynamic viscosity, T_{film} in $^\circ\text{K}$

$$\mu = 1.34\text{E-}5 \times 10^{\left[\frac{503}{T_{\text{film}} - 2.15}\right]}$$

$$\mu = 4.88\text{E-}4 \text{ kg/m-s}$$

Specific heat, T_{film} in $^\circ\text{C}$

$$C_p = 929.0 + (1.03 \times T_{\text{film}})$$

$$C_p = 981.71 \text{ J/kg-K}$$

Density, T_{film} in $^\circ\text{C}$

$$\rho = 1620.7479 - T_{\text{film}}[2.2186346 + T_{\text{film}}(0.0023578291)]$$

$$\rho = 1501.1 \text{ kg/m}^3$$

Thermal conductivity of R-113, T_{film} in $^\circ\text{C}$

$$k = 0.071 - (0.000261 \times T_{\text{film}})$$

$$k = 5.765\text{E-}2 \text{ W/mK}$$

Prandtl number

$$\text{Pr} = C_p \times \frac{\mu}{k}$$

$$\text{Pr} = 981.71 \times \frac{4.88\text{E-}4}{5.7645\text{E-}2}$$

$$\text{Pr} = 8.31$$

Thermal expansion

$$\beta = -(1/\rho)(\Delta\rho/\Delta T)$$

$$\rho_{51.07} = 1501.29 \text{ kg/m}^3$$

$$\rho_{51.27} = 1500.8 \text{ kg/m}^3$$

$$\beta = -(1/1501.1)(0.49/0.2)$$

$$\beta = 1.63\text{E-}3 \text{ (1/K)}$$

Kinematic viscosity

$$v = \frac{\mu}{\rho}$$

$$v = \frac{4.88\text{E-}4}{1501.1}$$

$$v = 3.25\text{E-}7 \text{ m}^2/\text{s}$$

Thermal diffusivity

$$\alpha = \frac{k}{\rho \times C_p}$$

$$\alpha = \frac{5.7645\text{E-}2}{1501.1 \times 981.71}$$

$$\alpha = 3.912\text{E-}8 \text{ m}^2/\text{s}$$

Knowing the above properties, the heat transfer coefficient, h_b , can be obtained by iteration.

$$h_b = 185.42 \text{ W/m}^2\cdot\text{K}$$

knowing this we calculate n

$$n = \left[\frac{h_b \times p}{k_{cu} \times A_c} \right]^{0.5}$$

$$n = \left[\frac{185.42 \times 44.45E-3}{401.17 \times 3.0578E-5} \right]^{0.5}$$

$$n = 25.92$$

then we can obtain q_f

$$q_f = (h_b \times p \times k_{cu} \times A_c)^{0.5} \times \theta_b \times \tanh(n \times L_c)$$

$$q_f = (185.42 \times 44.45E-3 \times 401.17 \times 3.0578E-5)^{0.5} \times 7.3 \times \tanh(25.92 \times 0.0258)$$

$$q_f = 1.36 \text{ W}$$

The corresponding results for the three inch section are

$$h_b = 158.27 \text{ W/m}^2\text{-K}$$

$$q_f = 2.04 \text{ W}$$

Therefore the heat transfer through the heated length of the tube is

$$q_s = q - q_f(1 \text{ inch section}) - q_f(3 \text{ inch section})$$

$$q_s = (911.45 - 1.36 - 2.04) \text{ W}$$

$$q_s = 908 \text{ W}$$

and the heat flux and the heat transfer coefficient are as follows

$$q'' = q_s/A_s$$

$$= q_s/(\pi \times D_o \times L)$$

$$= 908/(\pi \times 0.01415 \times 0.2032)$$

$$= 908/9.033E-3$$

$$= 1.005E+5 \text{ W/m}^2$$

and finally the heat transfer coefficient.

$$\begin{aligned}h &= \frac{q_s}{A_s \times (\bar{T}_{wo} - T_{sat})} \\ &= 908 / (9.033E-3 \times 7.3) \\ h &= 1.376E+4 \text{ W/m}^2\text{-K}\end{aligned}$$

APPENDIX D: UNCERTAINTY ANALYSIS

The same data run (DTB03) was chosen for the uncertainty analysis. Therefore, the measured and calculated parameters found in the sample calculation were used in this section. The uncertainty analysis performed was for a high heat flux but the same procedure could be performed at any heat flux to determine the uncertainty bands. All uncertainties are presented as a percentage of the calculated parameter. The uncertainty associated with the experimental parameters is calculated from the equation suggested by Kline and McClintock [Ref 28]. For example, if

$$R = R(x_1, x_2, \dots, x_n)$$

then

$$\delta R = \left[\left(\frac{\partial R}{\partial x_1} \delta x_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \delta x_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} \delta x_n \right)^2 \right]^{0.5}$$

where:

δR = uncertainty of the desired dependant variables

x_n = measured variables

δx_n = uncertainty in measured variables

The boiling heat transfer coefficient is given by

$$h = \frac{q_s}{A_s \times (\bar{T}_{wo} - T_{sat})}$$

where

$$\bar{T}_{wo} = \bar{T}_{wi} - \frac{q [\ln(\frac{D_o}{D_i})]}{2\pi(kcu)(L)}$$

In the above equation, the second term on the right hand side is usually called the Fourier heat transfer conduction term. If we define this as Φ , then

$$\Phi = \frac{q \left[\ln\left(\frac{D_o}{D_i}\right) \right]}{2\pi(kcu)(L)}$$

and

$$\theta_b = \bar{T}_{wo} - T_{sat_c}$$

With this notation, the uncertainty in the heat transfer coefficient is obtained using the following equation.

$$\frac{\delta h}{h} = \left[\left[\frac{\delta q}{q} \right]^2 + \left[\frac{\delta A_s}{A_s} \right]^2 + \left[\frac{\delta \bar{T}_{wi}}{\theta_b} \right]^2 + \left[\frac{\delta \Phi}{\theta_b} \right]^2 + \left[\frac{\delta T_{sat}}{\theta_b} \right]^2 \right]^{\frac{1}{2}}$$

where

$$q = V \times I$$

$$q = V(V) \times I(V) \times 60(V/V) \times 1(A/V)$$

and the uncertainty is

$$\frac{\delta q}{q} = \left[\left[\frac{\delta V}{V} \right]^2 + \left[\frac{\delta I}{I} \right]^2 \right]^{\frac{1}{2}}$$

The accuracy in the voltage and current sensors are as follows

$$\delta V_{as} = \pm 0.05 \text{ V}$$

$$\delta A_{as} = \pm 0.025 \text{ A}$$

From the sample calculation section

$$V_{as} = 3.958V$$

$$A_{as} = 3.838V$$

Therefore,

$$\delta q/q = ((\delta V_{as}/V_{as})^2 + (\delta A_{as}/A_{as})^2)^{0.5}$$

$$\delta q/q = ((0.05/3.958)^2 + (0.025/3.838)^2)^{0.5}$$

$$\delta q/q = 1.42 \text{ percent}$$

Calculation of the surface area and the uncertainty of it are done as follows

$$A_s = \pi \times D_o \times L$$

$$\frac{\delta A_s}{A_s} = \left[\left[\frac{\delta D_o}{D_o} \right]^2 + \left[\frac{\delta L}{L} \right]^2 \right]^{1/2}$$

Knowing the dimensions of the tube from the manufacturer and estimated inaccuracies from work shop tools and human error, the uncertainty was calculated.

Dimensions

$$D_o = 14.15 \text{ mm}$$

$$L = 203.2 \text{ mm}$$

Inaccuracies in measurements

$$\delta D_o = 0.1 \text{ mm}$$

$$\delta L = 0.2 \text{ mm}$$

Uncertainty analysis performed

$$\delta A_s/A_s = ((\delta D_o/D_o)^2 + (\delta L/L)^2)^{0.5}$$

$$\delta A_s/A_s = ((0.1/14.15)^2 + (0.2/203.2)^2)^{0.5}$$

$$\delta A_s/A_s = 0.7135 \text{ percent}$$

The uncertainty calculation for the Fourier conduction term is given below

$$\frac{\delta \Phi}{\Phi} = \left[\left[\frac{\delta q}{q} \right]^2 + \left[\frac{\delta k_{cu}}{k_{cu}} \right]^2 + \left[\frac{\delta L}{L} \right]^2 \right]^{1/2}$$

k_{cu} was calculated using

$$\begin{aligned} k_{cu} &= 434.0 - [0.1(\bar{T}_{wi}-K)] \\ &= 434.0 - [0.1(328.32)] \\ &= 401.17 \text{ W/mK} \end{aligned}$$

and its uncertainty

$$\delta k_{cu} = \left[(0.1 \times \delta \bar{T}_{wi}-K)^2 \right]^{1/2}$$

$\delta \bar{T}_{wi}$ and δT_{sat} are obtained using uncertainties in the thermocouple readings. Average wall inside temperature \bar{T}_{wi} was obtained taking the average of six thermocouple readings inside the tube. The uncertainty associated with this variable is

$$\delta \bar{T}_{wi} = \left[6 \times \left[\frac{\delta T_c}{6} \right]^2 \right]^{1/2}$$

where δT_c was obtained as $\pm 0.5^\circ\text{C}$ from "Omega 1987 Complete Temperature Measurements Handbook pp. T-37. Using engineering judgement this seems high will use 0.1°C .

$$\delta \bar{T}_{wi} = \left[6 \times \left[\frac{0.1}{6} \right]^2 \right]^{\frac{1}{2}}$$

$$\delta \bar{T}_{wi} = 0.04 \text{ } ^\circ\text{C}$$

Saturation temperature was obtained by taking the average of two thermocouple readings and the uncertainty in this temperature was calculated from the following equation.

$$\delta T_{sat} = \left[2 \times \left[\frac{\delta T_c}{2} \right]^2 \right]^{\frac{1}{2}}$$

$$\delta T_{sat} = \left[2 \times \left[\frac{0.1}{2} \right]^2 \right]^{\frac{1}{2}}$$

$$\delta T_{sat} = 0.07^\circ\text{C}$$

Knowing the uncertainty in the temperatures, we can now calculate the uncertainties in the following.

$$\delta k_{cu} = \left[(0.1 \times \delta \bar{T}_{wi} - K)^2 \right]^{\frac{1}{2}}$$

$$\delta k_{cu} = \left[(0.1 \times 273.19)^2 \right]^{\frac{1}{2}}$$

$$\delta k_{cu} = 27.32 \text{ W/mK}$$

Now we can calculate the uncertainty in the Fourier conduction term

$$\frac{\delta \Phi}{\Phi} = \left[\left[\frac{\delta q}{q} \right]^2 + \left[\frac{\delta k_{cu}}{k_{cu}} \right]^2 + \left[\frac{\delta L}{L} \right]^2 \right]^{\frac{1}{2}}$$

$$\frac{\delta \Phi}{\Phi} = \left[[0.0142]^2 + \left[\frac{27.32}{401.17} \right]^2 + \left[\frac{0.2}{203.2} \right]^2 \right]^{\frac{1}{2}}$$

$$\frac{\delta\Phi}{\Phi} = 6.96 \text{ percent}$$

from the sample calculations we know that $\Phi = 0.3567 \text{ }^\circ\text{C}$ or

$$\delta\Phi = 0.3567 \times 6.96 \text{ percent} = 0.025 \text{ }^\circ\text{C}$$

therefore:

$$\frac{\delta h}{h} = \left[\left[\frac{\delta q}{q} \right]^2 + \left[\frac{\delta A_s}{A_s} \right]^2 + \left[\frac{\delta \bar{T}_{wi}}{\theta_b} \right]^2 + \left[\frac{\delta \Phi}{\theta_b} \right]^2 + \left[\frac{\delta T_{sat}}{\theta_b} \right]^2 \right]^{\frac{1}{2}}$$

$$\frac{\delta h}{h} = \left[[0.0142]^2 + [0.07135]^2 + \left[\frac{0.04}{7.3} \right]^2 + \left[\frac{0.025}{7.3} \right]^2 + \left[\frac{0.07}{7.3} \right]^2 \right]^{\frac{1}{2}}$$

$$\frac{\delta h}{h} = 7.4 \text{ percent}$$

Table 3 shows the results of the uncertainty analysis performed. The high and low heat flux correspond to the approximate values of $1.005\text{E}+5 \text{ W/m}^2$ and 597 W/m^2 respectively.

TABLE 3. UNCERTAINTY ANALYSIS RESULTS

<u>Variable</u>	<u>High Heat Flux</u>	<u>Low Heat Flux</u>
ΔT	7.3	0.38
\bar{T}_{wi}	55.17	48.04
T_{sat}	47.47	47.6
$\frac{\delta V}{V}$	1.26%	16.4%
$\frac{\delta I}{I}$	0.65%	8.3%
$\frac{\delta q}{q}$	1.42%	18.%
$\frac{\delta D_o}{D_o}$	0.707%	0.707%
$\frac{\delta L}{L}$	0.098%	0.098%
$\frac{\delta A_s}{A_s}$	0.714%	0.714%
$\frac{\delta k_{cu}}{k_{cu}}$	6.8%	6.8%
$\frac{\delta \Phi}{\Phi}$	6.96%	21.9%
$\frac{\delta h}{h}$	7.4%	22.4%

APPENDIX E: OPERATING PROCEDURES

SYSTEM LIGHT-OFF

1. Power to the 8 ton refrigeration unit is provided by the breakers located in the main distribution panel located in the laboratory. These breakers were never secured. However, if power to this panel was lost then these breakers must be reset.

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. This switch is always left on, unless unit was taken down for long repairs.

2. Push the start button in the control box for the recirculation pump. This control box is located on the bulkhead above the recirculation pump in the outside area adjacent to the refrigeration unit.

3. Set the desired temperature on the roughly graduated Fahrenheit scale on the control panel thermostat. It requires approximately one hour to chill the sump 5°C. The thermometer 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 desired pumps by switching on the breakers in the main distribution power panel. Once the power is energized in the main power panel 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"(Pump #2) and "instrumented tube condenser"(Pump #1), respectively in the breaker box. Flow in the auxiliary condensate system can be controlled with the individual globe 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.

5. Energize the heater variacs desired by switching on the breakers (Auxiliary, Simulation, and/or Bundle) in the main distribution power panel (located near entrance of lab) and individual breakers for each of these in the power distribution box (near apparatus).

6. After ensuring that the breakers for the heater tubes desired are in the "on" position, adjust variac/s to the desired amount of heat flux. Monitor apparatus pressure through the pressure gage at the top of the apparatus, ensuring system pressure does not exceed 30 psig.

SYSTEM SHUTDOWN

1. Turn all variacs to the zero position and switch off all breakers in the power panels.

2. 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".

3. Allow the recirculation pump to operate for at least five minutes after switching off the refrigeration unit to dissipate any back pressure in the system.

4. Turn the breakers for the pumps to the off position at the switch boxes near the ethylene glycol sump, and then secure power at the main distribution power panel.

EMERGENCY SHUTDOWN

1. Secure all power at the main distribution power panel

2. Pull fire alarm

3. Evacuate building

APPENDIX F: PROGRAM DRP4A

```

1000! FILE NAME: DRP4A
1004! DATE: November 22, 1988
1008! REVISED: May 1991 (S. MEMORY)
1012!
1016 BEEP
1020 PRINTER IS 1
1024 Idp=0
1028!
1032 PRINT USING "4X,""Select option default is 0:"""
1036 PRINT USING "6X,""0 Taking data or re-processing previous data""
1040 PRINT USING "6X,""1 Plotting data on Log-Log ""
1044 PRINT USING "6X,""2 Plotting data on Linear""
1048 PRINT USING "6X,""3 Purge""
1052 PRINT USING "6X,""4 Fixup""
1056 PRINT USING "6X,""5 Move""
1060 PRINT USING "6X,""6 Comb""
1064 PRINT USING "6X,""7 Read Plot""
1068!
1072! IDP IS A PROGRAM VARIABLE TO SELECT A SUBROUTINE
1076 INPUT Idp
1080 IF Idp=0 THEN CALL Main
1084 IF Idp=1 THEN CALL Plot
1088 IF Idp=2 THEN CALL Plin
1092 IF Idp=3 THEN CALL Purg
1096 IF Idp=4 THEN CALL Fixup
1100 IF Idp=5 THEN CALL Move
1104 IF Idp=6 THEN CALL Comb
1108 IF Idp=7 THEN CALL Readplot
1112 END
1116!
1120 SUB Main
1124! ICAL=THERMOCOUPLE CALIBRATION
1128 COM /Cc/ C(7)
1132 DIM Emf(35),T(35),D1a(6),D2a(6),Dia(6),Doe(6),La(6),Lua(6),Kcua(6),Et(19),
Ldtc(20),Volt(2),Amp(11),Twa(5),Tw(5),Theta(5),Thetab(5),Q(5),Q1(5),Qdp(5)
1136 DIM Htube(5)
1140!
1144! THERMOCOUPLE ARRAY (C( )) INITIALIZATION
1148 DATA 0.10086091,25727.94369,-767345.8295,78025595.81
1152 DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
1156 READ C(*)
1160!
1164! PRINT HEADER AND INITIALIZE TIME CLOCK
1168 PRINTER IS 701
1172 BEEP
1176 INPUT "ENTER MONTH, DATE AND TIME (MM:DD:HH:MM:SS)",Date$
1180! OUTPUT DIRECTED TO DATA AQUISITION SYSTEM (4P 3497A)
1184 OUTPUT 709:"TD":Date$
1188 OUTPUT 709:"TD"
1192 ENTER 709:Date$
1196 PRINT
1200 PRINT " Month, date and time ":"Date$
1204 PRINT
1208 PRINT USING "10X,""NOTE: Program name : DRP4""
1212 BEEP
1216!

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1220! DN IS THE VARIABLE FOR DISC NUMBER FOR RECORD KEEPING ONLY
1224 INPUT "ENTER DISK NUMBER",Dn
1228 PRINT USING "16X,""Disk number = "",ZZ":Dn
1232 BEEP
1236 Im=0
1240 INPUT "ENTER INPUT MODE (0=3497A,1=FILE) 0=DEFAULT",Im
1244!
1248! INPUT MODE ZERO IS FROM THE DATA AQUISITION SYSTEM
1252 IF Im=0 THEN
1256     BEEP
1260     INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2file$
1264     PRINT USING "16X,""File name: "",14A":D2file$
1268!
1272!     CREATE BDAT FILE ON THE MASS STORAGE MEDIA
1276     CREATE BDAT D2file$,60
1280!     CREATE AN INPUT/OUTPUT LINK TO OPEN FILES
1284     ASSIGN @File2 TO D2file$
1288!
1292!     CREATE DUMMY FILE UNTIL Nrun KNOWN
1296     Dfile$="DUMMY"
1300     CREATE BDAT Dfile$,60
1304     ASSIGN @File1 TO Dfile$
1308     OUTPUT @File1:Date$
1312!
1316!     CREATE A PLOT FILE
1320     BEEP
1324     INPUT "GIVE A NAME FOR THE PLOT FILE",Pfile$
1328     CREATE BDAT Pfile$,30
1332     ASSIGN @Plot TO Pfile$
1336     BEEP
1340!
1344!     IDTC = NUMBER (TOTAL) OF DEFECTIVE THERMOCOUPLES
1348     INPUT "ENTER NUMBER OF DEFECTIVE TCS (0=DEFAULT)",Idtc
1352!     LDTC = LOCATION OF DEFECTIVE THERMOCOUPLE
1356!
1360     IF Idtc=0 THEN
1364         PRINT USING "16X,""No defective TCs exist""
1368         ELSE
1372         PRINT USING "16X,""Defective Thermocouples Indicated by -99.99""
1376     END IF
1380!
1384     BEEP
1388!     DEFECTIVE THERMOCOUPLES MAY BE IN CHANNELS 40-69
1392!     THERMOCOUPLES ARE ENTERED AS DEFECTIVE BY COMPUTER CHANNEL NO.
1396!     JDTC=COUNTER IN LOOP FOR DEFECTIVE THERMOCOUPLES
1400!
1404     IF Idtc>0 THEN
1408         FOR Jdtc=0 TO Idtc-1
1412             INPUT "ENTER DEFECTIVE TC LOCATION (BY COMPUTER CHANNEL NUMBER)
",Ldtc(Jdtc)
1416                 BEEP
1420                 NEXT Jdtc
1424         END IF
1428         PRINTER IS 701
1432         OUTPUT @File1:Ldtc(*)
1436 !
1440 !     Im=1 option (THIS OPTION ALLOWS DATA ENTRY WITH DATA FILE)
1444 ELSE
1448     BEEP
1452     INPUT "GIVE THE NAME OF THE EXISTING DATA FILE",D2file$

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1456 PRINT USING "16X,""File name: "",14A":D2file$
1460 ASSIGN @File2 TO D2file$
1464 ENTER @File2:Nrun
1468 ENTER @File2:Dold$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
1472 BEEP
1476 INPUT "GIVE A NAME FOR PLOT FILE",Pfile$
1480 CREATE BDAT Pfile$,30
1484 ASSIGN @Plot TO Pfile$
1488 PRINT USING "16X,""This data set taken on : "",14A":Dold$
1492 BEEP
1496 PRINTER IS 1
1500 PRINT USING "4X,""SELECT TUBE TYPE""
1504 PRINT USING "6X,"" 0 SMOOTH""
1508 PRINT USING "6X,"" 1 FINNED(19/IN) ""
1512 PRINT USING "6X,"" 2 HIGH FLUX ""
1516 PRINT USING "6X,"" 3 TURBO-B ""
1520 INPUT Itt
1524 END IF
1528 IF Im=1 THEN GOTO 1768
1532 PRINTER IS 1
1536!
1540 IF Im=0 THEN
1544 PRIN. USING "4X,""Select tube type""
1548 PRINT USING "6X,"" 0 Smooth ""
1552 PRINT USING "6X,"" 1 FINNED 19/IN (DEFAULT)""
1556 PRINT USING "6X,"" 2 HIGH FLUX""
1560 PRINT USING "6X,"" 3 TURBO-B""
1564 PRINT USING "6X,"" 4 GROWTH""
1568 PRINT USING "6X,"" 5 GROWTH""
1572 PRINT USING "6X,"" 6 GROWTH""
1576! ITT=TUBE TYPE
1580 INPUT Itt
1584 OUTPUT @File1:Itt
1588 END IF
1592 PRINTER IS 701
1596! Itt=2
1600 PRINT USING "16X,""Tube Type:      "",DD":Itt
1604!
1608 BEEP
1612 Bop=0
1616 INPUT "ENTER BULK OIL % (DEFAULT=0%) ",Bop
1620 OUTPUT @File1:Bop
1624 PRINT USING "16X,""Bulk oil%="",DD":Bop
1628!
1632 BEEP
1636! NHT=NUMBER OF HEATED TUBES
1640 Nht=5
1644 INPUT "Enter number of heated instrumented tubes(default=5)",Nht
1648 OUTPUT @File1:Nht
1652 PRINT USING "16X,""Number of heated instrumented tubes="",DD":Nht
1656 BEEP
1660!
1664! Natp=Number of active dummy pairs
1668 Natp=0
1672 INPUT "Enter number of active dummy pairs (Default=0)",Natp
1676 OUTPUT @File1:Natp
1680 PRINT USING "16X,""Number of active dummy pairs="",DD":Natp
1684 BEEP
1688!
1692! NRT=NUMBER OF ADDED HEATED TUBES TO ENHANCE BUNDLE EFFECT

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1696 Nrt=0
1700 INPUT "Enter number of added heated tubes from simulation heaters(Default=
0)",Nrt
1704 OUTPUT @File1:Nrt
1708 PRINT USING "16X,""Number of added heated tubes(from simulation heaters)=-
",DD":Nrt
1712 BEEP
1716!
1720! CORR IS CORRECTION FOR INSTRUMENTED TUBE HEIGHT
1724 Corr=0
1728 INPUT "WANT TO CORRECT TSAT FOR TUBE HEIGHT (0=YES(DEFAULT),1=NO)",Corr
1732 IF Corr=0 THEN PRINT USING "16X,""TSAT is corrected instrumented heat
ed tube height""
1736 IF Corr=1 THEN PRINT USING "16X,""TSAT is NOT corrected for instrumen
ted heated tube height""
1740 OUTPUT @File1:Corr
1744 BEEP
1748! ILQV=INPUT MODE: LIQUID, VAPOR,OR LIQUID VAPOR AVERAGE
1752 Ilqv=0
1756 INPUT "SELECT (0=LIQ(default),1=VAP,2=(LIQ+VAP)/2)",Ilqv
1760!
1764! DIA=Diameter at thermocouple positions (meters)
1768 DATA .0122,0.0098,0.0106,0.0116,0,0,0
1772 READ Dia(*)
1776 D1=Dia(1)
1780!
1784! D2=Diameter to base of fins (outside dia for smooth)(meters)
1788 DATA .0158,0.0125,0.0158,0.01415,0,0,0
1792 READ D2a(*)
1796 D2=D2a(1)
1800!
1804! Di=Inside diameter of unenhanced ends (meters)
1808 DATA .0132,0.0109,0.0116,0.0127,0,0,0
1812 READ Dia(*)
1816 Di=Dia(1)
1820!
1824! Do=Outside diameter of unenhanced ends (meters)
1828 DATA .015875,0.0125,0.015875,0.01415,0,0,0
1832 READ Doa(*)
1836 Do=Doa(1)
1840!
1844! L=Length of enhanced surface (meters)
1848 DATA .2032,.2032,.2032,.2032,.2032,.2032,.2032
1852 READ La(*)
1856 L=La(1)
1860!
1864! Lu=CORRECTED Length of unenhanced surface at the ends (METERS)
1868! LU=LFIN + THICKNESS/2
1872 DATA .0261,.0254,.0264,0.0258,0,0,0
1876 READ Lua(*)
1880 Lu=Lua(1)
1884!
1888! LV=corrected length of 3 inch finned like end
1892 DIM Lva(6)
1896 DATA .0769,.0762,.0773,0.0766,0,0,0
1900 READ Lva(*)
1904 Lv=Lva(1)
1908! Kcua=Thermal Conductivity of tube
1912! DATA 401,0,0,0,0,0,0
1916! READ Kcua(*)

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```

1920! Kcu=Kcua(1tt)
1924 A=PI*(Do^2-Di^2)/4
1928 P=PI*Do
1932 J=1
1936 Sx=0
1940 Sy=0
1944 Sxs=0
1948 Sxy=0
1952 Repeat: !
1956!
1960 IF Im=0 THEN
1964!   Dtlid=desired temperature of liquid
1968   Dtlid=47.5   !R-113
1969!   Dtlid=2.2   !R-114
1972   Ido=2
1976   ON KEY 0,15 RECOVER 1952
1980   PRINTER IS 1
1984   PRINT USING "4X,""SELECT OPTION ""
1988   PRINT USING "6X,""0=TAKE DATA""
1992   PRINT USING "6X,""1=SET HEAT FLUX""
1996   PRINT USING "6X,""2=SET Tsat (DEFAULT SET FOR R-113)""
2000   PRINT USING "4X,""NOTE: KEY 0 = ESCAPE""
2004!   Ido=desired option
2008   BEEP
2012   INPUT Ido
2016!
2020   BEEP
2024!   Set default value for input
2028   IF Ido>2 THEN Ido=2
2032!   Take data option
2036   IF Ido=0 THEN 2440
2040!
2044! LOOP TO SET HEAT FLUX (FOR TOP INSTRUMENTED TUBE)
2048   IF Ido=1 THEN
2052     Qdp=100000
2056     PRINT USING "4X,""Qdp           QDPsim           Nrt           Qdpaux
           Qtot""
2060     PRINT USING "4X,"" (W/m^2)           (W/m^2)           (W/m^2)
           (W)""
2064     Err=1
2068!     Reset,read channel 25-30,automatic scaling
2072!     Channel 25=aux amps,26=sim amps,27=inst volts,28=sim volts,29=aux
           volts,30=inst amps
2076     OUTPUT 709:"AR AF25 AL30 VRS"
2080     FOR I=10 TO 11
2084       OUTPUT 709:"AS SA"
2088       ENTER 709:Amp(I)
2092     NEXT I
2096     FOR I=0 TO 2
2100       OUTPUT 709:"AS SA"
2104       ENTER 709:Volt(I)
2108     NEXT I
2112     OUTPUT 709:"AS SA"
2116     ENTER 709:Amp(0)
2120!     Calculate actual heat flux
2124     Q(0)=60*Volt(0)*Amp(0)
2128     Qdp(0)=Q(0)/(PI*D2*L)
2132     Qsim=60*20*Volt(1)*Amp(11)
2136     Qdpsim=Qsim/(PI*D2*.2032*3)
2140     Qaux=60*20*Volt(2)*Amp(10)

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2144      Qdpaux=Qaux/(PI*.0160*.1776*4)
2148      Qtot=Q(0)*Nht+Qsim+Qaux
2152      Nrt=Qdpsim/Qdp(0)
2156      IF ABS(Aqdp-Dqdp)>Err THEN
2160          IF Aqdp>Dqdp THEN
2164              BEEP 4000,.2
2168          ELSE
2172              BEEP 250,.2
2176          END IF
2180          IF Nrt<.1 THEN Nrt=0
2184          IF Qdpaux<100 THEN Qdpaux=0
2188          IF Qdpsim<100 THEN Qdpsim=0
2192          PRINT USING "4X,2(MZ.3DE,2X),2X,(MOD.DD),2X,2(MZ.3DE,2X)":Qdp
(0),Qdpsim,Nrt,Qdpaux,Qtot
2196          WAIT 2
2200          GOTO 2076
2204      END IF
2208  END IF
2212!
2216!  LOOP TO SET Tsat
2220  IF Ido=2 THEN
2224      IF Ikdt=1 THEN 2240
2228          BEEP
2232          INPUT "ENTER DESIRED Tsat (DEFAULT=47.5 C - R-113)",Dt1d
2233!      INPUT "ENTER DESIRED Tsat (DEFAULT=2.2 C - R-114)",Dt1d
2236          Ikdt=1
2240          Old1=0
2244          Old2=0
2248          Nn=1
2252          Nrs=Nn MOD 15
2256          Nn=Nn+1
2260          IF Nrs=1 THEN
2264              PRINT USING "4X," DTsat      T1d1      T1d2      Tibb
                Tvat      Tvab      Tlav      ""
2268          END IF
2272!      Read thermocouple voltages for vapor, liquid
2276          OUTPUT 709:"AR AF0 ALS VRS"
2280!      Sample each thermocouple 20 times and report temp for each the
rmocouple, vapor=0,1,2; liquid=3&4
2284          FOR I=0 TO 5
2288              Sum=0
2292              OUTPUT 709:"AS SA"
2296              FOR Ji=1 TO 20
2300                  ENTER 709:Eliq
2304                  Sum=Sum+Eliq
2308              NEXT Ji
2312              Emf(I)=Sum/20
2316              T(I)=FNTvsv(Emf(I))
2320          NEXT I
2324!      Compute average temperature of liquid
2328          Tlav=(T(3)+T(4))*5
2332!      Compute average temperature of vapor
2333          Tvav1=(T(0)+T(1))/2
2334          Tvav2=T(2)
2336          Tvav=(T(0)+T(1)+T(2))/3
2340          IF ABS(Tlav-Dt1d)>.2 THEN
2344              IF Tlav>Dt1d THEN
2348                  BEEP 4000,.2
2352              ELSE
2356                  BEEP 250,.2

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2360         END IF
2364     ELSE
2368         IF ABS(Tlav-Dtld)>.1 THEN
2372             IF Atld>Dtld THEN
2376                 BEEP 3000,.2
2380             ELSE
2384                 BEEP 800,.2
2388             END IF
2392         END IF
2396     END IF
2400     Err1=Tlav-Old1
2404     Old1=Tlav
2408     Err2=Tvav-Old2
2412     Old2=Tvav
2416     PRINT USING "4X,7(MDDD.DD,3X)";Dtld,T(3),T(4),T(5),Tvav1,Tvav2,Tla
v
2420     WAIT 2
2424     GOTO 2252
2428 END IF
2432!
2436! TAKE DATA IF Im=0 LOOP
2440 IF Ikol=1 THEN 2452
2444     BEEP
2448     Ikol=1
2452     OUTPUT 709;"AR AF0 ALS VRS"
2456     FOR I=0 TO 5
2460         OUTPUT 709;"AS SA"
2464         Sum=0
2468         FOR Ji=1 TO 20
2472             ENTER 709;E
2476             Sum=Sum+E
2480             IF I>2 THEN Et(Ji-1)=E
2484         NEXT Ji
2488         Kdl=0
2492         IF I>2 THEN
2496             Eave=Sum/20
2500             Sum=0.
2504             FOR Jk=0 TO 19
2508                 IF ABS(Et(Jk)-Eave)<5.0E-6 THEN
2512                     Sum=Sum+Et(Jk)
2516                 ELSE
2520                     Kdl=Kdl+1
2524                 END IF
2528             NEXT Jk
2532             IF I>2 THEN PRINT USING "4X,""Kdl = "",DD";Kdl
2536                 IF Kdl>10 THEN
2540                     BEEP
2544                     BEEP
2548                     PRINT USING "4X,""Too much scattering in data - re
peat data set""
2552                         GOTO 1980
2556                     END IF
2560                 END IF
2564                 Emf(I)=Sum/(20-Kdl)
2568             NEXT I
2572     OUTPUT 709;"AR AF40 AL69 VRS"
2576     FOR I=6 TO 35
2580         OUTPUT 709;"AS SA"
2584         Sum=0
2588         FOR Ji=1 TO 5

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2592             ENTER 709:E
2596             Sum=Sum+E
2600             NEXT Ji
2604             Emf(I)=Sum/S
2608             NEXT I
2612!
2616!           READ VOLTAGES (27=Inst,28=Sim,29=Aux)
2620           OUTPUT 709:"AR AF27 AL29 VRS"
2624           FOR I=0 TO 2
2628             OUTPUT 709:"AS SA"
2632             ENTER 709:Volt(I)
2636           NEXT I
2640!
2644!           READ CURRENTS (30-34=Inst tubes;35-39=ACTIVE Dummy)
2648           OUTPUT 709:"AR AF30 AL39 VRS"
2652           FOR I=0 TO 9
2656             OUTPUT 709:"AS SA"
2660             ENTER 709:Amp(I)
2664           NEXT I
2668!           Read Currents(25=Aux amps,26=Sim amps)
2672           OUTPUT 709:"AR AF25 AL26 VRS"
2676           FOR I=10 TO 11
2680             OUTPUT 709:"AS SA"
2684             ENTER 709:Amp(I)
2688           NEXT I
2692           ELSE
2696           ENTER @File2:Emf(*),Volt(*),Amp(*)
2700           END IF
2704!
2708!           CONVERT EMF'S TO TEMP,VOLT,CURRENT
2712           FOR I=0 TO 35
2716             T(I)=FNTvsv(Emf(I))
2720             IF I>5 AND Idtc>0 THEN
2724               FOR Ii=0 TO Idtc-1
2728                 IF Ldte(Ii)=I-5+39 THEN T(I)=-99.99
2732               NEXT Ii
2736             END IF
2740           NEXT I
2744!           Ntc=nr of thermocouples
2748           Ntc=6
2752           FOR Ii=0 TO 4
2756             Q(Ii)=60*Volt(0)*Amp(Ii)
2760!           Twa=Average temperature of the wall
2764           Twa(Ii)=0
2768           Ndtc=0
2772           FOR I=1 TO Ntc
2776!           Nn is counter in temp array, start at 6 (this is the first th
ermocouple in the tube bank)
2780           Nn=Ii*6+I+5
2784           IF ABS(T(Nn))>99 THEN
2788             T(Nn)=-99.99
2792             Ndtc=Ndtc+1
2796           ELSE
2800             Twa(Ii)=Twa(Ii)+T(Nn)
2804           END IF
2808           NEXT I
2812           Twa(Ii)=Twa(Ii)/(6-Ndtc)
2816           NEXT Ii
2820           Tlav=(T(3)+T(4))/2
2821           Tvav=T(2)

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2824!   Tvav=(T(0)+T(1)+T(2))/3
2828!
2829!   Tlav=T(5)
2832   Tcu=Tw(0)
2836   Kcu=FNKcu(Tcu)      !THERMAL CONDUCTIVITY OF COPPER
2840!   !IF CURVE FIT NOT AVAIL USE ARRAY KCU(*)
2844! FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
2848   FOR I=0 TO 4
2852     Tw(I)=Twa(I)-Q(I)*LOG(D2/D1)/(2*PI*Kcu*L)
2856     IF Ilqv=0 THEN Txs=Tlav
2860     IF Ilqv=1 THEN Txs=Tvav
2864     IF Ilqv=2 THEN Txs=(Tlav+T(2))*5
2868     IF Corr=1 THEN Thetab(I)=Tw(I)-Txs
2872!   IF Corr=0 THEN Thetab(I)=Tw(I)-(Txs+.056+I*.129) !R-114
2876     IF Corr=0 THEN Thetab(I)=Tw(I)-(Txs+.054+I*.144) !R-113
2880   NEXT I
2884!
2888!   COMPUTE VARIOUS PROPERTIES
2892   Tfilm=(Tw(0)+Txs)*.5 !FILM TEMPERATURE
2896   Rho=FNrho(Tfilm)     !DENSITY
2900   Mu=FNmu(Tfilm)       !VISCOSITY
2904   K=FNK(Tfilm)        !THERMAL CONDUCTIVITY
2908   Cp=FNcp(Tfilm)      !SPECIFIC HEAT
2912   Beta=FNbeta(Tfilm)  !THERMAL EXPANSION
2916   Ni=Mu/Rho           !KINEMATIC VISCOSITY
2920   Alpha=K/(Rho*Cp)    !THERMAL DIFFUSIVITY
2924   Pr=Ni/Alpha         !PRANDTL
2928!
2932!   COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
2936!   FOR UNENHANCED END(S)
2940   Lu=Lua(itt)
2944   Hbar=190
2948   Fe=(Hbar*P/(Kcu*A))*.5*Lu
2952   Tanh=FNtanh(Fe)
2956   Theta(0)=Thetab(0)*Tanh/Fe
2960   Xx=(9.81*Beta*Thetab(0)*Do^3*Tanh/(Fe*Ni*Alpha))*.166667
2964   Yy=(1+(.559/Pr)^(9/16))^(8/27)
2968   Hbarc=K/Do*(.6+.387*Xx/Yy)^2
2972   IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
2976     Hbar=(Hbar+Hbarc)*.5
2980     GOTO 2948
2984   END IF
2988!
2992!   COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S)
2996   Q1(0)=(Thetab(0)*Tanh)*((Hbar*P*Kcu*A)^.5)
3000   Qq=Q1(0)+Qq
3004   Z=Z+1
3008   IF Z=1 THEN
3012     Lu=Lv
3016     GOTO 2944
3020   END IF
3024   Z=0
3028   Q1pct=Qq/Q(0)
3032   Qq=0
3036   As=PI*D2*L
3040   FOR I1=0 TO 4
3044     Q1(I1)=Q1pct*Q(I1)
3048     Qdp(I1)=(Q(I1)-Q1(I1))/As
3052     Htube(I1)=Qdp(I1)/Thetab(I1)
3056   NEXT I1

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3060     PRINTER IS 701
3064!
3068!   RECORD TIME OF DATA TAKING
3072     IF Im=0 THEN
3076         OUTPUT 709;"TD"
3080         ENTER 709:Told$
3084     END IF
3088!
3092!   OUTPUT DATA TO PRINTER
3096     PRINTER IS 701
3100     PRINT
3104     PRINT USING "10X,""Data Set Number = "" ,DDD,2X,14A":J,Told$
3108     PRINT
3112     PRINT USING "10X,"" Tv1      Tv2      Tv3      Tld1      Tld2      Tld3
Tvav      Tldav ""
3116     PRINT USING "10X,8(MDD.DD,2X)":T(0),T(1),T(2),T(3),T(4),T(5),Tvav,Tlav
3120     PRINT
3124     PRINT USING "6X,""Tube      Wall Temperatures (Deg C)      Tnave      Qdp
H          Thetab""
3128     PRINT USING "6X,"" $      1      2      3      4      5      6 (Deg C) (W/m^
2) (W/m^2.K) (K)""
3132     Jj=0
3136     FOR Ii=0 TO Nht-1
3140         FOR Jj=0 TO 5
3144             Tp(Jj)=T(Ii*5+Jj+6)
3148             Jj=Jj+1
3152         NEXT Jj
3156         Jj=Ii+1
3160         FOR Jj=0 TO 4
3164             Tn(Jj)=1+Jj
3168         NEXT Jj
3172     PRINT USING "6X,D,1X,7(MDD.DD),1X,2(MZ.3DE),1X,1(MDD.DD)":Tn(Ii),T
p(0),Tp(1),Tp(2),Tp(3),Tp(4),Tp(5),Twa(Ii),Qdp(Ii),Htube(Ii),Thetab(Ii)
3176     NEXT Ii
3180     Ok=1
3184     IF Im=0 THEN
3188         BEEP
3192         INPUT "OK TO STORE THIS DATA SET (1=Y(default),0=N)?",Ok
3196     END IF
3200!   J=the counter for data sets
3204     IF Ok=1 OR Im=1 THEN J=J+1
3208     IF Ok=1 AND Im=0 THEN OUTPUT @File1:Enf(*),Volt(*),Amp(*)
3212     IF Im=1 OR Ok=1 THEN OUTPUT @Plot:Qdp(*),Htube(*),Thetab(*)
3216     Go_on=1
3220     IF Im=0 THEN
3224         BEEP
3228         INPUT "WILL THERE BE ANOTHER RUN (1=Y(default),0=N)?",Go_on
3232         Nrun=J
3236         IF Go_on=0 THEN 3272
3240         IF Go_on > 0 THEN Repeat
3244     ELSE
3248         IF J=Nrun+1 THEN Repeat
3252     END IF
3256     St=1
3260     BEEP
3264     INPUT "ARE YOU SURE YOUR READY TO TERMINATE (1=Y(DEFAULT),0=NO)?",St
3268     Go_on=1
3272     IF St>0 THEN 3280
3276     IF St=0 THEN GOTO 3240
3280     IF Im=0 THEN

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3284      BEEP
3288      PRINT
3292      PRINT USING "10X,""NOTE: "" ,ZZ,"" data runs were stored in file ""
,10A":J-1,02file$
3296      ASSIGN @File1 TO *
3300      OUTPUT @File2:Nrun-1
3304      ASSIGN @File1 TO Dfile$
3308      ENTER @File1:Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
3312      OUTPUT @File2:Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
3316      FOR I=1 TO Nrun-1
3320          ENTER @File1:Emf(*),Volt(*),Amp(*)
3324          OUTPUT @File2:Emf(*),Volt(*),Amp(*)
3328      NEXT I
3332      ASSIGN @File1 TO *
3336      PURGE "DUMMY"
3340      END IF
3344      BEEP
3348      PRINT
3352      PRINT USING "10X,""NOTE: "" ,ZZ,"" X-Y pairs were stored in plot data f
ile "" ,10A":J-1,Pfile$
3356      ASSIGN @File2 TO *
3360      ASSIGN @Plot TO *
3364      BEEP
3368      SUBEND
3372!
3376!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3380!
3384      DEF FNKcu(Tcu)
3388! OFHC COPPER
3392      Tk=Tcu+273.15      !C TO K
3396! Kcu=434-.112*Tk      !250-300K USE FOR R-114 @2.2 C
3400      Kcu=433.0-.1*Tk      !200-400K USE FOR R-113 @47.5 C
3404      RETURN Kcu
3408      FNEND
3412!
3416      DEF FNMu(T)
3420! CURVE FIT OF VISCOSITY
3424      Tk=T+273.15      !C TO K
3428! Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3      !R-114 170-360 K
3432      Mu=.0000134*(10^(503/(Tk-2.15)))      !R113
3436      RETURN Mu
3440      FNEND
3444!
3448      DEF FNCp(T)
3452! CURVE FIT OF Cp
3456      Tk=T+273.15      !C TO K
3460! Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3      !R-114 180-400 K
3464      Cp=(929+1.03*T)*.001      !R-113
3468      Cp=Cp*1000
3472      RETURN Cp
3476      FNEND
3480!
3484      DEF FNRho(T)
3488      Tk=T+273.15      !C TO K
3492      X=1-(1.8*Tk/753.95)      !K TO R
3496! Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^1.5+1.119828*X^2
3500! Ro=Ro/.062428      !R-114
3504      Ro=1.6207479E+3-T*(2.2186346+T*2.3578291E-3)      !R-113
3508      RETURN Ro
3512      FNEND

```

```

3516!
3520 DEF FNPr(T) 1GOOD FOR R-114/R-113
3524 Pr=FNCp(T)*FNMu(T)/FNK(T)
3528 RETURN Pr
3532 FNEND
3536!
3540 DEF FNK(T)
3544 T<360 K WITH T IN C
3548 K=.071-.000261*T
3552 RETURN K
3556 FNEND
3560!
3564 DEF FNTanh(Fe)
3568 P=EXP(Fe)
3572 Q=EXP(-Fe)
3576 Tanh=(P-Q)/(P+Q)
3580 RETURN Tanh
3584 FNEND
3588!
3592 DEF FNTvsv(V)
3596 COM /Cc/ C(7)
3600 T=C(0)
3604 FOR I=1 TO 7
3608 T=T+C(I)*V^I
3612 NEXT I
3616 RETURN T
3620 FNEND
3624!
3628 DEF FNBeta(T)
3632 Rop=FNRho(T+.1)
3636 Rom=FNRho(T-.1)
3640 Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
3644 RETURN Beta
3648 FNEND
3652 DEF FNPoly(X)
3656 COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
3660 X1=X
3664 Poly=B(0)
3668 FOR I=1 TO Nop
3672 IF Ilog=1 THEN X1=LOG(X)
3676 Poly=Poly+B(I)*X1^I
3680 NEXT I
3684 IF Ilog=1 THEN Poly=EXP(Poly)
3688 RETURN Poly
3692 FNEND
3696!
3700XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
3704!
3708 SUB Poly(Dfile$(*),Np,Itn)
3712 DIM R(10),S(10),Sy(12),Sz(12),Xx(100),Yy(100),Xy(17)
3716 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
3720 COM /Xyy/ Xp(5),Yp(5)
3724 FOR I=0 TO 4
3728 B(I)=0
3732 NEXT I
3736 In=1
3740 BEEP
3744 INPUT "ENTER DATA FILE NAME",Dfile$(0)
3748 BEEP
3752 INPUT "ENTER NUMBER OF X-Y PAIRS",Np

```

```

3756 BEEP
3760 INPUT "LIKE TO EXCLUDE DATA PAIRS (I=Y,0=N(DEFAULT))?",Ied
3764 IF Ied=1 THEN
3768     BEEP
3772     INPUT "ENTER NUMBER OF PAIRS TO BE EXCLUDED",Ipex
3776 END IF
3780 ASSIGN @File TO Dfiles(0)
3784 N=2
3788 BEEP
3792 INPUT "ENTER THE ORDER OF POLYNOMIAL (DEFAULT=2) ",N
3796 FOR I=0 TO N
3800     Sy(I)=0
3804     Sx(I)=0
3808 NEXT I
3812 IF Ied=1 AND In=1 THEN
3816     FOR I=1 TO Ipex
3820         ENTER @File;Xy(*)
3824     NEXT I
3828 END IF
3832 FOR I=1 TO Np-Ipex
3836     ENTER @File;Xy(*)
3840     IF Opo=0 THEN
3844         Y=Xy(Itn-1)
3848         X=Xy(11+Itn)
3852     END IF
3856     IF Opo=1 THEN
3860         Y=Xy(5+Itn)
3864         X=Xy(11+Itn)
3868     END IF
3872     IF Opo=2 THEN
3876         Y=Xy(5+Itn)
3880         X=Xy(Itn-1)
3884     END IF
3888     IF Ilog=1 THEN
3892         X=LOG(X)
3896         Y=LOG(Y)
3900     END IF
3904     Xx(I)=X
3908     Yy(I)=Y
3912     R(0)=Y
3916     Sy(0)=Sy(0)+Y
3920     S(1)=X
3924     Sx(1)=Sx(1)+X
3928     FOR J=1 TO N
3932         R(J)=R(J-1)*X
3936         Sy(J)=Sy(J)+R(J)
3940     NEXT J
3944     FOR J=2 TO N+2
3948         S(J)=S(J-1)*X
3952         Sx(J)=Sx(J)+S(J)
3956     NEXT J
3960 NEXT I
3964 Sx(0)=Np
3968 FOR I=0 TO N
3972     C(I)=Sy(I)
3976     FOR J=0 TO N
3980         A(I,J)=Sx(I+J)
3984     NEXT J
3988 NEXT I
3992 FOR I=0 TO N-1

```

```

3996     CALL Divide(I)
4000     CALL Subtract(I+1)
4004     NEXT I
4008     B(N)=C(N)/A(N,N)
4012     FOR I=0 TO N-1
4016         B(N-1-I)=C(N-1-I)
4020         FOR J=0 TO I
4024             B(N-1-I)=B(N-1-I)-A(N-1-I,N-J)*B(N-J)
4028         NEXT J
4032         B(N-1-I)=B(N-1-I)/A(N-1-I,N-1-I)
4036     NEXT I
4040     IF Iprnt=0 THEN
4044         PRINT USING "12X,""EXPONENT    COEFFICIENT""
4048         FOR I=0 TO N
4052             PRINT USING "15X,00,5X,MD.7DE":I,B(I)
4056         NEXT I
4060         PRINT " "
4064         PRINT USING "12X,""DATA POINT    X            Y            Y(CALCULATED) DI
SCREPANCY""
4068             FOR I=1 TO Np
4072                 Yc=B(0)
4076                 FOR J=1 TO N
4080                     Yc=Yc+B(J)*Xx(I)^J
4084                 NEXT J
4088                 D=Yy(I)-Yc
4092                 PRINT USING "15X,3D,4X,4(MD.SDE,1X)":I,Xx(I),Yy(I),Yc,D
4096             NEXT I
4100     END IF
4104     ASSIGN @File TO *
4108     SUBEND
4112!
4116     SUB Divide(M)
4120     COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4124     FOR I=M TO N
4128         Ao=A(I,M)
4132         FOR J=M TO N
4136             A(I,J)=A(I,J)/Ao
4140         NEXT J
4144         C(I)=C(I)/Ao
4148     NEXT I
4152     SUBEND
4156!
4160     SUB Subtract(K)
4164     COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4168     FOR I=K TO N
4172         FOR J=K-1 TO N
4176             A(I,J)=A(K-1,J)-A(I,J)
4180         NEXT J
4184         C(I)=C(K-1)-C(I)
4188     NEXT I
4192     SUBEND
4196!
4200     SUB Plin
4204     COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
4208     COM /Xxyy/ Xx(5),Yy(5)
4212     PRINTER IS 705
4216     BEEP
4220     INPUT "SELECT (0=h/h0% same tube,1=h(HF)/h(sm)",Irt
4224     BEEP
4228     INPUT "WHICH Tsat (1=6.7,0=-2.2)",Isat

```

```

4232 Xmin=0
4236 Xmax=10
4240 Xstep=2
4244 IF Irt=0 THEN
4248     Ymin=0
4252     Ymax=1.4
4256     Ystep=.2
4260 ELSE
4264     Ymin=0
4268     Ymax=15
4272     Ystep=5
4276 END IF
4280 BEEP
4284 PRINT "IN:SP1:IP 2300,2200,8300,6800:"
4288 PRINT "SC 0,100,0,100;TL 2,0:"
4292 Sfx=100/(Xmax-Xmin)
4296 Sfy=100/(Ymax-Ymin)
4300 PRINT "PU 0,0 PD"
4304 FOR Xa=Xmin TO Xmax STEP Xstep
4308     X=(Xa-Xmin)*Sfx
4312     PRINT "PA":X,",",0: XT:"
4316 NEXT Xa
4320 PRINT "PA 100,0;PU:"
4324 PRINT "PU PA 0,0 PD"
4328 FOR Ya=Ymin TO Ymax STEP Ystep
4332     Y=(Ya-Ymin)*Sfy
4336     PRINT "PA 0,";Y,"YT"
4340 NEXT Ya
4344 PRINT "PA 0,100 TL 0 2"
4348 FOR Xa=Xmin TO Xmax STEP Xstep
4352     X=(Xa-Xmin)*Sfx
4356     PRINT "PA":X,",",100: XT"
4360 NEXT Xa
4364 PRINT "PA 100,100 PU PA 100,0 PD"
4368 FOR Ya=Ymin TO Ymax STEP Ystep
4372     Y=(Ya-Ymin)*Sfy
4376     PRINT "PD PA 100,";Y,"YT"
4380 NEXT Ya
4384 PRINT "PA 100,100 PU"
4388 PRINT "PA 0,-2 SR 1.5,2"
4392 FOR Xa=Xmin TO Xmax STEP Xstep
4396     X=(Xa-Xmin)*Sfx
4400     PRINT "PA":X,",",0:"
4404     PRINT "CP -2,-1:LB":Xa:""
4408 NEXT Xa
4412 PRINT "PU PA 0,0"
4416 FOR Ya=Ymin TO Ymax STEP Ystep
4420     IF ABS(Ya)<1.E-5 THEN Ya=0
4424     Y=(Ya-Ymin)*Sfy
4428     PRINT "PA 0,";Y,""
4432     PRINT "CP -4,-.25:LB":Ya:""
4436 NEXT Ya
4440 Xlabels="Oil Percent"
4444 IF Irt=0 THEN
4448     Ylabels="h/h0%"
4452 ELSE
4456     Ylabels="h/hsmooth"
4460 END IF
4464 PRINT "SR 1.5,2;PU PA 50,-10 CP":-LEN(Xlabels)/2:"0:LB":Xlabels:""
4468 PRINT "PA -11,50 CP 0,";-LEN(Ylabels)/2*5/6:"DI 0,1:LB":Ylabels:""

```

```

4472 PRINT "CP 0,0"
4476 Ipn=0
4480 BEEP
4484 INPUT "WANT TO PLOT DATA FROM A FILE (1=Y,0=N)?",Okp
4488 Icn=0
4492 IF Okp=1 THEN
4496 BEEP
4500 INPUT "ENTER THE NAME OF THE DATA FILE",D_files$
4504 BEEP
4508 INPUT "SELECT (0=LINEAR, 1=LOG(X,Y))",Ilog
4512 ASSIGN @File TO D_files$
4516 BEEP
4520 INPUT "ENTER THE BEGINNING RUN NUMBER",Md
4524 BEEP
4528 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED",Npairs
4532 BEEP
4536 INPUT "ENTER DESIRED HEAT FLUX",Q
4540 BEEP
4544 PRINTER IS 1
4548 PRINT USING "4X,""Select a symbol: ""
4552 PRINT USING "4X,""1 Star 2 Plus sign ""
4556 PRINT USING "4X,""3 Circle 4 Square ""
4560 PRINT USING "4X,""5 Rombus ""
4564 PRINT USING "4X,""6 Right-side-up triangle ""
4568 PRINT USING "4X,""7 Up-side-down triangle ""
4572 INPUT Sym
4576 PRINTER IS 705
4580 PRINT "PU DI"
4584 IF Sym=1 THEN PRINT "SM*"
4588 IF Sym=2 THEN PRINT "SM+"
4592 IF Sym=3 THEN PRINT "SMo"
4596 Nn=4
4600 IF Ilog=1 THEN Nn=1
4604 IF Md>1 THEN
4608     FOR I=1 TO (Md-1)
4612         ENTER @File: Xa,Ya
4616     NEXT I
4620 END IF
4624 Q1=Q
4628 IF Ilog=1 THEN Q=LOG(Q)
4632 FOR I=1 TO Npairs
4636     ENTER @File: Xa,B(*)
4640     Ya=B(0)
4644     FOR K=1 TO Nn
4648         Ya=Ya+B(K)*Q^K
4652     NEXT K
4656     IF Ilog=1 THEN Ya=EXP(Ya)
4660     IF Ilog=0 THEN Ya=Q1/Ya
4664     IF Irt=0 THEN
4668         IF Xa=0 THEN
4672             Yo=Ya
4676             Ya=1
4680         ELSE
4684             Ya=Ya/Yo
4688         END IF
4692     ELSE
4696         Hsm=FNHsmooth(Q,Xa,Isat)
4700         Ya=Ya/Hsm
4704     END IF
4708     Xx(I-1)=Xa

```

```

4712 Yy(I-1)=Ya
4716 X=(Xa-Xmin)*Sfx
4720 Y=(Ya-Ymin)*Sfy
4724 IF Sym>3 THEN PRINT "SM"
4728 IF Sym<4 THEN PRINT "SR 1.4,2.4"
4732 PRINT "PA",X,Y,""
4736 IF Sym>3 THEN PRINT "SR 1.2,1.6"
4740 IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0,:"
4744 IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6:"
4748 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8:"
4752 IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8:"
4756 NEXT I
4760 BEEP
4764 ASSIGN @File TO *
4768 END IF
4772 PRINT "PU SM"
4776 BEEP
4780 INPUT "WANT TO PLOT A POLYNOMIAL (I=Y,0=N)?",Okp
4784 IF Okp=1 THEN
4788 BEEP
4792 INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
4796 Iprnt=1
4800 CALL Poly(Itn)
4804 FOR Xa=Xmin TO Xmax STEP Xstep/25
4808 Icn=Icn+1
4812 Ya=FNPoly(Xa)
4816 Y=(Ya-Ymin)*Sfy
4820 X=(Xa-Xmin)*Sfx
4824 IF Y<0 THEN Y=0
4828 IF Y>100 THEN GOTO 4868
4832 Pu=0
4836 IF Ipn=1 THEN Idf=Icn MOD 2
4840 IF Ipn=2 THEN Idf=Icn MOD 4
4844 IF Ipn=3 THEN Idf=Icn MOD 8
4848 IF Ipn=4 THEN Idf=Icn MOD 16
4852 IF Ipn=5 THEN Idf=Icn MOD 32
4856 IF Idf=1 THEN Pu=1
4860 IF Pu=0 THEN PRINT "PA",X,Y,"PD"
4864 IF Pu=1 THEN PRINT "PA",X,Y,"PU"
4868 NEXT Xa
4872 PRINT "PU"
4876 Ipn=Ipn+1
4880 GOTO 4480
4884 END IF
4888 BEEP
4892 INPUT "WANT TO QUIT (I=Y,0=N)?",Iquit
4896 IF Iquit=1 THEN 4904
4900 GOTO 4480
4904 PRINT "PU SP0"
4908 SUBEND
4912 SUB Stats
4916 PRINTER IS 701
4920 J=0
4924 K=0
4928 BEEP
4932 INPUT "PLOT FILE TO ANALYZE?",Files
4936 ASSIGN @File TO Files
4940 BEEP
4944 INPUT "LAST RUN No?(0=QUIT)",Nn
4948 IF Nn=0 THEN 5092

```

```

4952 Nn=Nn-J
4956 Sx=0
4960 Sy=0
4964 Sz=0
4968 Sxs=0
4972 Sys=0
4976 Szs=0
4980 FOR I=1 TO Nn
4984 J=J+1
4988 ENTER @File:Q,T
4992 H=Q/T
4996 Sx=Sx+Q
5000 Sxs=Sxs+Q^2
5004 Sy=Sy+T
5008 Sys=Sys+T^2
5012 Sz=Sz+H
5016 Szs=Szs+H^2
5020 NEXT I
5024 Qave=Sx/Nn
5028 Tave=Sy/Nn
5032 Have=Sz/Nn
5036 Sdevq=SQR(ABS((Nn*Sxs-Sx^2)/(Nn*(Nn-1))))
5040 Sdevt=SQR(ABS((Nn*Sys-Sy^2)/(Nn*(Nn-1))))
5044 Sdevh=SQR(ABS((Nn*Szs-Sz^2)/(Nn*(Nn-1))))
5048 Sh=100*Sdevh/Have
5052 Sq=100*Sdevq/Qave
5056 St=100*Sdevt/Tave
5060 IF K=1 THEN 5084
5064 PRINT
5068 PRINT USING "11X,""DATA FILE:"",14A":File$
5072 PRINT
5076 PRINT USING "11X,""RUN Htube      SdevH      Qdp          SdevQ      Thetab SdevT""
"
5080 K=1
5084 PRINT USING "11X,DD,2(2X,D.3DE,1X,3D.2D),2X,DD.3D,1X,3D.2D":J,Have,Sh,Qave
,Sq,Tave,St
5088 GOTO 4940
5092 ASSIGN @File1 TO *
5096 PRINTER IS 1
5100 SUBEND
5104 SUB Coef
5108 COM /Cply/ A(10,10),C(10),B(4),N,Iprnt,Opo,Ilog
5112 BEEP
5116 INPUT "GIVE A NAME FOR CROSS-PLOT FILE",Cpf$
5120 BEEP
5124 INPUT "OUTPUT TYPE (0=q vs Dt, 1=h vs Dt, 2=h vs q)",Opo
5128 CREATE BDAT Cpf$,6
5132 ASSIGN @File TO Cpf$
5136 BEEP
5140 INPUT "SELECT (0=LINEAR,1=LOG(X,Y))",Ilog
5144 BEEP
5148 INPUT "ENTER OIL PERCENT (-1=STOP)",Bop
5152 BEEP
5156 INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5160 IF Bop<0 THEN 5176
5164 CALL Poly(Itn)
5168 OUTPUT @File:Bop,B(*)
5172 GOTO 5144
5176 ASSIGN @File TO *
5180 SUBEND

```

```

5184
5188 !XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
5192!
5196 SUB Plot
5200 COM /Cply/ A(10,10),C(10),B(4),Nop,Iprnt,Opo,Ilog
5204 DIM Xy(17)
5208 INTEGER Ii
5212 PRINTER IS 1
5216 BEEP
5220 Idv=1
5224 INPUT "LIKE DEFAULT VALUES FOR PLOT (1=Y(DEFAULT),0=N)?",Idv
5228 Opo=0
5232 BEEP
5236 PRINT USING "4X,""Select Option:"""
5240 PRINT USING "6X,""0 q versus delta-T(DEFAULT)""
5244 PRINT USING "6X,""1 h versus delta-T""
5248 PRINT USING "6X,""2 h versus q""
5252 INPUT Opo
5256 BEEP
5260 INPUT "SELECT UNITS (0=SI(DEFAULT),1=ENGLISH)",Iun
5264 PRINTER IS 705
5268 IF Idv<>1 THEN
5272 BEEP
5276 INPUT "ENTER NUMBER OF CYCLES FOR X-AXIS",Cx
5280 BEEP
5284 INPUT "ENTER NUMBER OF CYCLES FOR Y-AXIS",Cy
5288 BEEP
5292 INPUT "ENTER MIN X-VALUE (MULTIPLE OF 10)",Xmin
5296 BEEP
5300 INPUT "ENTER MIN Y-VALUE (MULTIPLE OF 10)",Ymin
5304 ELSE
5308 IF Opo=0 THEN
5312 Cy=2
5316 Cx=2
5320 Xmin=1
5324 Ymin=1000
5328 END IF
5332 IF Opo=1 THEN
5336 Cy=2
5340 Cx=2
5344 Xmin=1
5348 Ymin=100
5352 END IF
5356 IF Opo=2 THEN
5360 Cy=2
5364 Cx=2
5368 Xmin=1000
5372 Ymin=100
5376 END IF
5380 END IF
5384 BEEP
5388 PRINT "IN:SP1:IP 2300,2200,8300,6800:"
5392 PRINT "SC 0,100,0,100:TL 2,0:"
5396 Sfx=100/Cx
5400 Sfy=100/Cy
5404 BEEP
5408 INPUT "WANT TO BY-PASS CAGE (1=Y, 0=NO(DEFAULT))",Ibp
5412 IF Ibp=1 THEN 5908
5416 PRINT "PU 0,0 PD"
5420 Nn=9

```

```

5424 FOR I=1 TO Cx+1
5428   Xat=Xmin*10^(I-1)
5432   IF I=Cx+1 THEN Nn=1
5436   FOR J=1 TO Nn
5440     IF J=1 THEN PRINT "TL 2 0"
5444     IF J=2 THEN PRINT "TL 1 0"
5448     Xa=Xat*J
5452     X=LGT(Xa/Xmin)*Sfx
5456     PRINT "PA":X,",",0: XT:"
5460   NEXT J
5464 NEXT I
5468 PRINT "PA 100,0:PU:"
5472 PRINT "PU PA 0,0 PD"
5476 Nn=9
5480 FOR I=1 TO Cy+1
5484   Yat=Ymin*10^(I-1)
5488   IF I=Cy+1 THEN Nn=1
5492   FOR J=1 TO Nn
5496     IF J=1 THEN PRINT "TL 2 0"
5500     IF J=2 THEN PRINT "TL 1 0"
5504     Ya=Yat*J
5508     Y=LGT(Ya/Ymin)*Sfy
5512     PRINT "PA 0,",Y,"YT"
5516   NEXT J
5520 NEXT I
5524 PRINT "PA 0,100 TL 0 2"
5528 Nn=9
5532 FOR I=1 TO Cx+1
5536   Xat=Xmin*10^(I-1)
5540   IF I=Cx+1 THEN Nn=1
5544   FOR J=1 TO Nn
5548     IF J=1 THEN PRINT "TL 0 2"
5552     IF J>1 THEN PRINT "TL 0 1"
5556     Xa=Xat*J
5560     X=LGT(Xa/Xmin)*Sfx
5564     PRINT "PA":X,",",100: XT"
5568   NEXT J
5572 NEXT I
5576 PRINT "PA 100,100 PU PA 100,0 PD"
5580 Nn=9
5584 FOR I=1 TO Cy+1
5588   Yat=Ymin*10^(I-1)
5592   IF I=Cy+1 THEN Nn=1
5596   FOR J=1 TO Nn
5600     IF J=1 THEN PRINT "TL 0 2"
5604     IF J>1 THEN PRINT "TL 0 1"
5608     Ya=Yat*J
5612     Y=LGT(Ya/Ymin)*Sfy
5616     PRINT "PD PA 100,",Y,"YT"
5620   NEXT J
5624 NEXT I
5628 PRINT "PA 100,100 PU"
5632 PRINT "PA 0,-2 SR 1.5,2"
5636 I1=LGT(Xmin)
5640 FOR I=1 TO Cx+1
5644   Xa=Xmin*10^(I-1)
5648   X=LGT(Xa/Xmin)*Sfx
5652   PRINT "PA":X,",",0:"
5656   IF I1=0 THEN PRINT "CP -2,-2:LB10:PR -2,2:LB":I1:""
5660   IF I1<0 THEN PRINT "CP -2,-2:LB10:PR 0,2:LB":I1:""

```

```

5664     Ii=Ii+1
5668 NEXT I
5672 PRINT "PU PA 0,0"
5676 Ii=LGT(Ymin)
5680 Y10=10
5684 FOR I=1 TO Cy+1
5688     Ya=Ymin*10^(I-1)
5692     Y=LGT(Ya/Ymin)*Sfy
5696     PRINT "PA 0,":Y,""
5700     PRINT "CP -4,-.25:LB10:PR -2,2:LB":Ii:""
5704     Ii=Ii+1
5708 NEXT I
5712 BEEP
5716 Idl=1
5720 INPUT "WANT USE DEFAULT LABELS (1=Y(DEFAULT),0=N)?",Idl
5724 IF Idl<>1 THEN
5728     BEEP
5732     INPUT "ENTER X-LABEL",Xlabels$
5736     BEEP
5740     INPUT "ENTER Y-LABEL",Ylabels$
5744 END IF
5748 IF Opo<2 THEN
5752     PRINT "SR 1,2:PU PA 40,-14:"
5756     PRINT "LB(T:PR -1.6,3 PD PR 1.2,0 PU:PR .5,-4:LBwo:PR .5,1:"
5760     PRINT "LB-T:PR .5,-1:LBsat:PR .5,1:"
5764     IF Iun=0 THEN
5768         PRINT "LB) / (K)"
5772     ELSE
5776         PRINT "LB) / (F)"
5780     END IF
5784 END IF
5788 IF Opo=2 THEN
5792     IF Iun=0 THEN
5796         PRINT "SR 1.5,2:PU PA 40,-14:LBq / (W/m:SR 1,1.5:PR 0.5,1:LB2:SR 1
.5,2:PR 0.5,-1:LB)"
5800     ELSE
5804         PRINT "SR 1.5,2:PU PA 34,-14:LBq / (Btu/hr:PR .5,.5:LB.:PR .5,-.5:
.
5808         PRINT "LBft:PR .5,1:SR 1,1.5:LB2:SR 1.5,2:PR .5,-1:LB):"
5812     END IF
5816 END IF
5820 IF Opo=0 THEN
5824     IF Iun=0 THEN
5828         PRINT "SR 1.5,2:PU PA -12,40:DI 0,1:LBq / (W/m:PR -1,0.5:SR 1,1.5:L
B2:SR 1.5,2:PR 1,.5:LB)"
5832     ELSE
5836         PRINT "SR 1.5,2:PU PA -12,32:DI 0,1:LBq / (Btu/hr:PR -.5,.5:LB.:PR
.5,.5:"
5840         PRINT "LBft:SR 1,1.5:PR -1,.5:LB2:PR 1,.5:SR 1.5,2:LB)"
5844     END IF
5848 END IF
5852 IF Opo=0 THEN
5856     IF Iun=0 THEN
5860         PRINT "SR 1.5,2:PU PA -12,38:DI 0,1:LBh / (W/m:PR -1,.5:SR 1,1.5:LB
2:SR 1.5,2:PR .5,.5:"
5864         PRINT "LB.:PR .5,0:LBK)"
5868     ELSE
5872         PRINT "SR 1.5,2:PU PA -12,28:DI 0,1:LBh / (Btu/hr:PR -.5,.5:LB.:PR
.5,.5:"
5876         PRINT "LBft:PR -1,.5:SR 1,1.5:LB2:SR 1.5,2:PR .5,.5:LB.:PR .5,.5:

```

```

LBF:
5880     END IF
5884 END IF
5888 IF Id1=0 THEN
5892     PRINT "SR 1.5,2:PU PA 50,-16 CP";-LEN(Xlabels)/2:"0;LB";Xlabels;"
5896     PRINT "PA -14,50 CP 0,";-LEN(Ylabels)/2*5/6;"DI 0,1;LB";Ylabels;"
5900     PRINT "CP 0,0 DI"
5904 END IF
5908 Ipn=0
5912 Repeat:1
5916 X11=1.E+6
5920 Xul=-1.E+6
5924 Icn=0
5928 BEEP
5932 Ok=1
5936 INPUT "WANT TO PLOT DATA FROM A FILE (1=Y(DEFAULT),0=N)?",Ok
5940 IF Ok=1 THEN
5944 BEEP
5948 INPUT "ENTER THE NAME OF THE DATA FILE",Dfiles(0)
5952 ASSIGN @file TO Dfiles(0)
5956 BEEP
5960 Npairs=20
5964 INPUT "ENTER THE NUMBER OF X-Y PAIRS STORED(DEFAULT=20)",Npairs
5968 BEEP
5972 Itn=Itn+1
5976 INPUT "ENTER TUBE NUMBER (1, 2, 3, 4, OR 5)",Itn
5980 BEEP
5984 PRINTER IS 1
5988 INPUT "WANT DEFAULT SYMBOLS? (YES=0 (DEFAULT),NO=1)",Symb
5992 Symb=Itn+2
5996 IF Symb=0 THEN
6000     GOTO 6036
6004 END IF
6008 PRINT USING "4X,""Select a symbol: ""
6012 PRINT USING "6X,""1 Star    2 Plus sign ""
6016 PRINT USING "6X,""3 Circle  4 Square ""
6020 PRINT USING "6X,""5 Rombus ""
6024 PRINT USING "6X,""6 Right-side-up triangle ""
6028 PRINT USING "6X,""7 Up-side-down triangle ""
6032 INPUT Symb
6036 PRINTER IS 705
6040 PRINT "PU DI"
6044 IF Symb=1 THEN PRINT "SMo"
6048 IF Symb=2 THEN PRINT "SM+"
6052 IF Symb=3 THEN PRINT "SMo"
6056 FOR I=1 TO Npairs
6060 ENTER @file:Xy(*)
6064 IF Opo=0 THEN
6068     Ya=Xy(Itn-1)
6072     Xa=Xy(11+Itn)
6077 END IF
6080 IF Opo=1 THEN
6084     Ya=Xy(5+Itn)
6088     Xa=Xy(11+Itn)
6092 END IF
6096 IF Opo=2 THEN
6100     Ya=Xy(5+Itn)
6104     Xa=Xy(Itn-1)
6108 END IF
6112 IF Xa<X11 THEN X11=Xa

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```

6116 IF Xa>Xul THEN Xul=Xa
6120 IF Iun=1 THEN
6124     IF Opo<2 THEN Xa=Xa*1.8
6128     IF Opo>0 THEN Ya=Ya*.1761
6132     IF Opo=0 THEN Ya=Ya*.317
6136     IF Opo=2 THEN Xa=Xa*.317
6140 END IF
6144 X=LGT(Xa/Xmin)*Sfx
6148 Y=LGT(Ya/Ymin)*Sfy
6152 Kj=0
6156 CALL Symb(X,Y,Sym,Icl,Kj)
6160 GOTO 6212
6164 IF Sym>3 THEN PRINT "SM"
6168 IF Sym<4 THEN PRINT "SR 1.4,2.4"
6172 IF Icl=0 THEN
6176     PRINT "PA",X,Y,""
6180 ELSE
6184     PRINT "PA",X,Y,"PD"
6188 END IF
6192 IF Sym>3 THEN PRINT "SR 1.2,1.6"
6196 IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0:"
6200 IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6:"
6204 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8:"
6208 IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8:"
6212 NEXT I
6216 PRINT "PU"
6220 BEEP
6224 Ilab=1
6228 INPUT "WANT TO LABEL? (1=Y(DEFAULT),0=N)",Ilab
6232 IF Ilab=1 THEN
6236     PRINT "SP0:SP2"
6240     BEEP
6244     IF Klab=0 THEN
6248         Xlab=65
6252         Ylab=85
6256         INPUT "ENTER INITIAL X,Y LOCATIONS",Xlab,Ylab
6260         Xtt=Xlab-5
6264         Ytt=Ylab+8
6268         PRINT "SR 1,1.5"
6272         PRINT "SM:PA",Xtt,Ytt,"LB      Tube % File"
6276         Ytt=Ytt-3
6280         PRINT "PA",Xtt,Ytt,"LB      No Oil Name"
6284         IF Sym=1 THEN PRINT "SM+"
6288         IF Sym=2 THEN PRINT "SM+"
6292         IF Sym=3 THEN PRINT "SMo"
6296         Klab=1
6300     END IF
6304     Kj=1
6308     CALL Symb(Xlab,Ylab,Sym,Icl,Kj)
6312     PRINT "SR 1,1.5:SM"
6316     IF Sym<4 THEN PRINT "PR 2,0"
6320     PRINT "PR 2,0:LB";Itn:""
6324     BEEP
6328     INPUT "ENTER BOP(0=DEFAULT)",Bop
6332     IF Bop<10 THEN PRINT "PR 3,0:LB";Bop:""
6336     IF Bop>9 THEN PRINT "PR 1.5,0:LB";Bop:""
6340     PRINT "PR 2,0:LB";Ofile$(0):""
6344     PRINT "SP0:SP1:SR 1.5,2"
6348     Ylab=Ylab-5
6352 END IF

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```

6330 BEEP
6360 ASSIGN @File TO *
6364 X11=X11/1.2
6368 Xul=Xul*1.2
6372 ! GOTO 8040
6376 END IF
6380 PRINT "PU SM"
6384 BEEP
6388 Go_on=1
6392 INPUT "WANT TO PLOT A POLYNOMIAL (1=Y(DEFAULT),0=N)?" ,Go_on
6396 IF Go_on=1 THEN
6400 BEEP
6404 PRINTER IS 1
6408 INPUT "WANT DEFAULT LINE TYPE? (YES=0 (DEFAULT),NO=1)" ,Ln
6412 Ipn=Itn
6416 IF Ln=0 THEN
6420 GOTO 6448
6424 END IF
6428 PRINT USING "4X," "Select line type:"
6432 PRINT USING "6X," "0 Solid line"
6436 PRINT USING "6X," "1 Dashed"
6440 PRINT USING "6X," "2,,,5 Longer line - dash"
6444 INPUT Ipn
6448 PRINTER IS 705
6452 BEEP
6456 Ilog=1
6460 INPUT "SELECT (0=LIN,1=LOG(DEFAULT))" ,Ilog
6464 Iprnt=1
6468 CALL Poly(Dfile$(*),Npairs,Itn)
6472 FOR Xx=0 TO Cx STEP Cx/200
6476 Xa=Xmin+10*Xx
6480 IF Xa<X11 OR Xa>Xul THEN 6572
6484 Icn=Icn+1
6488 Pu=0
6492 IF Ipn=1 THEN Idf=Icn MOD 2
6496 IF Ipn=2 THEN Idf=Icn MOD 4
6500 IF Ipn=3 THEN Idf=Icn MOD 8
6504 IF Ipn=4 THEN Idf=Icn MOD 16
6508 IF Ipn=5 THEN Idf=Icn MOD 28
6512 IF Idf=1 THEN Pu=1
6516 Ya=FNPoly(Xa)
6520 IF Ya<Ymin THEN 6572
6524 IF Iun=1 THEN
6528 IF Opo<2 THEN Xa=Xa+1.8
6532 IF Opo>0 THEN Ya=Ya+.1761
6536 IF Opo=0 THEN Ya=Ya+.317
6540 IF Opo=2 THEN Xa=Xa+.317
6544 END IF
6548 Y=LGT(Ya/Ymin)*Sfy
6552 X=LGT(Xa/Xmin)*Sfx
6556 IF Y<0 THEN Y=0
6560 IF Y>100 THEN GOTO 6572
6564 IF Pu=0 THEN PRINT "PA",X,Y,"PD"
6568 IF Pu=1 THEN PRINT "PA",X,Y,"PU"
6572 NEXT Xx
6576 . PRINT "PU"
6580 END IF
6584 BEEP
6588 INPUT "WANT TO QUIT (1=Y,0=N(DEFAULT))" ,Iqt
6592 IF Iqt=1 THEN 6500

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```

6596 GOTO 5916
6600 PRINT "PU PA 0,0 SP0"
6604 SUBEND
6608!
6612!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6616!
6620 SUB Symb(X,Y,Sym,Icl,Kj)
6624 IF Sym>3 THEN PRINT "SM"
6628 IF Sym<4 THEN PRINT "SR 1.4,2.4"
6632 Yad=0
6636 IF Kj=1 THEN Yad=.8
6640 IF Icl=0 THEN
6644 PRINT "PA",X,Y+Yad,""
6648 ELSE
6652 PRINT "PA",X,Y+Yad,"PD"
6656 END IF
6660 IF Sym>3 THEN PRINT "SR 1.2,1.6"
6664 IF Sym=4 THEN PRINT "UC2,4,99,0,-8,-4,0,0,8,4,0:"
6668 IF Sym=5 THEN PRINT "UC3,0,99,-3,-6,-3,6,3,6,3,-6:"
6672 IF Sym=6 THEN PRINT "UC0,5.3,99,3,-8,-6,0,3,8:"
6676 IF Sym=7 THEN PRINT "UC0,-5.3,99,-3,8,6,0,-3,-8:"
6680 IF Kj=1 THEN PRINT "SM:PR 0,-.8"
6684 SUBEND
6688!
6692!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6696!
6700 SUB Fixup
6704! FILE: FIXUP
6708!
6712 DIM Emf(34),Amp(11),Volt(4),Ldte(4)
6716 BEEP
6720 INPUT "OLD FILE TO FIXUP",D2files
6724 ASSIGN @File2 TO D2files
6728 Dfiles="TEST"
6732 CREATE BDAT Dfiles,60
6736 ASSIGN @File1 TO Dfiles
6740 ENTER @File2:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
6744 OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
6748 FOR I=1 TO Nrun
6752 ENTER @File2:Told$,Emf(*),Volt(*),Amp(*)
6756 IF I=1 THEN 6764
6760 OUTPUT @File1:Bop,Told$,Emf(*),Volt(*),Amp(*)
6764 NEXT I
6768 ASSIGN @File2 TO *
6772 ASSIGN @File1 TO *
6776! RENAME "TEST" TO D2_files
6780 BEEP 2000,.2
6784 BEEP 4000,.2
6788 BEEP 4000,.2
6792 SUBEND
6796!
6800!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6804!
6808 SUB Move
6812! FILE NAME: MOVE
6816!
6820 DIM A(66),B(66),C(66),D(66),E(66),F(66),G(66),H(66),I(66),K(66),L(66),M(66)
)
6824 DIM N(66),Emf(34),Volt(2),Amp(11),Ldte(4)
6828 BEEP

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6832 INPUT "OLD FILE TO MOVE",D2_files$
6836 ASSIGN @File2 TO D2_files$
6840 ENTER @File2:Nrun,Told$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
6844 FOR I=1 TO Nrun
6848     ENTER @File2:Told$
6852     ENTER @File2:A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M
        I),N(I)
6856     ENTER @File2:Emf(*),Volt(*),Amp(*)
6860 NEXT I
6864 ASSIGN @File2 TO *
6868 BEEP
6872 INPUT "SHIFT DISK AND HIT CONTINUE",Ok
6876 BEEP
6880 INPUT "INPUT BDAT SIZE",Size
6884 CREATE BDAT D2_files$,Size
6888 ASSIGN @File1 TO D2_files$
6892 OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
6896 FOR I=1 TO Nrun
6900     OUTPUT @File1:Told$
6904     OUTPUT @File1:A(I),B(I),C(I),D(I),E(I),F(I),G(I),H(I),J(I),K(I),L(I),M
        (I),N(I)
6908     OUTPUT @File1:Emf(*),Volt(*),Amp(*)
6912 NEXT I
6916 ASSIGN @File1 TO *
6920! RENAME "TEST" TO D2_files$
6924 BEEP 2000,.2
6928 BEEP 4000,.2
6932 BEEP 4000,.2
6936 PRINT "DATA FILE MOVED"
6940 SUBEND
6944!
6948!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6952!
6956 SUB Purg
6960 BEEP
6964 INPUT "ENTER FILE NAME TO BE DELETED",Files$
6968 PURGE Files$
6972 GOTO 6960
6976 SUBEND
6980!
6984!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
6988!
6992 SUB Comb
6996! FILE NAME: COMB
7000!
7004 DIM Emf(34),Volt(2),Amp(11),Ldte(4)
7008 BEEP
7012 INPUT "OLD FILE TO FIXUP",D2_files$
7016 ASSIGN @File2 TO D2_files$
7020 D1_files$="TEST"
7024 CREATE BDAT D1_files$,30
7028 ASSIGN @File1 TO D1_files$
7032 ENTER @File2:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
7036 IF K=0 THEN OUTPUT @File1:Nrun,Date$,Ldte(*),Itt,Bop,Nht,Natp,Nrt,Corr
7040 FOR I=1 TO Nrun
7044     ENTER @File2:Bop,Told$,Emf(*),Volt(*),Amp(*)
7048     OUTPUT @File1:Bop,Told$,Emf(*),Volt(*),Amp(*)
7052 NEXT I
7056 ASSIGN @File2 TO *
7060! RENAME "TEST" TO D2_files$

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```

7064 BEEP 4000,.2
7068 BEEP
7072 Oka=1
7076 INPUT "WANT TO ADD ANOTHER FILE (1=Y,0=N(default))?",Oka
7080 IF Oka=1 THEN
7084 K=1
7088 BEEP
7092 INPUT "GIVE NEW FILE NAME",Nfiles$
7096 ASSIGN @File2 TO Nfiles$
7100 GOTO 7032
7104 END IF
7108 ASSIGN @File2 TO *
7112 SUBEND
7116!
7120!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
7124!
7128 SUB Readplot
7132 DIM Qdp(5),Htube(5),Thetab(5)
7136 PRINTER IS 701
7140 INPUT "ENTER FILE NAME",Files$
7144 INPUT "ENTER THE NUMBER OF DATA PAIRS",Nrun
7148 ASSIGN @File1 TO Files$
7152 FOR I=1 TO Nrun
7156     ENTER @File1:Qdp(*),Htube(*),Thetab(*)
7160     PRINT Qdp(*)
7164     PRINT
7168     PRINT Htube(*)
7172     PRINT
7176     PRINT Thetab(*)
7180     PRINT
7184     PRINT
7188 NEXT I
7192 SUBEND

```

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