Please return

OAK RIDGE NATIONAL LABORATORY LIBRARIES
3 4456 0549505 0

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL-TM-721

COPY NO. - 2

DATE - November 7, 1963

PERFORMANCE AND ENDURANCE TESTS OF ART NaK-TO-AIR TEST RADIATORS NO. 1 AND NO. 2

J. C. Amos
D. R. Ward

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report. The information is not to be abstracted, reprinted or otherwise given public dissemination without the approval of the ORNL patent branch, Legal and Information Control Department.

Table of Contents

		Page No.
	List of Illustrations	3
1.0	Introduction	4
2.0	Summary	4
3.0	Radiator Design	5
4.0	Experimental Program	
	4.1 Test Stand Design	10
	4.2 Test Program	10
5.0	Radiator Performance	
	5.1 Heat Transfer Characteristics	14
	5.2 Air Pressure Drop Characteristics	14
	5.3 NaK Pressure Drop Characteristics	14
	5.4 Reliability	24
6.0	Appendix	
	6.1 ART Radiator Specifications	30
	6.2 Radiator Pre-Operational Inspection Reports	45
	6.3 Detailed Operating History Test Radiator No. 1	48
	6.4 Detailed Operating History Test Radiator No. 2	49
	6.5 Experimental Report No. 7405-B-1 "Method of Calculating Radiator Heat Transfer Coefficients"	50
	6.6 Performance Data Tabulations	
	6.6.1 Test Radiator No. 1 Heat Transfer Data	69
	6.6.2 Test Radiator No. 2 Heat Transfer Data	70
	6.6.3 Test Radiator No. 1 Room Temperature Air Pressure Drop Data	71
	6.6.4 Test Radiator No. 2 Room Temperature Air Pressure Drop Data	72
	6.6.5 Test Radiator No. 1 High Temperature Air Pressure Drop Data	73
	6.6.6 Test Radiator No. 2 High Temperature Air Pressure Drop Data	74
	6.6.7 Test Radiator No. 1 Initial NaK Pressure Drop Data	75
	6.6.8 Test Radiator No. 2 Initial NaK Pressure Drop Data	76
	6.6.9 Sample Raw Data Sheet, Calculation Sheet and Curves Used With Calculation Sheet	77
	6.7 Post-Operational Metallurgical Examination Reports	82

OAK RIDGE NATIONAL LABORATORY LIBRARIES

3 4456 0549505 0

Figure No.		Page No.
1	Photograph of ART NaK-to-Air Radiator Unit	6
2	Photograph of ART Prototype NaK-to-Air Radiator Test Unit	7
3	Photograph of ART Prototype NaK-to-Air Radiator Test Unit Showing Modification to Reduce Stresses	8
4	Table of Dimensional Parameters for ART Radiators and Prototype Test Units.	9
5	Elementary Flow Diagram of ART Radiator Test Facility	11
6	Photograph of ART Prototype Radiator Test Facility	12
7	Summary of ART Test Radiators No. 1 and 2 Operating History	13
8	Heat Transfer Composite Data Plot for ART Radiator Test Units No. 1 and 2	15
9	Heat Transfer Performance Plot for ART Radiator Test Unit No. 1	16
10	Heat Transfer Performance Data Plot for ART Radiator Test Unit No. 2	17
11	Room Temperature Air Pressure Drop Composite Data Plot for ART Test Radiators No. 1 and 2	18
12	Hot Air Pressure Drop Composite Data Plot for ART Test Radiators No. 1 and 2	19
13	ART Test Radiator No. 1 Air Pressure Drop Data Plot	20
14	ART Test Radiator No. 2 Air Pressure Drop Data Plot	21
15	ART Test Radiator No. 1 NaK Pressure Drop Data Plot	22
16	ART Test Radiator No. 2 NaK Pressure Drop Data Plot	23
17	ART Test Radiator No. 1 NaK Temperature and Pressure Drop History	25
18	ART Test Radiator No. 2 NaK Temperature and Pressure Drop History	26
19	Photograph of ART Test Radiator After Removal From Test Stand	27

1.0 Introduction

The Aircraft Reactor Test (ART) main heat dump design included sixteen pairs of high-performance, NaK-to-air radiator matrices, each designed to remove 3.5 MW of heat from the reactor main NaK system. Since this radiator design was based on results from an experimental program conducted with smaller single units (0.5 MW)[1], it was considered essential to determine the reliability and performance of full scale prototypes prior to final acceptance of the design for ART application.

The ART radiator design provided for two identical tube-fin matrices to be mounted in a common plane on either side of common inlet and outlet NaK headers. For test purposes, one tube-fin matrix was omitted from the radiator unit. This provided a single tube-fin matrix of 1.73 MW capacity possessing all the design features of the paired full scale radiator arrangement. This report covers the performance and endurance testing of two such test units.

2.0 Summary

The performance data obtained on the two ART prototype test units were in substantial agreement. The heat transfer performance of these units represented approximately 30% improvement at design air flow over the smaller 500 KW test units on which the full scale design was based. The air pressure drop was approximately 10% higher than the 500 KW units. The initial NaK pressure drop correlated on the basis of a modified friction factor was in substantial agreement with the 500 KW unit data. This pressure drop increased throughout radiator ΔT operation. This increase has been observed in all previous radiator tests and is attributed to a metal mass transfer buildup which occurs in the radiator tubes during ΔT operation.

Both radiators failed during endurance testing. Radiator No. 1 operated 880 hours, including 480 hours with a heat load, and was subjected to 9 thermal cycles. Radiator No. 2 operated 862 hours, including 431 hours with a heat load, and endured 181 thermal cycles representing 6 times the maximum number of cycles proposed for the ART radiators.

Metallographic examination of representative tubes from Radiator No. 1 disclosed no evidence of incipient cracking. Examination of tubes from the failure area of Radiator No. 2 disclosed grain boundary voids in one of forty tubes examined. These voids could have been caused by excessive plastic strain in this tube and may have been responsible for the failure. In any event, the failure of these two ART test radiator units indicate that additional test and development work would be required before ART radiator life could be predicted with any degree of confidence.

[1] MacPherson, R. E. et al, "ART Prototype Radiators Development Program and Metallurgical Results", ORNL 2436.

3.0 Radiator Design

The ART NaK-to-air radiator units each consisted of two identical round-tube, flat-plate fin matrices mounted in a common plane on either side of common inlet and outlet NaK headers, as shown in Figure 1. The radiator is a counter-current-crossflow design with air flowing perpendicular to the NaK tubes and parallel to the surface of the fins. NaK enters the inlet header on the air outlet side and leaves the NaK outlet header on the air inlet side. Since the tubes are U-shaped, the NaK makes two passes through the air stream. The units tested included only one fin matrix, as shown in Figure 2. After the test units were fabricated, the ART radiator design was revised to increase the distance between the NaK header and the first row of fins by 1/2" and reduce the maximum individual fin length to 3.3". The test units were modified to simulate these revisions by slitting the fin matrix, as shown in Figure 3. The slits at the U-bend end of the matrix were to minimize thermal stresses due to the mounting arrangement required in the test stand to simulate the ART radiator mounting. The dimensional parameters of the ART radiator unit and the test units are shown in Figure 4.

The test units were fabricated by York Corporation, the ART radiator vendor, from ORNL designs and specifications under close ORNL inspection and quality control. Test radiator specifications and preoperational inspection reports are included in the Appendix.

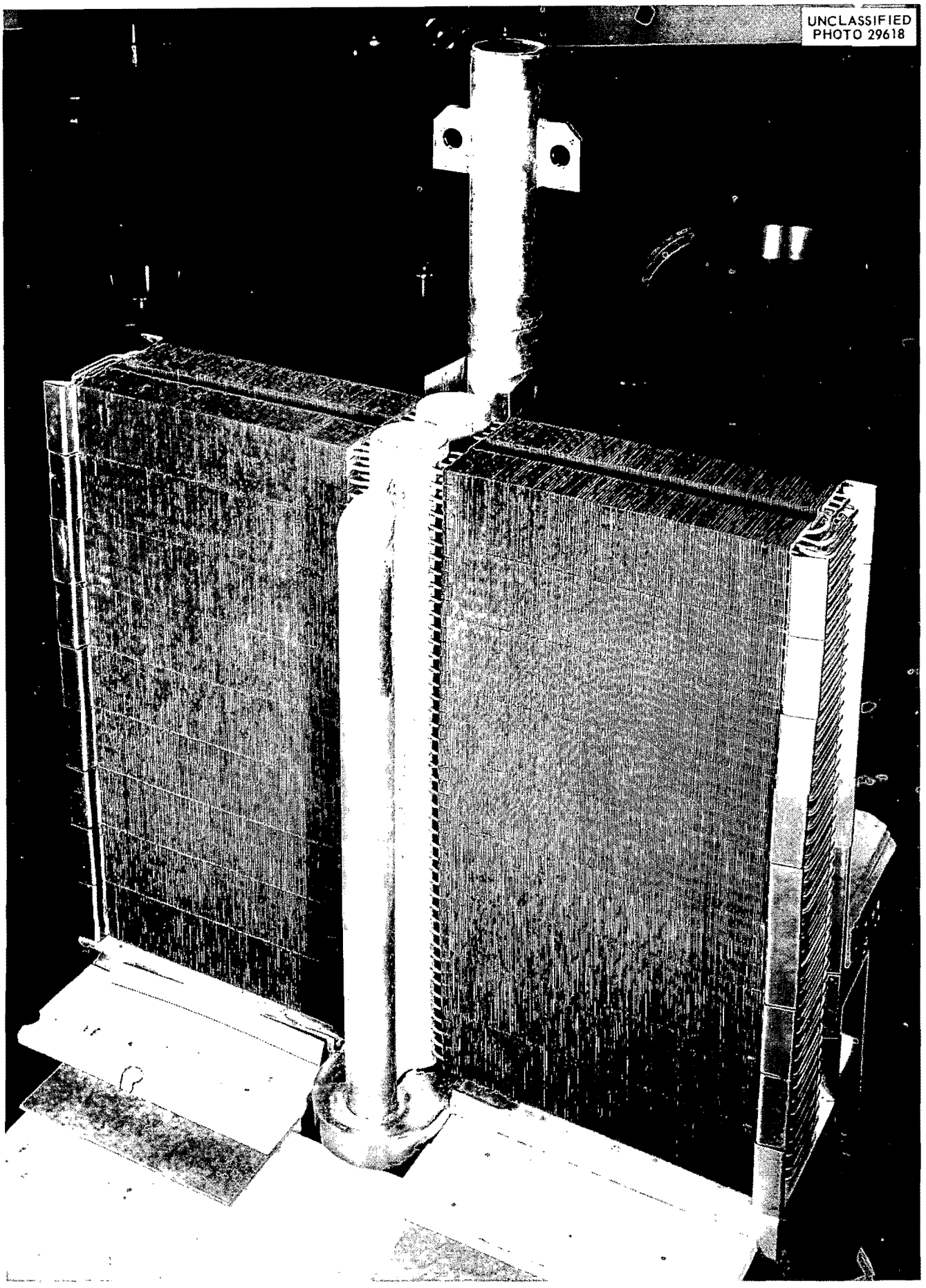


Fig. 1. Photograph of ART NaK-to-Air Radiator Unit.

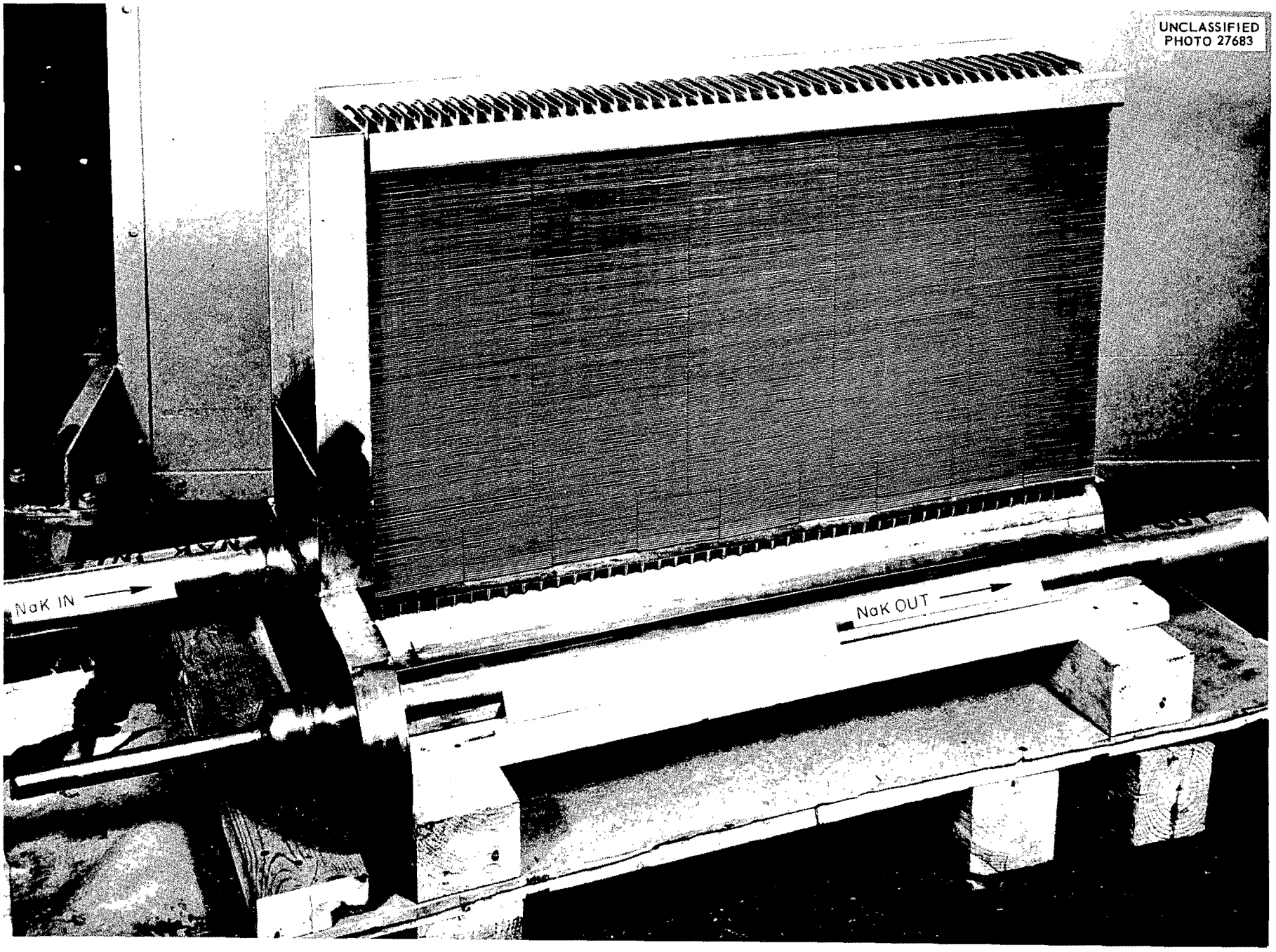
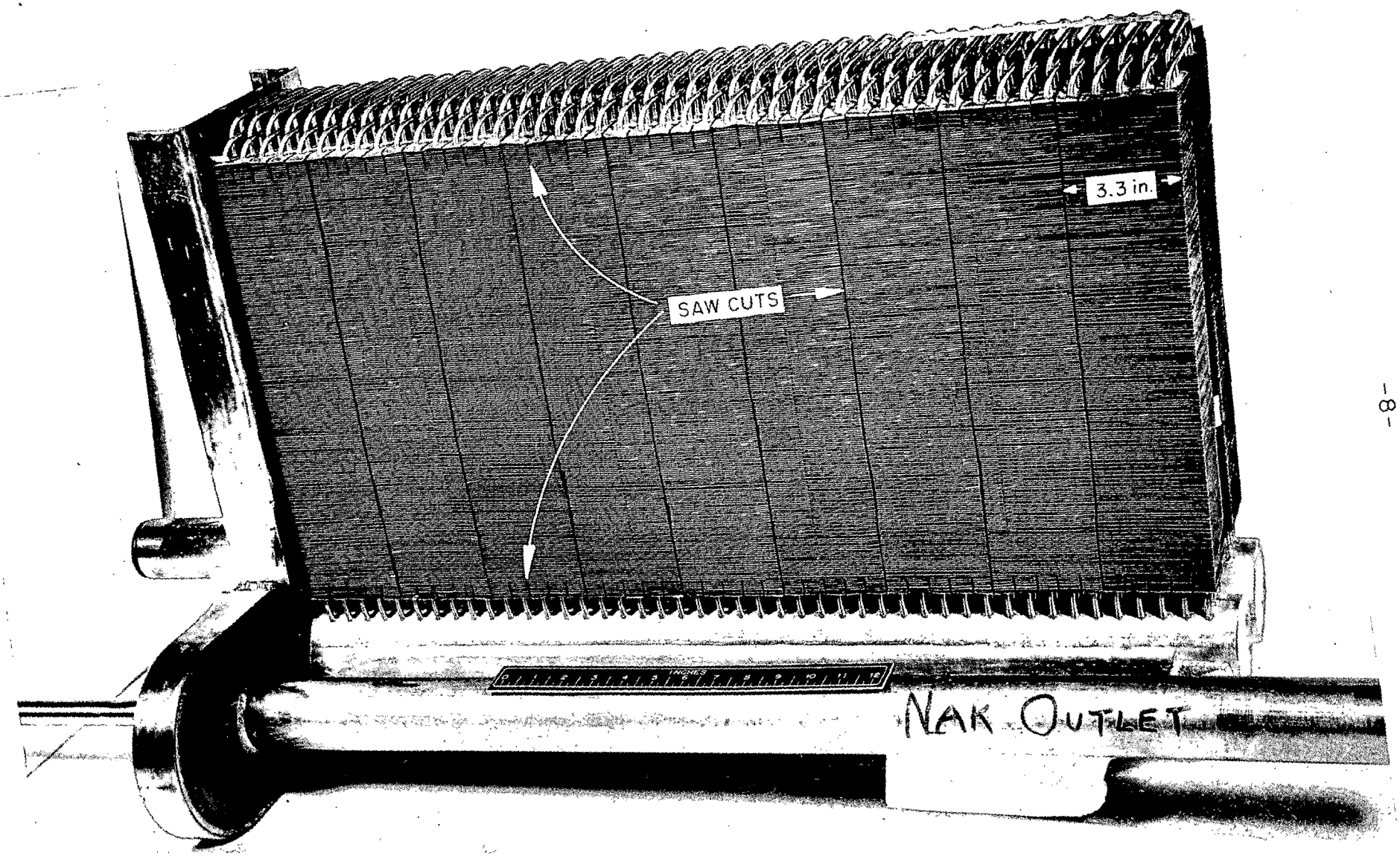


Fig. 2. Photograph of ART Prototype NaK-to-Air Radiator Test Unit.

UNCLASSIFIED
PHOTO 29336



7. Photograph of ART Prototype NaK-to-Air Radiator Test Unit Showing Modification to Reduce Stresses.

Figure 4

Table of Dimensional Parameters for ART Radiators and Prototype Test Units

	Paired ART Radiator Units	Prototype Test Unit
Rating, MW	3.5	1.73
Tube material	Inconel	Inconel
Tube size	3/16" O.D. .025" wall	3/16" O.D. .025" wall
Fin material	.005" copper, clad with .0025" stainless steel type 310	
Face area, ft^2	6.25	3.14
Minimum air free flow area, ft^2	3.66	1.81
Collar & tube wall thickness, in	.035	.035
Fin area, ft^2	922	492
Exposed collar area, ft^2	5.2	20.6
Inside tube area, ft^2	42.7	16.4
Mean tube area, ft^2	44.2	20.5
No. of tubes	360	180
No. of tube rows	8	8
NaK flow area, ft^2	.0374	.0187
NaK flow area, in^2	5.34	2.69
Air equivalent Dia., ft. $\left(4 \times \frac{\text{Matrix Air Volume}}{\text{Matrix Heat Transfer Surface}}\right)$	8.7×10^{-3}	8.43×10^{-3}
No. of fins per bank	235	240
Mean NaK flow length, in	37.1	37.1
Length of air flow passage, ft	.5451	.5531
L/D	269	269

4.0 Experimental Program

4.1 Test Stand Design

An elementary flow diagram of the radiator test facility is shown in Figure 5. A photograph of this test facility is shown in Figure 6. The NaK was circulated by a centrifugal, sump-type pump (type DANA), belt driven by a 40 HP Ajusto-Spede motor. The heat source consisted of a Struthers-Wells gas-fired NaK furnace (rated at 1 MW) equipped with a stack extension which increased the maximum heat output capacity to 1.6 MW. This furnace modification made it possible to operate the radiator test units up to approximately 90% design heat load at design NaK temperatures. Air was supplied to the radiator by an American Blower Corporation type PB, size 9-42 blower driven by a 50 HP Ajusto-Spede motor. The main NaK loop piping was 2" schedule 40 Inconel. The NaK system was equipped with an ART-type circulating cold trap for oxide removal and a plug indicator for monitoring the oxide level in the NaK.

Test stand instrumentation included Moore Nullmatic pressure measuring devices, electromagnetic and venturi flowmeters for NaK flow measurements, a Dall Tube installed on the blower air intake for air flow measurements, and chromel-alumel thermocouples for temperature measurements.

4.2 Test Program

The test programs proposed for both test radiators were alike and consisted of an initial run to obtain performance data over the maximum range of operating conditions, followed by endurance testing under thermal cycling conditions.

Performance data were taken on each radiator up to approximately 90% design heat load at design NaK inlet temperature of 1500°F. Additional performance data were taken for air flows up to maximum blower capacity (representing approximately 130% of radiator design air flow) by permitting the NaK inlet temperature to drop to 1200°F.

Endurance testing consisted of thermal cycling the radiator between 1200°F isothermal operation and power operation at ART design power NaK temperatures (1500°F in, 1070°F out). Each thermal cycle required 4 hours as follows:

30 minutes transition from isothermal to design power conditions
90 minutes steady state operation at design power
2 minutes transition from power to isothermal operation
118 minutes isothermal operation

Test Radiator No. 1 failed during the first controlled thermal cycle. However, it had been exposed to 8 incidental thermal cycles during the performance run. Test Radiator No. 2 failed on the 182nd controlled thermal cycle. Both radiators failed during the power phase of the cycle. Table 7 shows a summary of operating times for each unit. A detailed operating history for each radiator is included in the Appendix.

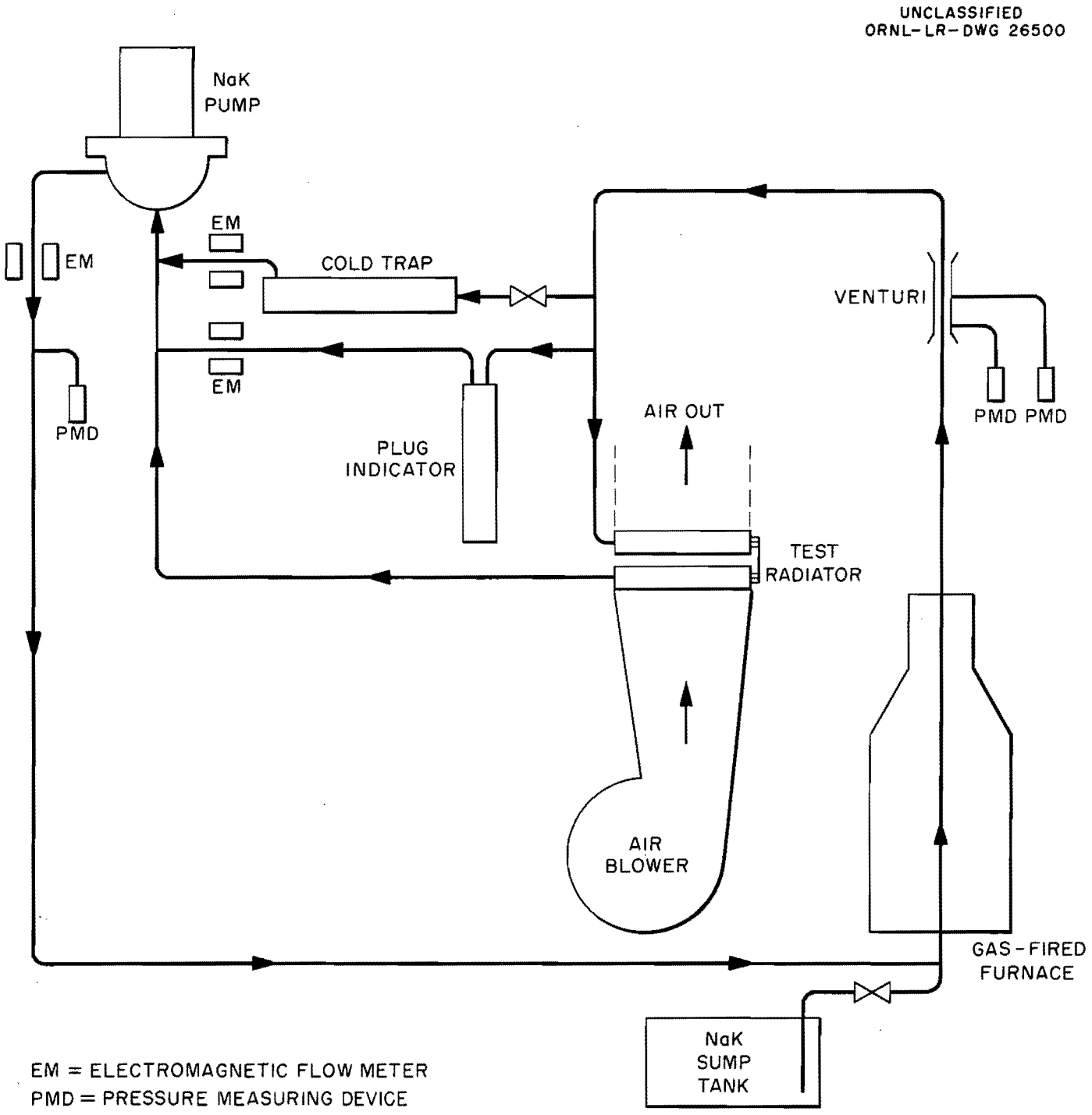


Fig. 5. Elementary Flow Diagram of ART Radiator Test Facility (IHE Stand C).

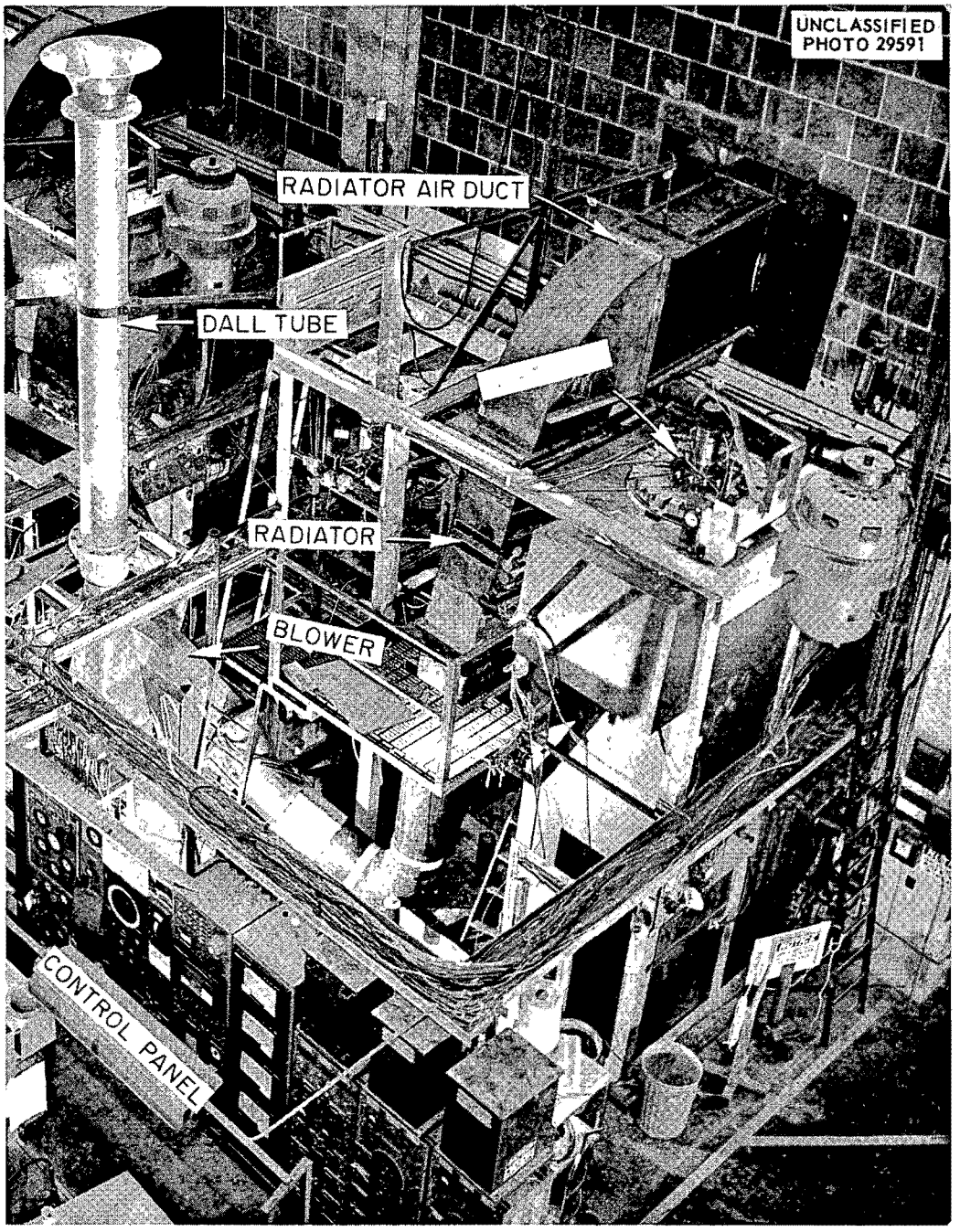


Fig. 6. Photograph of ART Prototype Radiator Test Facility (Gas Fired Nak Furnace is Located Outside Building Wall).

Figure 7

Summary of ART Test Radiator Operating History

	Test Unit No. 1	Test Unit No. 2
Total Operating Hours 1200°F or Above	880	862
Total Operating Hours With a Heat Load	480	431
Total Operating Hours ART Design Temperature Conditions	73	310
Total No. Thermal Cycles	9	181
Cause of Termination	Radiator Tube Failure	Radiator Tube Failure
Location of Failure	Between NaK Inlet Header and Fin Matrix	Between NaK Inlet Header and Fin Matrix

5.0 Radiator Performance

5.1 Heat Transfer Characteristics

A composite data plot of airside Nusselt Number versus air Reynolds Number, shown in Figure 8, compares the heat transfer performance of both test units with a curve established from the data obtained for 10 - 500 KW radiators of similar design fabricated by York Corporation.

It will be noted that the performance data for the two ART test units are in excellent agreement and are approximately 30% above the 500 KW radiator curve at ART design air Reynolds Number. These performance data are presented separately for each radiator in Figure 9 and Figure 10. Data tabulations for these curves are included in the Appendix. The same method of data reduction used for the 500 KW units was used for the ART test units. This method is described in detail in Experimental Report No. 7405-B-1 included in the Appendix of this report.

5.2 Air Pressure Drop Characteristics

Radiator air pressure drop data were taken both at room temperature and during the high temperature performance run for each radiator unit. These data have been correlated on the basis of air pressure drop in inches of water per tube row corrected to 60°F versus air mass velocities in pounds per square foot of air free flow area per second. Figure 11 shows a composite plot of room temperature air pressure drop data compared to data taken by York Corporation on Unit No. 2. Figure 12 shows a composite plot of the air pressure drop data taken during the high temperature run for both radiators compared to a curve established from 500 KW York radiator test data. Figure 13 and 14 show complete air pressure drop data plots for Test Radiators 1 and 2 respectively. Data tabulations for these curves are included in the Appendix.

5.3 NaK pressure Drop Characteristics

Initial radiator NaK pressure drop data are presented in the form of a modified friction factor versus NaK tube Reynolds Numbers for Test Units 1 and 2 in Figures 15 and 16 respectively. Data tabulations for these curves are included in the Appendix. The modified friction factor is calculated from the standard straight tube or pipe friction factor equation

$$f = \frac{\Delta P}{\frac{L}{D}\,\frac{V^2}{2g}\,\frac{\rho}{144}}$$

Where:

ΔP = pressure drop, PSI
$\frac{L}{D}$ = length to diameter ratio
V = velocity, ft/sec
g = acceleration of gravity, ft/sec^2
ρ = density of fluid, lb/ft^3

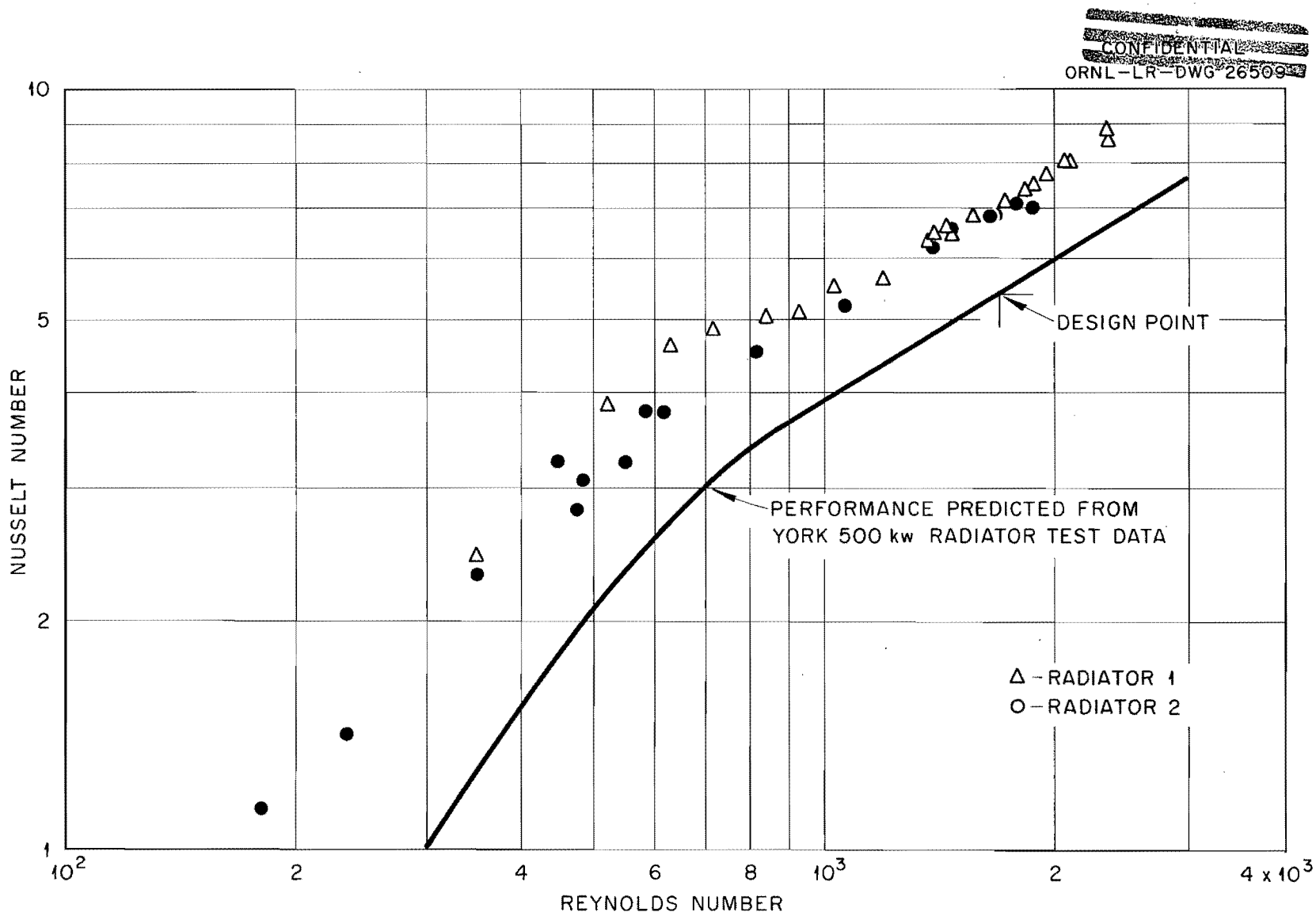


Fig. 8. Heat Transfer Composite Data Plot for ART Radiator Test Units No. 1 and 2.

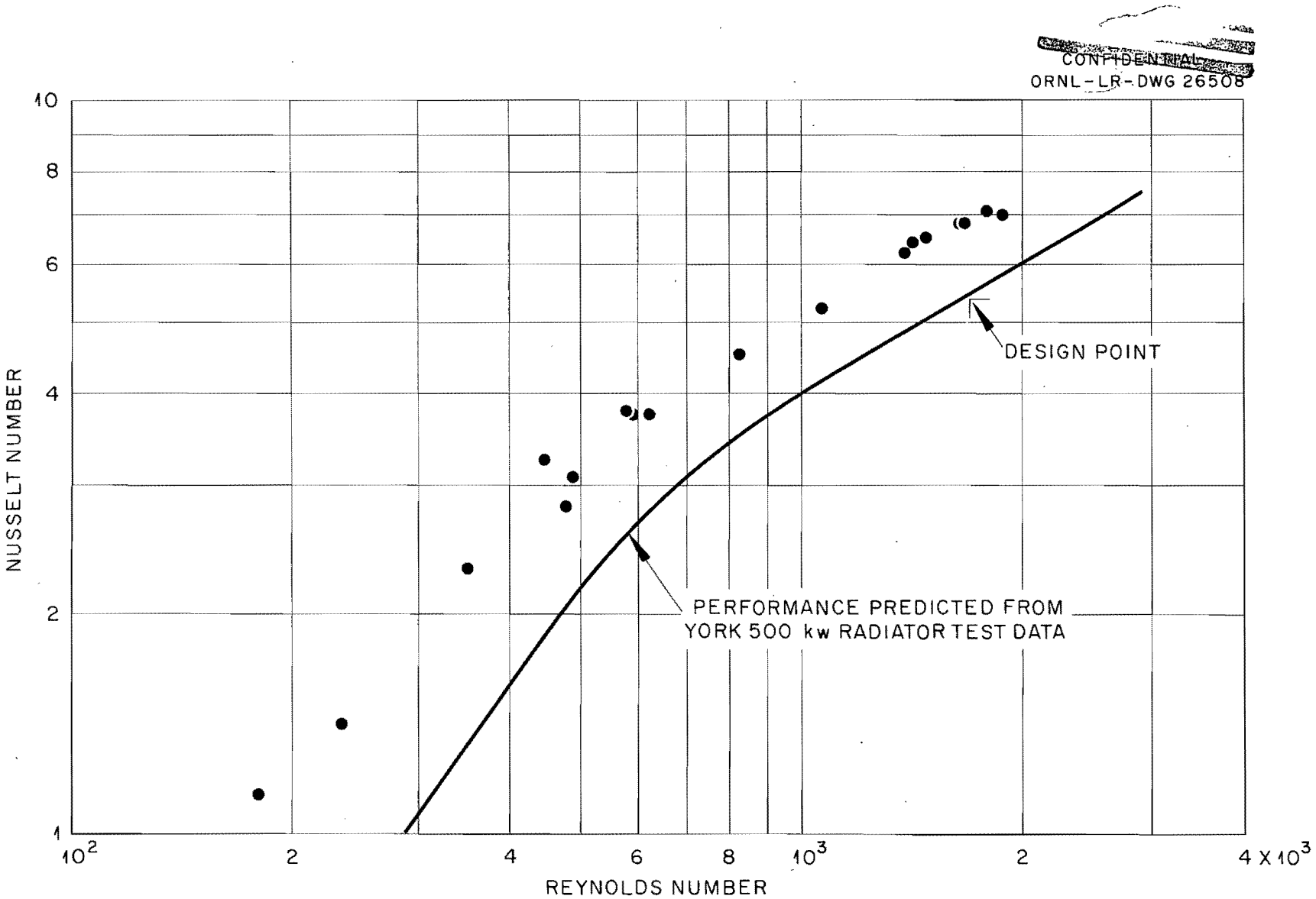


Fig. 9. Heat Transfer Performance Plot for ART Radiator Test Unit No. 1.

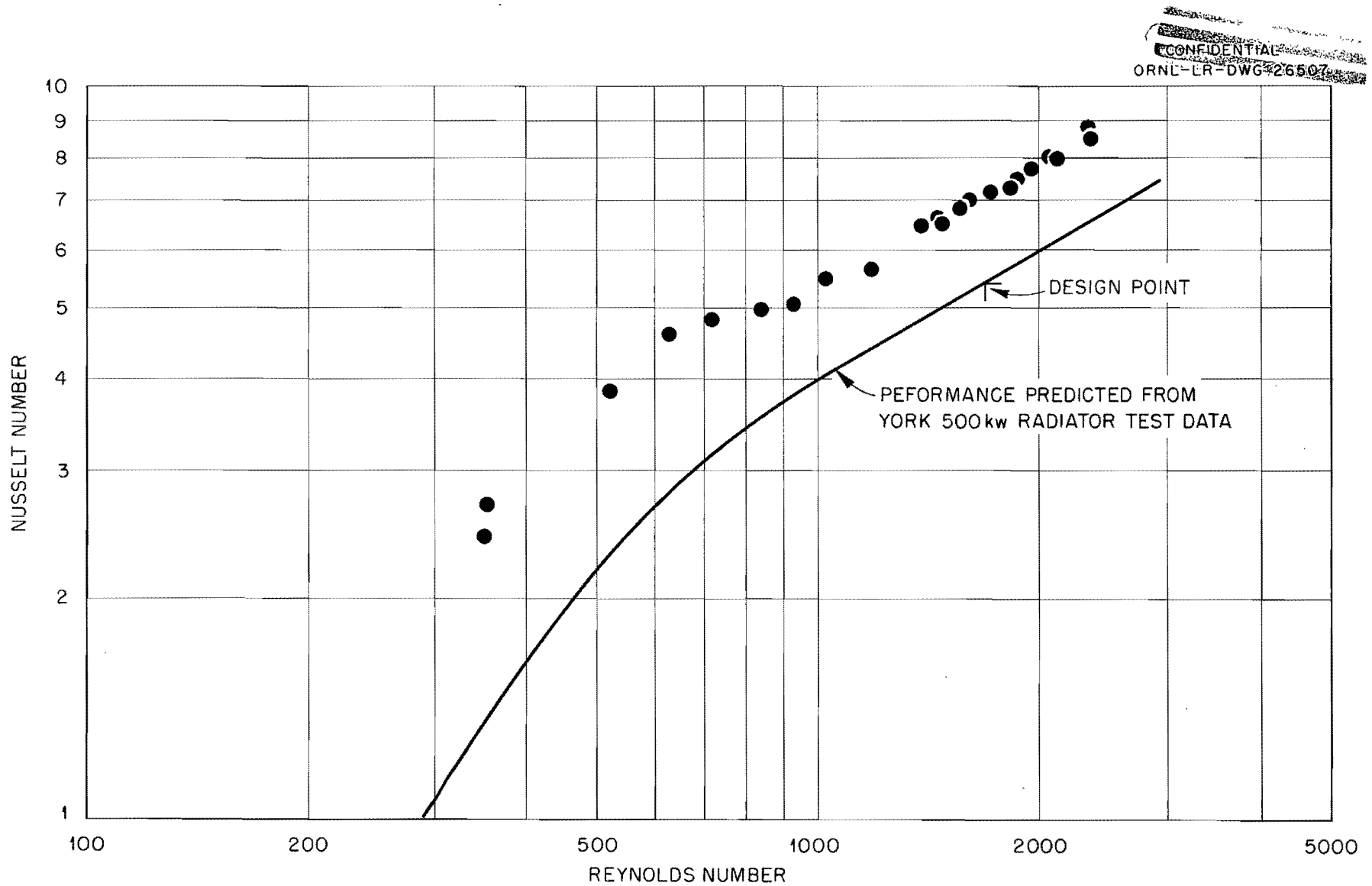


Fig. 10. Heat Transfer Performance Data Plot for ART Radiator Test Unit No. 2.

ORNL-LR-Dwg. 26506

CONFIDENTIAL
ORNL-LR-DWG 26506

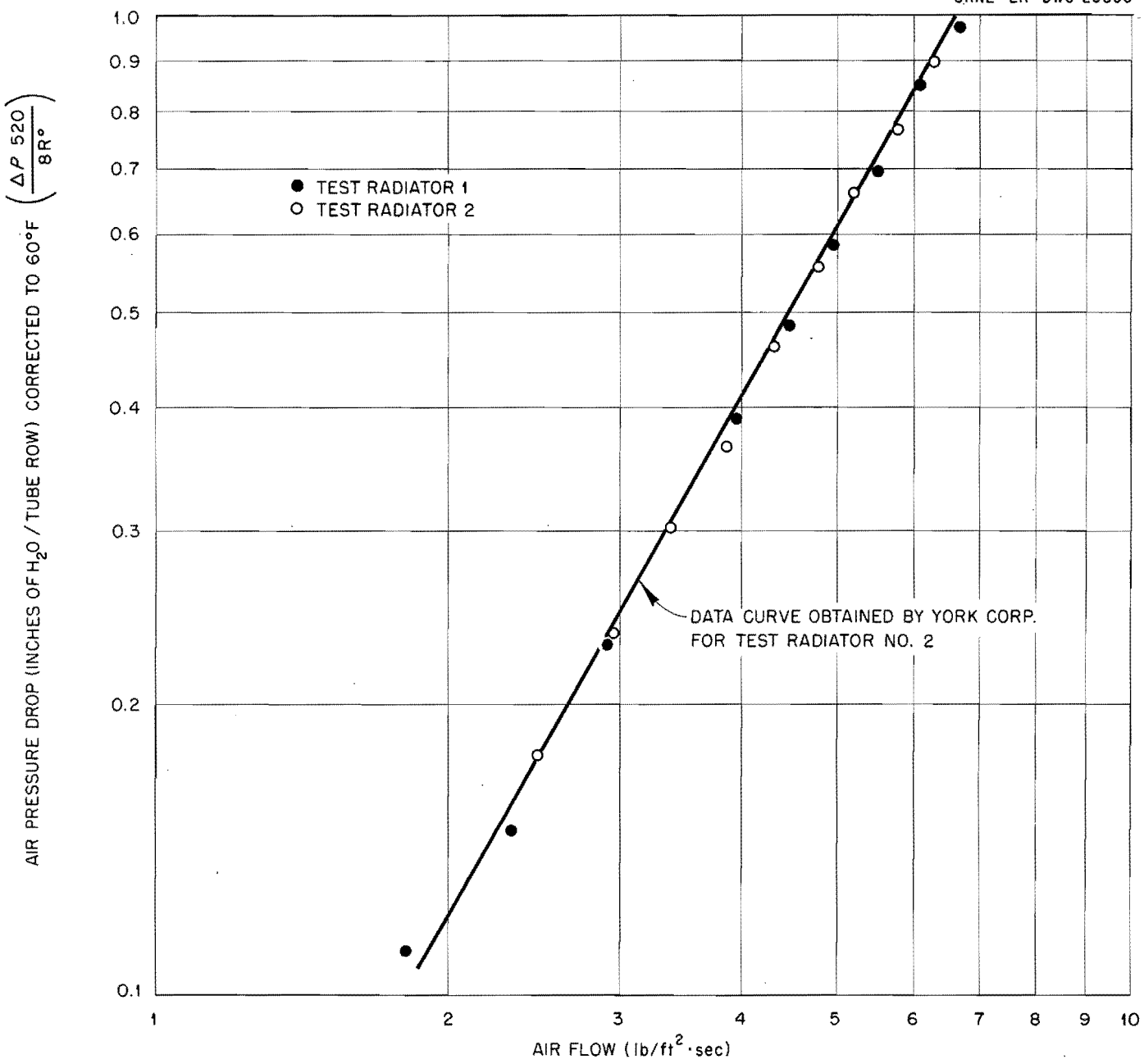


Fig. 11. Room Temperature Air Pressure Drop Composite Data Plot for ART Test Radiators No. 1 and 2.

[redacted]

CONFIDENTIAL

ORNL-LR-DWG 26505

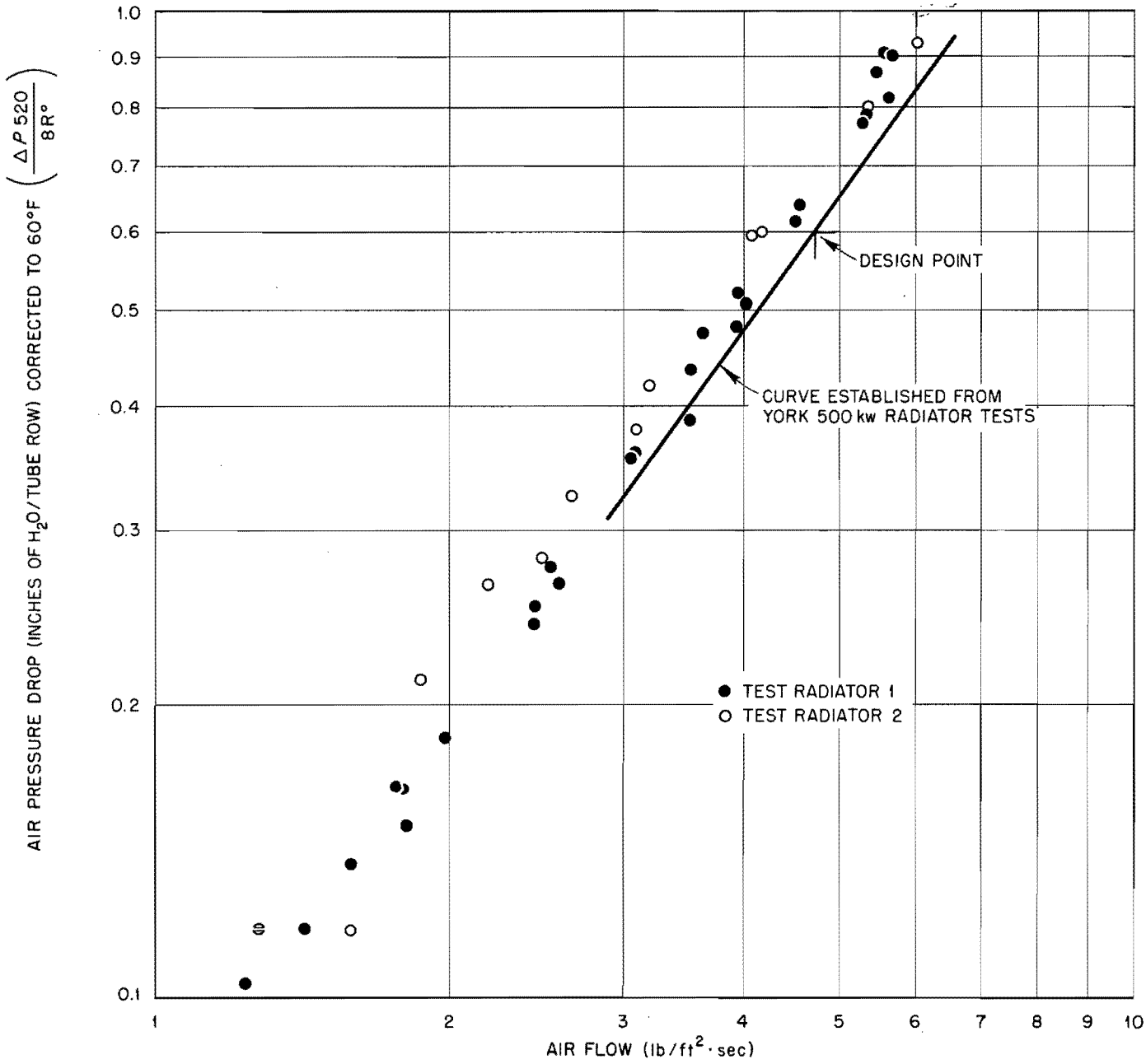


Fig. 12. Hot Air Pressure Drop Composite Data Plot for ART Test Radiators No. 1 and 2.

CONFIDENTIAL

ORNL-LR-DWG 26504

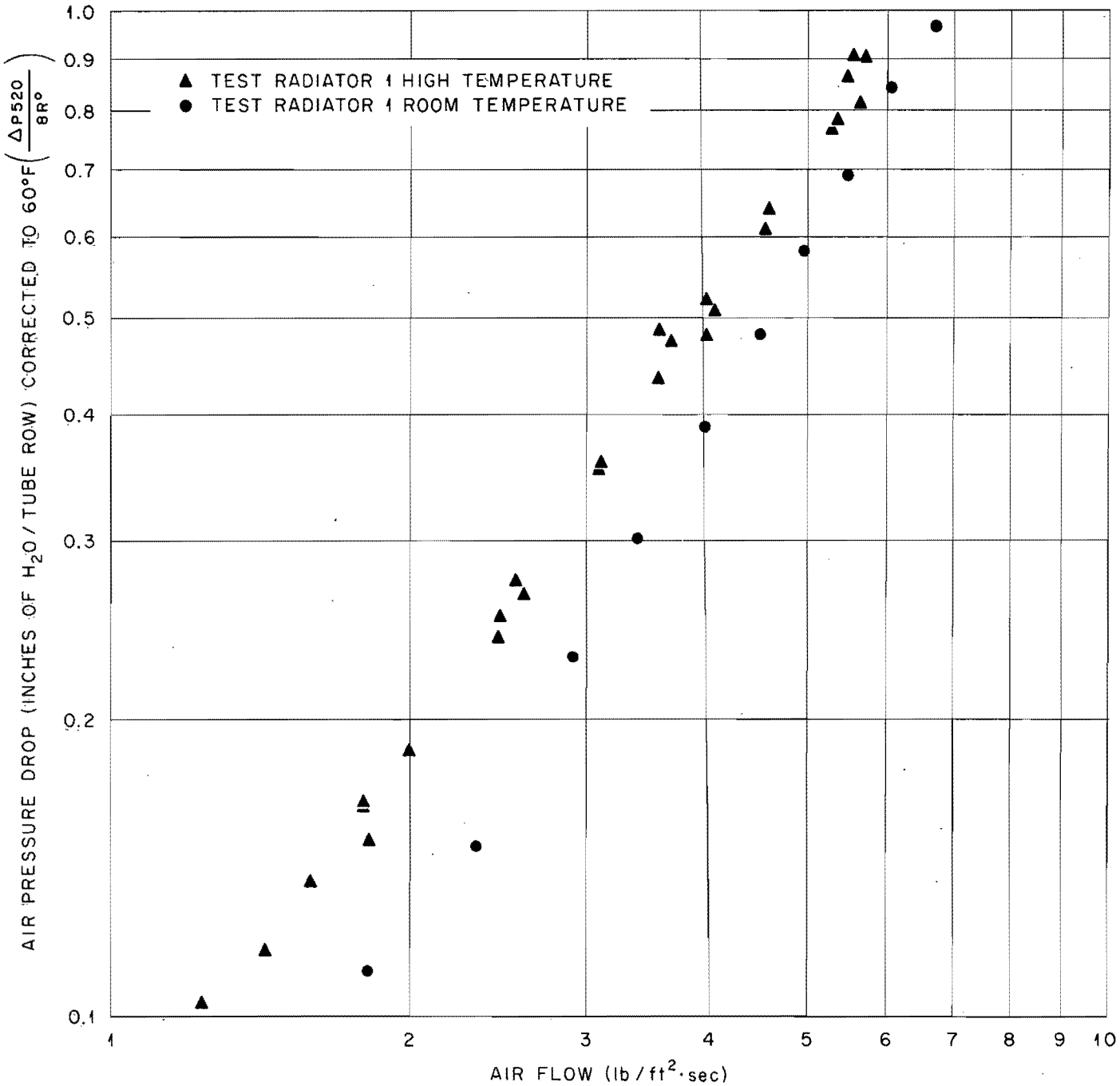


Fig. 13. ART Test Radiator No. 1 Air Pressure Drop Data Plot.

CONFIDENTIAL

ORNL-LR-DWG 26503

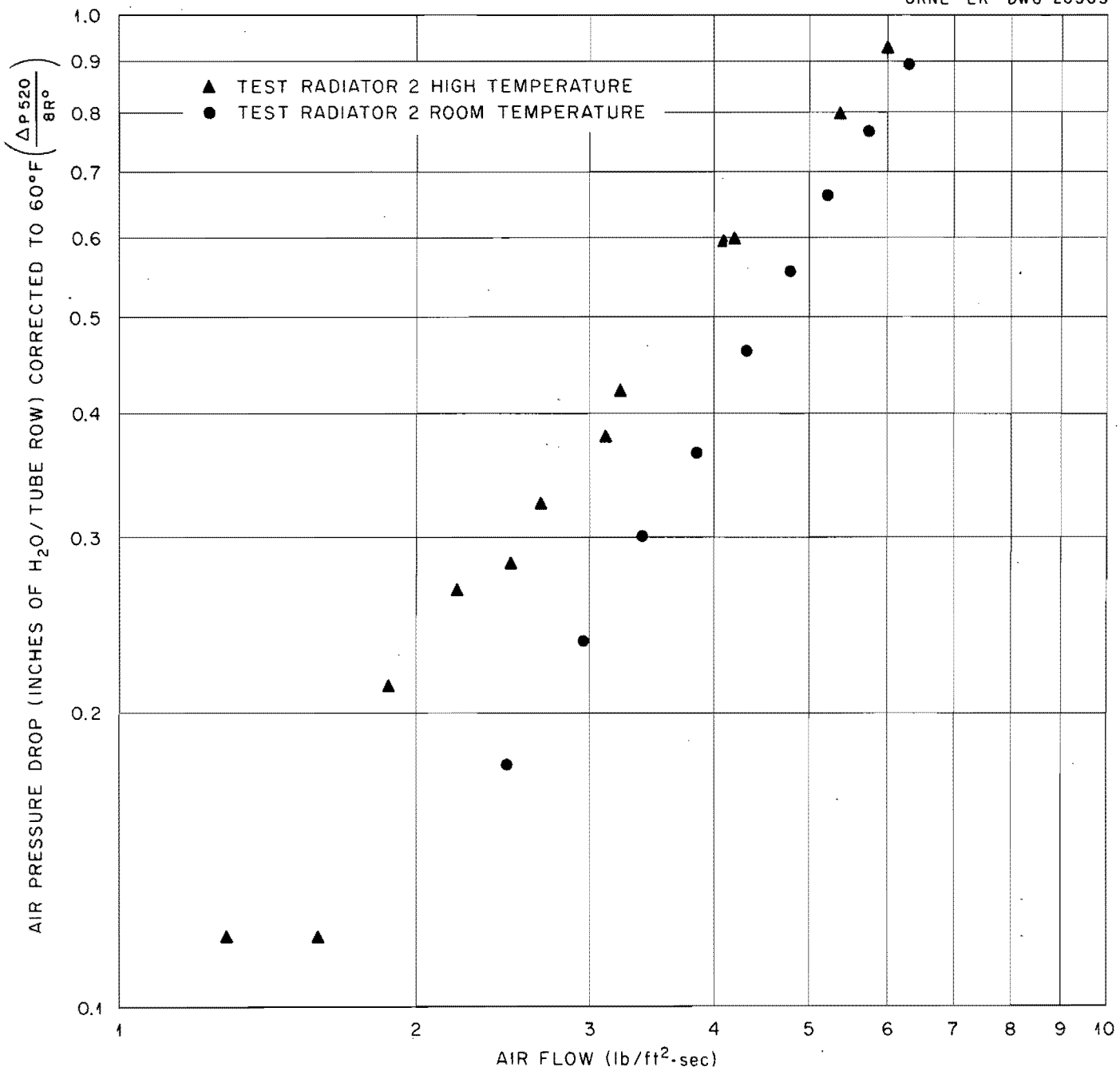


Fig. 14. ART Test Radiator No. 2 Air Pressure Drop Data Plot

CONFIDENTIAL
ORNL-LR-DWG 26502

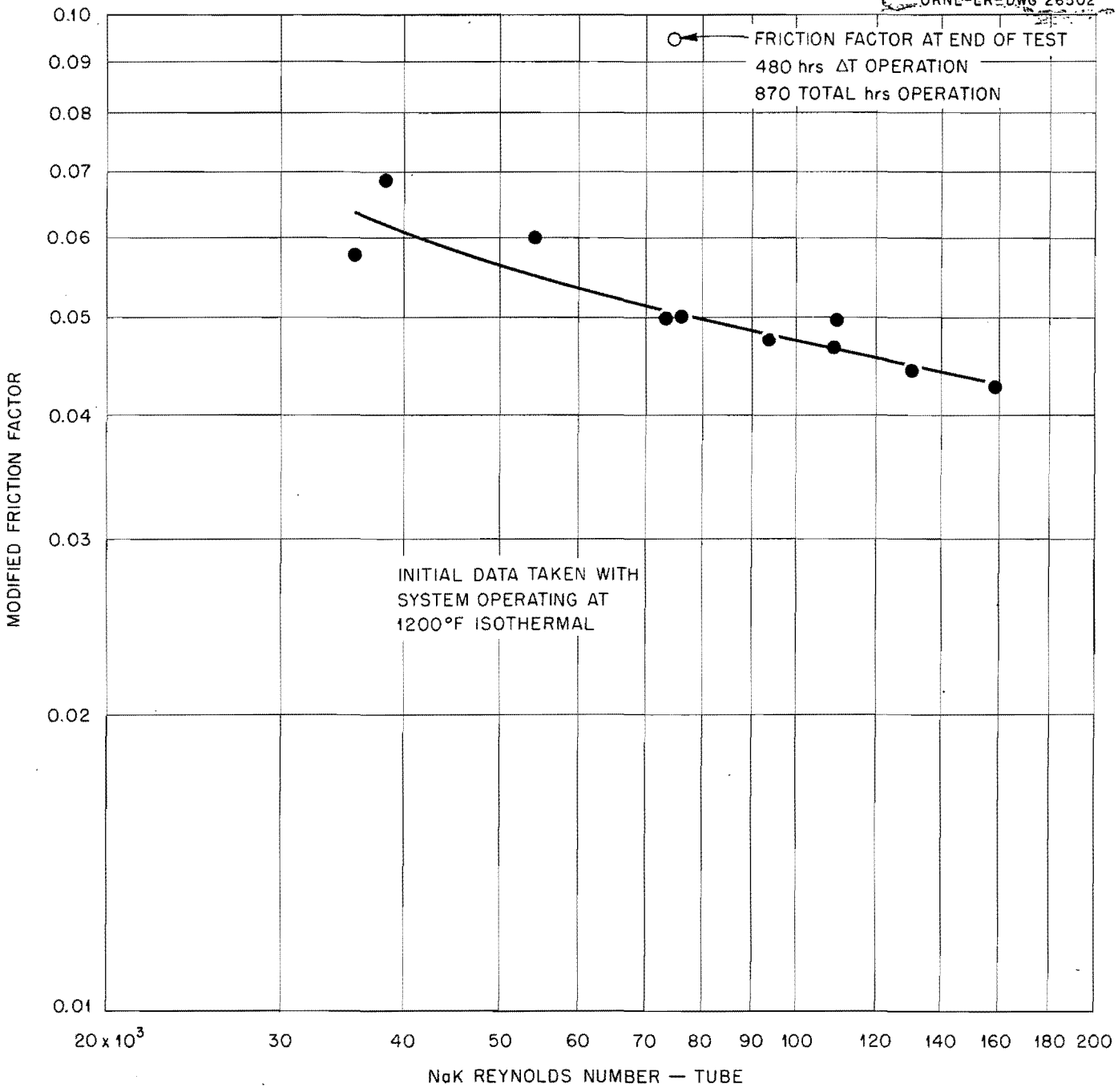


Fig. 15. ART Test Radiator No. 1 NaK Pressure Drop Data Plot.

CONFIDENTIAL

ORNL-LR-DWG 26501

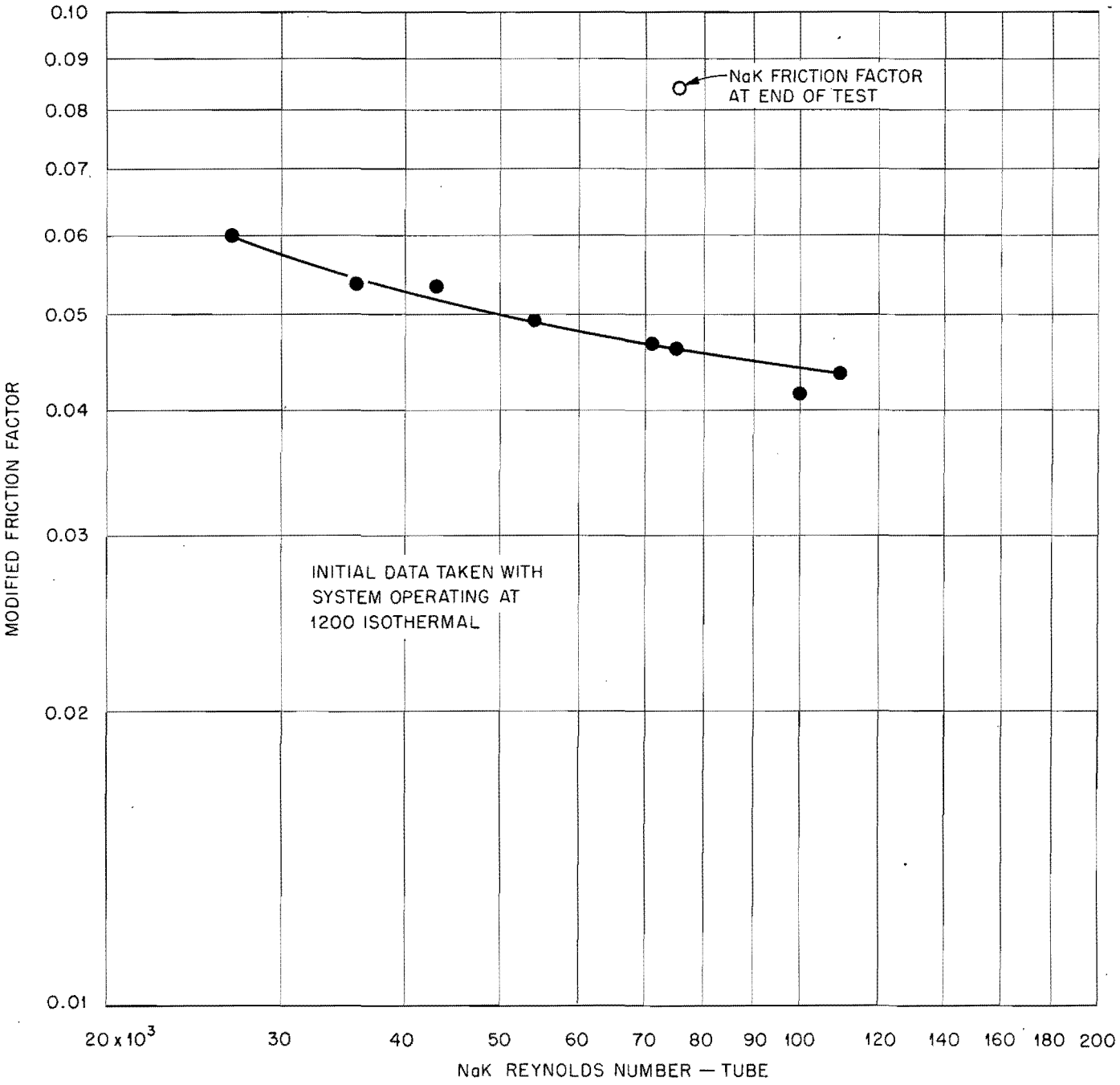


Fig. 16. ART Test Radiator No. 2 NaK Pressure Drop Data Plot.

However, since the radiator pressure drop measured experimentally includes entrance and exit losses, header losses and losses due to tube bends, the friction factor calculated from the experimental data does not represent a true tube wall friction factor and is therefore referred to as a modified friction factor.

As was the case with 500 KW radiator operation, both test units exhibited a NaK pressure drop buildup during radiator ΔT operation. Figures 17 and 18 show radiator NaK modified friction factor plotted versus time compared to radiator NaK inlet and outlet temperatures plotted versus time for Test Units 1 and 2 respectively.

NaK pressure drop for both radiators increased rapidly during initial steady state ΔT operation when radiator NaK inlet temperatures were above 1300°F. This rate of increase was greatly reduced during thermal cycling operation. The difference in the appearance of the modified friction factor curves for the two radiators can be attributed to the fact that Radiator No. 1 was subjected to a longer period of initial steady state ΔT operation prior to thermal cycling than was Radiator No. 2.

5.4 Reliability

Both radiators operated for approximately the same number of total hours and approximately the same number of hours with a heat load. However, Radiator No. 1 survived only 9 thermal cycles, while Radiator No. 2 was exposed to 182 thermal cycles.

Figure 19 shows a photograph of Test Radiator No. 1 after removal from the test stand. Post-operation metallographic examination of this radiator disclosed no evidence of incipient failure in other sections of the radiator or even in the failed tube in the vicinity of the failure. One of the forty tubes examined from the failure area of Radiator No. 2 exhibited grain boundary voids in various stages of development up to continuous grain boundary separation. Although this tube containing evidence of grain boundary voids also was associated with a Nak leak, it is uncertain that this tube was the site of the original leak, since the damaged area in the radiator was sufficiently large to mask the original site of failure. The grain boundary separations are typical of microstructures which have undergone severe plastic strain. Thus, it is indicated that failure may have occurred as a result of overstressing during thermal cycling, although, as discussed below, the appearance of voids in only one tube points to the possibility of additional causes. Details of these examinations are covered in Metallurgy reports No. 299 and 304 included in the Appendix.

Since no evidence of incipient failure was found in radiator No. 1, it is probable that this failure was due to a tube imperfection which was either not detected by material inspection prior to fabrication or caused by damage during fabrication or installation in the test stand. While the actual failure of radiator No. 2 has been attributed to plastic strain, the lack of evidence of incipient failure in other than one tube implies that this excessive plastic strain may have been due to some undetected weakness in this particular tube rather than due to stresses inherent to

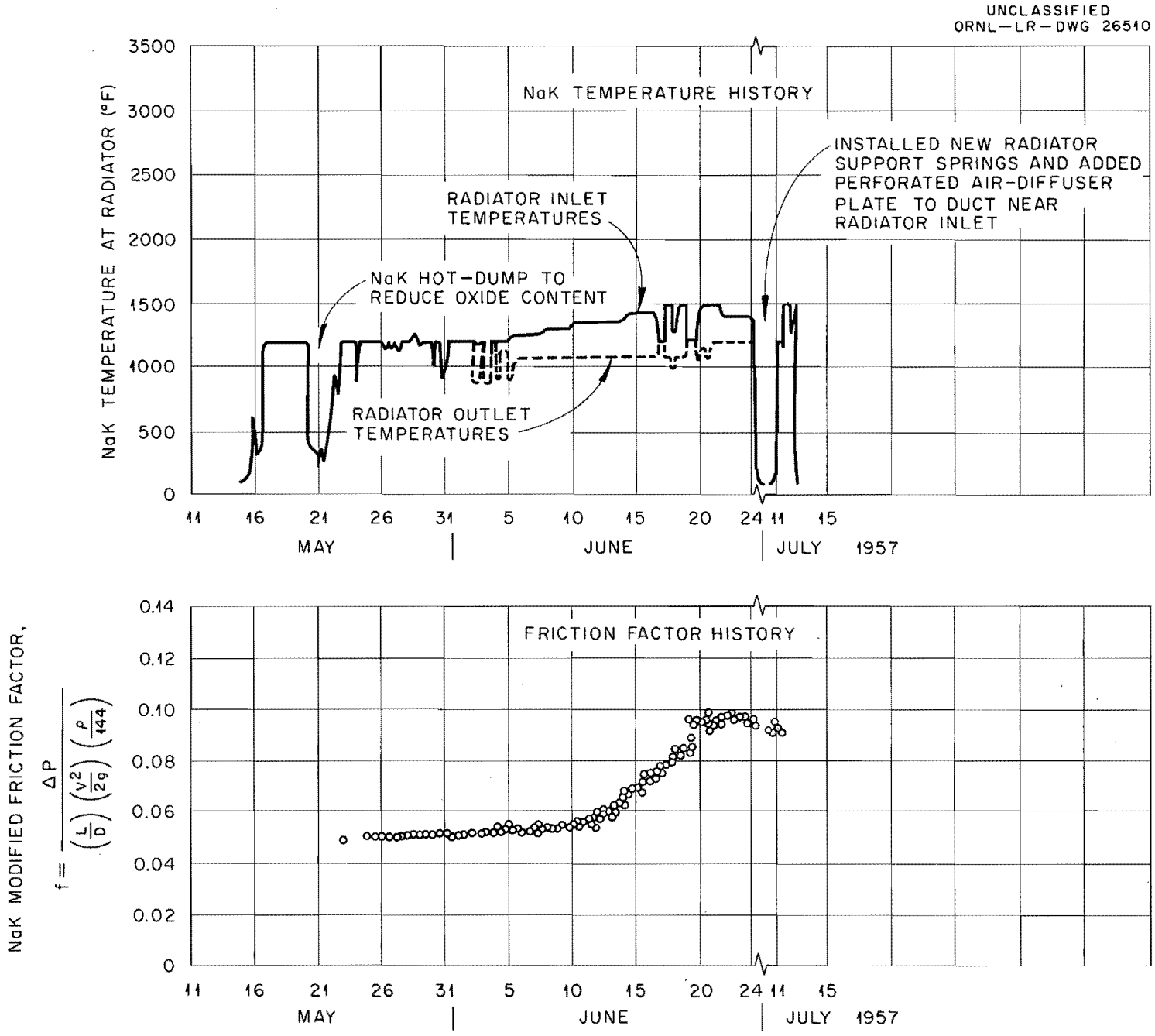


Fig. 17. ART Test Radiator No. 1 NaK Temperature and Pressure Drop History.

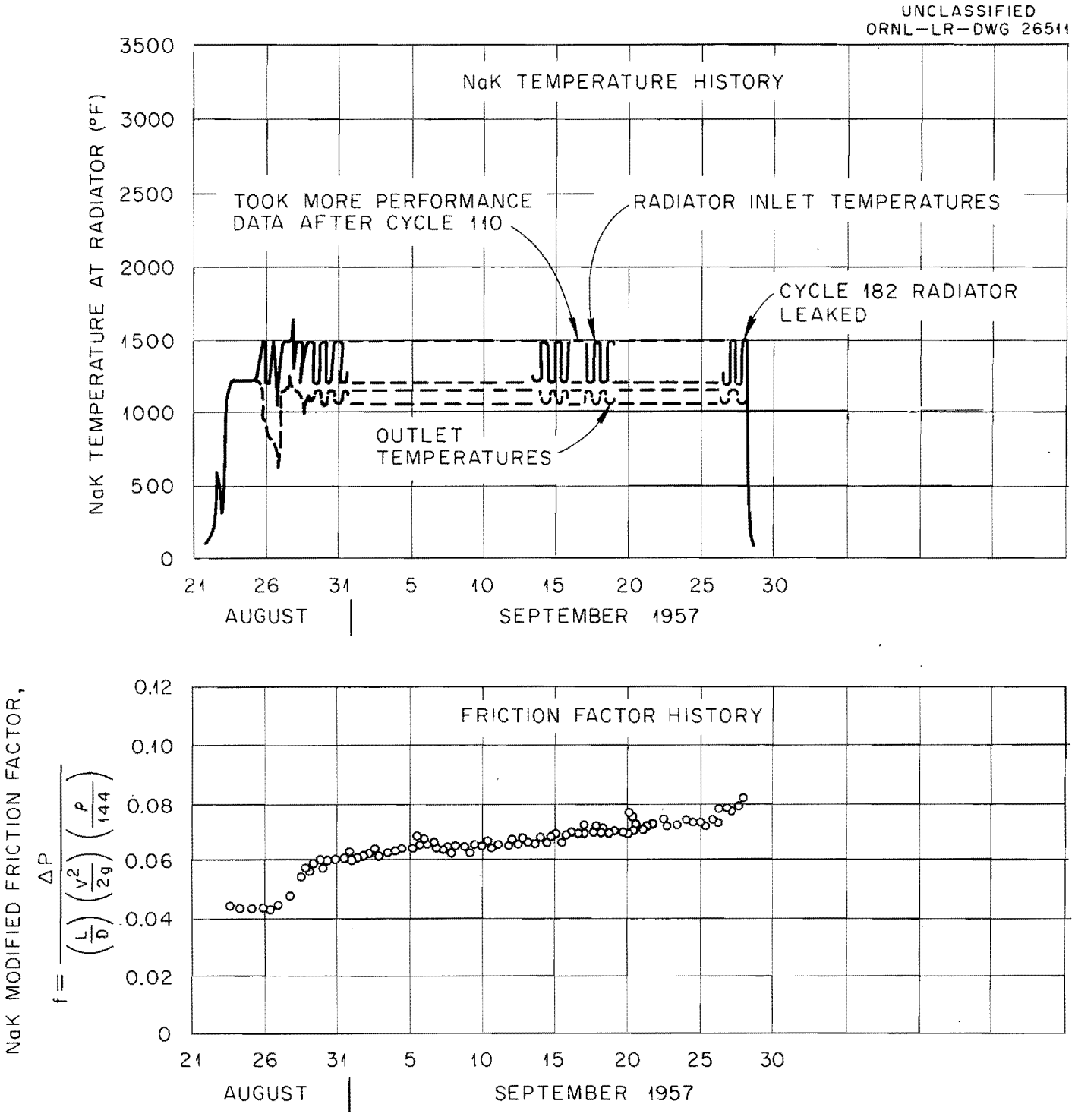


Fig. 18. ART Test Radiator No. 2 NaK Temperature and Pressure Drop History.

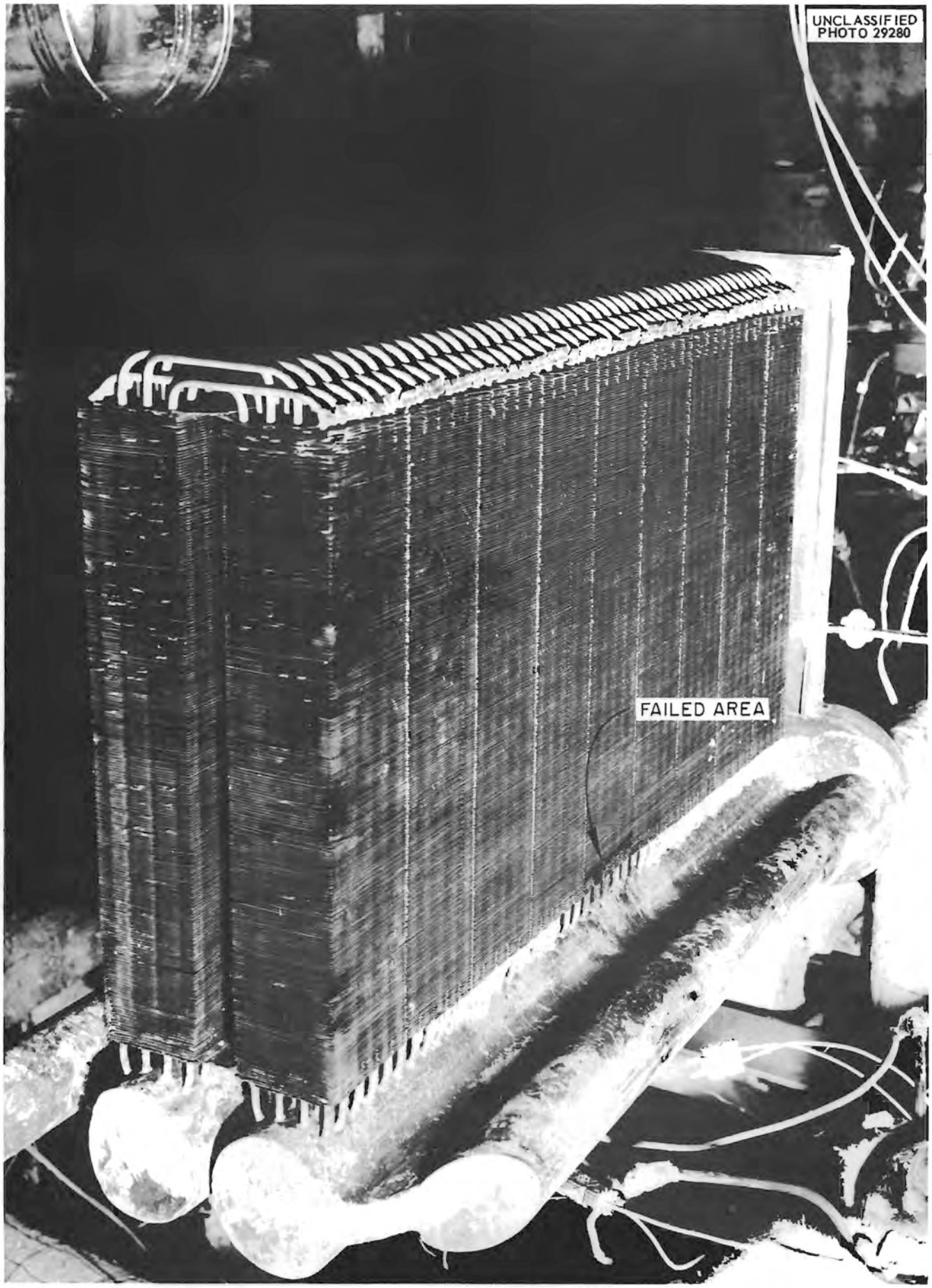


Fig. 19. Photograph of ART Test RADIATOR After Removal from Test Stand.

the radiator design. However, the fact that both failures occurred in an area between the hot NaK inlet heater and the fin matrix, the same area where failure has occurred in four smaller 500 KW units of similar design, indicates the area of the radiator most vulnerable to failure. The fact that all radiators of this basic design which have failed have operated with 1500°F NaK inlet temperatures during heat load operation and that similar units operated successfully with NaK inlet temperatures of 1450°F and below for up to 2500 hours, implies that this temperature may be critical with regard to radiator reliability. These tests also strongly imply that the reliability of this design is extremely sensitive to the quality of material inspection which can be maintained during fabrication. In any event, the results of these radiator endurance tests indicate that the reliability of the ART NaK-to-air heat dump design cannot be guaranteed for ART design power operation without additional radiator test and development work.

6.0 Appendix

UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation
Oak Ridge, Tennessee

Oak Ridge National Laboratory

SPECIAL ENGINEERING DIVISION SPECIFICATION

Date of Issue:	September 23, 1955	Job Specification:	JS-P3-19
Revised:	February 10, 1956		Revision 1
Revised:	March 22, 1956		Revision 2
Revised:	September 7, 1956		Revision 3

SPECIFICATION FOR MAIN RADIATORS

I. SCOPE

These specifications set forth the requirements for the material, fabrication, assembly, and testing of a system of extended surface air-cooled heat exchangers (radiators), including necessary attendant manifolds and piping.

II. DESCRIPTION OF UNIT

The entire unit shall consist of individual cores made up of flat plate fins metallurgically bonded to straight tubes in a two-pass arrangement with tubes terminating at tube header manifolds common to two core sections. The tube header manifolds are welded to supply and return headers, as shown on Drawings, F-2-02-054-2397, F-2-02-054-2509, F-2-02-054-4189, E-2-02-054-4082, F-2-02-054-4160, F-2-02-054-4161, which are attached to and form a part of, this specification.

III. SERVICE REQUIREMENTS AND CONDITIONS

The Buyer assumes the responsibility for the performance of the unit insofar as heat transfer and general design characteristics are concerned. The Seller shall be responsible for meeting the air pressure drop requirements stated in these specifications. It is intended that these specifications establish rigid requirements since the service conditions require a close approach to perfection in every phase of manufacture.

IV. MATERIALS OF CONSTRUCTION

In consideration of the delivery schedule for complete units, the Buyer has ordered all material specified in Section IV-A of these specifications and will supply the Seller with sufficient quantities of material in mill sizes to fabricate the number of units ordered at no cost to the Seller. Any material received by the Seller and found to be not in accordance with these specifications will be replaced by the Buyer at no

IV. MATERIALS OF CONSTRUCTION (Continued)

cost. However, any costs incurred by the Seller in handling or storing shall be to the Seller's account. All material required to replace parts damaged or rendered unusable as a result of the Seller's workmanship will be supplied by the Buyer. In this instance the Seller will reimburse the Buyer for material and transportation costs as incurred by the Buyer.

A. Materials

The Buyer will procure the listed material according to the following specifications:

Inconel plate	- ASTM B-168
Inconel pipe	- ASTM B-167
Inconel tubing	- ASTM B-167 (Buyer's Grade CX-900A) MMS-1
Inconel welding wire	- INCO No. 62
Fin material	- 310 stainless steel clad copper, Schedule 25-50-25. Fin to be 0.010 in. thick ± 0.001 in.
Brazing material	- Coast Metals brazing alloy No. 52
Aluminum powder (atomized)	- 325 mesh
Binder material	- Colmonoy Nicrobraze cement
Acrylic resin	- 100%

B. Material Inspection

All materials shipped by the Buyer will undergo the following inspections and procedures to be performed by the Buyer, and will be certified as satisfactory for fabrication:

1. Before any material is released for construction it shall be visually inspected for cracks, scale, inclusions, pinholes, etc. A liquid penetrant dye check shall be used for disclosing pinholes and cracks on the exterior of the tubes.

2. All tubing shall be inspected as described in inspection procedure IPS-2 attached to these specifications. Tubing not meeting this specification shall be rejected. Additional methods for tube inspection may be employed by the Buyer at his discretion.

IV. MATERIALS OF CONSTRUCTION (Continued)

3. The Seller shall establish a material identification system and the necessary controls to satisfy the Buyer that only Buyer inspected and accepted material is used in the fabrication of the units. This procedure shall be approved by the Buyer in writing prior to the start of fabrication.

4. All material received by the Seller from the Buyer shall be inspected for damage during shipment and any material found damaged shall be rejected and reported to the Buyer's representative for disposition. The Seller shall demonstrate to the Buyer's satisfaction that sufficient skill is exercised in the inspection techniques to insure thorough and complete inspection for damage during shipment of all material prior to its use in fabrication.

V. GENERAL WELDING REQUIREMENTS

A. All welders employed on fabrication of radiator units must be qualified according to the attached welding operator's qualification test, QTS-1, and procedure specification, PS-1, prior to doing any work on the radiator unit or component parts thereof.

1. The Buyer shall be notified a minimum of three working days in advance of the actual date when the test will be taken. This is required to allow the Buyer an opportunity to have a representative present while the test is in progress. Failure to do so will be cause for repeating the test at the expense of the Seller.

2. The "Inspector" referred to in Welder's Qualification Test Procedures shall be designated by the Buyer.

B. The quality of workmanship as approved in the welder's qualification tests shall be maintained throughout all production units. Inferior workmanship shall be cause for requalification of the welder.

C. Welds carried out with the use of a filler material shall employ a base Inconel rod of INCO No. 62, or approved equivalent. Welding of the plates and headers shall be carried out with a filler material. The weld joint shall be completely blanketed with inert gas both above and below the welded surfaces.

D. It is the basic responsibility of the Seller to use welding practices which will result in strong, sound, leak-tight welds, and approval of materials, practices, or procedures by the Buyer is

V. GENERAL WELDING REQUIREMENTS (Continued)

not to be construed as relieving the Seller of this responsibility in any manner; however, any change from procedures provided is subject to review and acceptance by the Buyer.

E. All critical welds, including tube-to-header welds, are to be inspected in accordance with IPS-1, a copy of which is attached and becomes a part of this specification. 100% radiography is required on all accessible critical welds. Critical welds with the exception of tube-to-header welds are marked "C" on the drawings.

VI. RADIATOR CONSTRUCTION

A. Introduction

The design and construction requirements set forth in this section of the specifications are the result of considerable experimental work and the actual construction of a number of radiator cores of similar geometry.

B. Preparation and Cleaning of Parts

1. All parts shall be machined, dimensioned, finished, and/or bent to within the tolerances shown on the drawings.

2. The Seller shall eliminate any foreign contaminations, including welding scale, oxides, or other foreign matter from the radiator core. Particular cleanliness emphasis shall be taken on the inside surfaces of the radiator core and attendant piping.

3. Before assembly all components shall be thoroughly cleaned free of all oxides, oil, grease, dust, or any other foreign material. All internal and external surfaces shall have a bright finish. From this point every precaution shall be taken that all parts and subassemblies are kept in this condition through the completion of the unit. No pickling of the material is permitted.

4. After final completion of required leak tests the entire tube side shall be flushed with clean hot dry air and capped off vapor-tight.

C. Edge Treatment of Fins

It is required that the exposed copper along the edges of the fin be protectively coating against oxidation effects. The following

VI. RADIATOR CONSTRUCTION (Continued)

procedure for edge treatment of fins has been employed and satisfactory results obtained:

1. A mixture of aluminum powder (approximately -325 mesh) and acrylic resin is prepared, having the consistency of paint. The material should be applied to the edge of the fins in a thin uniform coating.

2. The fins should then be furnaced for one hour at a temperature of 800°C in an inert dry atmosphere of helium having a dew point of -70°F or less.

3. No coating of the flat faces of the fins is permitted. It is recommended that fin edges be coated prior to the hole punching operation. Fins may then be tightly clamped, coated, and furnaced in a block form. Excessive temperatures or furnace time may result in sticking of the fins. Excessive undiffused aluminum should be removed from the fin edges and flat surfaces. Minimum penetration for edge treating shall be 0.003".

R

4. Alternate methods for edge treatment of fins may be used by the Seller, but in any event the method to be employed must first be submitted to the Buyer in writing for prior approval. All materials to be employed in the process should be included in this submittal.

D. Bending of Tubes

1. Tubes shall be bent to radii specified on Drawing F-2-02-054-2509. All tube bends are to be smooth uniform bends, free from tube kinks, nicks, or flats.

2. The amount of flattening of any tube shall not exceed 5% of the nominal tube diameter as a result of the bending operation.

3. The ends of the tubes may be tapered on the OD to facilitate assembly in the tube sheet providing all of the tapered portion is removed after assembly.

4. After tube bends are made, each bend is to be dye-checked in accordance with IPS-2. Any indication of a defect will be cause for rejection of the tube.

E. Special Welding Requirements

1. Tube-to-header joint welds shall be carried out without use

VI. RADIATOR CONSTRUCTION (Continued)

of a filler material. Minimum cross sectional area of tube ends, after welding, shall pass a 1/8 in. plug gage inserted into the welded tube end. The weld shall be equivalent to that shown in Fig. 1.

N

a. No reaming permitted

b. No undersize holes are permitted. Headers having undersize holes will be examined on an individual basis for our purposes to determine the disposition of the unit.

2. Machine welding equipment (recommended)

a. D.C. power supply with an available current in the range of 3 to 100 amperes, such as a motor-generator set equipped with a resistance supplement.

b. Remote current control device to vary the current at the location of work from 75 amps to approximately 3 amps.

c. High frequency current superimposed on the D.C. welding current for remote striking.

d. A welding contactor.

e. A variable speed rotating head (0 to 8 in. per minute, circumferentially).

3. Manual welding equipment required is the same as in (a) and (b) above.

4. Welding Technique

The data listed below produced satisfactory welds and is included here as typical only. The Seller shall develop satisfactory techniques and shall demonstrate these techniques to the satisfaction of the Buyer prior to the production of the radiator units:

Tubes - 0.190-in.-OD, 0.017-in.-wall

Tube sheet - 0.183 in.

Arc distance - 0.050 in.

Welding arc travel- 6 in/min.

Cup size - 3/8 in. opening (min)

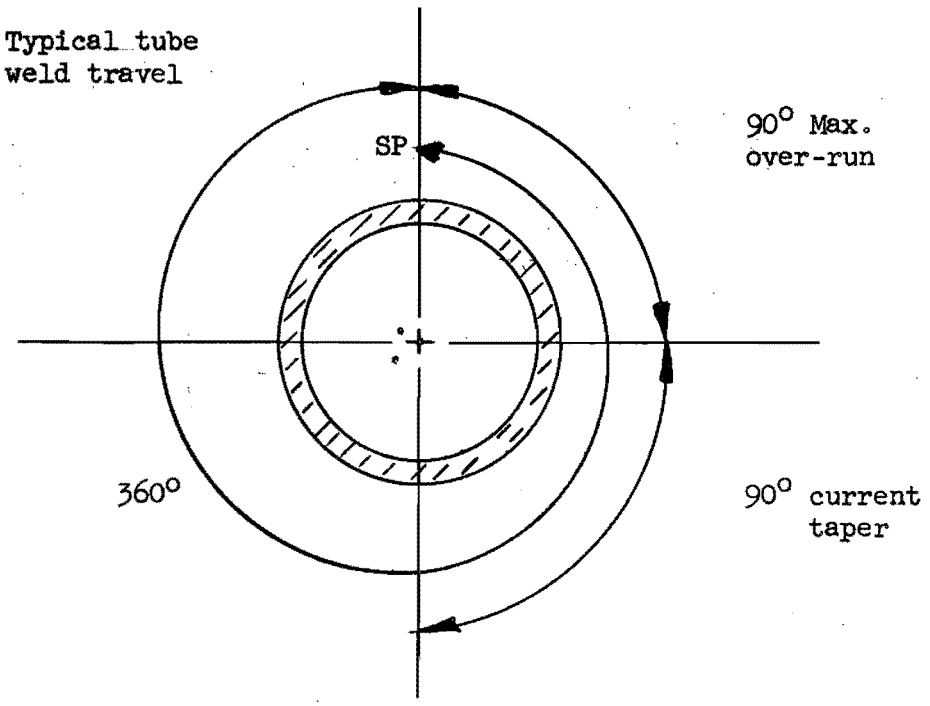
Electrode - thoriated tungsten 1/16 in. and pointed

Electrode projection from cup - 1/4 in.

VI. RADIATOR CONSTRUCTION (Continued)

Argon flow through torch - 20 cfh

Argon backup gas flow - sufficient to prevent oxidation of internal surfaces



F. Brazing Requirements

1. Fins shall be metallurgically bonded to the tubing by brazing of the fin collar.

2. Brazing material

   Brazing material to be Coast Metals brazing alloy No. 52, or approved equivalent. Binder material shall be "Colmonoy Nicro-braze Cement" or approved equivalent. The brazing material must be applied to the fin tube joints in the form of pre-sintered rings, slurry, or dry powder. The application of the brazing alloy shall be the responsibility of the Seller but the Buyer will, upon request, make suggestions and recommendations.

3. Application

   a. Fin-to-tube joint

      Brazing material shall be applied at each fin collar tube joint in a manner and quantity to produce a uniform

VI. RADIATOR CONSTRUCTION (Continued)

distribution of the braze material around the joint. Excess application of braze material will cause a blocking of the air-flow passages between the fins, while insufficient use of braze material will result in a poor metallurgical fin bond.

The quantity of braze material applied must be sufficient to cover the exposed copper at the fin collar with braze material and produce a joint equivalent to that shown in Fig. 2. Proper clearance must be provided between the fin collar and tube in order to insure production of a good metallurgical bond without the use of excessive brazing alloy. Excess brazing alloy may cause dilution of the tube walls. The method of application of the brazing alloy and the brazing technique shall be approved by the Buyer.

N Excessive brazing alloy is defined as follows:

Throat measurements for a true radius fillet braze shall be between 0.010 and 0.040 inches from corner of tube and header or fin intersection to surface of braze material. The maximum height shall not exceed the height of the fin collar.

Care shall be taken to prevent block-off of the free flow cross sectional area of the exchanger by excess brazing compound or fin warping.

b. Tube-to-header joints

All tube-to-header joints shall be backed up with braze material as shown in Drawing F-2-02-054-2509 and shall produce a brazed joint equivalent to that pictured in Fig. 1.

4. Brazing

Brazing shall be carried out in a closed retort completely purged with helium to eliminate all oxygen before heat is applied. Brazing shall be carried out in an inert atmosphere of hydrogen having a dew point of -70°F. The exchanger core is to be brazed in such a way that the core is held for one-half hour at a temperature of 1870°F to 1905°F. Caution should be exercised in controlling the cooling rate to prevent warping of the core. The core is to be brazed on the side to preventexcessive buildup of brazing alloy at the bottom of the tubes. Provisions should be made whenever possible to prevent dripping of brazing alloy from one section of the radiator to another.

VI. RADIATOR CONSTRUCTION (Continued)

Alternate proposals for brazing techniques will be considered by the Buyer. The entire brazing techniques to be employed by the Seller shall be approved by the Buyer.

The Seller shall provide the Buyer with a small sample core section consisting of six tubes and a minimum finned length of two inches. This sample core section shall be brazed with each large core section and shall serve to permit a means of examining the brazing on the larger core section. Tube sizes and spacing, fin spacing, and materials shall be identical to the large core section. A photograph of a sectioned brazing core sample is shown in Fig. 3. Brazed samples shall be accompanied by information as to brazing time and temperature. A system should be established to permit identification of each brazed sample with the accompanying radiator core.

The core sample shall be air expressed to the Buyer, accompanied by the brazing report, for approval prior to assembly of the production core into a radiator unit. Within 48 hours after receipt of the braze sample, the Buyer shall notify the Seller as to the acceptability of the brazing. In the event the sample section is rejected, a representative of the Buyer shall inspect the production core. If the production core is unsatisfactory, the Buyer's representative shall determine the extent to which repairs are permissible on the radiator core. Repairs are to be at no cost to the Buyer.

G. Assembly Sequence for Radiator Core (Recommended)

The assembly sequence for the radiator unit appears on Drawing F-2-02-054-2509.

Trimming and fitting of the tube ends projecting into the tube header shall be carried out without the use of abrasive, grinding compound, or cutting oil. Extreme care shall be taken to prevent trapping any foreign material between the tube wall and header holes.

R Positioning of the tubes into the tube header shall be carried out in such a manner as to prevent cracking or stressing of the tube and to permit proper flow of braze material between the tube and header. Tubes are to be expanded to a maximum depth of 1/8 in. Reduction of the tube wall thickness shall not exceed 5%. To insure maintenance of tolerances on the tube expanding procedure, a quality control procedure shall be established and submitted to the Buyer for prior approval.

VI. RADIATOR CONSTRUCTION (Continued)

No tube that is nicked, dented, scratched, or damaged in any way before or during assembly shall be used in the radiator core assembly. Use of any damaged tube in a radiator core shall be cause for rejection of the unit.

VII. MECHANICAL TESTING

R A. Leak Tests

1. Leaks shall be determined by use of a mass spectrometer leak detector (Consolidated Vacuum Corporation Standard Model or equivalent) with a sensitivity of 5×10^{-4} ft^3/hr. System sensitivity shall be established before each individual test is made through calibration of the detector unit with a standard leak.

2. After completion of the tube-to-header welds and prior to the back-brazing of the tube-to-header joints, the tubes shall be exhausted to a pressure of 10 microns or less. The outside of the radiator core shall be submerged in an atmosphere of helium and the unit tested for leaks.

3. In the event leaks are found they shall be repaired and the core tested, as in VII-2 above.

4. Upon completion of the leak testing above, the unit shall be brazed. After the inside weld tying the two core halves together at the header is made, the unit is exhausted to 10 microns or less and the outside of the unit is probed with helium using the mass spectrometer on highest sensitivity. All leaks are to be repaired and the unit retested until leak tight.

R 5. The completed assembly of radiators, headers, and manifold piping shall be hydrostatically tested with clean trichloroethylene at a pressure of 315 psig. The bundle unit shall be sniff tested with a halide torch and all leaks found shall be repaired.

6. The entire completed assembly of radiators, headers, and manifold piping shall be leak tested as in Part 2 above.

R 7. In the event leaks occur, they shall be reported immediately to the Buyer. Repair techniques to be employed must have prior Buyer approval. The unit is then retested as in Parts 5 and 6 above.

8. Any and all leaks found are to be recorded and such information be made available to the Buyer.

VII. MECHANICAL TESTING (Continued)

9. Any connections made for testing by the Seller are to be removed by the Seller after testing unless otherwise specified.

B. Air Pressure Drop

1. After brazing and prior to assembly of the radiator core halves, an air pressure drop test shall be carried out on each radiator core section.

The test shall be carried out under isothermal flow conditions with measurements made to determine air pressure drop and air flow rate. Air flow measurements shall be made by calibrated flow nozzle, pitot tube or pitot venturi methods. The test setup, methods, and instrumentation shall be approved by the Buyer prior to running any radiator core tests.

Pressure drop measurements on the unit shall be made to determine that the total drop does not exceed the value indicated by data taken on air pressure drop tests carried out in the Buyer's plant on similar core geometries. Information will be furnished by the Buyer to the Seller giving the pressure drop in inches of water versus air flow rate for the radiator tests. A mass velocity flow range of approximately 1.5 to 5.0 lb/ft^2 sec will be required across the radiator core. It is estimated that the pressure drop will not exceed 11 in of water at the high flow. A minimum of five test points scattered at approximately equal intervals through the test range shall be taken. All test data points taken shall be reported in the test. Methods of calculation and treating of the data shall be the responsibility of the Seller but final acceptance of the test results shall be reserved to the Buyer.

The Buyer shall be notified sufficiently in advance of all pressure drop tests to permit witness of such tests.

2. Additional tests may be required by the Buyer but these tests will be at the Buyer's expense.

VIII. GENERAL SPECIFICATIONS

A. Bids

Basic bid proposals shall be in strict accordance with these specifications, and shall bear a statement to that effect. Adequate information shall be submitted with the bid so that it may be properly evaluated by the Buyer.

VIII. GENERAL SPECIFICATIONS (Continued)

Bid proposals in strict accordance with these specifications will be given prior consideration. However, if the bidder desires to submit an alternate proposal, the bid shall fully state any exception to this specification and shall list such under a separate section headed "Exceptions to the Specification".

Information given in drawings or otherwise supplied by the Buyer constitutes assistance to the Seller, but shall not remove the responsibility from the Seller to produce a mechanically sound product in accordance with these specifications and with the best engineering and manufacturing practices.

B. Design Approval

Within four weeks after the order has been received by the Seller and before fabrication is begun, the Seller shall submit to the Buyer six copies of approval drawings covering complete fabrication of the unit, together with presentation of all methods and procedures proposed by the Seller which differ from recommendations of the Buyer. This submission may be Union Carbide Nuclear Company drawings revised as necessary by the Seller, accompanied by such shop drawings and instructions as may be necessary for the fabrication of the units.

Within two weeks after receiving the above material, the Buyer shall notify the Seller on the design approval. Only after the Buyer grants approval in writing shall the Seller proceed with fabrication.

The applicable Union Carbide Nuclear Company job specification and purchase order number and revision number shall be marked on each drawing, preferably in the title block.

Checking and/or approval of drawings, bills of materials, etc., by the Buyer shall not relieve the Seller of the responsibility for errors of omission or commission. Approval by the Buyer shall not be construed as waiving any part of the specification, unless it includes a specific written statement to that effect.

Any proposed variation from these specifications and any proposed changes after design approval has been granted shall be reduced to writing by the Seller and submitted to the Buyer for consideration. The minutes of any meetings between the Buyer and the Seller shall also be reduced to writing by the Seller with a copy to the Buyer. No change shall be put into effect until written approval has been granted by the Buyer.

VIII. GENERAL SPECIFICATIONS (Continued)

C. Correspondence

All correspondence shall bear reference to the Buyer's purchase order number and to the applicable Union Carbide Nuclear Company job specification number and revision number.

D. Reproducible Drawings

Within two weeks after the receipt of design approval from the Buyer, the Seller shall supply to the Buyer the number of complete sets of positive reproducible drawings specified on the Inquiry and Purchase Order. Drawings shall bear a signed statement certifying that they are correct and complete for the products to be furnished under this specification.

All drawings shall bear the Buyer's purchase order number and the applicable Union Carbide Nuclear Company job specification number and revision number. Reproducible material shall be shipped flat or in a tube, not folded. Submission of reproducible drawings may be made by revising those furnished by the Buyer and certifying as stated above. Included with the drawings shall be an outline of the procedures employed in assembly, brazing, and welding operations.

Any of the above material which is revised shall be submitted to the Buyer within one week after the change is approved.

E. Certification of Materials

When requested by the Buyer or where called for in the specification, the Seller shall furnish certification that all materials furnished by the Seller for use in the fabrication of the products covered by this specification are in accordance with these specifications, applicable ASTM standards (or other standard specifications) and/or the manufacturing material list.

F. Identification

Each assembly shall be plainly marked on a nameplate securely wired to the manifold piping with the manufacturer's model and serial numbers, and the applicable Union Carbide Nuclear Company job specification and purchase order number and revision number, for example: "JS-P3-19, Rev. 0".

In the absence of such marking, the material may be rejected and returned to the Seller for correction; transportation charges in both directions to be paid by the Seller.

VIII. GENERAL SPECIFICATIONS (Continued)

G. Progress and Delivery Schedules

R Upon receipt of order approval, the Seller shall initiate a monthly progress report covering the work performed under these specifications. These reports shall contain information relating to the status of the work in the Seller's plant and the status of drawings, tooling, and supply of the materials and equipment. In general, the reports shall indicate items pertinent to the successful completion of the job on schedule. Four copies of this report shall be forwarded to the Buyer.

H. Tests and Inspection

The Buyer shall have the right to have representatives who shall be given free entry to all parts of the manufacturing works which concern the products covered by this specification, at all times when work on the products is being performed. The Buyer shall be furnished, without charge, all reasonable facilities to satisfy him that the work is being performed within specifications.

To permit the Buyer to witness all tests, welding, and brazing, the Seller shall notify the Buyer at least three days in advance of performance of all test, welding, and brazing operations required by this specification.

The Buyer shall have the right, at any time, to reject any and all products upon which the material, workmanship, identification and/or performance does not comply with the tests and specifications as outlined or referenced herein.

A complete inspection report covering each radiator unit produced shall be forwarded to the Buyer on completion of the radiator unit. The report shall include all photographs, dimension checks, vacuum tests, temperature time reports on brazing cycles, etc., for every unit.

The results of all tests and other information required under these specifications shall be recorded and four copies or one reproducible copy shall be submitted to the Buyer prior to shipment of the product to which the test results are applicable.

J. Preparation for Shipment

Each assembly furnished under this specification shall be packaged in such a manner as to provide ample protection from damage during handling, shipment, and storage.

VIII. GENERAL SPECIFICATIONS (Continued)

Each package shall be marked with the Manufacturer's name and address, the Buyer's purchase order number, the quantity of units, and the applicable Union Carbide Nuclear Company job specification and purchase order number and revision number.

A packing slip shall be attached to each shipping container and shall contain all the information requested in the preceding paragraph.

K. Warranty

All equipment specified under this specification shall be covered by the provisions of the Buyer's standard warranty clause.

L. Brand or Trade Names

Any use in this specification of brand or trade names is intended to be descriptive and not restrictive and is solely for the purpose of indicating the type or quality that will be acceptable.

Original prepared by: B. E. Black
Original approved by: A. P. Fraas
Original approved for issue by: W. F. Boudreau
Revision 1 prepared by: M. M. Yarosh
Revision 1 approved by: A. P. Fraas, W. G. Piper
Revision 1 approved for issue by: W. F. Boudreau
Revision 2 prepared by: M. M. Yarosh
Revision 2 approved by: A. P. Fraas, M. Bender
Revision 2 approved for issue by: W. F. Boudreau
Revision 3 prepared by: J. W. Teague

Approved by: A. P. Fraas
A. P. Fraas

Approved by: M. Bender
M. Bender

Approved for Issue by: for W. F. Boudreau

Appendix 6.2

Radiator Pre-Operational Inspection Reports

York Test Unit No.1, P.O. No.34003

March 25, 1957

The subject test unit has been received and evaluated. This unit was initially rejected by E. A. Jaggers, the resident inspector at the vendor's plant, for incomplete brazing. The unit was sent to ORNL at the task engineer's request to be used for test purposes.

The inspection comments on the unit as received at ORNL, are listed below:

Visual Inspection

Outlet pipe: Weld C-18, the cap weld at the end of the outlet pipe, has small areas of incomplete penetration and what appear to be small craters.

Header A: Weld C-4, the outside seam weld, has a very uneven appearance. Weld has apparently been repaired in several areas. Several cover passes terminate in the same location.

Header B: Acceptable.

Inlet Pipe: Weld C-15, the inlet cap weld, has uneven penetration and small craters on the stringer beads. Some weld splatter noted at the weld bead edges.

Tube-to-Header Brazing: Joints on the outer tube rows of both headers exhibit some lack of brazing alloy flow.

Tube-to-Fin-Brazing: Almost all joints have skulls, indicating extreme lack of brazing alloy flow. A number of broken brazing alley rings can be seen near the ends of the fin banks. These appear to have been broken during assembly.

alloy

Dye Penetrant Inspection

No defects noted, other than the surface defects discussed above.

Radiographic Inspection

Welds C-1 thru C-10, and C-15 thru C-17 are acceptable.

Weld C-12 exhibits one area of apparent lack of penetration or undercut. Weld C-14 exhibits one questionable defect.

Tube-to-Header Welds - Acceptable.

Control Sample Inspection

See Met. Insp. Request No. 319.

The unit was modified at the Y-12 shops by saving the fin bank in several areas. Inspection comments of the unit after modification are listed below:

Visual Inspection:

1. Mechanical cut, approximately 0.005" deep, on tube No. 360 close to the fin collar on the header end of the fin bank. This defect could not be repaired because of the proximity of the brazing alloy.

2. Sharp dent, approximately 0.3" long by 0.005" deep, on the return bend of tube No. 330. This defect was repaired at the Y-12 weld shop.

3. Mechanical cut, about 0.001" deep, on the return bend of tube No. 360.

4. Nine minor defects on the return bends of tubes No. 348 thru 353. Defects range from 0.0005" to 0.001" deep.

5. Several flat dents on the return bends of tubes No. 325 thru 328, 331 thru 336, 338 thru 340, 343 thru 345, 347 thru 350 and 352 thru 356, inclusive.

6. Dent approximately 0.001" deep, on the return bend of tube No. 45.

Photographs of the above defects are on file, along with the resident inspector reports, vendor reports and drawings and pertinent correspondence, in the Met. Insp. group files. The tube numbers referred to are shown on York Corp. drawing No. 91956.

A. Goldman
Met. Insp.

Visual Inspection Report No. 2

York Radiator Test Unit No. 1

Defects Numbered 1 thru 5:

Defect No. 1: Mechanical cut 5 to 10 mils deep located on tube No. 360. Close to fins, header side of fin bank.

Defect No. 2: Sharp dent 5/16" long x approximately 10 mils deep. Located on return bend of tube No. 330.

Defect No. 3: Mechanical cut approximately 1 mil deep. Located on return bend of tube No. 360.

Defect No. 4: Nine cut places (6 different tubes) tube return bend section between tube No. 348 and tube No. 353. Defects run from 1/2 to 1 mil in depth and 1/16" to 1/8" in length.

Defect No. 5: Flat dents return bend area, tube Nos. 325 thru 328, 331 thru 336, 338 thru 340, 343 thru 345, 347 thru 350 and 352 thru 356, inclusive.

Defect No. 6: 1 mil defect on return bend of tube No. 45.

Numbers as per York Co. Dwg. No. 91956.

York Radiator Test Unit No. 2

Visual Inspection After Modification by Y-12 Shops

Defect on Tube No. 315 was .009 to .013 in depth. Repaired by welding. Depth of defect on tubes No. 310 thru 314, inclusive. Range from .001 to .009, not repaired.

Tubes No. 188, 190, 207 thru 223, inclusive. Have scratch indicators 1/8" from fin bank. Estimated depth 1/2 to 2 mils in depth. These defects were made during modification.

SECRET

Appendix 6.3

Detailed Operatin History York Test Radiator No. 1

Description of Operation	Time Started Day/Hr	Time Finished Day/Hr	NaK Temp. In °F	NaK Temp. Out °F	NaK ΔT °F	Hours on Condition	Near Isothermal Hrs. above 1200°F	Design ΔT Above 1200°F	Misc. ΔT Hrs. Above 1200°F	Total Hours Above 1200°F	Air Out of Radiation °F	Air Into Radiator °F
Took cold air flow & pressure drop data	5-13-57	5-14-57										
Reached 1200°F isothermal	5-17/1630											
Circulated isothermal, then hot-dumped	5-17/1630	5-20/0830	1200	1200	0	64	64			64	-	
Reached 1200°F, circulated isothermal	5-22/0600	5-28/1400	1200	1200	0	152	216			216	-	
Took performance data	5-28/1400	5-28/1600	1200	900-1200	0-300	2			2	218	700-900	80-100
Circulated isothermal	5-28/1600	5-29/1000	1200	1200	0	18	234			236	-	-
Took performance data	5-29/1000	5-29/1600	1200	900-1200	0-300	6			8	242	700-900	80-100
Circulated isothermal	5-29/1600	5-31/0800	1200	1200	0	40	274			282	-	-
Took performance data	5-31/0800	5-31/1600	1200	900-1200	0-300	8			16	290	750-1020	80-100
Circulated isothermal	5-31/1600	6-3/0900	1200	1200	0	65	339			355	-	-
Took performance data	6-3/0900	6-3/1600	1130-1200	840-1200	0-300	7			23	362	660-1060	80-100
Circulated isothermal	6-3/1600	6-4/0900	1200	1200	0	17	356			379	-	-
Took performance data	6-4/0900	6-4/1600	1200	900-1200	0-300	7			30	386	740-1020	80-100
Circulated isothermal	6-4/1600	6-5/0800	1200	1200	0	16	372			402	-	-
Took performance data	6-5/0800	6-5/1600	1200-1230	880-1130	70-300	8			38	410	780-1150	80-100
Circulated at ΔT	6-5/1600	6-10/0900	1240-1300	1070-1140	100-200	113			151	523	1100-1200	80-100
Circulated at ΔT	6-10/0900	6-14/1000	1340-1360	1060-1080	260-280	97			248	620	1100-1200	80-100
Circulated at ΔT	6-14/1000	6-17/1000	1420-1440	1050-1070		72			320	692	1100-1200	80-100
Circulated isothermal	6-17/1000	6-17/1500	1200	1200	0	5	377			697	-	-
Circulated at design ΔT	6-17/1500	6-18/1200	1500	1070	430	21		21		714	1100-1250	80-100
Took performance data	6-18/1200	6-18/1600	1260-1500	930-1070	330-440	4			324	722	850-1200	80-100
Circulated at design ΔT	6-18/1600	6-19/0900	1500	1070	430	17		38		739	1100-1250	80-100
Took performance data	6-19/0900	6-19/1700	1360-1500	1070-1260	230-440	8			332	747	1200-1330	80-100
Circulated isothermal	6-19/1700	6-20/0900	1200	1200	0	16	393			763	-	-
Took performance data	6-20/0900	6-20/1600	1360-1440	1030-1260	180-330	7			339	770	980-1290	80-100
Circulated at design ΔT	6-20/1600	6-21/1500	1480-1500	1070-1100	380-420	23		61		793	1020-1120	80-100
Circulated at ΔT	6-21/1500	6-24/0800	1400	1200	200	65			404	858	1200-1280	80-100
Dumped NaK into sump	6-24/0800											
New radiator support springs & new perforated air-diffuser plate were installed												
Reached 1200°F, circulated isothermal	7-11/1200	7-11/1500	1200	1200	0	3	396			861	-	
Circulated at design ΔT	7-11/1500	7-12/0300	1500	1070	430	12		73		873	1140-1240	80-100
Circulated at ΔT	7-12/0300	7-12/1000	1350	1100	250	7			411	880	1160-1240	80-100
Dumped NaK into sump	7-12/1000											

SECRET

Appendix 6.4

Detailed Operating History York Test Radiator No. 2

Description of Operation	Time Started Day/Hr	Time Finished Day/Hr	NaK Temp. In F	NaK Temp. Out F	NaK ΔT F	Hours on Condition	Near Isothermal Hrs. above 1200°F	Design ΔT Above 1200°F	Misc. ΔT Hrs. Above 1200°F	Total Hours Above 1200°F	Air Out of Radiator °F	Air Into Radiator °F	Remarks
Took cold air flow data	8-20-57	8-21-57											
Reached 1200°F isothermal	8-23/1500	8-26/0830	1220	1170	50	65-1/2	65-1/2			65-1/2	-		
Took hot air flow data	8-26/0830	8-26/1630	1050-1260	660-1150	50-390	8			8	73-1/2	650-1030	80-100	
Near isothermal over night	8-26/1630	8-27/0830	1210	1160	50	16	81			89-1/2	-		
Took hot air flow data	8-27/0830	8-27/1330	1200-1500	850-1150	50-430	5			13	94-1/2	850-1200	80-100	
Design ΔT	8-27/1330	8-27/1800	1500	1070	430	4-1/2		4-1/2		99	1230-1260	80-100	
Misc. ΔT	8-27/1800	8-27/2100	1200-1500	1070-1150	50-430	3			16	102	900-1260	80-100	
Design ΔT	8-27/2100	8-28/0800	1500	1070	430	11		15-1/2		113	1230-1260	80-100	
Took hot air flow data	8-28/0800	8-28/1100	1200-1500	1110-1310	50-300	3			19	116	1120-1360	80-100	
Design ΔT	8-28/1100	8-28/1230	1500	1070	430	1-1/2		17		117-1/2	1230-1260	80-100	
Misc. ΔT	8-28/1230	8-28/1500	1200-1500	1110-1310	500-300	2-1/2			21-1/2	120	900-1260	80-100	
Design ΔT	8-28/1500	8-29/1000	1500	1070	430	19		36		139	1230-1260	80-100	
Isothermal	8-29/1000	8-29/1100	1200	1120-1150	50-80	1	82			140	-		
Misc ΔT	8-29/1100	8-29/1130	1200-1150	1070-1150	50-430	1/2			22	140-1/2	900-1260	80-100	
Design ΔT	8-29/1130	8-29/1400	1500	1070	430	2-1/2		38-1/2		143	1230-1260	80-100	
Isothermal	8-29/1400	8-29/1500	1200	1120-1150	50-80	1	83			144	-		
Misc. ΔT	8-29/1500	8-29/1530	1200-1500	1070-1150	50-430	1/2			22-1/2	144-1/2	900-1260	80-100	
Design ΔT	8-29/1530	8-29/1600	1500	1070	430	1/2		39		145	1230-1260	80-100	
Isothermal	8-29/1600	8-29/1800	1200	1120-1150	50-80	2	85			146	-		
Misc. ΔT	8-29/1800	8-29/1830	1200-1500	1070-1150	50-430	1/2			23	147	900-1260	80-100	
Design ΔT	8-29/1830	8-30/0800	1500	1070	430	14		53		161	1230-1260	80-100	
102 thermal cycles (4 hr) at:	8-30/0800	9-15/0800											
2 hours at 1200°F isothermal			1200	1120-1150	50-80	204	289			365	-		
1-1/2 hours at			1500	1070	430	153		206		416	1230-1260	80-100	
1/2 hours at design ΔT			1200-1500	1070-1150	50-430	51			74	569	900-1260	80-100	
Took hot performance data after 110 cycles	9-16/0800	9-16/1600	1115-1500	745-1150	50-525	8	290-1/2		80-1/2	577	700-960	80-100	
cycling cond. during night	9-16/1600	9-17/0800	1200-1500	1070-1150	50-430	16	298-1/2	212	82-1/2	593	1230-1260	80-100	
Took more performance data	9-17/0800	9-17/1600	1150-1500	815-1150	50-430	10	301	213-1/2	88-1/2	603	750-960	80-100	
64 thermal cycles (4 hrs.) at:	9-17/1600	9-28/1000											
2 hours at 1200°F isothermal			1200	1120-1150	50-80	128	429			731	-		
1-1/2 hrs at design ΔT			1500	1070	430	96		309-1/2		763	1230-1260	80-100	
1/2 hour at transition ΔT			1200-1500	1070-1150	50-430	32			120-1/2	859	900-1260	80-100	
Part of final (182) cycle	9-28/1000	9-28/1300	1200-1500	1070-1150	50-430	3	431	310	121	862	1230-1260	80-100	
Radiator failed	9-28/1300		1500	1070	430								

WCX-1915 (4-51) K-25 NRC - Power Data Sheet

SECRET

Appendix 6.5

EXPERIMENT REPORT COVER SHEET

S. J. Cromer
H. W. Savage
J. P. Lane
E. R. Dytko
A. P. Fraas
H. Poppendiek
J. C. Amos
L. H. Devlin
J. G. Turner
J. W. Cooke
L. R. Enstice
R. E. MacPherson
R. D. Schultheiss
R. D. Peak

Task No. 7405

Experiment No. 7405-B-1

Date Jan. 11, 1956

Title Method of Calculating 500 KW Radiator Heat Transfer Coefficients

Work Requested by E. R. Dytko

Prepared By R. D. Peak

Performed By R. D. Peak

Approved By R. E. MacPherson

Work Required of Others and When Promised None

Experiment Status: Complete X Continuing ____ Other ____ *

References: See Page 10

*Explain

INTRODUCTION

A large number of heat transfer calculations must be made from the experimental data collected on a number of very similar 500 kw NaK-to-Air radiator units. As the method outlined in Reference 1 could lead to very tedious calculations, a number of assumptions have been made and a series of charts have been prepared which simplify greatly the task of reducing the experimental data. The purpose of this report is to outline the assumptions and calculations which were necessary for the preparation of the charts and to show the resultant method for data reduction.

The parameters of the radiators vary because of tubing size, number of fins, and thickness of fins. However, the method is the same for all and the only correction required is that for the number of fins which effects the air side heat transfer area, free flow area, and equivalent diameter. The parameters of a particular radiator unit are given in Table 1 in order to show the calculations necessary for the charts and to demonstrate the method. The calculations follow a series of steps listed below:

1. Radiator tube Reynolds Number, Figure 1
2. NaK side heat transfer coefficient
3. Tube-wall plus fin-collar heat transfer resistance
4. Tube-wall, fin-collar, and NaK side combined resistances, Fig. 2
5. Log mean temperature difference correction factor
6. Average fin thermal conductivity, Figure 3
7. Fin efficiency, Figure 4
8. Air property values, Figures 5, 6, 7
9. Radiator calculation (A sample calculation is included)

1. RADIATOR TUBE REYNOLDS NUMBER

$$Re = \frac{D\,G}{\mu} = \frac{(.0115\ ft)\ (gpm)\ (60)\ (\rho)}{(\mu)\ (7.48)\ (.00742\ ft)} = \frac{12.43(gpm)(\rho)}{(\mu)}$$

$$Re = (Factor)(gpm), \text{ where } Factor = 12.43\ \frac{(\rho)}{(\mu)}$$

Temp. °F	Factor for NaK, 56%-44%
700	1093
1000	1318
1300	1472
1600	1593

Figure 1 shows the plot: Factor vs. Temperature.

2. NaK SIDE HEAT TRANSFER COEFFICIENT

The Lubarsky-Kaufmann equation of Reference 2 was used.

$$Nu = .625\ (Re\ Pr)^{.4}$$

$$h_N = \frac{k\ (.625)(Re\ Pr)^{.4}}{D}$$

$$h_N = \frac{k\ (.625)(Factor)^{.4}(gpm)^{.4}(Pr)^{.4}}{(.0115\ ft)}$$

The temperature dependence of h_N was calculated and is shown below:

Temp. °F	$h_N/(gpm)^{.4}$
700	2180
1000	2160
1300	2160
1600	2140

Since the values of $h_N/(gpm)^{.4}$ are nearly constant with temperature, it is assumed that h_N can be adequately expressed by:

$$h_N = 2160\ (gpm)^{.4} = BTU/hr\ ft^2\,°F$$

3. TUBE-WALL PLUS FIN-COLLAR HEAT TRANSFER RESISTANCE

The Inconel thermal conductivity of Reference 3 was used. No allowance was made for the higher conductivity of the fin-collar nor for the braze material.

$$R_t = \frac{t}{k\,A_t} = \frac{.035\ \text{in}}{k(8.68\ \text{ft}^2)} = \text{hr °F/BTU}$$

The temperature dependence of R_t is shown below:

Temp. °F	R_t
700	3.01×10^{-5}
1000	2.60×10^{-5}
1300	2.25×10^{-5}
1600	1.98×10^{-5}

4. TUBE-WALL, FIN-COLLAR, AND NaK SIDE COMBINED RESISTANCES

The combined resistances are a function of both temperature and NaK flow. A multiplier of 10,000 was introduced to make the numbers more convenient to work with.

$$\text{Combined Resistances} = \frac{10{,}000}{h_N\,A_N} + \frac{10{,}000\ t}{k\,A_t} = \frac{10{,}000}{2160(\text{gpm})^{.4}(6.92\ \text{ft}^2} + 10{,}000R_t$$

$$= 10{,}000\ \frac{1}{2160(\text{gpm})^{.4}(6.92\ \text{ft}^2)} + R_t\ \frac{\text{hr °F}}{\text{BTU}}$$

The table below lists the combined resistances as a function of temperature and NaK flow:

NaK Flow, gpm	30	50	70	90
Temp. °F				
700	.473	.441	.424	.412
1000	.432	--	--	.371
1300	.397	--	--	.336
1600	.370	.339	.321	.310

Figure 2 is a plot of the Combined Resistances vs. Temperature and NaK flow.

In the calculation method it is assumed that the temperature drop through the NaK film and the tube-wall plus fin-collar could be neglected and that the combined resistances could be based on the average NaK temperature. At the rated heat load, 500 kw, with a NaK flow of 70 gpm, and average temperature of 1200°F, the total temperature drop through the combined resistances is 62°F which would shift the combined resistance only 1.4%.

5. LOG MEAN TEMPERATURE DIFFERENCE CORRECTION FACTOR

The correction factor for the log mean temperature difference given in Reference 4 for the case of cross flow, shell fluid mixed, two tube passes, shell fluid flows across second and first passes in series, was calculated for 14 different radiator heat transfer tests. The correction factor varied from .98 to 1.00 and so for further radiator tests it was assumed that it could be neglected.

6. FIN AVERAGE THERMAL CONDUCTIVITY

The fins are copper clad with Stainless Steel type 310. They are approximately 50% copper and 50% stainless steel. The thermal conductivity of copper given in Reference 5, and of stainless steel type 310 given in Reference 6, were averaged in order to obtain a reasonable fin thermal conductivity. The data is summarized below: The k is listed in BTU/hr ft^2°F/in.

Temp. °F	Copper k	Stainless Steel 310 k	Fin k
600	2550	114	1332
800	2510	120	1315
1000	2470	137	1304
1200	2440	166	1303
1400	2400	208	1304

Figure 3 is a plot of the Fin Thermal Conductivity vs. Temperature.

As the figure shows, the thermal conductivity is very nearly independent of temperature over a wide range of temperatures so it is assumed that the fin temperature used for obtaining the thermal conductivity can be taken at the Average NaK temperature.

7. FIN EFFICIENCY

The fin efficiency curve given in Reference 1 was replotted in a more convenient scale and is shown in Figure 4.

8. AIR PROPERTY VALUES

A number of air property values are necessary for calculating the radiator heat transfer data so three figures were made for convenience. The air density was calculated using the Ideal Gas Law and assuming that 29 lb of air occupied 359 ft^3 at 32°F and 14.7 psia. Figure 5 is a plot of Air Density vs. Temperature and Pressure. The viscosity and thermal conductivity of air were taken from Reference 7. Figure 6 is a plot of Air Viscosity vs. Temperature, while Figure 7 is a plot of Air Thermal Conductivity vs. Temperature.

Air enthalpy values for calculating heat loads are most conveniently taken from Reference 8. However, this assumes that only dry air is heated in the radiator and no correction is made for the water present as humidity. Reference 9 gives air at 80°F with 100% humidity to contain only .022 lb water per lb dry air. In the sample calculation which follows and using the heat capacity chart of Reference 10, an assumption of 100% humidity changes the air heat load from 506,000 BTU/hr for dry air to 509,000 BTU/hr, or less than 1%.

All air flow calculations are based on the assumption that atmospheric pressure is constant at 14.7 psia. The atmospheric pressure does vary and may be only 29.1 in Hg. Taking in account the actual atmospheric pressure in reducing the pitot-venturi or the pitot-static output pressures to air flow in lb/hr would decrease the air flow only about 3%. The decrease air flow would then decrease the best average heat load, the air heat transfer coefficient, and finally the Nusselt Number by about 2%. However, as the decreased air flow also decreases the Reynolds Number by 3%, the assumption is largely self compensating and does not change the final heat transfer correlation.

9. RADIATOR CALCULATION

The method follows from Reference 1 which gives the following heat transfer equation in the form of a summation of resistances:

$$\frac{10{,}000\ \Delta T_{LM}}{q} = \frac{10{,}000}{h_N A_N} + \frac{10{,}000\ t}{k\ A_t} + \frac{10{,}000}{h_a (A_c + \phi\ A_f)}$$

q = BTU/hr, best average heat load

ΔT_{LM} = °F, log mean temperature difference

t = in, tube-wall plus fin-collar thickness

h_N = BTU/hr ft^2°F, NaK heat transfer coefficient

k = BTU/hr ft^2°F/in, tube-wall plus fin-collar thermal conductivity.

h_a = BTU/hr ft^2°F, air heat transfer coefficient

A_N = ft^2, NaK side heat transfer area

A_t = ft^2, mean tube-wall plus fin-collar heat transfer area

A_c = ft^2, air side tube-collar heat transfer area

A_f = ft^2, air side fin heat transfer area

ϕ = fin efficiency

Step 1. From the NaK flow and the in-out temperatures, calculate the NaK heat load based on the heat capacity at the average temperature.

Step 2. From the air flow and the in-out temperatures, calculate the air heat load based on the enthalpy values given in Reference 8.

Step 3. Average the air and NaK heat loads to obtain q, the best average heat load. If there are several NaK heat loads obtained from the venturi and the E.M. flowmeter, and several air heat loads obtained from the pitot-venturi, the pitot-static, and nozzle, select the best two to average. If there are two radiator units, divide the heat load by 2 in order to get the heat load per unit.

Step 4. Calculate the log mean temperature difference, ΔT_{LM}, from the NaK temperatures in and out, and air temperatures in and out.

Step 5. Calculate the air film temperature by averaging the NaK and air temperatures, in and out.

Step 6. Calculate:

$$\frac{10{,}000\ \Delta T_{LM}}{q}$$

Step 7. From the NaK flow (divide by two if there are two radiator units) and the average NaK temperature, obtain from Figure 2:

$$\frac{10{,}000}{h_N\ A_N} + \frac{10{,}000\ t}{k\ A_t}$$

Step 8. Calculate $\dfrac{10{,}000}{h_a(A_c + \phi A_f)}$ by the following equation:

$$\frac{10{,}000}{h_a(A_c + \phi A_f)} = \frac{10{,}000\ \Delta T_{LM}}{q} - \frac{10{,}000}{h_N\ A_N} + \frac{10{,}000\ t}{k\ A_t}$$

Step 9. Several trial and error calculations are usually required using Figures 3 and 4 - before the terms: ϕ, h_a, k_f, all agree such that h_a can be calculated from:

$$\frac{10,000}{h_a(A_c + \phi A_f)}$$

Step 10. Using Figure 7 and h_a, calculate the Nusselt Number based on the air film temperature.

Step 11. Using the air flow rate, divided by two if there are two radiators, and Figure 6, calculate the Reynolds Number based on the air film temperature.

SAMPLE CALCULATION

The example is from the data taken on the radiator, York Corp. No. 2, on 10/8/55, at 0230 hr, after the radiator had been hot for 224 hours.

Step 1. NaK temp. in 1061°F NaK flow, venturi 75.2 gpm
out 963°F
Difference 98°F

Average 1012°F cp = .248 BTU/lb °F, ρ = 48.7 lb/ft^3

$$q = \frac{75.2 \text{ gpm } (60)(48.7)(.248)(98°F)}{7.48} = 714,000 \text{ BTU/hr}$$

Step 2. Air temp. in 80°F Air Flow, pitot-venturi 2350 lb/hr
out 946°F
Difference 866°F

Average 513°F

at 946°F, air enthalpy 344.47 BTU/lb
80°F 129.06 BTU/lb
Difference 215.41 BTU/lb

q = (215.41)(2350 lb/hr) = 506,000 BTU/hr

Step 3. $q = \frac{714,000 + 506,000}{2} = 610,000$ BTU/hr

Step 4. NaK temp. in 1061°F NaK temp. out 963°F
Air temp. out 946°F Air temp. in 80°F
Difference 115°F Difference 883°F

$$\Delta T_{LM} = \frac{883 - 115}{\ln \frac{883}{115}} = 377°F$$

Step 5. Air film temperature = $\frac{1061 + 963 + 946 + 80}{4}$ = 762°F

Step 6. $\frac{10{,}000\ \Delta T_{LM}}{q} = \frac{10{,}000\ (377°F)}{610{,}000\ BTU/hr} = 6.18$

Step 7. From figure 2, with a NaK flow of 75 gpm and mean temperature of 1012°F, $\frac{10{,}000}{h_N\ A_N} + \frac{10{,}000\ t}{k\ A_t} = .38$

Step 8. $\frac{10{,}000}{h_a(A_c + \phi A_f)} = 6.18 - .38 = 5.80$

Step 9. For this radiator, $A_c = 8\ ft^2$, and $A_f = 210\ ft^2$, assume $h_a = 8.25$, then: $\frac{h_a}{k_f} = .757$ using $k_f = 109$ from Figure 3. From Figure 4, $\phi = .956$. Then h_a is calculated again to check:

$$h_a = \frac{10{,}000}{(8 + .956 \times 210)(5.80)} = 8.25\ BTU/hr\ ft^2 °F$$

Step 10. For this radiator, the air side equivalent diameter is .00832 ft. At the air film temperature of 762°F, k is .0305 BTU/hr ft°F.

$$\text{Nusselt Number} = \frac{h_a\ D}{k} = \frac{(8.25)(.00832)}{(.0305)} = 2.25$$

Step 11. For this radiator, the air free flow area is .509 ft^2. At the air film temperature of 762°F, μ is .0793 lb/hr ft.

$$\text{Reynolds Number} = \frac{D\ G}{\mu} = \frac{(.00832)(2350\ lb/hr)}{(.0793)(.509)} = 485$$

Table 1

Parameters of 500 kw NaK-to-Air Radiator, York Corp. No. 1

Drawing Number	DSK 16590
Tube Material	Inconel
Number of Tubes	72
Tube outside diameter, in.	.1875
Tube wall thickness, in.	.025
NaK side equivalent diameter, ft.	.0115
NaK free flow area, ft^2	.00742
NaK side heat transfer area, ft^2	6.92
Tube-wall plus fin-collar thickness, in.	.035
Mean tube-wall plus fin-collar heat transfer area, ft^2	8.68
Fin Material	Stainless Steel type 310 clad Copper, .010 in thick, schedule 25-50-25
Number of fins in vertical stack	254
Air side fin heat transfer area, ft^2	210
Air side tube-collar heat transfer area, ft^2	8
Air free flow area, ft^2	.509
Air side equivalent diameter, ft.	.00832

REFERENCES

1. ART Design Memo. No. 5-B-2, R. D. Schultheiss and M. M. Yarosh, August 1, 1955

2. Review of Experimental Investigations of Liquid-Metal Heat Transfer, B. Lubarsky and S. J. Kaufmann, NACA TN 3336, March 1955

3. National Bureau of Standards Report 3901, 1955

4. Heat Transmission, Figure 8-7, pg 195, W. H. McAdams, 3rd Ed. 1954

5. Introduction to the Transfer of Heat and Mass, Table 13, pg 268, E. R. G. Eckert, 1950

6. Chemical Engineering Magazine, pg 302, May 1953

7. Gas Tables, Thermodynamic Properties of Air, Table 2, pg 34, J. H. Keenan and J. Kaye, 1948

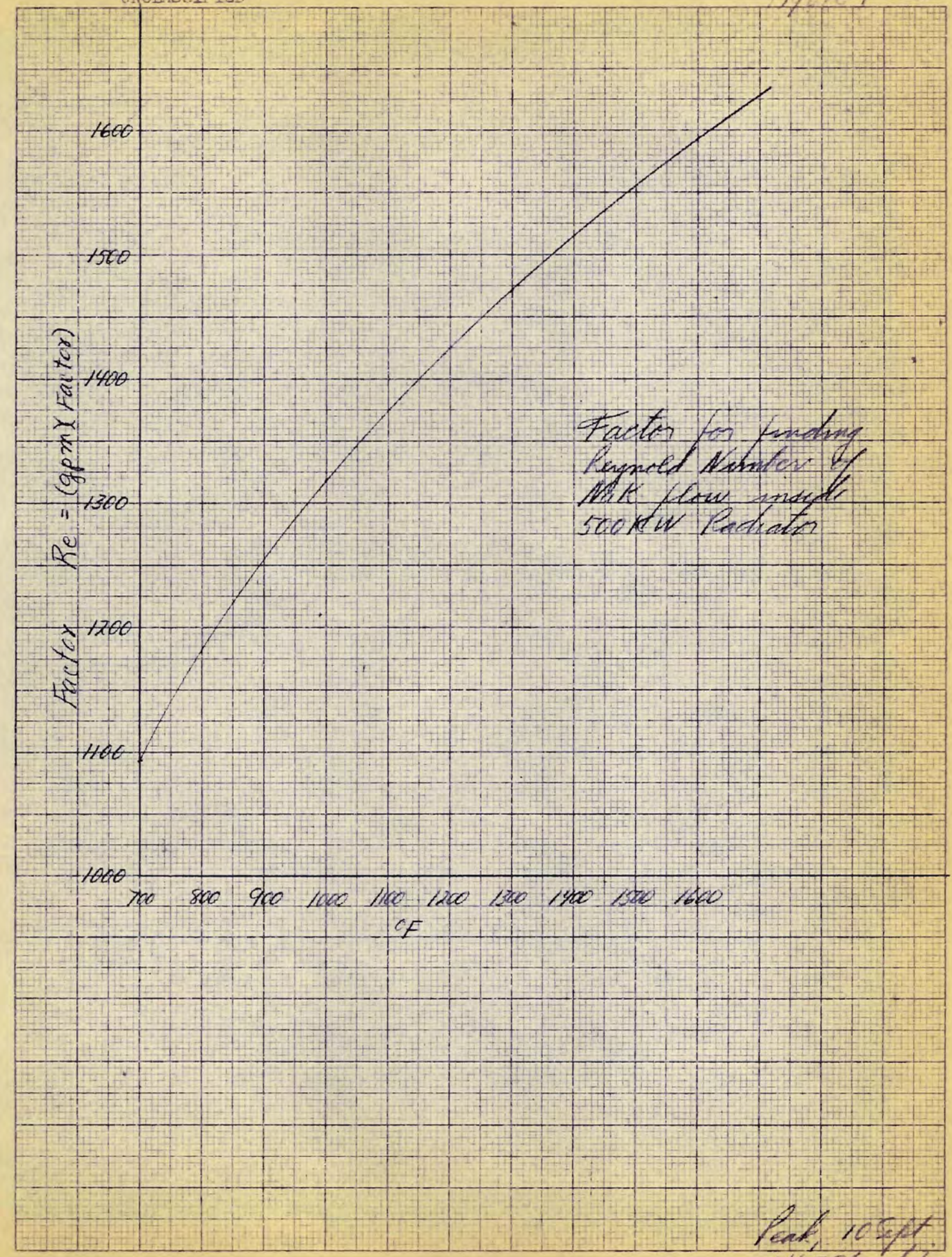
8. Ibid, Table 1

9. Chemical Process Principles, Part One, Material and Energy Balances, Figure 9, pg 101, O. A. Hougen and K. M. Watson, 1943

10. Ibid, Figure 37, pg 217

ORNL-LR-Dwg.-27372
UNCLASSIFIED

Figure 1 - 61 -



Peak, 10 Sept.
IHE Stand 1

K&E 10 X 10 TO THE 1/2 INCH KEUFFEL & ESSER CO. 359-12 MADE IN U.S.A.

NO. 340-L110 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
1 CYCLE X 10 DIVISIONS PER INCH

EUGENE DIETZGEN CO.
MADE IN U.S.A.

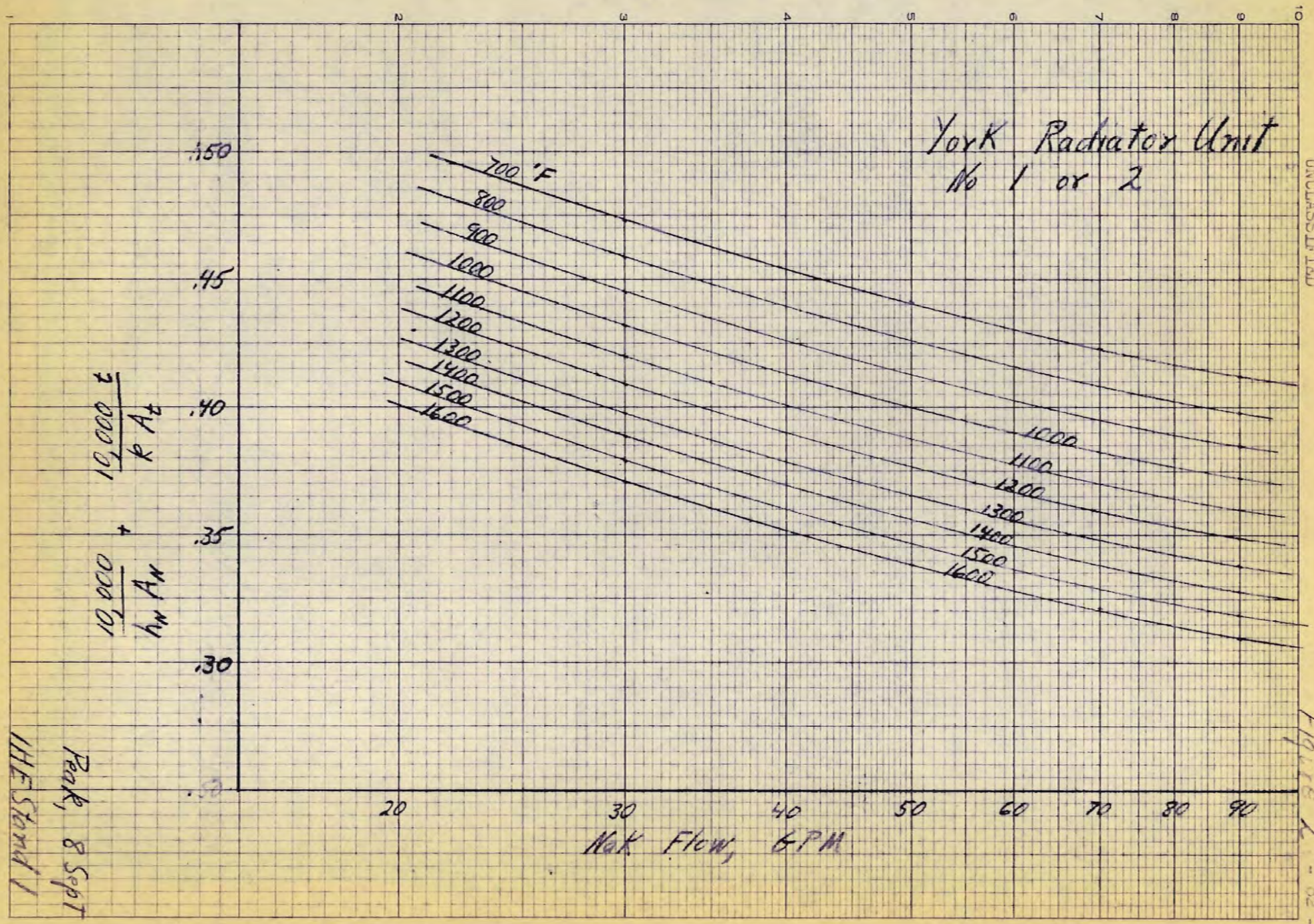


Figure 2

ORNL-LR-Dwg.-27373
UNCLASSIFIED

THE STANDARD
Rank 8 Sept

K+E 10 X 10 TO THE ½ INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.

ORNL-LR-Dwg.-27374
UNCLASSIFIED

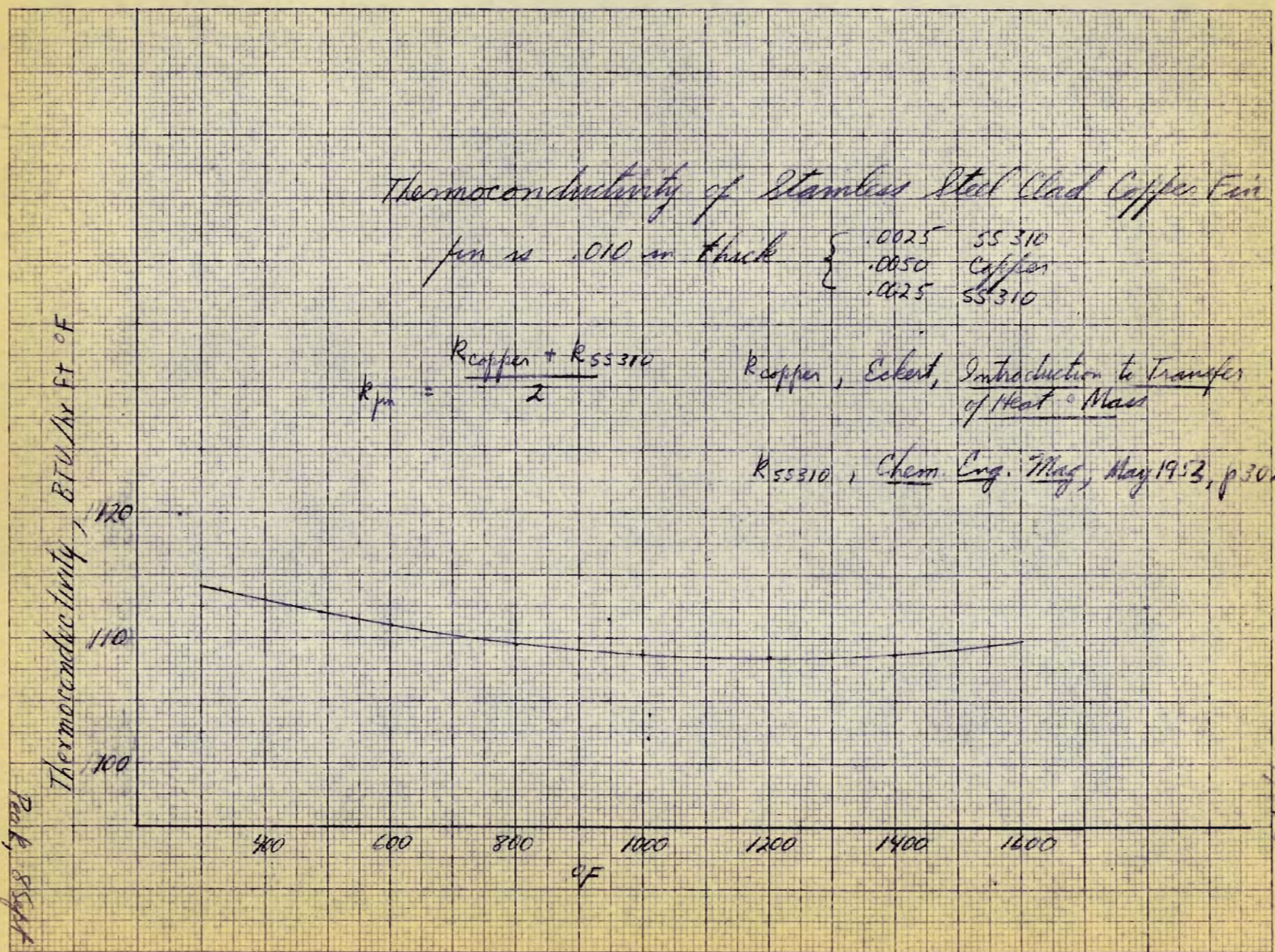
Thermoconductivity of Stainless Steel Clad Copper Fin

fin is .010 in thick { .0025 SS 310, .0050 Copper, .0025 SS 310

$$k_{fin} = \frac{k_{copper} + k_{SS310}}{2}$$

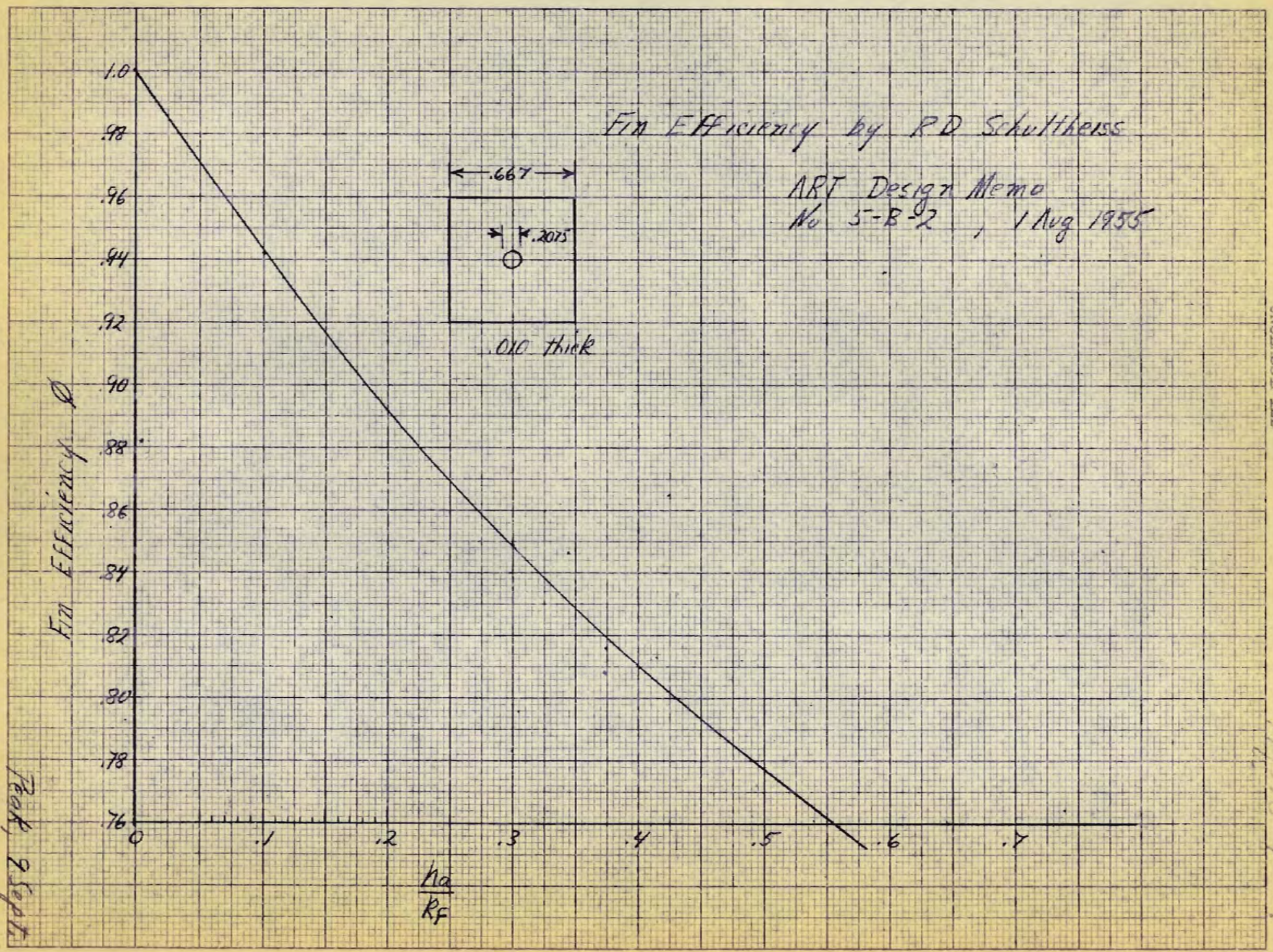
k_{copper}, Eckert, Introduction to Transfer of Heat & Mass

k_{SS310}, Chem. Eng. Mag, May 1953, p 302



Page 85 Part

K+E 10 X 10 TO THE ½ INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.

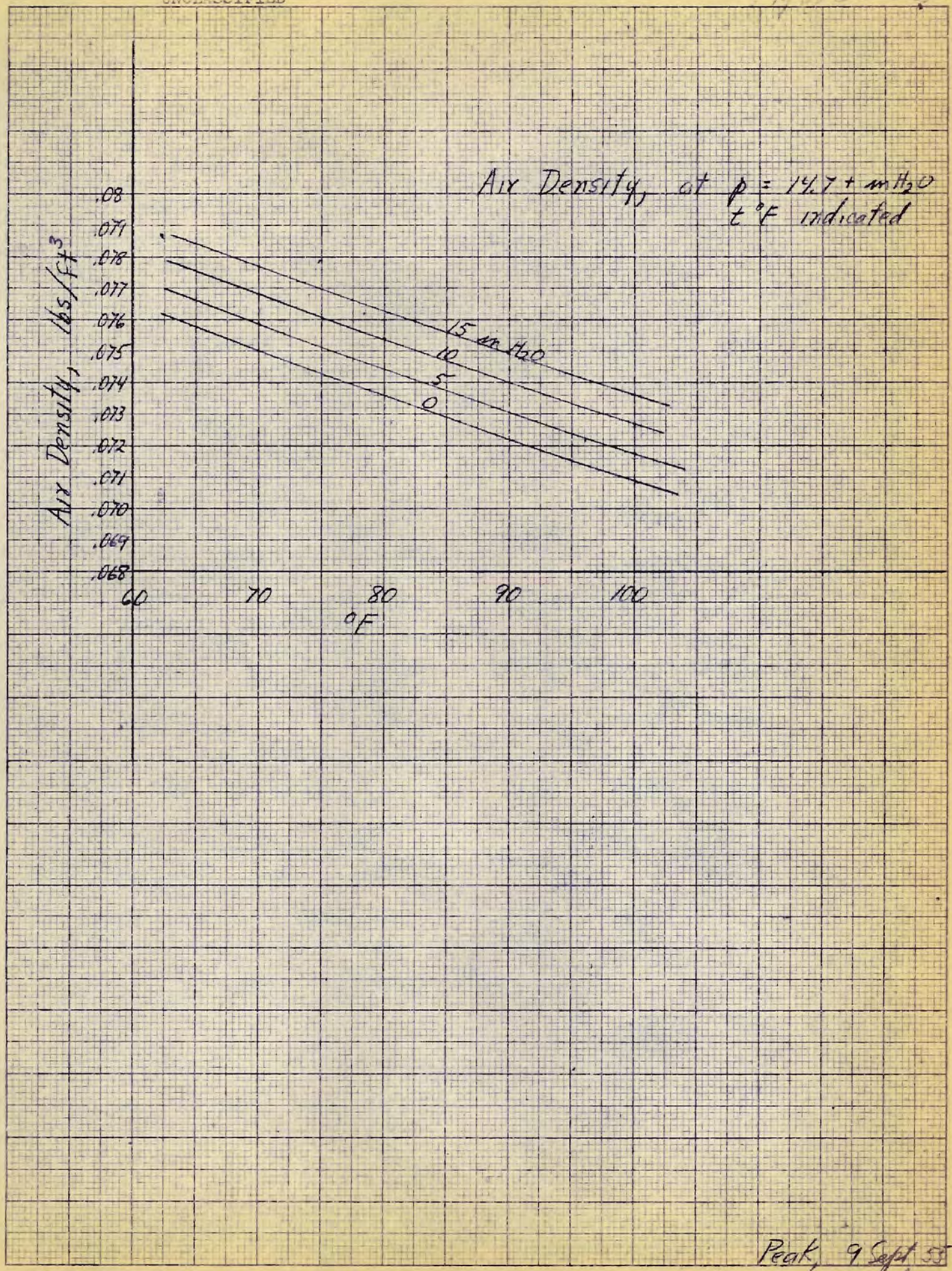


CONL-L-DWG.-27375
UNCLASSIFIED

FIG. 16 4-04-

ORNL-LR-Dwg.-27376
UNCLASSIFIED

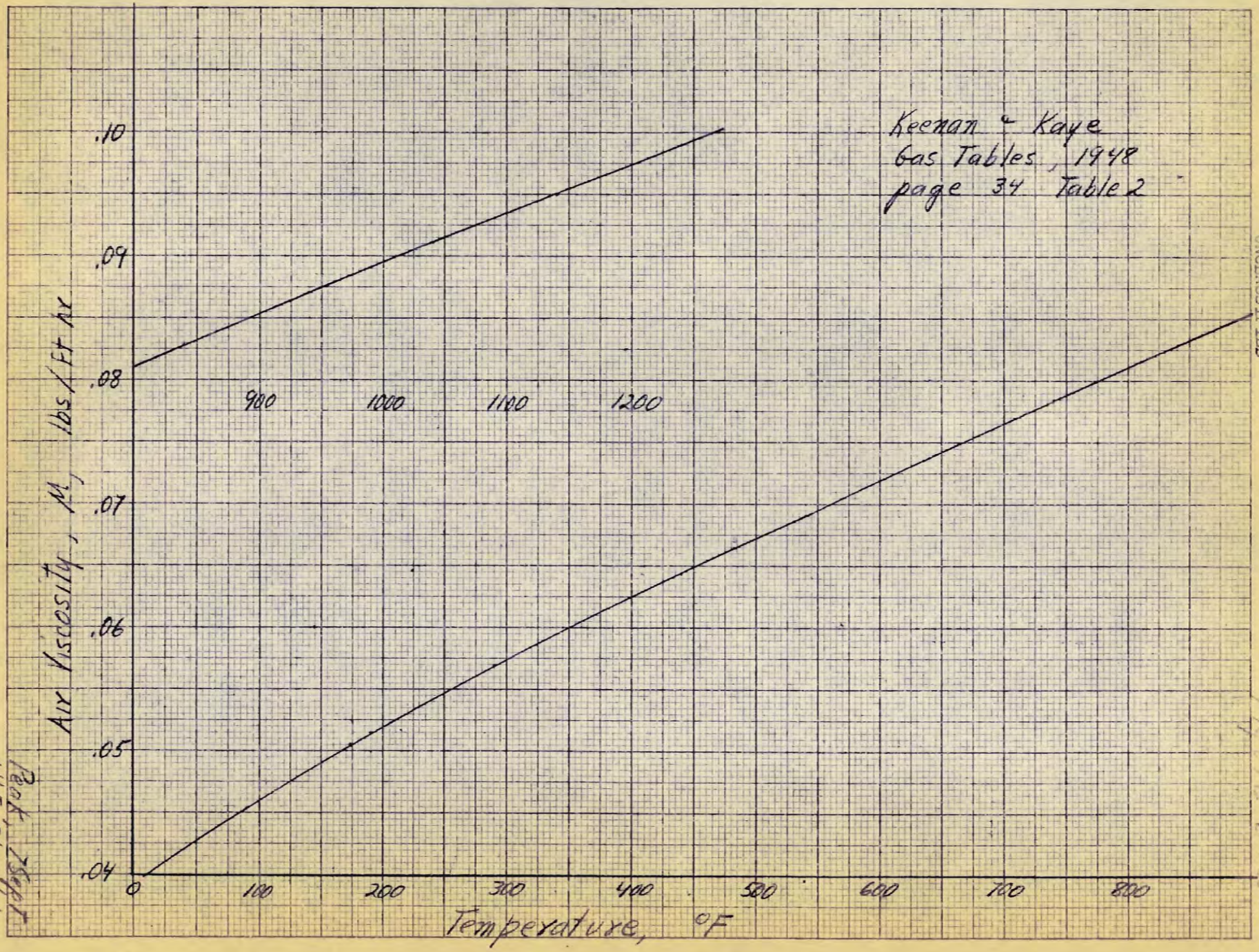
Figure 5 - 65 -



Peak, 9 Sept 55
IHE Stand 1

K&E 10 X 10 TO THE 1/2 INCH KEUFFEL & ESSER CO. 359-12 MADE IN U.S.A.

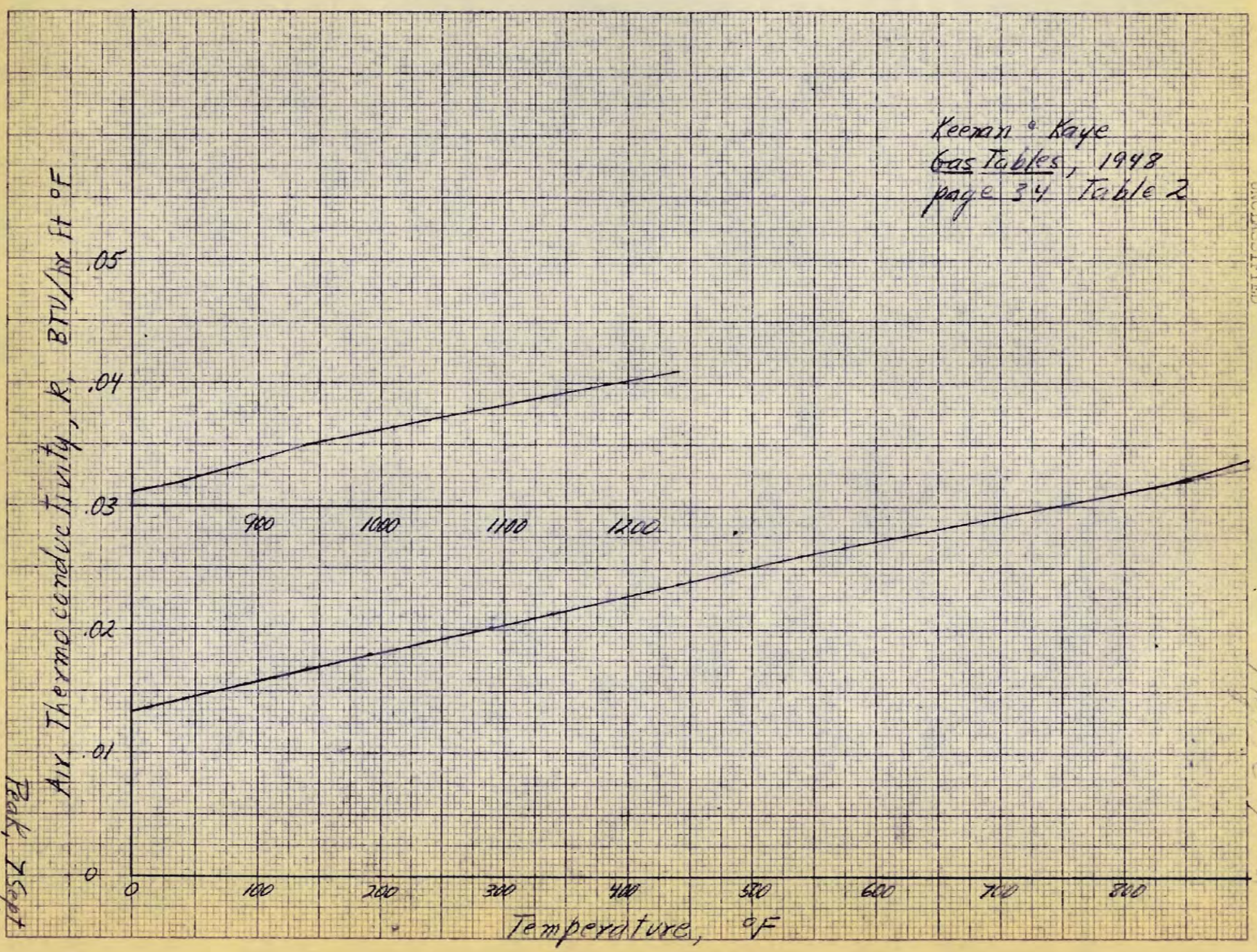
K+E 10 X 10 TO THE ½ INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.



ORNL-LR-DWG.-27377
UNCLASSIFIED

THE Stanall
Page 2 of 2

K·E 10 X 10 TO THE ½ INCH 359-12
KEUFFEL & ESSER CO. MADE IN U.S.A.



ORNL-LR-Lw.--27378
UNCLASSIFIED

Page 2561
1HE Standard

Appendix 6.6

Performance Data Tabulations

TEST RADIATOR NO. 1

HEAT TRANSFER DATA

Appendix 6.6.1

NaK Flow EM FM #/Hr	Air Flow Dall Tube #/Hr	Temperature Air In °F	Air Out °F	NaK In °F	NaK Out °F	NaK Flow EM FM BTU/hr	Air Flow BTU/hr	Air Reynolds Number	Air Nusselt No. from Air Heat Bal.
63,800	32,700	97	786	1188	877	4,960,000	5,525,000	1880	7.0
66,100	31,500	106	850	1263	933	5,345,000	5,920,000	1780	7.1
63,290	29,200	93	826	1195	902	4,640,000	5,270,000	1670	6.8
78,290	29,200	95	851	1200	950	4,890,000	5,445,000	1650	6.8
63,300	26,000	96	873	1204	926	4,400,000	4,980,000	1480	6.5
66,480	26,000	108	979	1353	1015	5,550,000	5,745,000	1420	6.4
63,755	25,700	102	982	1363	1033	5,198,000	5,725,000	1390	6.2
48,985	20,500	107	1121	1487	1068	5,110,000	5,248,000	1065	5.2
40,270	15,800	108	1200	1505	1069	4,422,000	4,376,000	820	4.5
53,270	12,200	100	1281	1491	1204	3,823,000	3,665,000	620	3.75
45,670	11,000	108	1177	1353	1070	3,230,000	2,978,000	585	3.75
45,250	10,950	113	1185	1358	1073	3,185,000	2,999,000	580	3.78
49,015	9,350	100	1322	1490	1233	3,150,000	2,913,000	485	3.07
46,790	8,820	117	1105	1210	1038	2,012,000	2,195,000	475	2.80
45,635	8,300	113	1157	1286	1067	2,464,000	2,191,000	445	3.23
42,355	6,950	100	1332	1489	1262	2,298,000	2,187,000	350	2.3
38,395	4,600	100	1290	1438	1253	1,775,000	1,395,000	233	1.42
45,700	3,320	100	1097	1196	1122	846,000	834,000	180	1.14

TEST RADIATOR NO. 2

HEAT TRANSFER DATA

Appendix 6.6.2

NaK Flow Venturi #/Hr	NaK Flow EM FM #/Hr	Air Flow Dall Tube #/Hr	Temperature Air In °F	Air Out °F	NaK In °F	NaK Out °F	Heat Lead from NaK Flow Venturi BTU/hr	NaK Flow EM FM BTU/hr	Air Flow BTU/hr	Air Reynolds No.	Air Nusselt No. from Air Heat Balance
57,330	54,330	37,800	90	704	1147	747	5,610,000	5,320,000	5,600,000	2350	8.9
68,200	64,700	37,800	88	704	1116	778	5,650,000	5,360,000	5,610,000	2365	8.55
67,260	64,260	34,300	90	752	1154	815	5,590,000	5,340,000	5,510,000	2110	8.0
55,040	52,740	34,000	87	760	1191	775	5,610,000	5,370,000	5,580,000	2080	8.08
67,170	64,270	32,300	88	783	1174	838	5,530,000	5,295,000	5,480,000	1960	7.78
54,760	52,760	32,100	85	784	1212	798	5,560,000	5,360,000	5,470,000	1960	7.75
55,070	52,770	30,800	85	814	1237	826	5,550,000	5,315,000	5,500,000	1845	7.36
66,900	63,800	30,800	87	807	1200	860	5,570,000	5,310,000	5,415,000	1885	7.5
66,818	63,818	29,300	87	843	1220	885	5,480,000	5,230,000	5,450,000	1730	7.21
45,590	44,390	27,700	85	888	1317	835	5,380,000	5,240,000	5,490,000	1575	6.84
66,170	63,370	27,700	85	882	1252	912	5,510,000	5,280,000	5,445,000	1620	7.06
41,340	39,840	26,000	82	915	1358	833	5,320,000	5,130,000	5,360,000	1495	6.53
65,678	62,378	25,800	85	919	1279	944	5,390,000	5,040,000	5,380,000	1480	6.67
65,470	62,370	24,300	84	960	1308	973	5,380,000	5,120,000	5,290,000	1397	6.49
41,340	39,540	24,200	85	961	1385	865	5,270,000	5,040,000	5,260,000	1375	6.34
48,410	47,810	21,800	94	935	1259	888	4,405,000	4,350,000	4,560,000	1198	5.66
72,430	69,230	19,600	94	1119	1404	1114	5,230,000	5,000,000	5,070,000	1030	5.5
44,770	43,970	17,600	98	1192	1503	1075	4,790,000	4,704,000	4,860,000	930	5.1
48,010	48,710	15,600	90	1033	1265	944	3,775,000	3,830,000	3,680,000	840	5.0
70,210	67,210	14,300	97	1300	1510	1245	4,650,000	4,450,000	4,415,000	720	4.85
70,690	67,190	12,200	102	1245	1407	1190	4,035,000	3,835,000	3,790,000	630	4.6
69,520	66,190	10,350	102	1366	1500	1310	3,300,000	3,143,000	3,345,000	520	3.85
69,990	66,190	6,900	105	1301	1408	1263	2,538,000	2,400,000	2,100,000	350	2.45
69,910	66,190	5,000	102	1291	1394	1287	1,869,000	1,770,000	1,515,000	253	2.7

Appendix 6.6.3

Test Radiator No. 1

Room Temperature Air Pressure Drop

Blower RPM	Dall Tube in H_2O	#/hr Air Flow	#/ft^2/sec Air Flow	Radiator ΔP in H_2O	Radiator ΔP in H_2O/Tube Row Corrected for 60°F
400	3.70	11,800	1.81	.95	.112
600	9.2	18,900	2.9	1.95	.23
800	17.4	25,600	3.93	3.3	.39
900	22.4	29,000	4.45	4.1	.484
1100	34.5	35,700	5.49	5.9	.696
1200	42.5	39,400	6.05	7.2	.850
1300	52.0	43,400	6.67	8.25	.974
1000	27.8	32,100	4.93	4.95	.584
500	6.0	15,200	2.33	1.38	.148
700	12.7	22,000	3.38	2.56	.301
1350	57.2	45,000	6.92	8.85	1.045
1500	75.8	51,400	7.90	10.95	1.294

Appendix 6.6.4

Test Radiator No. 2

Room Temperature Air Pressure Drop Data

Blower RPM	Dall Tube in H_2O	#/hr Air Flow	#/ft^2/sec Air Flow	Radiator ΔP in H_2O	Radiator ΔP in H_2O/Tube Row Corrected for 60°F
1500	-	-	-	8.8	-
1400	45.8	40,900	6.28	7.6	.898
1300	37.7	37,300	5.73	6.5	.768
1200	30.8	33,800	5.19	5.6	.662
1100	25.7	31,000	4.76	4.7	.556
1000	21.1	28,000	4.3	3.9	.461
900	16.3	25,000	3.84	3.1	.366
800	12.7	22,000	3.38	2.55	.301
700	9.5	19,200	2.95	2.0	.236
600	6.65	16,000	2.46	1.5	.177

Appendix 6.6.5

TEST RADIATOR NO. 1

HIGH TEMPERATURE AIR PRESSURE DROP DATA

Blower RPM	Average Air Temp. °F	#/Hr Air Flow	#/Ft^2.sec Air Flow	Radiator ΔP in H_2O	Radiator ΔP in H_2O/Tube Row Corrected for 60°F
1450	383	40,350	6.19	13.0	1.002
1400	405	36,850	5.66	12.0	0.901
1375	400	36,000	5.53	12.0	0.907
1375	421	36,500	5.61	11.1	0.819
1340	410	35,400	5.44	11.6	0.867
1300	420	34,650	5.32	10.6	0.783
1280	426	34,400	5.28	10.5	0.770
1200	441	29,340	4.5	8.5	0.613
1195	478	29,630	4.55	9.2	0.638
1100	460	25,700	3.94	7.35	0.52
1090	473	26,200	4.01	7.3	0.5085
1050	543	25,500	3.92	7.4	0.48
1048	542	23,580	3.62	7.3	0.474
1000	484	23,000	3.52	6.3	0.434
900	614	19,960	3.07	5.85	0.3545
900	482	22,900	3.52	5.6	0.3875
850	504	20,100	3.085	5.3	0.357
795	642	16,560	2.54	4.65	0.2745
760	654	15,960	2.45	4.3	0.251
730	535	16,800	2.58	4.05	0.2645
650	700	12,910	1.983	3.3	0.185
636	637	15,920	2.445	4.05	0.240
600	643	11,440	1.757	2.8	0.165
596	649	11,630	1.785	2.8	0.1642
550	581	11,800	1.813	2.4	0.150
550	727	10,350	1.59	2.5	0.137
480	635	9,325	1.43	1.95	0.1156
450	611	8,080	1.24	1.7	0.1031
450	737	7,540	1.157	1.75	0.095
360	637	6,020	0.925	1.13	0.0669
350	622	5,900	0.906	1.2	0.0721
350	723	6,150	0.945	1.17	0.0643
225	627	3,560	0.547	0.55	0.0329

Appendix 6.6.6

TEST RADIATOR NO. 2

HIGH TEMPERATURE AIR PRESSURE DROP DATA

Blower RPM	Average Air Temp. °F	#/Hr Air Flow	#Ft^2 sec Air Flow	Radiator ΔP in H_2O	Radiator ΔP in H_2O/Tube Row Corrected for 60°F
1590	376	42,400	6.51	13.6	1.057
1500	394	39,000	5.99	12.2	0.929
1400	419	34,700	5.34	10.8	0.799
1200	475	27,200	4.18	8.6	0.598
1200	470	26,500	4.07	8.5	0.594
1000	515	20,800	3.20	6.3	0.420
965	607	20,200	3.10	6.2	0.378
885	645	17,350	2.66	5.5	0.323
800	554	16,200	2.49	4.38	0.2808
800	699	14,300	2.195	4.7	0.264
700	673	12,200	1.872	3.7	0.212
600	734	10,350	1.59	2.15	0.117
500	703	8,330	1.28	2.10	0.1174
400	696	6,170	0.948	1.4	0.0787

INITIAL NaK PRESSURE DROP DATA

Appendix 6.6.7

Date	Pump Discharge Pressure Ind.	Pump Discharge Pressure Corrected	Pump Suction Pressure	Furnace Press. Drop	Radiator Pressure Drop	Main EM Flow MV	Cold Trap EM Flow MV	Main Flow #/hr	Main Flow GPM	Cold Trap #/hr	Radiator Flow #/hr	Re	f	
5-23-57	16.5	18.0	10.5	1.0	6.5	5.3	4.2	27,000	71	595	26,405	38,000	.0685	PMD's at 1000°F & calibrated
	23.0	24.2	10.5	2.3	11.4	7.55	4.15	38,000	100	590	37,410	54,000	.060	
	33.0	34.4	10.5	5.3	18.6	10.4	4.2	53,000	140	595	52,405	76,000	.050	
	33.0	34.4	10.5	5.3	18.6	10.4	4.5	53,000	140	630	52,370	75,000	.050	
	45.0	46.4	10.53	8.6	27.27	12.7	4.2	65,500	170	595	64,905	92,500	.0475	
	60.0	61.4	10.55	12.5	38.35	15.0	4.3	76,000	200	610	75,390	109,000	.0497	
	76.0	78.0	10.57	19.0	48.43	17.75	4.25	90,500	238	600	89,900	130,000	.044	
	95.0	97.0	10.58	26.0	60.42	20.25	4.25	103,000	271	600	102,400	158,500	.0425	
5-29-57	17.0	15.0	9.25	.9	4.85	50.25	4.475	25,500	68	630	24,870	35,500	.0576	PMD's at 1200°F & calibrated
	33.5	31.5	9.25	5.0	17.25	10.1	4.650	51,000	137	640	50,360	73,000	.050	
	59.5	57.0	9.28	12.3	35.42	14.9	4.75	75,500	198	650	74,850	108,000	.0465	

IHE-C TEST RADIATOR NO. 2

INITIAL NaK PRESSURE DROP DATA

1200°F NaK Temperature

(Using Venturi NaK Flow)

Date 8-23-57

6.5.8

Venturi Inlet Pressure		Venturi Throat Pressure		Venturi ΔP		Venturi ΔP psi	NaK Flow #/hr	Pump Suction Pressure	Radiator ΔP psi	NaK Reynolds Number	f
Indicated	Corrected	Indicated	Corrected	Indicated	Corrected						
18.2	15.7	17.5	14.5	4.2	6.2	1.24	18,200	13.0	2.7	26,800	.0598
19.8	17.2	18.1	15.1	8.5	10.5	2.1	23,700	13.08	4.12	35,800	.0537
21.4	19.0	18.75	15.75	13.0	15.0	3.0	28,500	13.1	5.9	43,000	.0533
24.3	21.8	19.85	17.0	22.0	24.0	4.8	36,000	13.1	8.7	54,000	.0492
29.4	27.0	21.6	18.8	39.2	41.2	8.24	47,000	12.96	14.04	71,000	.0466
32.0	29.7	22.8	19.9	47.0	49.0	9.8	51,500	13.1	16.6	77,500	.0460
40.8	38.2	25.7	22.7	76.3	78.3	16.5	66,500	13.1	25.1	100,000	.0417
47.2	44.8	27.6	24.7	97.8	99.8	19.95	73,000	13.1	31.7	110,000	.0437

Appendix 6.6.9

Sample Raw Data Sheet

IHE - Stand C

Data Taken by

D. R. Ward Engineer

B. C. Williams Technician

Run 111

Date 8/28/57

Upper Grid (West Side)

305	310	315	320
1359	1361	1361	1289
304	309	314	319
1360	1363	1369	1390
303	308	313	318
1368	1372	1389	1390
302	307	312	317
1370	1372	1363	1385
301	306	311	316
1355	1370	1372	1362

Upper Grid (East Side)

Avg. 1366 °F

1308 63

NaK 1311 °F 1

In 1312 °F 57

1310 °F avg.

NaK 1500 °F 2

Out 1500 °F 58

1500 °F avg.

NaK 190 °F

ΔT

NaK 39.4 psi

ΔP

NaK

Pump 2920 rpm

EM No.1 13.4 mv

67,000 lb/hr

Pump Disch. 62.5 psi _____ psi corrected

Pump Surge 11.2 psi

Cold Trap

EM No.3 5.56 mv

Flow 780 lb/hr

371 °F min. C.T. temp.

T/C 11

Flow .80 mv

Plug Indicator

Below 300 °F Oxide break temp.

RADIATOR

Cold Trap

Blower Speed 600 RPM

Venturi Temp. 1500 °F 69

Air ΔP 2.15 In. water

Venturi Inlet 50.6 psi _____ psi corrected

Air In 100 T.C. 3

104 °F 107

Venturi Throat 31.6 psi _____ psi corrected

Air Out 1328 °F 108

ΔP 94.5 % _____ % corrected

Air ΔT 1264 °F

Mean Air Temp. 734 °F

ΔP _____ psi corrected

Furnace

NaK Flow 70,300 lb/hr

Gas Flow 50.8 %

Gas Press. 45 psi

Dal Tube 2.85"

Dall Tube Inlet 0.3 Below atm.

Barometer 29.28"

IHE-C

Raw Data Sheet

D. R. Ward

4-22-57

Appendix 6.6.9
Sample Calculation Sheet
IHE - Stand C
Radiator Calculations

Computed by R. S. Holcomb — Run 11

Date Computed 8-30-57 — Date 8-28-57

NaK

Total NaK Flow 67,000 (EM Flow) / 70,300 Lb./Hr.

Cold Trap Flow 780 Lb./Hr.

69,520 Lb./Hr. Radiator Flow

NaK In 1500 °F
NaK Out 1310 °F

Sum/2 = 2810/2 = AV NaK = 1405 °F

Q_{NaK} = 69,520 (W) x 0.25 (Sp.Heat Curve 1) x 190 (NaK ΔT) = 3,300,000 Btu/Hr.

Air

Total Air Flow 10,350 Lb./Hr. [Dall Tube, Curve 2]

Air out 1366 °F H = 362
Air in 102 °F H = 38.7
ΔH = 323.3 [curve 3]

Q_{Air} = 10,350 (W) x 323.3 (ΔH) = 3,345,000 Btu/Hr.

NaK Out 1310 °F
Air In 102 °F
ΔT_1 1208 °F

NaK In 1500 °F
- Air Out 1366 °F
ΔT_2 134 °F

[Curve 4]
ΔT = °F
Log Mean

Air Film Temp. = Av. of:
NaK Out 1310 °F
Air In 102 °F
NaK In 1500 °F
Air Out 1366 °F
Sum = 4278 °F

Sum/4 = 4278/4 = 1069 °F Av.Air Film Temp.

Air Reynolds Number = 524
[Curve 5, using Air Film Temp. & Air Flow, Lb./Hr.]

$Q = UA\Delta T_{lm}$ $\frac{10,000}{UA} = \frac{10,000}{Q}\Delta T$ = 10,000 x 489 / 3,300,000 = 1.481 ← From This

NaK In °F
NaK Out °F
NaK Mean °F

Using NaK Mean Temp. & Curve 6 $\left[\frac{10,000}{h_n A_n} + \frac{10,000t}{K_t A_t}\right]$ = 0.161 ← Subtract This

$\left[\frac{10,000}{UA}\right] - \left[\frac{10,000}{h_n A_n} + \frac{10,000t}{KA_t}\right] = \left[\frac{10,000}{h_a A_a}\right]$ = 1.320 ← to get this

Air Nusselt Number = 3.6
[Curve 7, Using Air Film Temp.]

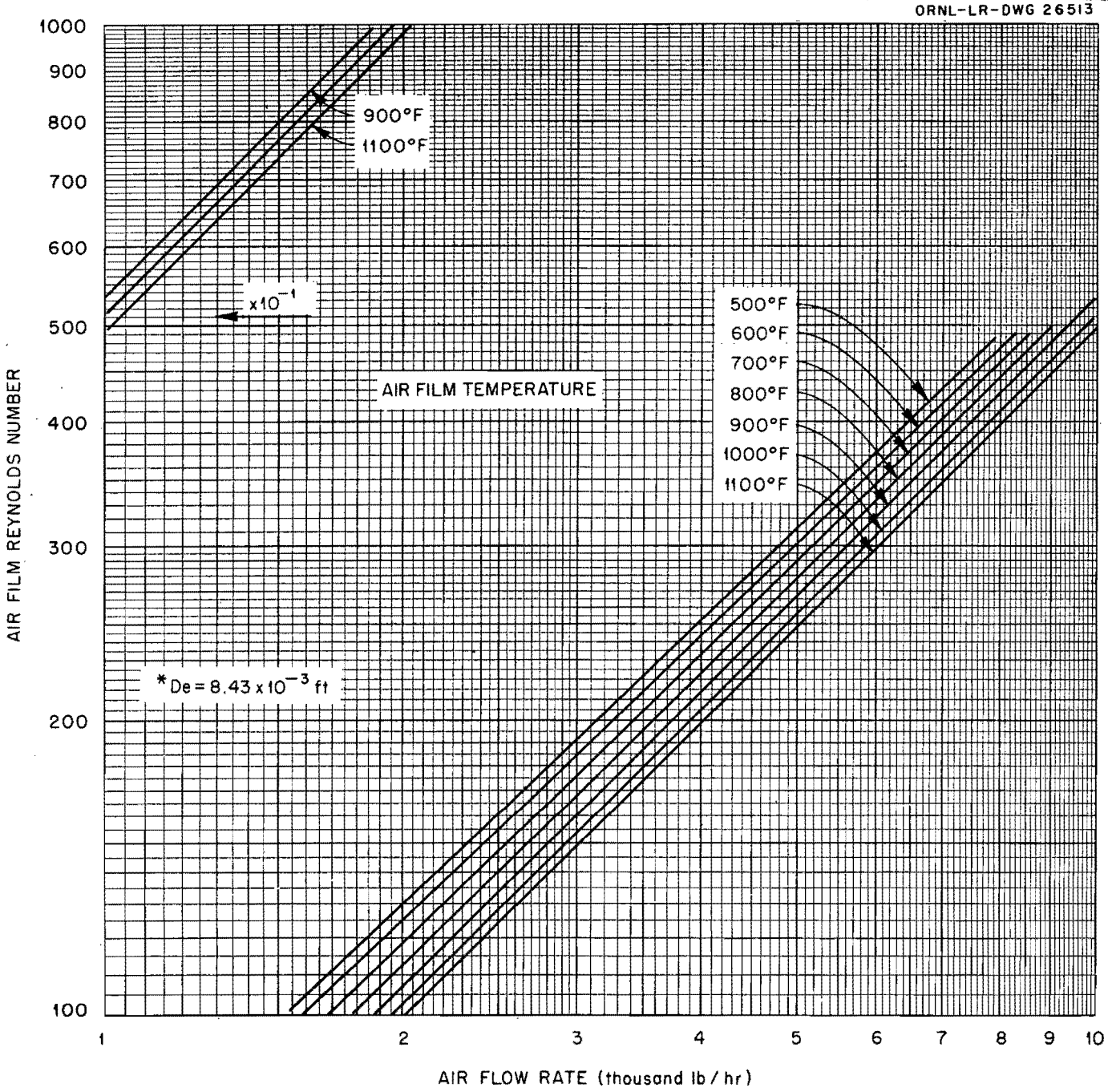
Av. Air Out 1366 °F
Air In 102 °F
Av. Air Temp. 734 °F
+ 460
Av.Air Temp. 1194 °R

Air ΔP x Std.Air Temp. °R(520) / No.of Rows(8) Av.Air Temp.°R = 65 x 2.15(ΔP) / 1194 (Av.°R) = 0.117 in. of water ΔP per tube row corrected to Std. 60°F Air Temp.

Air Flow = lb./Hr. / 1.81 x 3600 = 10,350 / 6516 = 1.59 Lb./Ft.^{2} sec.
[Free-Flow Area Thru Radiator]

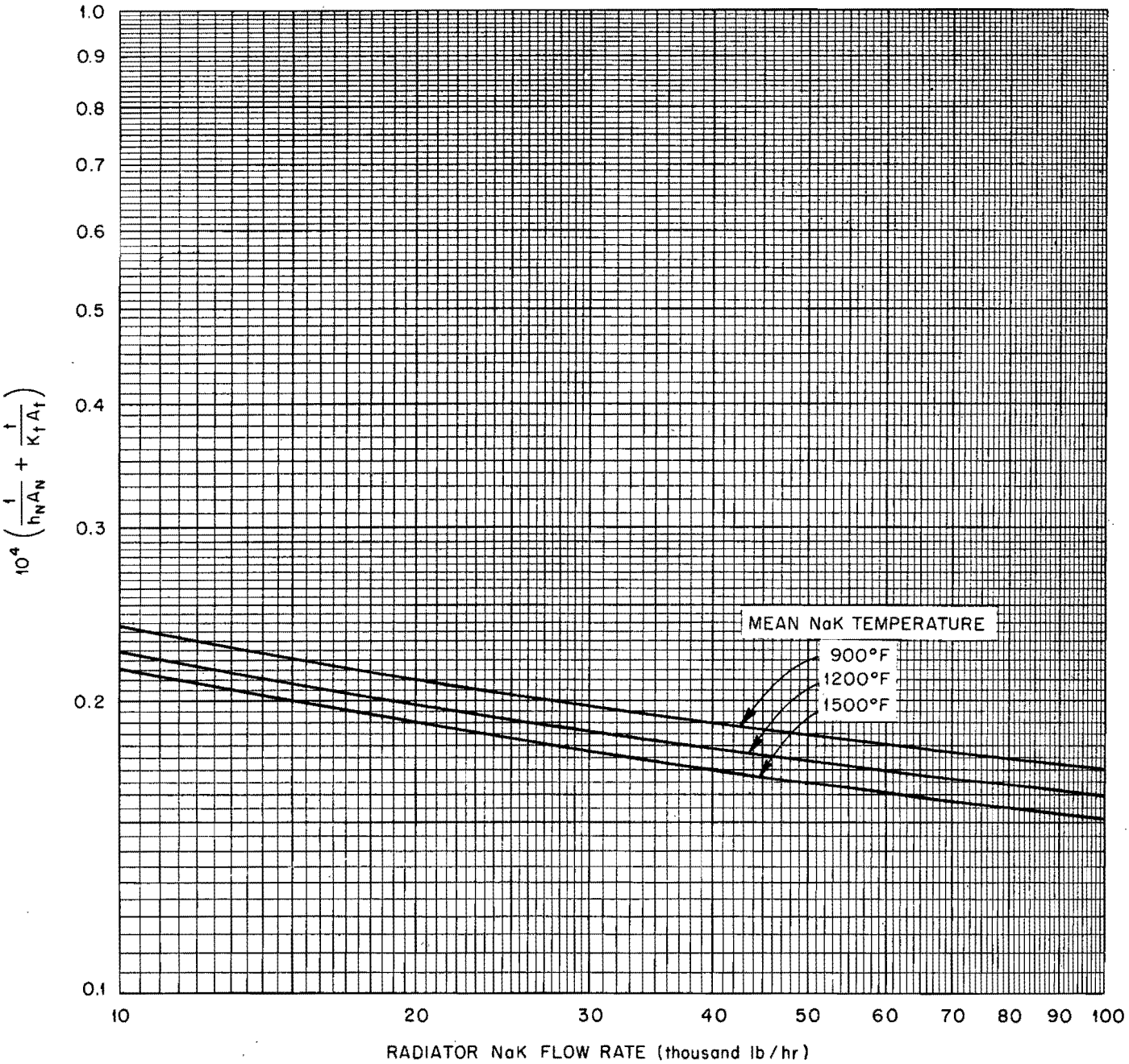
[redacted]

ORNL-LR-DWG 26513



Test Radiator Air Reynolds Number* vs. Air Flow Rate.

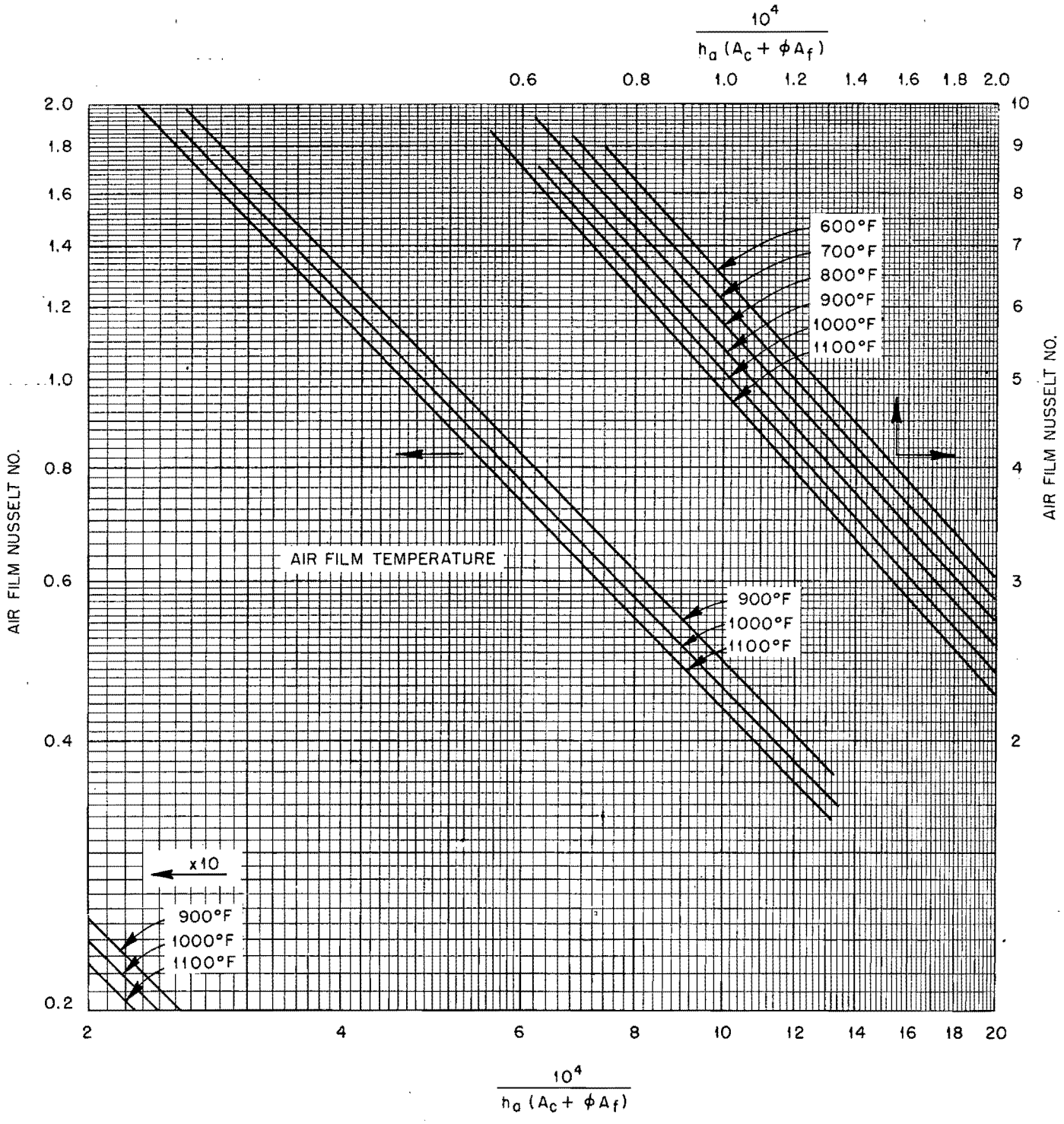
CONFIDENTIAL
ORNL-LR-DWG-26512



Test Radiator NaK Film and Tube Wall Resistance.

Appendix 6.6.9 Calculation Curve 7.

[redacted]
CONFIDENTIAL
ORNL-LR-DWG 26514



Air Film Nusselt Number as Function of Film Thermal Resistance.

INTER-COMPANY CORRESPONDENCE
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation

To: W. D. Manly

Copies To: H. W. Savage
J. H. DeVan
J. C. Amos
A. Taboada
Met. Files

Plant: X-10

Date: July 25, 1957

Subject: Metallurgical Examination of ART Test Radiator No. 1 Failure

Metallography Report No. 299

The radiator failed immediately after reaching full power conditions on the first controlled thermal cycle. Radiator NaK outlet temperature remained approximately constant during this transition and the inlet temperature was increased from 1350°F to 1500°F at a rate of 50°F/minute. The radiator had operated a total of 870 hours on the following conditions.

1200°F isothermal operation	390 hours
Various ΔT conditions with a maximum NaK temperature of 1200°F	47 hours
Various ΔT conditions with a maximum NaK Temperature of 1500°F	360 hours
Design conditions of 1500°F NaK in and 1070°F NaK out	73 hours

Thermal Cycles

Slow cycles, maximum NaK temperature 1200°F	7
Slow cycles, maximum NaK temperature 1500°F	2
Fast cycle, maximum NaK temperature 1525°F	1/2
Total Cycles	9-1/2 [1]

The radiator was received and cleaned July 17, 1957 and the section containing the failed tube was in the Metallography Section July 18, 1957. The rough cutting was done in the cut-up area in 9201-3 under the direction of J. H. DeVan. This same cut-up procedure, discussed by DeVan and the author is continuing to completion. The cut-up procedure involves only cutting through the headers so as to intersect the cuts previously made through the fin matrix. The piece removed contains twenty (20) tubes arranged in a four (4) by five (5) matrix. Figure 1 shows the removed piece. The arrow points to the tube containing the failure.

[1] Correspondence to J. H. DeVan from J. C. Amos, "Metallurgical Examination of ART Test Radiator No. 1", July 16, 1957.

Figure 2 is a close-up view of the failed area. The arrows point to the evident holes which were located by pressurizing the tube with water and observing the leaks. The holes appear bright due to inside lighting of the tube during photography. Metallographic examination did not indicate any evidence of complete penetration of the wall at the circumferential fissure nor at the longitudinal one near the two smaller holes.

Figure 3 shows the same tube as in Figure 2 only rotated approximately 90°. The dark area in the tube is the largest hole seen in the previous figure. This figure shows the curvature of the tube as it enters the header and the exemplory condition of the tube due to the promptness in extinguishing the fire.

Figure 4 shows hole number one which was the largest. The opening in the tube wall in this plane measures .030 inches. Figure 5 shows the tube wall which is only present at the extreme left edge of Figure 4.

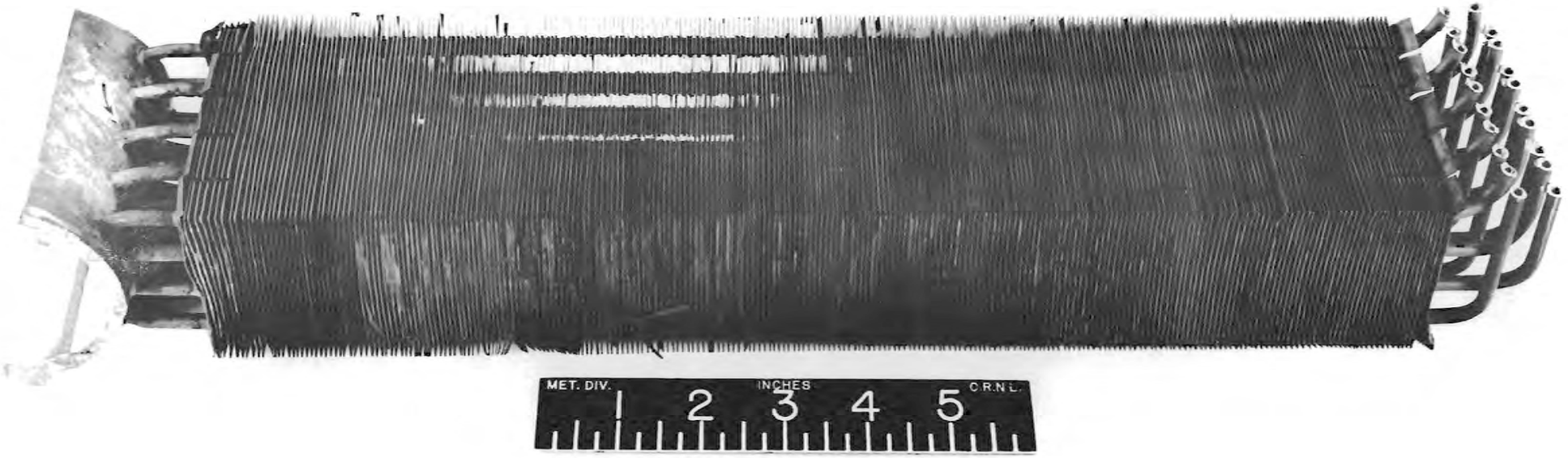
Figure 6 shows hole number two at 100X. Notice that the shape of the metal bordering the hole is similar to that bordering hole number one.

Figure 7 shows hole number two at 500X. The purpose of this photomicrograph is to show that there are no grain boundary voids nor any evidence of incipient failure even near the failed area.

Figure 8, 9, and 10 show the microstructure of the three tubes surrounding the failed tube. Notice again that there is no evidence of incipient failure in any respect.

The inside diameter, outside diameter and wall thickness of the failed tube were measured at various times during the polishing process. Variations in the outside diameter were noticed in several instances but all could be directly attributed to damage due to the fire. There was little or no variation in the inside diameter which would indicate a stress high enough to produce plastic flow in the tubes.

As of this time the cause of the failure is not determined. The failed tube and those immediately surrounding it have been examined and the investigation is continuing to other suspect areas. The fin-to-tube joint integrity will be determined and the degree of oxidation of the copper in the fins. The depth of mass transfer and corrosion will also be measured.



ART TEST RADIATOR NO. 1

Fig. 1

Y-23343
UNCLASSIFIED

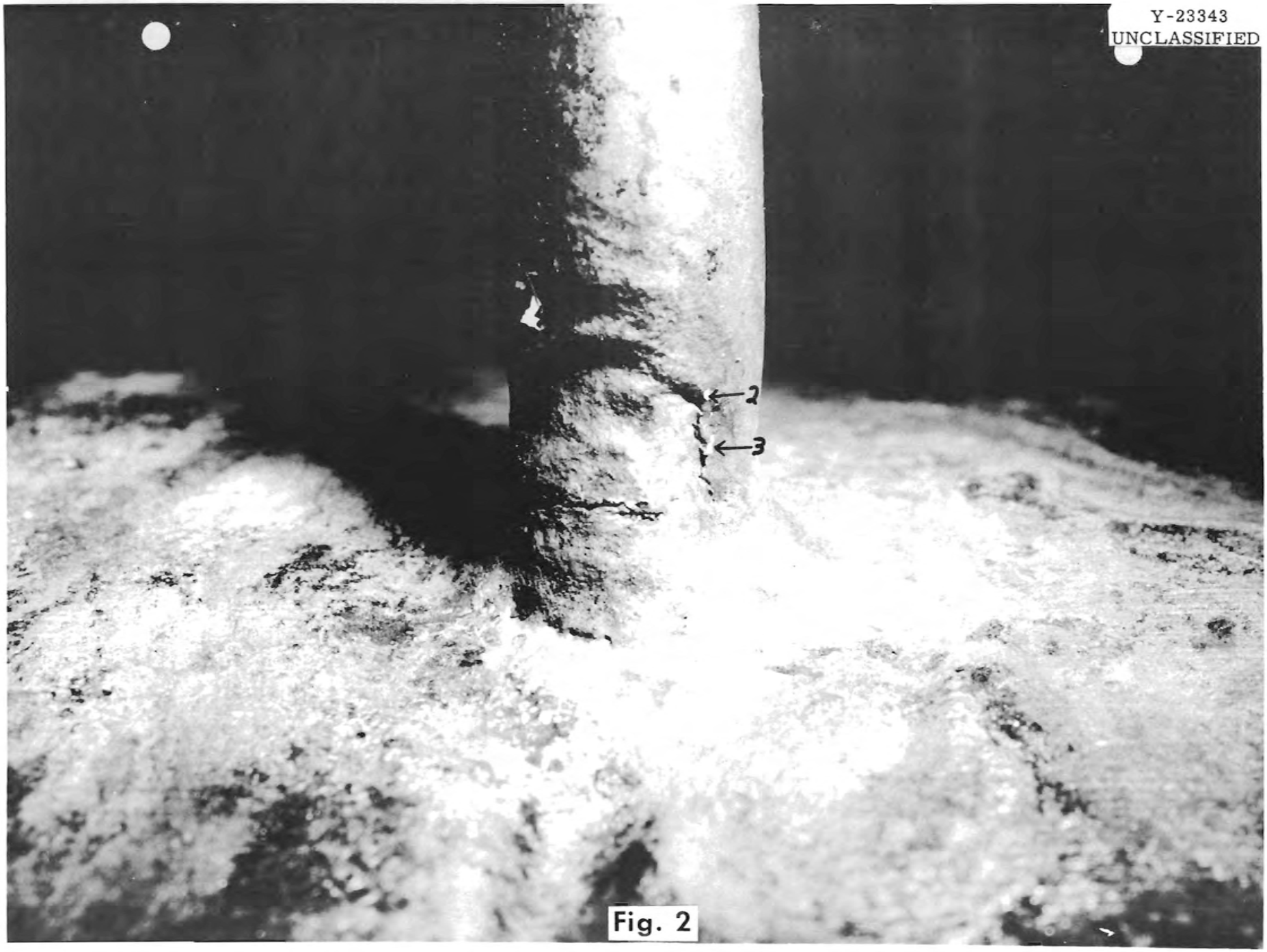


Fig. 2

Y-23341
UNCLASSIFIED

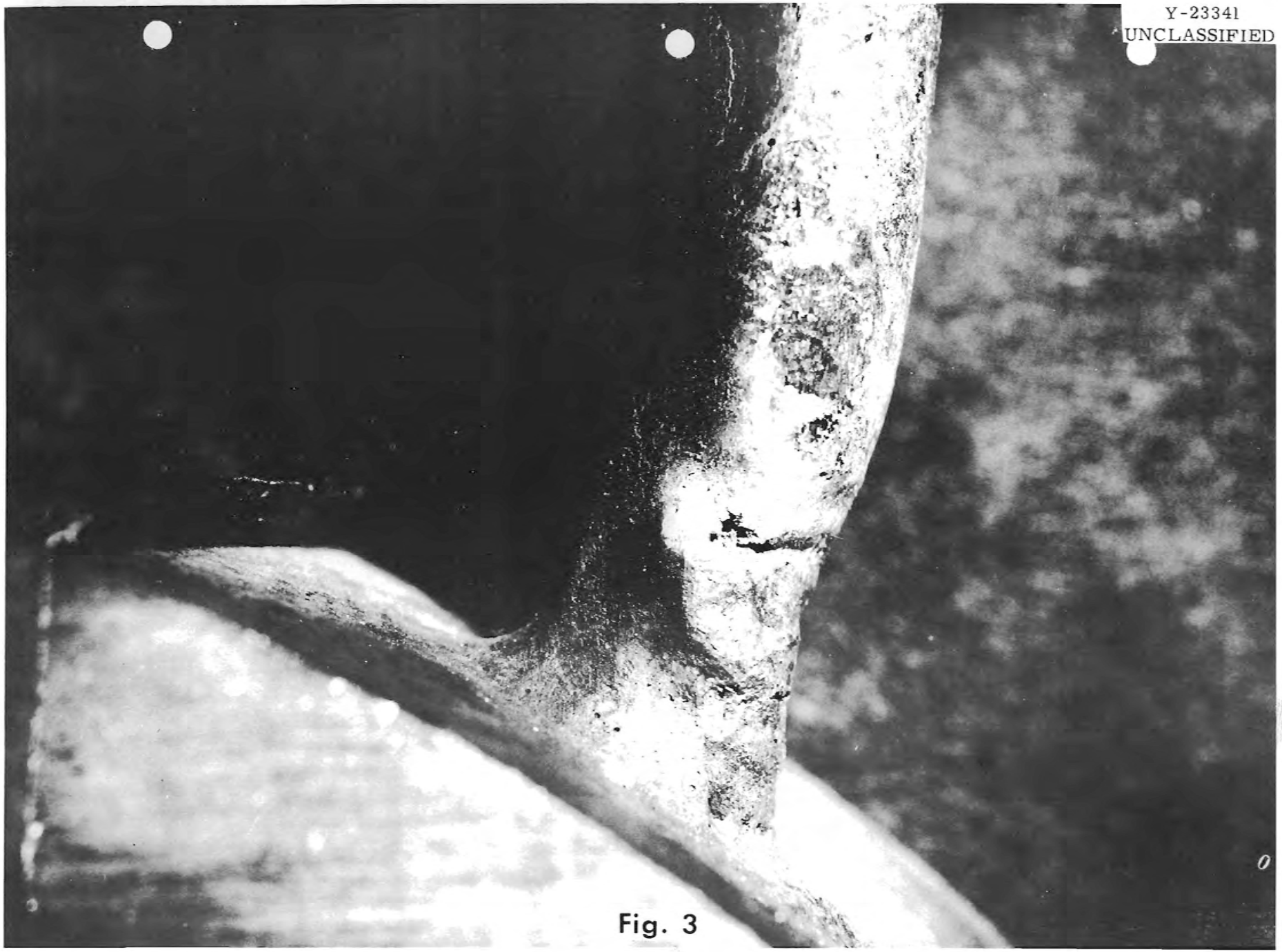
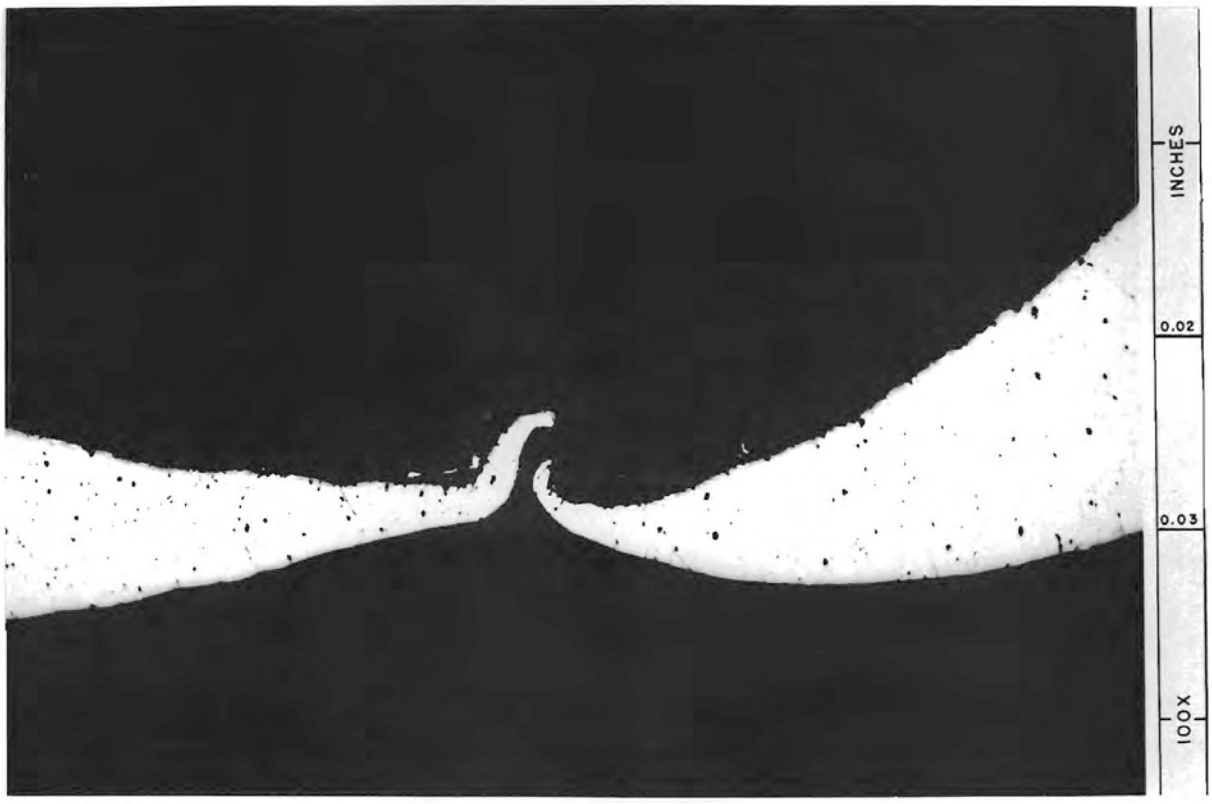
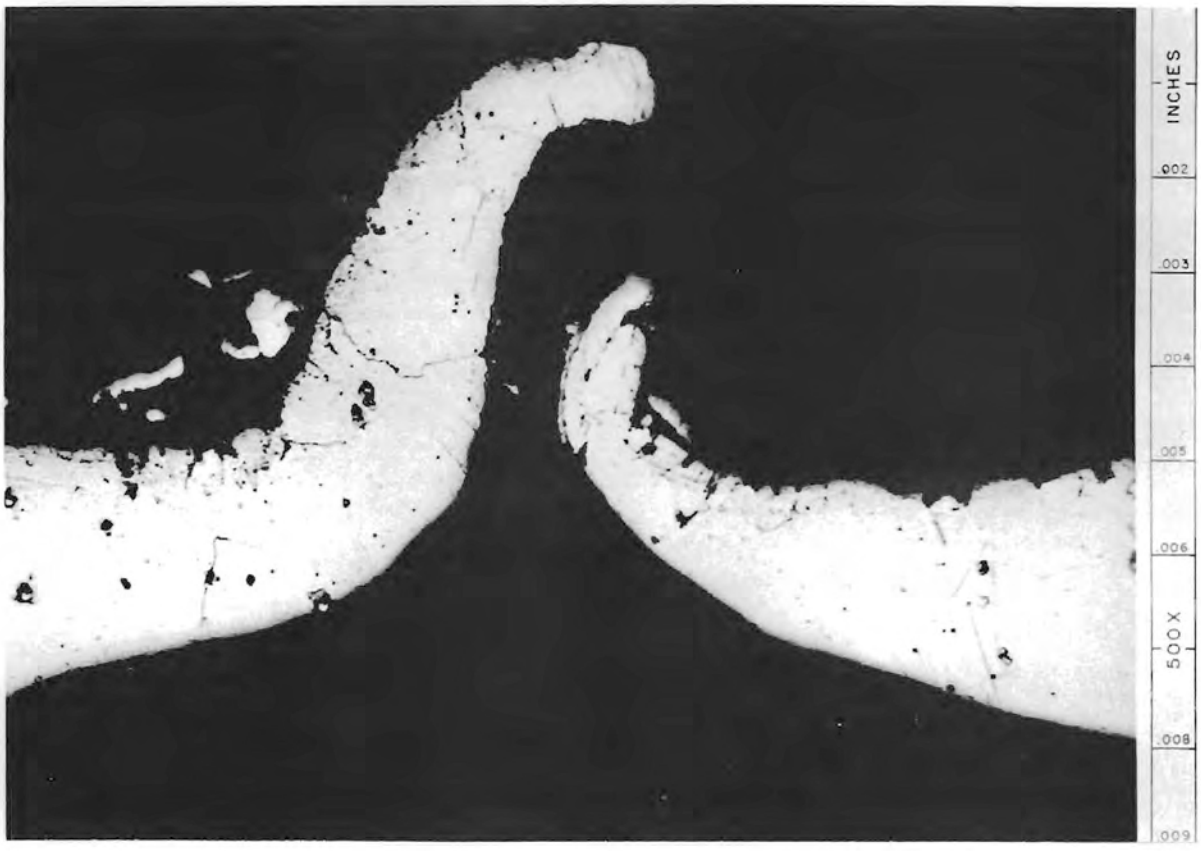


Fig. 3



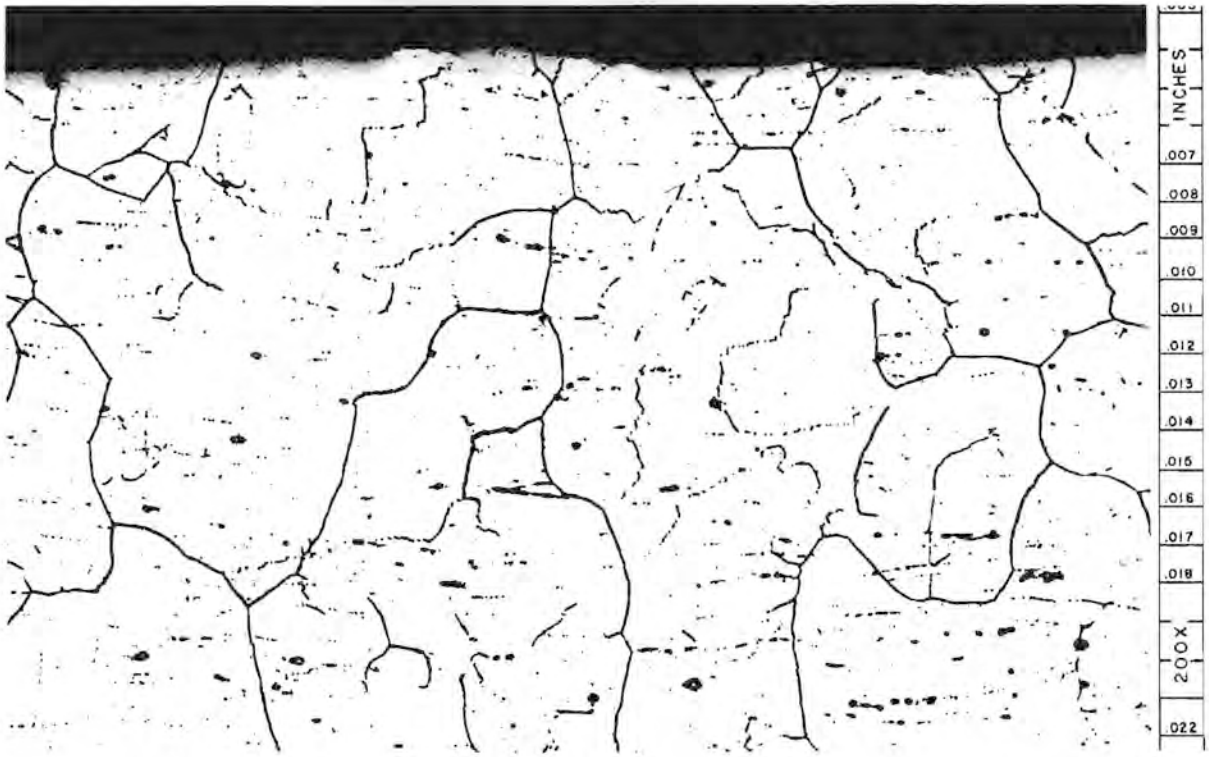
Y-23354 Fig. 6 100 X

Hole Number Two. Compare the size of this hole with that of number one, Fig. 4. Notice the same shape of the edge. Etched with 10% Oxalic Acid



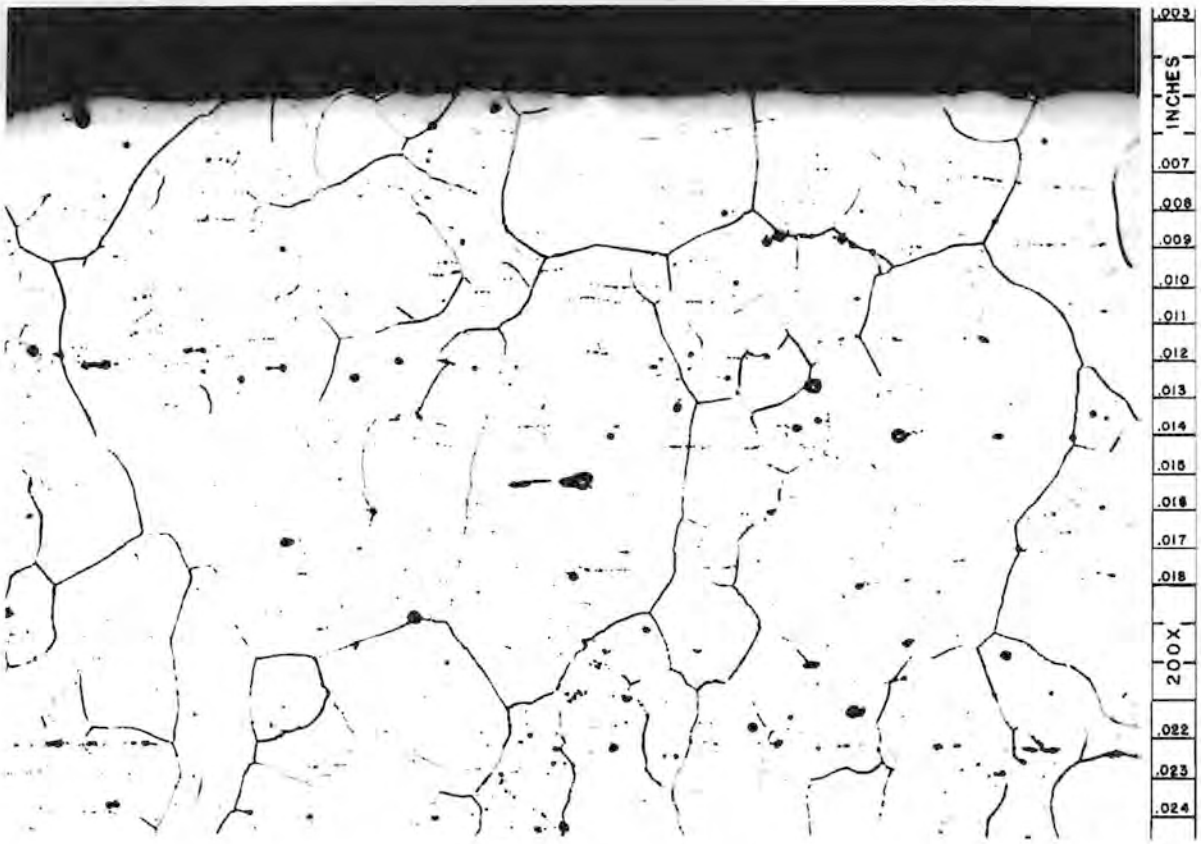
Y-23353 Fig. 7 500 X

Hole Number Two. Notice the absence of any grain boundary voids. Etched with 10% Oxalic Acid.



Y-23338 Fig. 8 200 X

Tube Number One. No evidence of incipient failure. Etched with 10% Oxalic Acid.



Y-23339 Fig. 9 200 X

Tube Number Two. No evidence of incipient failure. Etched with 10% Oxalic Acid.

Y-23340 Fig. 10 200 X

Tube Number Three. No evidence of incipient failure. Etched with 10% Oxalic Acid.

INTER-COMPANY CORRESPONDENCE
UNION CARBIDE NUCLEAR COMPANY
A Division of Union Carbide and Carbon Corporation

To: W. D. Manly

Copies To: J. C. Amos
J. H. DeVan
Met. File

Plant: X-10

Date: December 2, 1957

Subject: Metallographic Examination of the ART Test Radiator No. 2

Metallography Report No. 304.

The ART Test Radiator failed during the ΔT phase of the 182nd thermal cycle. The failure and resultant fire, due to a gross NaK-to-Air leak, was confined to the tubes between the NaK inlet header and the fin matrix.

The radiator history is briefly summarized in the following:

Total hours at 1200°F or above	862
Total hours ΔT operation	431
Total hours at design ΔT	310
Number of successful thermal cycles	181

The radiator was received, cleaned, and rough cuts made in 9201-3 under the direction of J. H. DeVan. The cut-up procedure was the same one as previously employed on the ART Test Radiator No. 1.[1] The samples received by the Metallography Section again consisted of a section containing twenty tubes arranged in a four by five matrix.

Figure 1 shows the radiator after cleaning prior to sectioning in 9201-3. The failed tubes were found in sections 1-8 and 1-7. In all, twelve tubes of the forty in these two sections were found having perferations after the fire.

Failure Analysis

The two sections containing the damage tubes are shown in Figures 2 and 3. The most severe damage was in section 1-7 where ten of the twenty tubes were found damaged.

All forty of the tubes in these two sections were cut out, mounted, ground, polished and examined for evidence of incipient failure. In thirty-nine of the forty tubes the microstructures of the tubes is represented by Figure 4. As can be seen there is no evidence of incipient failure.

Figure 5 and 6 show the microstructure of the one tube which showed any sign of incipient failure. This same type microstructure was previously found in York No. 7, 8, and 9 of which York No. 8 failed in operation.

Figure 7 is from the same tube from an area closer to the failure. There is some doubt as to the reliability of this microstructure being due solely to the mechanism of failure; however, one may compare these photomicrographs with those presented in the ART No. 1 examination and see that in the latter case no such voids were found even in areas bounding the failure.

The conclusion is that the radiator failed due to the absorption of plastic strain impressed upon the tubes.

J. E. VanCleve

R. J. Gray

[1] "Metallographic Examination of ART Test Radiator No. 1", J. E. VanCleve, Jr. Oct. 21, 1957 - Metallography Report No. 303.

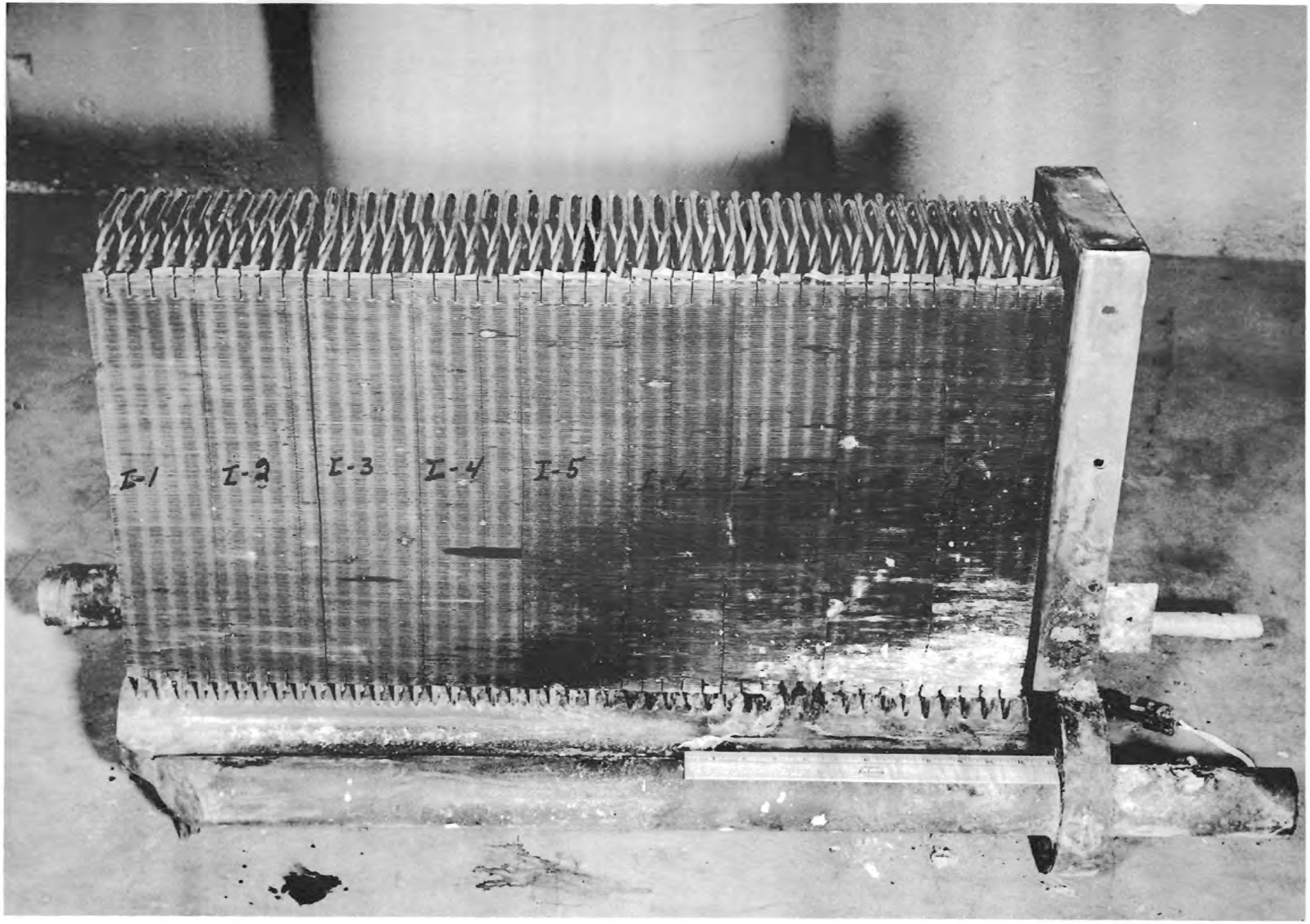


Fig. 1 (T-13561) ART No. 2 Radiator After Cleaning

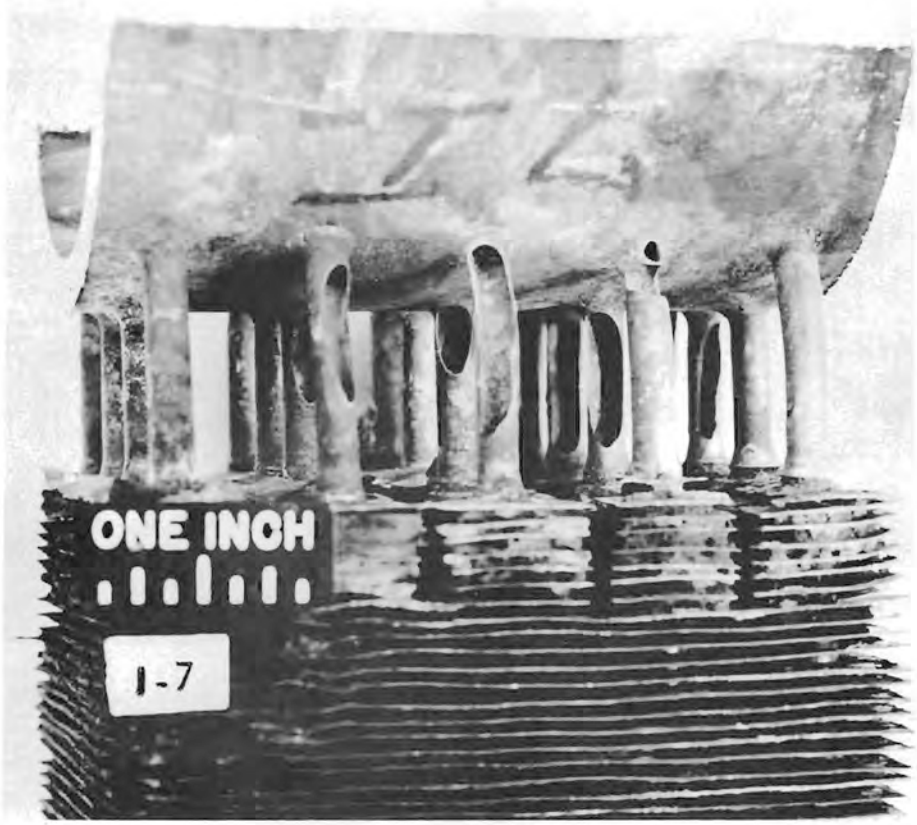


Fig. 2 Y-24193

Failure Section I-7. Contains ten damaged tubes

Fig. 3 Y-24194

Failure Section I-8. Contains two damaged tubes

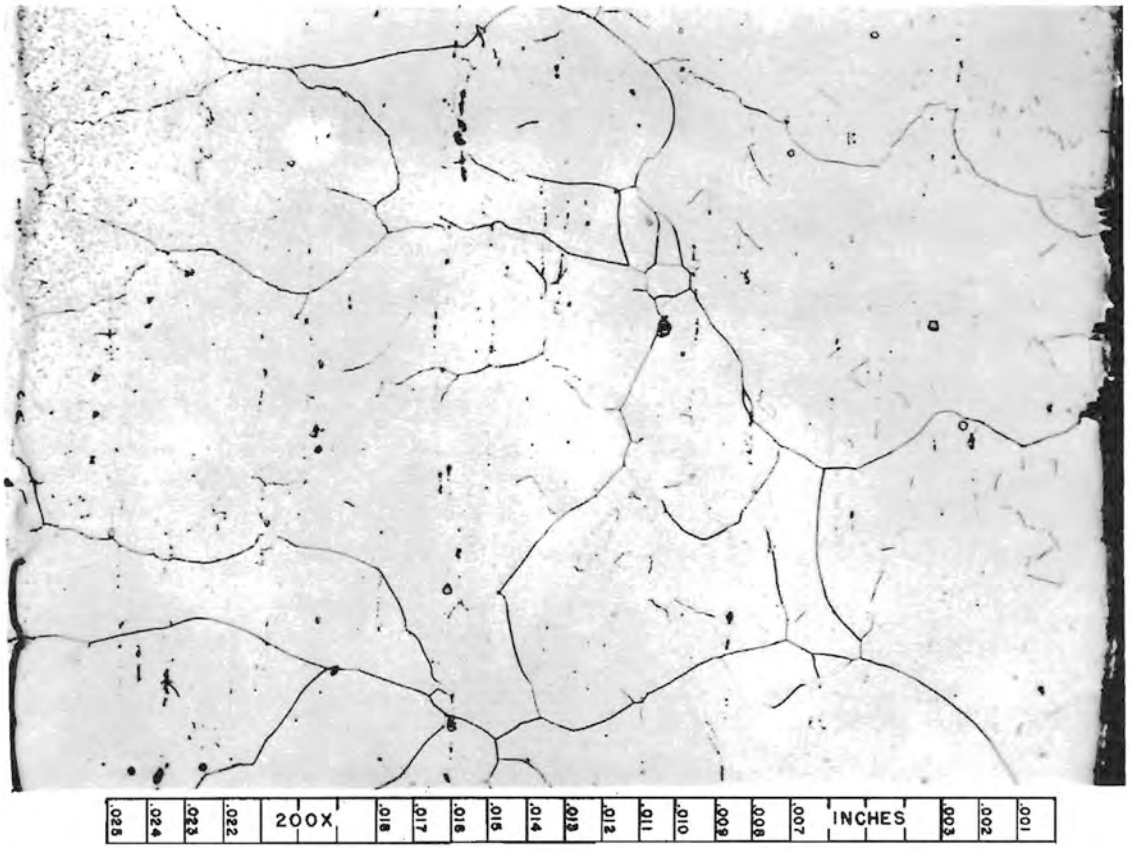


Fig. 4 Y-24374

Representative microstructure of thirty-nine of the forty tubes examined. No signs of incipient failure. Etch: 10% Oxalic Acid 200X

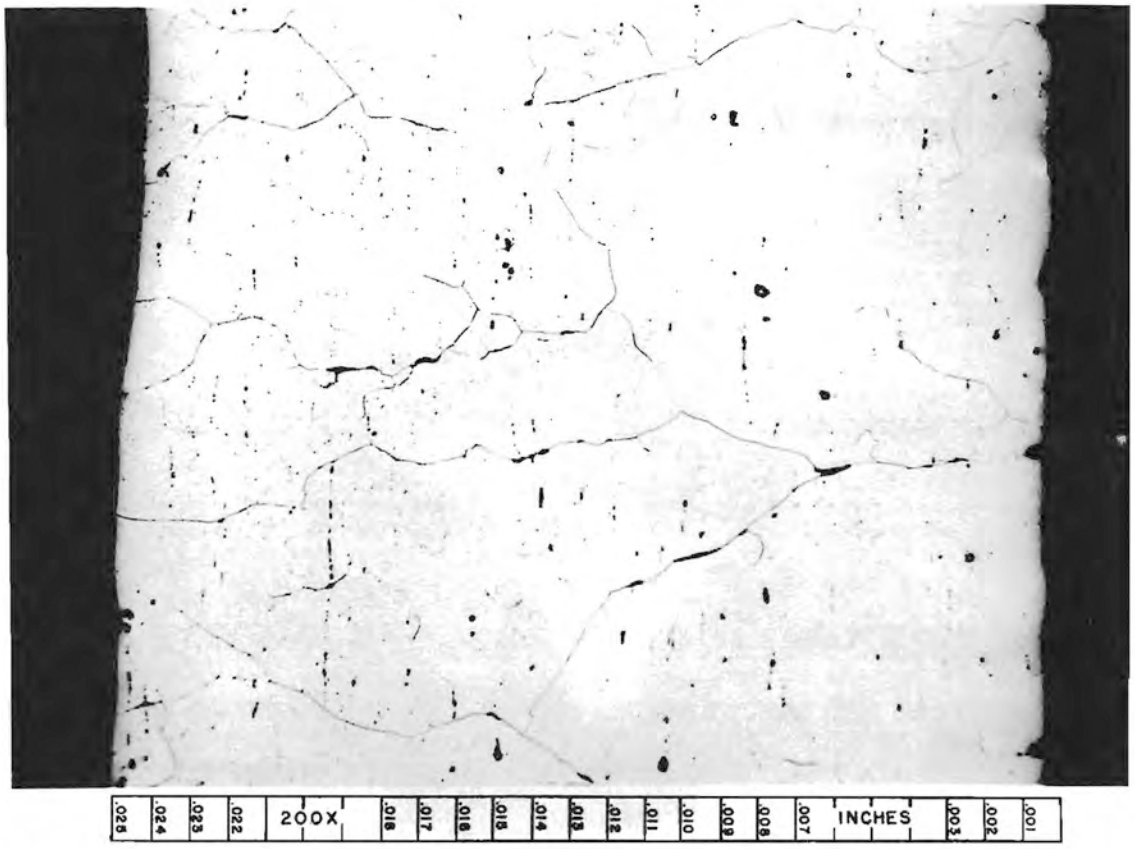


Fig. 5 Y-24276

Microstructures of the fortieth tube approximately 180° away from the hole. Notice the grain boundary voids. Etch: 10% Oxalic Acid 200 X

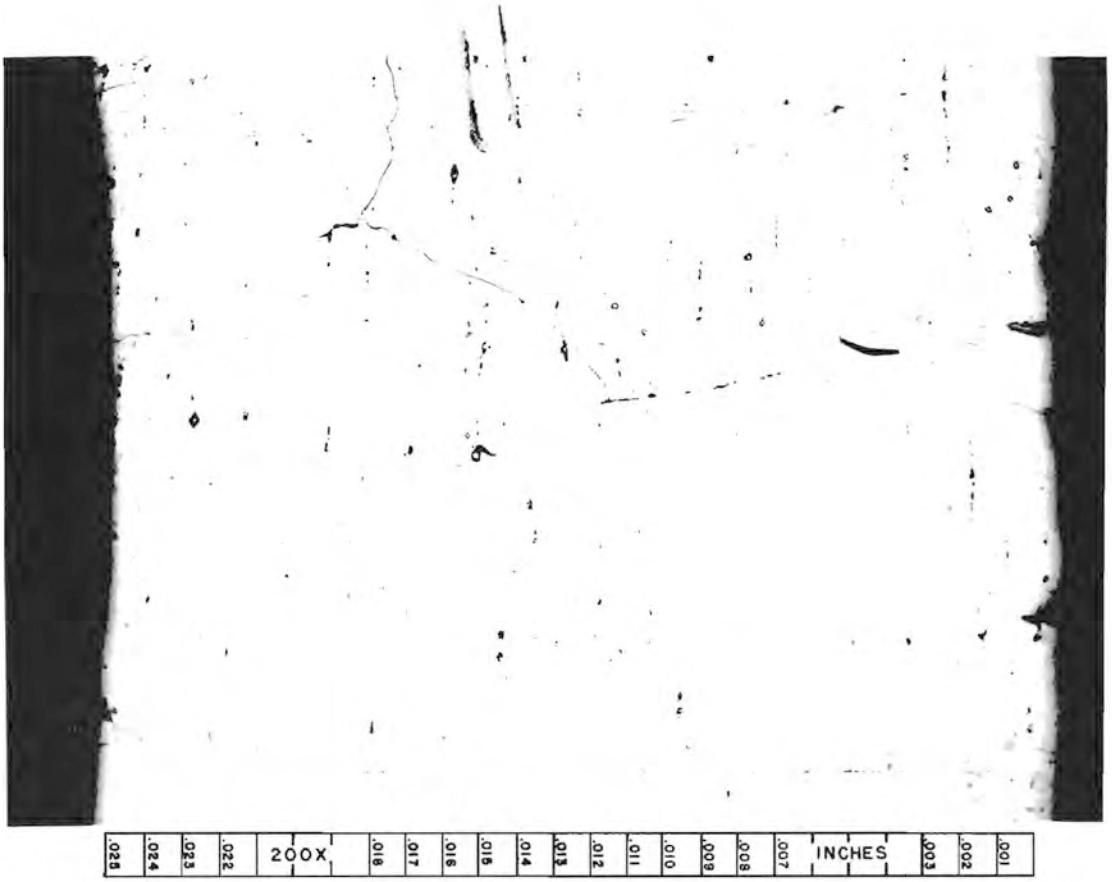


Fig. 6 Y-24275

Same tube as Fig. 5. More grain boundary voids. Etched with 10% Oxalic Acid (200X)

Fig. 7 Y-24274

Microstructure of the same tube very near the hole. Notice the progression from discontinuous voids to continuous grain boundary separation. Etched with 10% Oxalic Acid (200X)

Distribution

1. DTIE, AEC
2. Central Research Library
3. M. J. Skinner