CR 160874

Combustion Performance And Heat Transfer Characterization Of LOX/Hydrocarbon Type Propellants

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Contract NAS 9-15958
Task I Data Dump
August 1980

Prepared For:
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

By: R. S. Gross

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Company

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Aerojet Liquid Rocket Company
Sacramento, California

FOREWORD

This Data Dump Report on the Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants Program is being submitted as per the requirements of Contract NAS 9-15958. The work for this program is being performed by the Aerojet Liquid Rocket Company (ALRC) for the NASA - Lyndon B. Johnson Space Center. The contract period of performance is 24 September 1979 through 24 January 1981.

This report consists of a comprehensive summary and data dump of the Task I effort, Regenerative Cooling Characterization.

The NASA/JSC Project Manager is Mr. M. F. Lausten. The ALRC Program Manager is Mr. J. W. Salmon, and the Project Engineer is Mr. R. S. Gross.

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I. INTRODUCTION

Spacecraft orbit maneuvering and attitude control propulsion systems have almost exclusively utilized earth-storable hypergolic propellants. These typically pressure-fed systems are very simple and reliable. However, the propellants are toxic and corrosive. The hydrazine type fuels are also very expensive, and health hazards associated with their production have been identified. Preliminary studies indicate that LOX/HC (Hydrocarbon) type propellants are the best alternatives for all but the very high energy missions (transfer from low to geosynchronous earth orbits) since these require the high specific impulse LOX/Hydrogen propellant combination. It is recognized that increases in system complexity are unavoidable with the cryogenic LOX/Hydrocarbon and LOX/Hydrogen propellant combinations.

Studies have shown that two of the major keys to achieving low space transportation costs are minimizing engine development and operational costs. Consequently, major reductions in future space transportation costs will have to be achieved with highly reusable systems requiring a minimum of maintenance and utilizing low-cost propellants.

The present data base for the LOX/HC propellants is inadequate as a basis for selection of the most suitable technology and fuel(s) for spacecraft auxiliary propulsion systems. The objective of this program is to establish a sound data base by analytically and experimentally generating basic regenerative cooling, combustion performance, combustion stability, and combustion chamber heat transfer parameters for promising LOX/HC propellants, with specific application to "second generation" orbit maneuvering and reaction control systems (OMS/RCS) for the Space Shuttle Orbiter.

Introduction (cont.)

The technical effort for this program is being conducted in two major tasks:

Task I, Regenerative Cooling Characterization, consists of a cooling comparison study of candidate fuels, together with an experimental heated tube study of their heat transfer characteristics.

Task II, Subscale Injector Characterization, consists of the design, fabrication, and testing of subscale hardware in which the combustion characteristics of LOX/HC propellant combinations will be evaluated.

The Program Schedule is shown in the milepost chart of Figure I-1.

The objective of this report is to provide a comprehensive summary of the data generated during the Task I effort. This report is divided into the following principal sections: Section I, Introduction; Section II, Task I.1 - Cooling Correlation and Comparison; Section III, Task I.2 - Heated Tube Testing and Data Correlation; and Section IV, Task I - Conclusions and Recommendations.

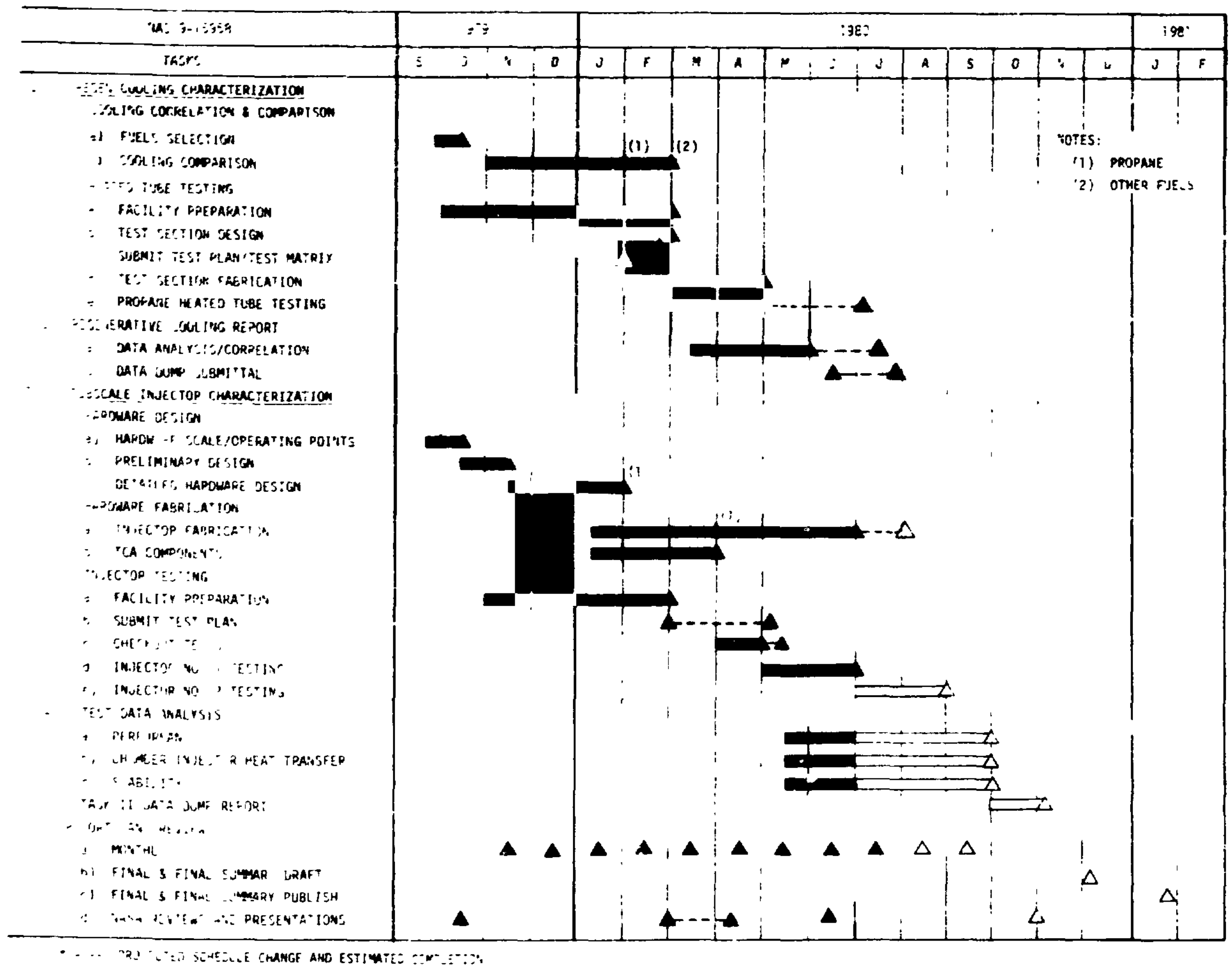

Figure I-1. Program Milepost Chart

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II. TASK I.1 - COOLING CORRELATION AND COMPARISON

A. OBJECTIVES AND SUMMARY

The objectives of the Task I.1 cooling correlation and comparison effort were as follows: (1) conduct a literature review of the cooling characteristics of propane, methane, RP-1, and ammonia; (2) conduct an analytical parametric study of these fuels as thrust chamber coolants for a thrust range of 1,000 to 10,000 lbF at 100 to 1000 psia chamber pressures; (3) submit recommendations for coolant capabilities; and (4) specify operating conditions for which resistance-heated tube testing is required to provide needed information or verification of existing correlations.

As illustrated in Figure II-1, the cooling regimes studied fall into the following broad categories: (1) supercritical pressure forced convection; (2) subcritical pressure, superheated vapor forced convection; and (3) subcritical subcooled forced convection and nucleate boiling. Extensive analyses in each of the categories were performed for propane. The evaluation of methane was limited to single-phase heat transfer at supercritical pressures and as a superheated vapor at subcritical pressures. Boiling heat transfer was not considered due to the little subcooling available. RP-1 was evaluated at supercritical pressures and as a subcritical liquid in forced convection with possible nucleate boiling. The high critical pressure of ammonia limited consideration to the superheated vapor state and to forced convection nucleate boiling regimes. All analyses were performed using the ALRC SCALER and BOSCALE programs.

The cooling capability of the four fuels was compared in a single up-pass zirconium copper thrust chamber with nickel closeout. Additional analyses for ammonia were conducted in a 304L stainless steel chamber since a copper/ammonia reaction would prohibit the use of a copper thrust chamber in practice. The analyses conducted in the 304L SS chamber

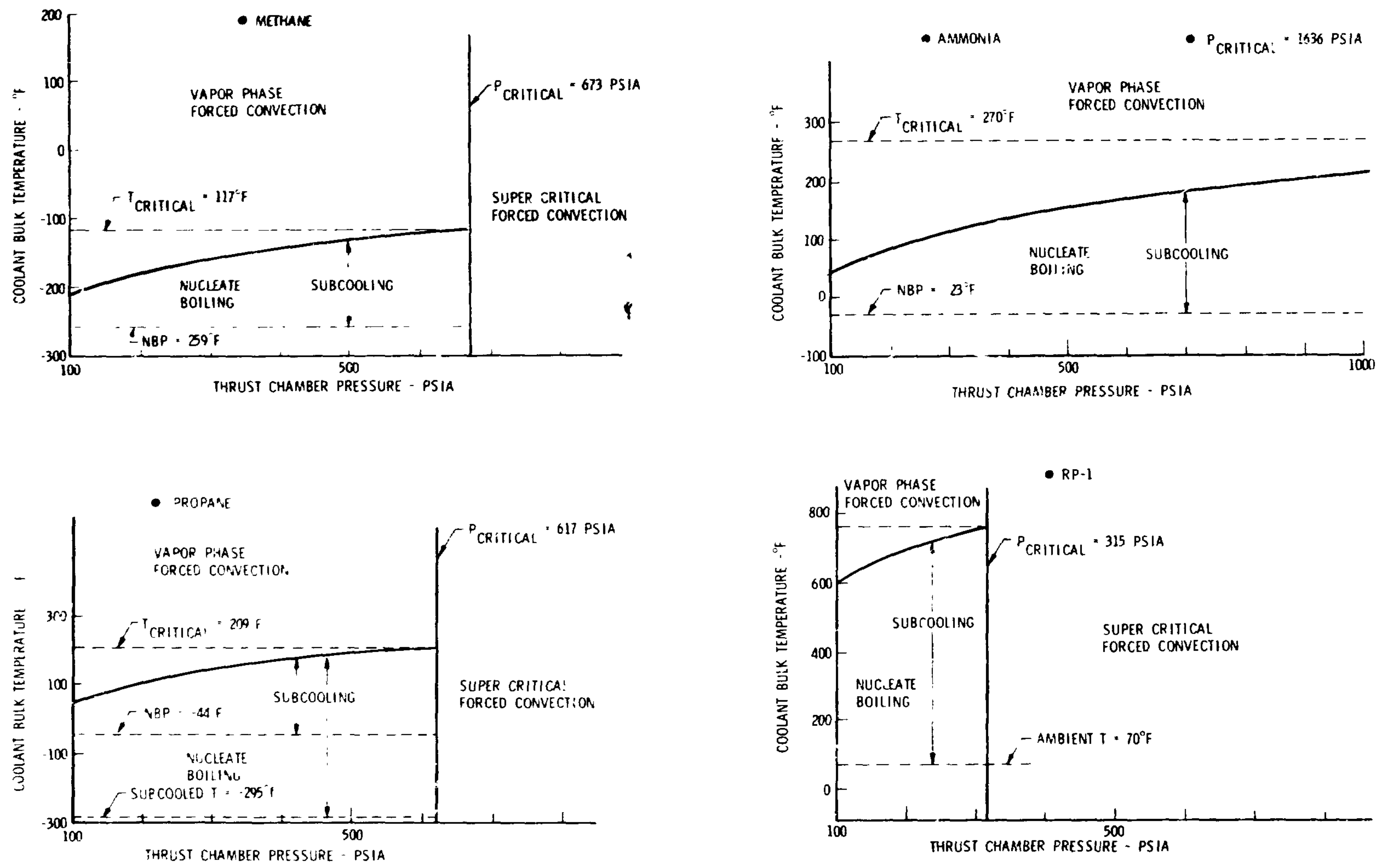


Figure II-1. Coolant Modes

were inconclusive because a solution convergence problem was encountered in each test case. Inspection of the data indicated an adverse cooling fin flux transformation resulting in substantially higher fluxes on the coolant-side than on the gas-side. After several channel design iterations had failed to improve the flux transformation, ammonia cooling in the 304 SS chamber was no longer pursued.

The cooling capability of the four fuels in the Zr-Cu chamber over the study ranges of thrust and chamber pressure was also found to be sensitive to channel design. Several different channel layouts were used to best accommodate the different operating and cooling regimes.

Results obtained using a Zr-Cu chamber show both propane and methane at supercritical pressures to have adequate cooling capability for an OMS application (6K to 10K lbF), with methane demonstrating the greater cooling margin. Propane and methane as a superheated vapor were satisfactory coolants at subcritical pressures for both the OMS and RCS application. Nucleate boiling heat transfer with propane was not satisfactory due to the low burnout heat fluxes calculated with currently available correlations. These correlations were suspect, however, as the design conditions are for outside the range of data for which the correlation was developed. RP-1 proved to be an unsatisfactory coolant. All cases were limited by the low coking temperature allowed (550°F). Ammonia analysis in the Zr-Cu chamber resulted in acceptable nucleate boiling and subcritical vapor cooling for the OMS/RCS application.

Based on the analyses conducted, Figure II-2 depicts an estimate of the most probable thrust and Pc ranges that could be accommodated by the cooling characteristics of the four fuels studied.

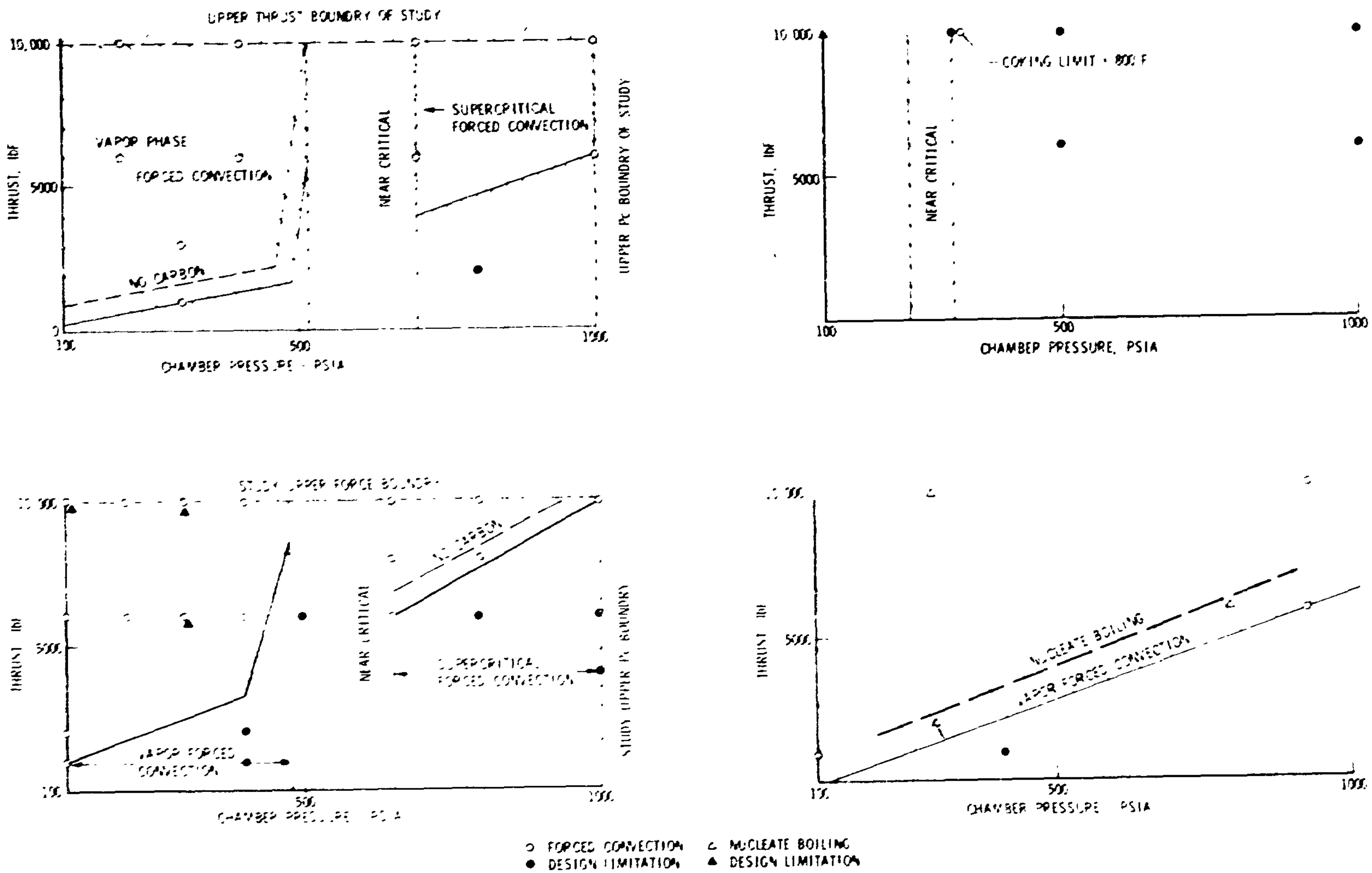


Figure II-2. Cooling Map

Heat availability from the low heat flux region of the OMS and RCS nozzle geometries was evaluated to determine whether subcritical coolant vaporization could be obtained. Propane and methane show promise, particularly with some bypass flow. The results of these evaluations are plotted in Figure II-3.

The analysis of propane as a coolant has shown the need for further experimentation to accomplish the following:

(1) Verify the applicability of the ALRC LOX correlation as an adequate characterization of the heat transfer characteristics of supercritical propane, or, if not applicable, develop a correlation specific to propane.

(2) Extend the burnout equation to cover the range of $V \Delta T_{sub}$ values typical of propane in channel flow.

(3) Obtain data on incipient nucleate boiling as a function of pressure, velocity, and bulk and wall temperatures, and evaluate the nucleate and film boiling heat transfer characteristics of propane.

(4) Determine the wall temperature threshold at which propane decomposition has practical significance.

B. TECHNICAL BASIS FOR THE COOLING COMPARISON ANALYSIS

1. Regenerative Cooling Comparison Model

Regenerative cooling comparisons of Task I.1 for single-phase fluids were generated with the SCALER Program, a program developed

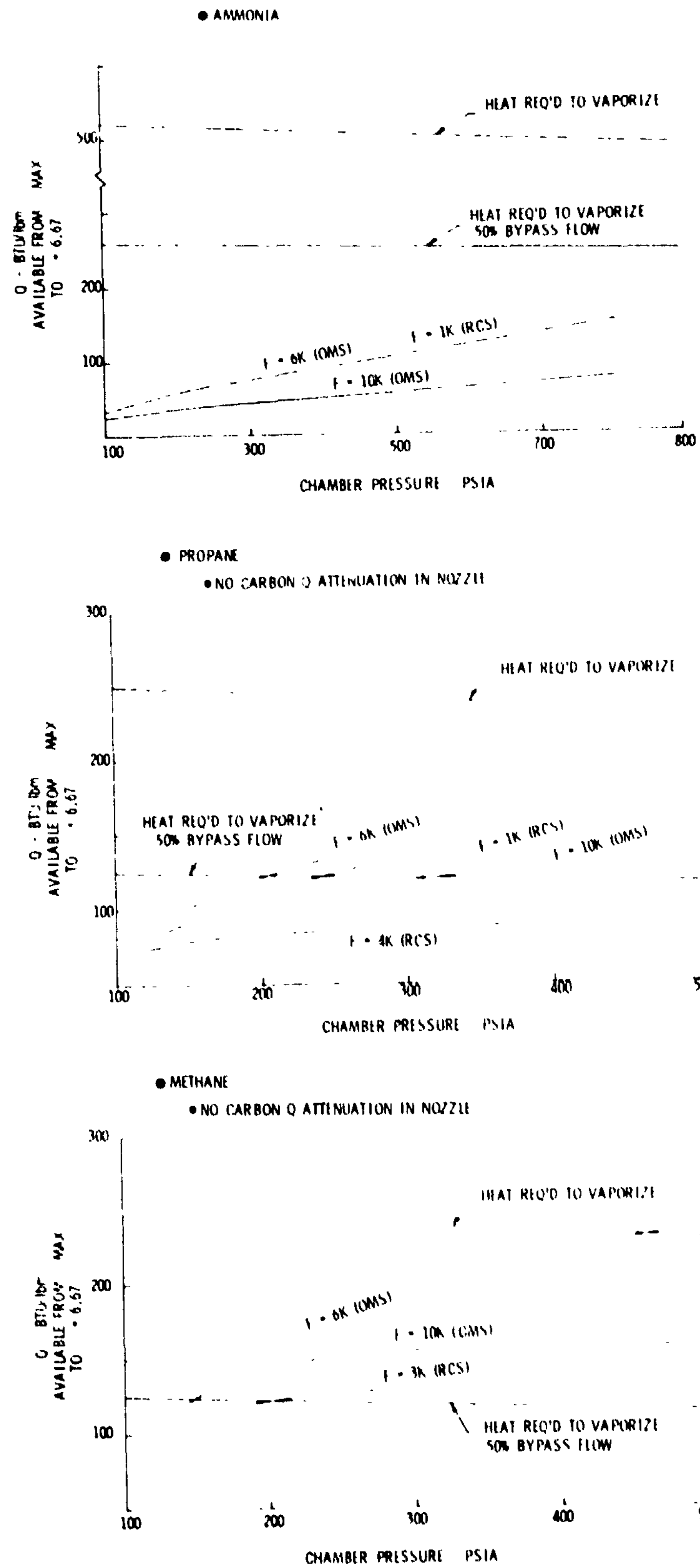


Figure II-3. Heat Availability Evaluations specifically for parametric design studies. With this program, it is economically feasible to generate a relatively large number of parametric design points for selected fuels and still obtain a detailed, multi-station analysis of a rectangular channel at each design point. This technique provides an analytic modeling base for comparing fuels at realistic, regeneratively cooled engine conditions.

The SCALER program scales the chamber geometry and the local gas-side heat transfer coefficients and coolant heat loads from reference input to other thrust and chamber pressures. The coolant channel geometry parameters are prescribed together with channel material(s) and their temperature-dependent properties and the coolant-side heat transfer correlation(s). Two-dimensional heat conduction around the coolant channel is included, providing a fin effectivity which results in a transformation of the gas-side heat flux to a lower-valued coolant-side flux. At each station, the program iterates to determine the channel depth required for satisfying (1) a gas-side wall temperature limit, which can be specified as a function of closeout wall temperature consistent with cycle life and creep criteria, and (2) an optional coolant-side wall temperature limit, which can be specified as the decomposition (or "coking") temperature for the coolant. The only simplifying assumption is that gas-side wall temperature differences between the reference input and the scaled cases have a negligible effect on gas-side heat transfer coefficients and heat loads. Normally, gas-side wall temperature limits are well-known in advance, so that local reference gas-side heat transfer analyses can be run at appropriate wall temperatures with the conventional HEAT program.

The SCALER program was developed for forced convection cooling. A modified version, BOSCALE, was prepared during this study to include subcooled nucleate boiling characteristics and the burnout heat flux as parameters. This version defines the required local coolant velocity based on a specified burnout safety factor. This factor is defined as the ratio of the maximum nucleate boiling heat flux predicted by an experimentally derived burnout correlation to the maximum value of the coolant-side heat flux. Iteration on channel depth thus satisfies both the gas-side wall temperature limit, as in SCALER, and the coolant-side heat flux limit.

2. Gas-Side Boundary Layer

Throat Reynolds numbers in the present study cover a range which yields three distinct boundary layer flow regimes as a result of flow acceleration in the convergent section. At high Reynolds numbers, the flow remains turbulent, and heat transfer coefficients are calculated from a standard pipe-flow correlation, as shown in Figure II-4. The dip in the turbulent correlation coefficient, shown in the figure, accounts for the effects of flow acceleration. At low Reynolds numbers, acceleration effects are strong enough to cause the boundary layer to undergo a reverse transition to laminar flow. At moderate Reynolds numbers, the reverse transition process is started but not completed, and the throat boundary layer is in a transition state. These regimes are shown in Figure II-5, in which the solid curve gives the throat Stanton number as a function of the diameter Reynolds number. The reverse transition regime spans the Reynolds number range of 6-13 x 10^5. This range, a well as the coefficient of the laminarized characteristic and the shape of the transition curve, is based on Refs. 2 and 18.

Figure II-5, also illustrates the calculation procedure used upstream of the throat when reverse transition or complete laminarization occurs at the throat. Consider first the laminarized case with the throat at point #1. A laminar boundary layer analysis, Ref. 19 is used to

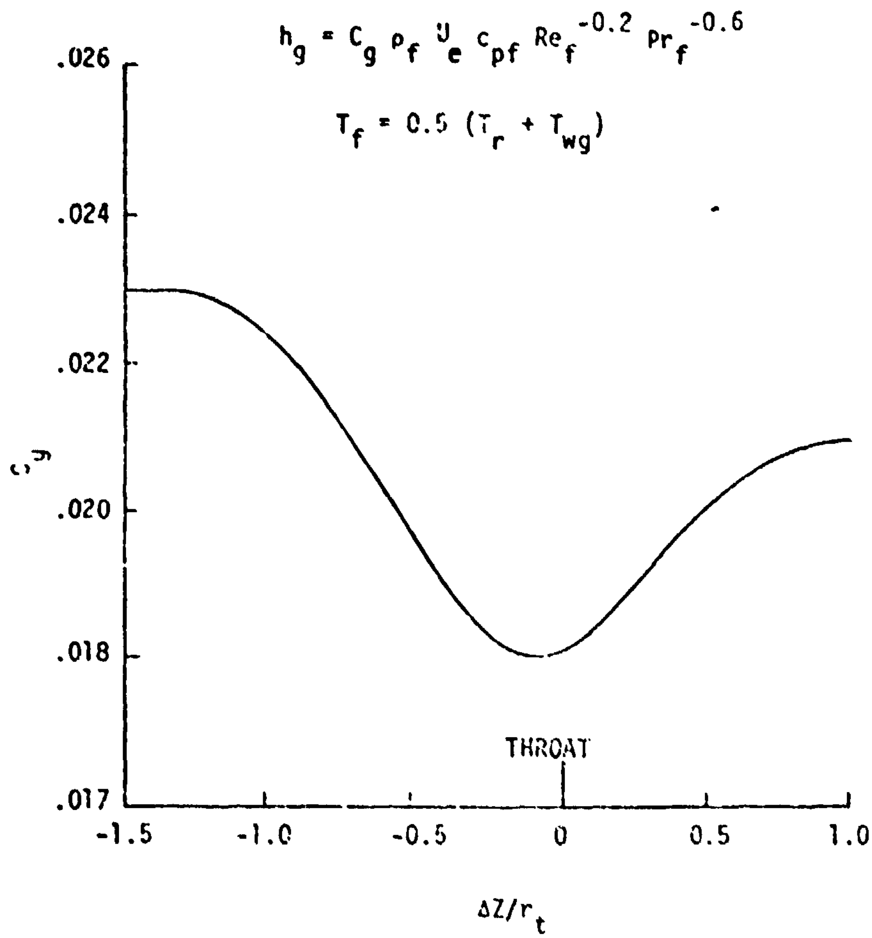


Figure II-4. Gas-Side Heat Transfer - Turbulent Regime

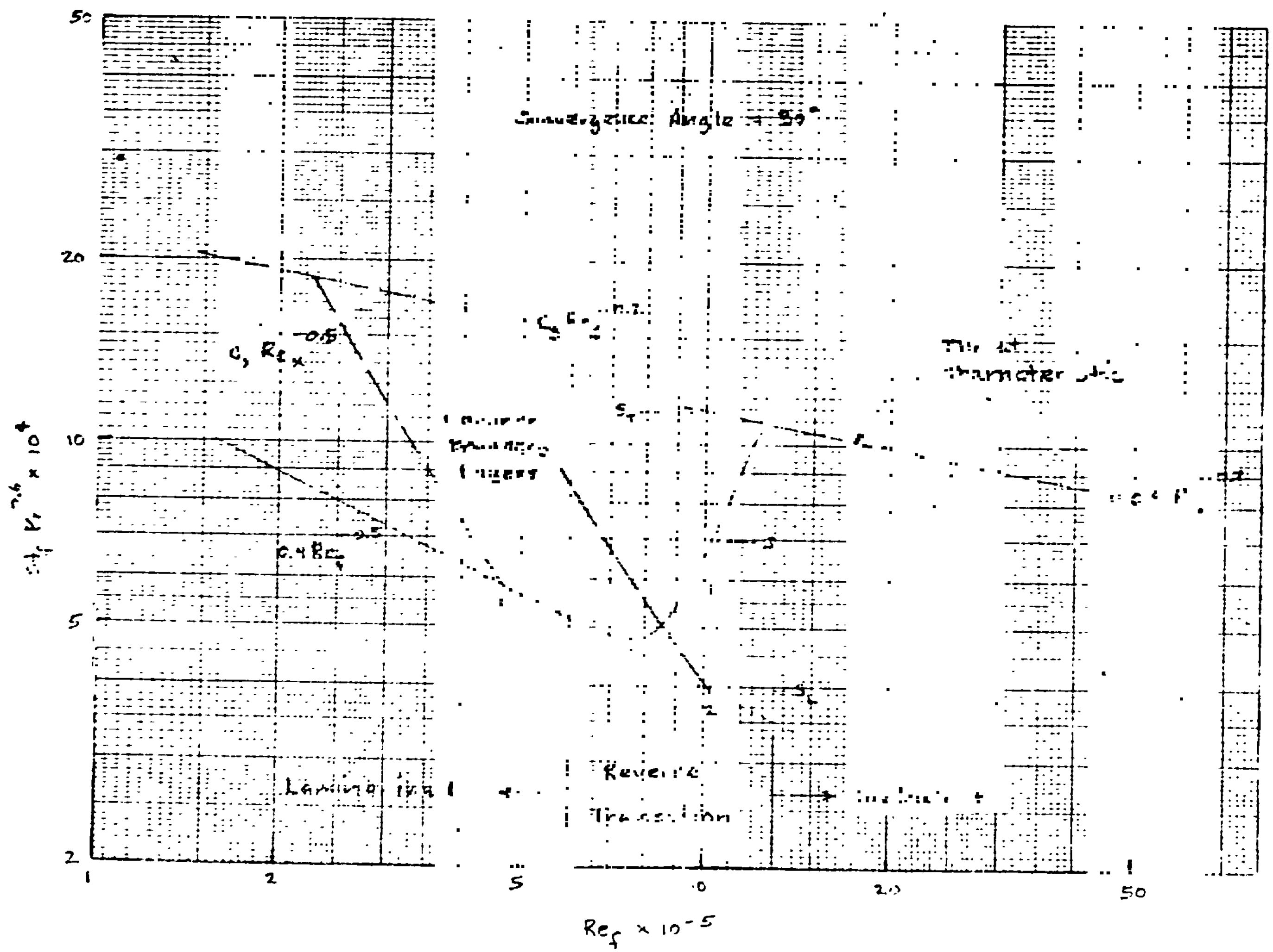


Figure II-5. Gas-Side Heat Transfer Characteristics predict the Stanton number upstream of the throat. This analysis is based on a length Reynolds number, with the effective starting point of the laminar boundary layer calculated such that the predicted throat Stanton number equals the empirical value from the solid curve of Figure II-5, i.e.:

$$C_{x_t} \ Re_{x_t}^{-0.5} = 0.4 \ Re_{f_t}^{-0.5}$$

This boundary layer analysis applies downstream of the point in the convergent section where the local turbulent and laminar Stanton numbers are equal, i.e.:

$$C_g \ Re_f^{-0.2} = C_x \ Re_x^{-0.5}$$

with C_g being the local turbulent correlation coefficient from Figure II-4.

When the throat Reynolds number is in the reverse transition region, as illustrated by the vertical dashed lines in Figure II-5 at $Re_f \approx 10 \times 10^5$, a fictitious laminar boundary layer analysis, based on an extension of the laminarized throat characteristic, is used. In this case, the boundary layer analysis is forced to match the fictitious Stanton number at point #2 in this figure. Local heat transfer coefficients are then calculated by weighting the laminar and turbulent coefficients as follows:

$$h_g = h_{g_L}\left(\frac{S_T - S}{S_T - S_L}\right) + h_{g_L}\left(\frac{S - S_L}{S_T - S_L}\right)$$

in which S is the actual throat Stanton number, while S_T and S_L are the throat values obtained by extension of the turbulent and laminar characteristics, respectively. These three Stanton numbers are identified in Figure II-5.

The reverse transition region limits, defined in Figure II-5, divide the thrust-chamber pressure box of interest therein into three regions, as is shown in Figure II-6. It is apparent that only a relatively small region at low thrust and low chamber pressure results in laminar flow in the throat boundary layer. Approximately three-quarters of the parametric range of interest is in the conventional, fully turbulent regime. Hydrocarbon fuels exhibit a small, low-thrust, low-Pc region characterized by a laminarized boundary flow regime.

3. Radiation-Cooled Nozzle Extension Attachment Area Ratio Criteria

The minimum area ratio at which a radiation-cooled nozzle extension can be attached for oxidation protection of a columbium alloy (FS-85 or C103) by a silicide coating (SYLCOR R512) was calculated on the basis of the lower temperature-duration curve of Figure II-7. Predicted wall temperatures were based on the simple energy balance:

$$hg\ (T_{aw} - T_{wg}) = \sigma\varepsilon\ (1 + f_i)\ (T_{wg})^4$$

in which:

ε = coating emissivity; typical value is 0.85

f_i = internal view factor to end planes from an axisymmetric view factor program

A 15-hour firing duration, compatible with the OMS application, results in a conservative wall temperature estimate of 2755°F for attachment of the radiation-cooled nozzle extension.

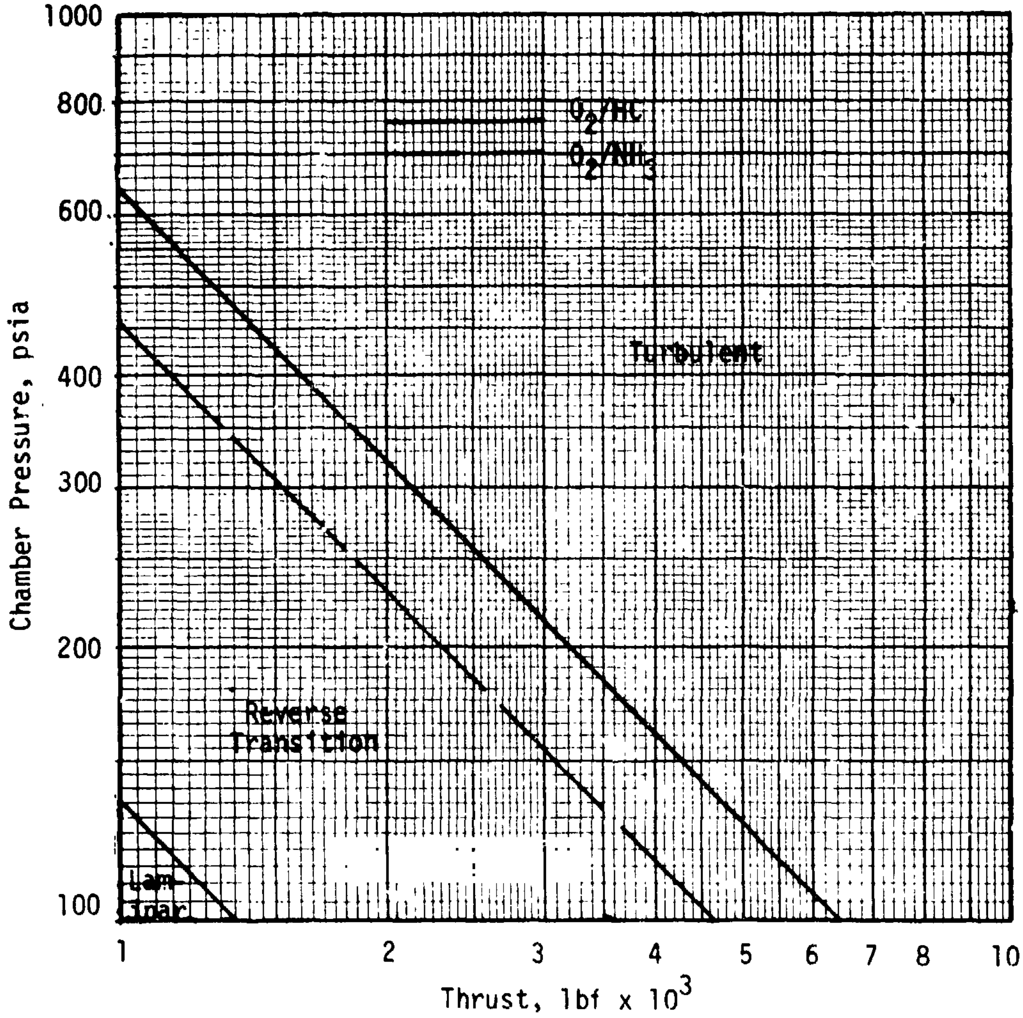


Figure II-6. Gas-Side Boundary Layer Flow Regimes

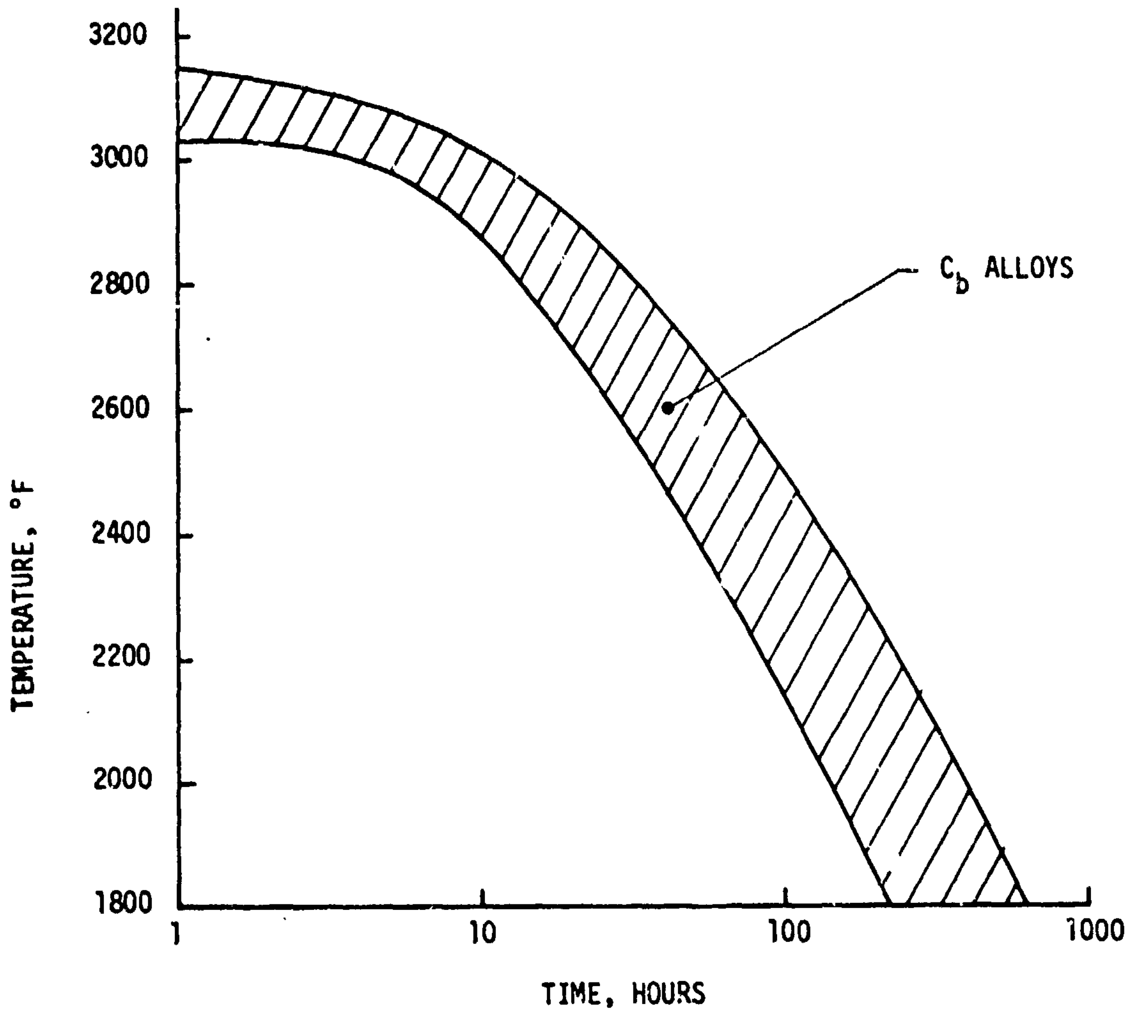


Figure II-7. R512 Silicide Coating Oxidation Protection

4. Thrust Chamber Geometry Definition

a. Chamber Length and Contraction Ratio

The respective mixture ratios and specific impulses of the four propellant combinations considered in this study were as follows:

	MR	I_{sp}
O_2/C_3H_8	3.0	365
O_2/CH_4	3.6	375
O_2/RP-1	2.85	356
O_2/NH_3	1.45	340

Fuel vaporization limits performance of the oxygen/RP-1 combination, resulting in a combustion chamber characterized by a large L' value. Since the study was limited to considering single-pass flow towards the injector, the O_2/RP-1 chamber length was estimated conservatively at a maximum value of 18.6 in., and station calculations for all fuels were carried to this L' limit, with the result that the actual L' could be selected at any point in the chamber as desired. In this parametric study, values of L' ranging from about 10 to 11 in. were selected as representative of the mean for a simplified evaluation of temperature rise and pressure drop. In a preliminary design, thrust and chamber pressure, as well as value judgments based on experience with the vaporization and combustion characteristics of each propellant combination, would be used to optimize L'.

Based upon the ALRC Integrated Thruster Assembly (ITA) engine design, a chamber contraction ratio of 3.3:1 was selected.

b. Chamber Contour Selection

The chamber contour used in this study is shown in Figure II-8. The convergent section contour was selected in order to promote boundary layer laminarization within the limits of standard design practice. Since this requires the use of a large convergence angle with a conical section of sufficient length, a 30° convergence angle along with a radius of curvature at the start of convergence just large enough to prevent flow separation and local heat transfer coefficient perturbations, was selected.

c. Nozzle Contour Selection

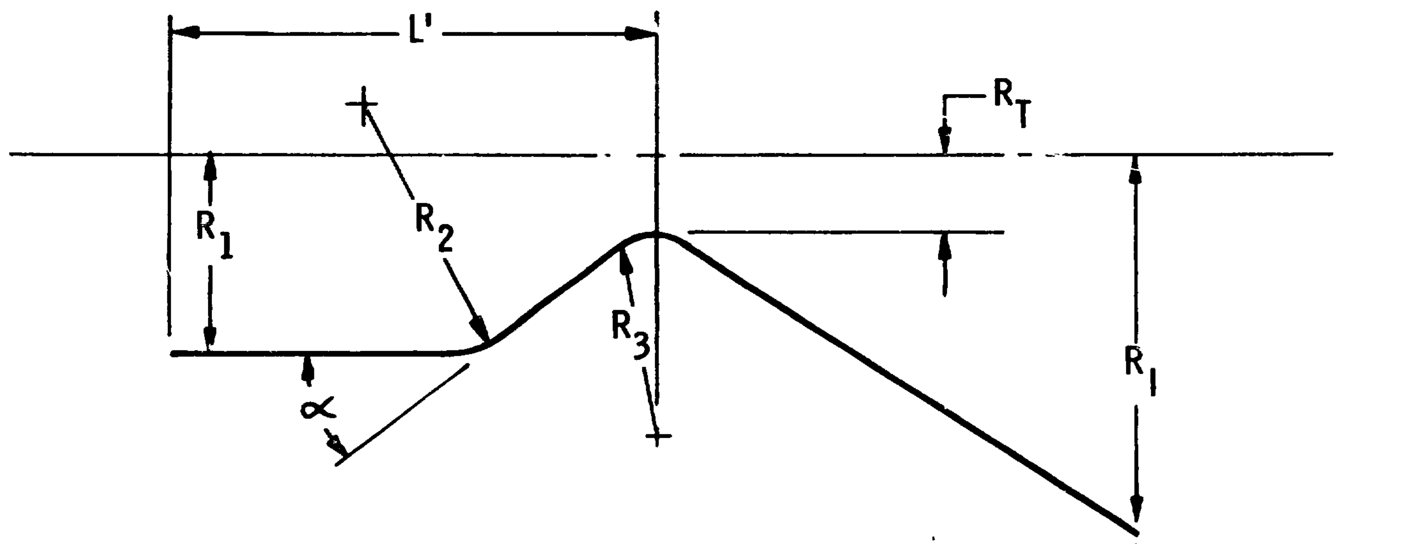
The non-dimensional contour data for a 400:1 area ratio, 90% bell nozzle is shown on Table II-I. The symbol R on this table represents the ratio of the nozzle radius to the throat radius, whereas Z stands for the ratio of the nozzle axial length (measured from the throat) to the throat radius. Packaging considerations limit the maximum diameter of the nozzle. For an OMS application, the largest expansion ratio for a nozzle exit diameter of 40 in. is shown as a function of the thrust/chamber pressure ratio as the upper curve of Figure II-9; the lower curve is for an RCS application, in which the nozzle exit diameter is limited to 20 in.

5. <u>Coolant Circuit and Material Selections</u>

a. Regeneratively Cooled Chambers

For hydrocarbon coolants, the designs analyzed considered rectangular slots in a zirconium-copper (aged at 1100°F) liner with an electroformed nickel closure. Since an ammonia-copper reaction is a possibility at high wall temperatures, 304L stainless steel was selected as

- **TCA GEOMETRY**



$R_1 = 1.82\ R_T$ (CR = 3.3)

$R_2 = 2.5\ R_T$

$R_3 = R_T$

R_I (COOLANT INLET) = 20 IN. (OMS), 10 IN. (RCS), RADIATION ATTACHMENT POINT

$\alpha = 30°$

NOZZLE CONTOUR = RAO 90% BELL

$L' \cong 19$ INCH

Figure II-8. Thrust Chamber Contour

Table II-I

Nozzle Contour (ϵ = 400:1)

EXPANSION COEFFICIENT = 1.20000
THROAT RADIUS = 1.25400
UPSTREAM WALL RADIUS OF CURVATURE = 1.00096
DOWNSTREAM WALL RADIUS OF CURVATURE = .34300
NOZZLE LENGTH = 79.39482
NOZZLE EXPANSION RATIO = 399.96822

				WALL CONDITIONS					
	R	Z	MACH	THETA	PRESSURE	RHO	TEMP	EPSILON	RHO*V
THROAT PT	1.000000	.000000	1.2033	.000	.88424+00	.50857+00	5619.32	1.0000	3.3451
TANGENT PT	1.074962	.214021	2.3306	38.606	.74046-01	.11427+00	4168.67	1.1555	3.1278
	1.078679	.218673	2.3331	38.642	.73713-01	.11384+00	4165.54	1.1635	3.1183
	1.121336	.271704	2.3629	38.978	.69834-01	.10882+00	4128.18	1.2574	3.0054
	1.164447	.32466	2.3923	39.285	.66184-01	.10406+00	4091.40	1.3559	2.8467
	1.208008	.377626	2.4218	39.556	.62716-01	.99499-01	4054.87	1.4593	2.7912
	1.252215	.430960	2.4494	39.703	.59619-01	.95380-01	4020.78	1.5680	2.6449
	1.297143	.484794	2.4766	39.942	.56707-01	.91486-01	3987.37	1.6826	2.6027
	1.342904	.539240	2.5040	40.097	.53914-01	.87717-01	3953.94	1.8034	2.5124
	1.389586	.594549	2.5306	40.211	.51323-01	.84190-01	3921.62	1.9309	2.4270
	1.437308	.650945	2.5568	40.298	.48891-01	.80852-01	3890.02	2.0659	2.3454
	1.486277	.708571	2.5834	40.367	.46538-01	.77596-01	3858.17	2.2090	2.2650
	1.536596	.767607	2.6097	40.406	.44314-01	.74494-01	3826.82	2.3611	2.1877
	1.588333	.828494	2.6358	40.422	.42210-01	.71534-01	3795.91	2.5228	2.1132
	1.641850	.891244	2.6624	40.422	.40159-01	.68625-01	3764.52	2.6957	2.0392
	1.697162	.950209	2.6889	40.394	.38217-01	.65849-01	3733.56	2.8804	1.9681
	1.754463	1.023607	2.7156	40.349	.36352-01	.63160-01	3702.56	3.0781	1.8985
	1.814200	1.093903	2.7431	40.264	.34526-01	.60505-01	3670.90	3.2913	1.8292
	1.876190	1.167255	2.7703	40.196	.32804-01	.57974-01	3639.71	3.5201	1.7627
	1.941043	1.244079	2.7984	40.092	.31115-01	.55480-01	3607.79	3.7676	1.6964
	2.008803	1.324750	2.8267	39.965	.29494-01	.53062-01	3575.77	4.0353	1.6316
	2.079412	1.409698	2.8558	39.820	.27923-01	.50696-01	3543.30	4.3256	1.5677
	2.154413	1.499387	2.8854	39.653	.26402-01	.48384-01	3510.37	4.6415	1.5047
	2.232827	1.594317	2.9157	39.466	.24932-01	.46128-01	3477.01	4.9855	1.4427
	2.315484	1.695058	2.9468	39.257	.23509-01	.43923-01	3443.12	5.3615	1.3816
	2.402781	1.802239	2.9787	39.027	.22129-01	.41764-01	3408.59	5.7734	1.3212
	2.494924	1.916506	3.0114	38.774	.20802-01	.39667-01	3373.64	6.2246	1.2621
	2.592729	2.038718	3.0452	38.498	.19512-01	.37605-01	3337.83	6.7222	1.2035
	2.696276	2.169639	3.0798	38.198	.18272-01	.35603-01	3301.50	7.2699	1.1461
	2.806275	2.310283	3.1155	37.873	.17076-01	.33651-01	3264.47	7.8752	1.0896
	2.923410	2.461789	3.1524	37.522	.15922-01	.31744-01	3226.61	8.5463	1.0340
	3.048285	2.625405	3.1905	37.144	.14811-01	.29587-01	3187.95	9.2920	.9794
	3.181551	2.802561	3.2299	36.738	.13745-01	.28063-01	3148.50	10.1223	.9258
	3.324009	2.994446	3.2705	36.303	.12723-01	.26332-01	3108.21	11.0490	.8734
	3.476787	3.204651	3.3129	35.837	.11743-01	.24631-01	3066.96	12.0880	.8220

Table II-I (cont.)

	3.641160	3.434196	3.3569	35.337	.10834-01	.22970-01	3024.66	13.2576	.7717
	3.818360	3.686763	3.4027	34.801	.99068-02	.21375-01	2981.24	14.5799	.7224
	4.010280	3.965980	3.4506	34.226	.90476-02	.19820-01	2936.54	16.0822	.6742
	4.773120	5.134808	3.6264	32.019	.64960-02	.15036-01	2778.78	22.7027	.5229
	5.158993	5.764284	3.7061	30.943	.55931-02	.13275-01	2710.33	25.6152	.4659
	5.561455	6.449194	3.7859	29.935	.48177-02	.11723-01	2643.75	30.9353	.4151
	5.856794	6.966772	3.8406	29.208	.43488-02	.10764-01	2599.01	34.3020	.3834
	6.409135	8.098173	3.9502	27.731	.35496-02	.90884-02	2512.53	41.8497	.3273
	6.896603	8.927160	4.0216	26.763	.31109-02	.81422-02	2457.89	47.5549	.2953
	7.254367	9.649906	4.0745	25.972	.27961-02	.74495-02	2414.57	52.6258	.2717
	7.761117	10.715478	4.1577	24.905	.24228-02	.66109-02	2357.57	60.2349	.2428
	8.318020	11.946631	4.2401	23.777	.20848-02	.58328-02	2299.27	69.1895	.2157
	8.869393	13.227904	4.3176	22.716	.18109-02	.51868-02	2245.92	78.6484	.1931
	9.366722	14.493012	4.3880	21.757	.15952-02	.46665-02	2198.96	88.0730	.1747
	9.835677	15.644436	4.4473	20.951	.14341-02	.42706-02	2160.29	96.7405	.1606
	10.251238	16.750788	4.5006	20.227	.13039-02	.39446-02	2126.25	105.0478	.1489
	10.615281	17.755406	4.5461	19.611	.12021-02	.36866-02	2097.68	112.6882	.1396
	10.946678	18.699808	4.5869	19.061	.11182-02	.34708-02	2072.53	119.8297	.1318
	11.552185	20.441044	4.6571	18.117	.96756-03	.31295-02	2030.05	132.9913	.1195
	11.957886	21.663908	4.7105	17.493	.89899-03	.28936-02	1998.51	143.7094	.1109
	12.696617	24.168977	4.7994	16.341	.78174-03	.25755-02	1952.48	160.9553	.0992
	13.409987	26.723749	4.8707	15.278	.67962-03	.22920-02	1907.47	179.8278	.0887
	13.771954	28.872875	4.9104	14.759	.63966-03	.21650-02	1885.83	189.6667	.0840
	14.119660	29.415843	4.9490	14.257	.59477-03	.20510-02	1865.55	199.3631	.0797
	14.446460	30.723066	4.9831	13.811	.56692-03	.19506-02	1846.92	209.7002	.0760
	14.759145	32.916191	5.0103	13.379	.52697-03	.18601-02	1829.44	217.8324	.0726
	15.350696	34.584676	5.0786	12.574	.47559-03	.17023-02	1797.30	235.6439	.0667
	15.876107	37.619849	5.1337	11.867	.43317-03	.15746-02	1769.53	252.1143	.0619
	16.344547	39.303951	5.1820	11.249	.39918-03	.14711-02	1745.59	267.1442	.0579
	16.756870	41.425358	5.2245	10.708	.37158-03	.13858-02	1724.87	280.7927	.0547
	17.1193[illegible]	43.347750	5.2618	10.235	.34902-03	.13154-02	1706.96	293.0721	.0520
	17.437489	45.149965	5.2946	9.821	.33039-03	.12566-02	1691.42	304.6835	.0498
	17.996037	48.543855	5.3522	9.047	.30019-03	.11601-02	1664.61	323.8789	.0461
	18.413903	51.231324	5.3953	8.557	.27986-03	.10936-02	1644.88	339.0718	.0435
	19.037556	55.587415	5.4693	7.740	.25103-03	.99948-03	1615.73	362.4285	.0399
	19.693491	61.269658	5.5234	6.950	.22596-03	.91559-03	1587.65	385.8063	.0367
EXIT PT	19.999206	63.313251	5.5627	6.476	.21226-03	.86707-03	1571.18	399.9682	.0349

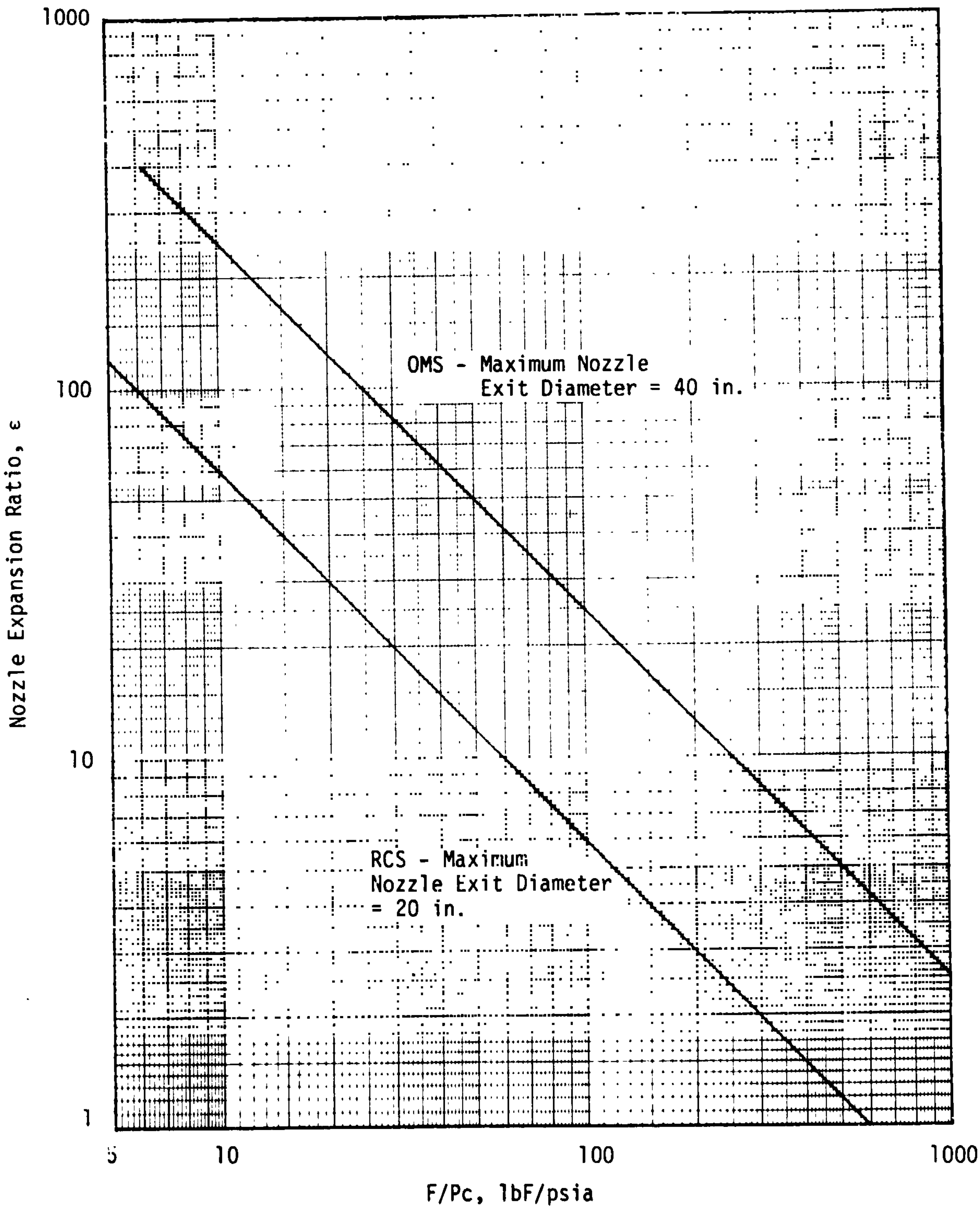


Figure II-9. Expansion Ratio versus F/Pc for Fixed Nozzle Exit Diameters the construction material for the slotted section (again with a nickel closeout) to conduct the cooling analyses with ammonia. These chambers were considered to extend normally to the area ratio (ϵ_A) at which a radiation-cooled nozzle extension can be utilized since these area ratios are relatively low. In case the two-phase heat transfer in the high-flux region of the nozzle was undesirable, however, it was considered to extend the nozzle channel design area ratio to 6:1, at which point it was assumed that superheated vapor at subcritical pressures, produced in a vaporizer section such as, for example, a tube bundle or channel design, would be provided to the primary nozzle channels. This type of vaporizer would thus extend from an area ratio of 6:1 to the area ratio determined by heat load requirements to vaporize the coolant and add some small amount of superheat (assumed as 10°R in this study).

Gas-side wall temperature limits for Zr-Cu were based on the creep and cycle life considerations shown in Figure II-10. This curve is based on 500 cycles, a safety factor of four, and a hold time of 15 hours. The hot gas-side wall thickness requirements for Zr-Cu are shown in Figure II-11. For cooling analyses with ammonia, the equivalent data for 304L stainless steel requirements are presented in Figures II-12 and II-13 for 250 cycles and a safety factor of four. Due to initial solution convergence failure, this data was not extended to 2,000 cycles. Note that creep allowance was not included in Figure II-12, limiting the hot gas-side wall temperature to 800°F. The strength data for a differential pressure of 1,000 psi were input to the channel design programs for the reference case hot wall aspect ratios at the cold and hot conditions. The actual pressure differentials across the hot wall were used in the program to determine wall thickness at each station.

A typical channel layout is shown in Figure II-14. Ideally, each set of input parameters (e.g., inlet pressure, bulk temperature,

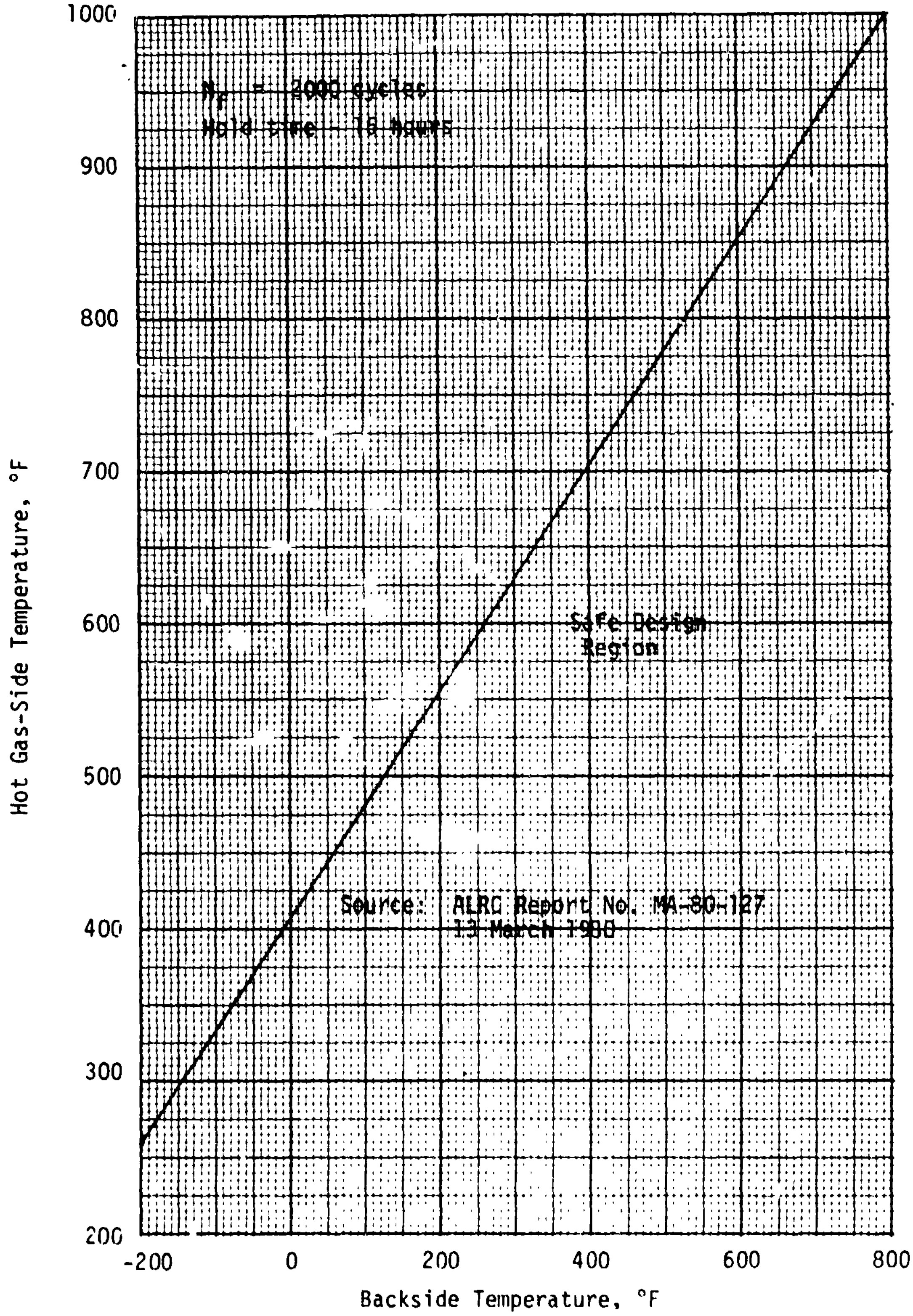


Figure II-10. Zr-Cu Design Envelope (Solution-Treated and Aged at 1100°F)

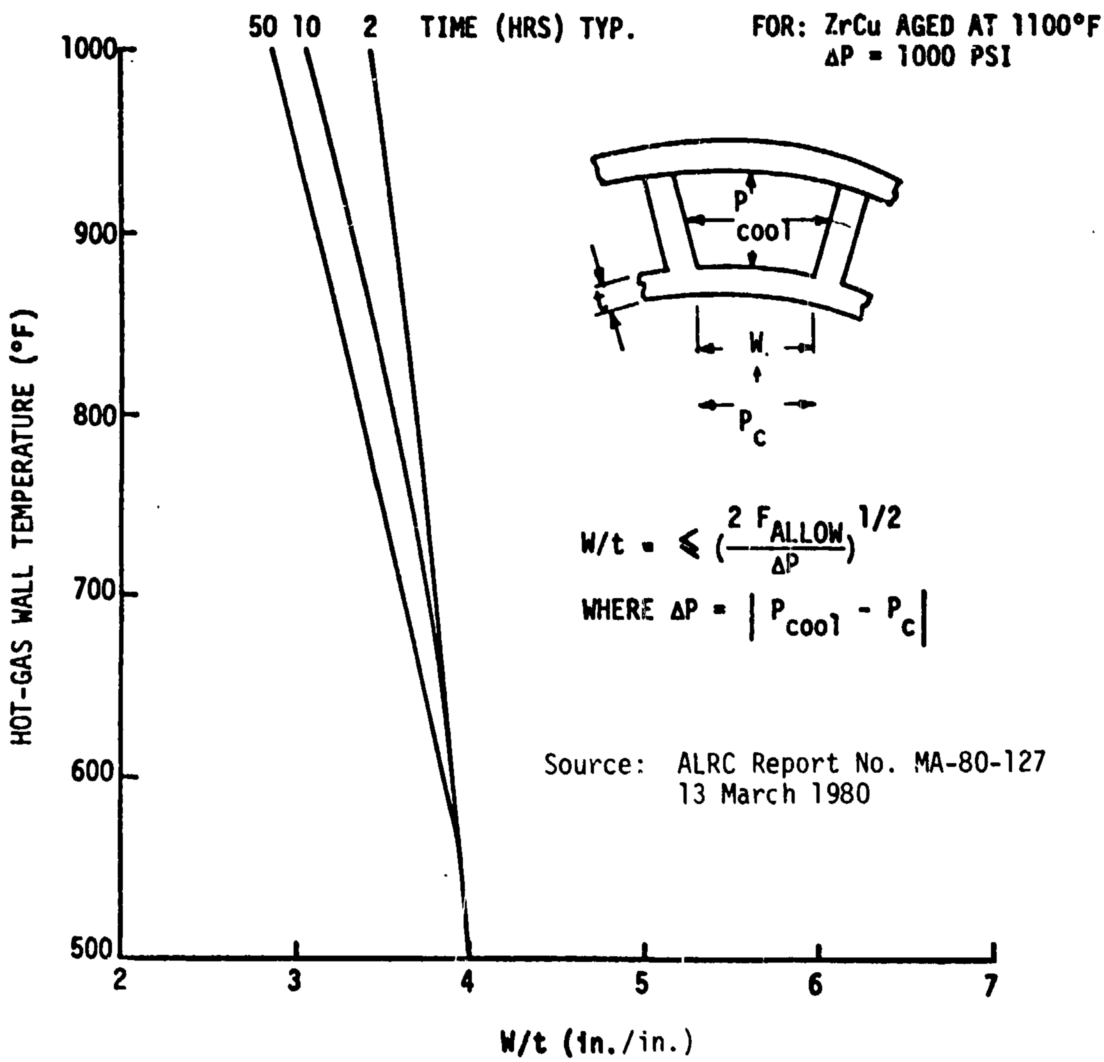


Figure II-11. Zr-Cu Chamber Wall Thickness Requirements

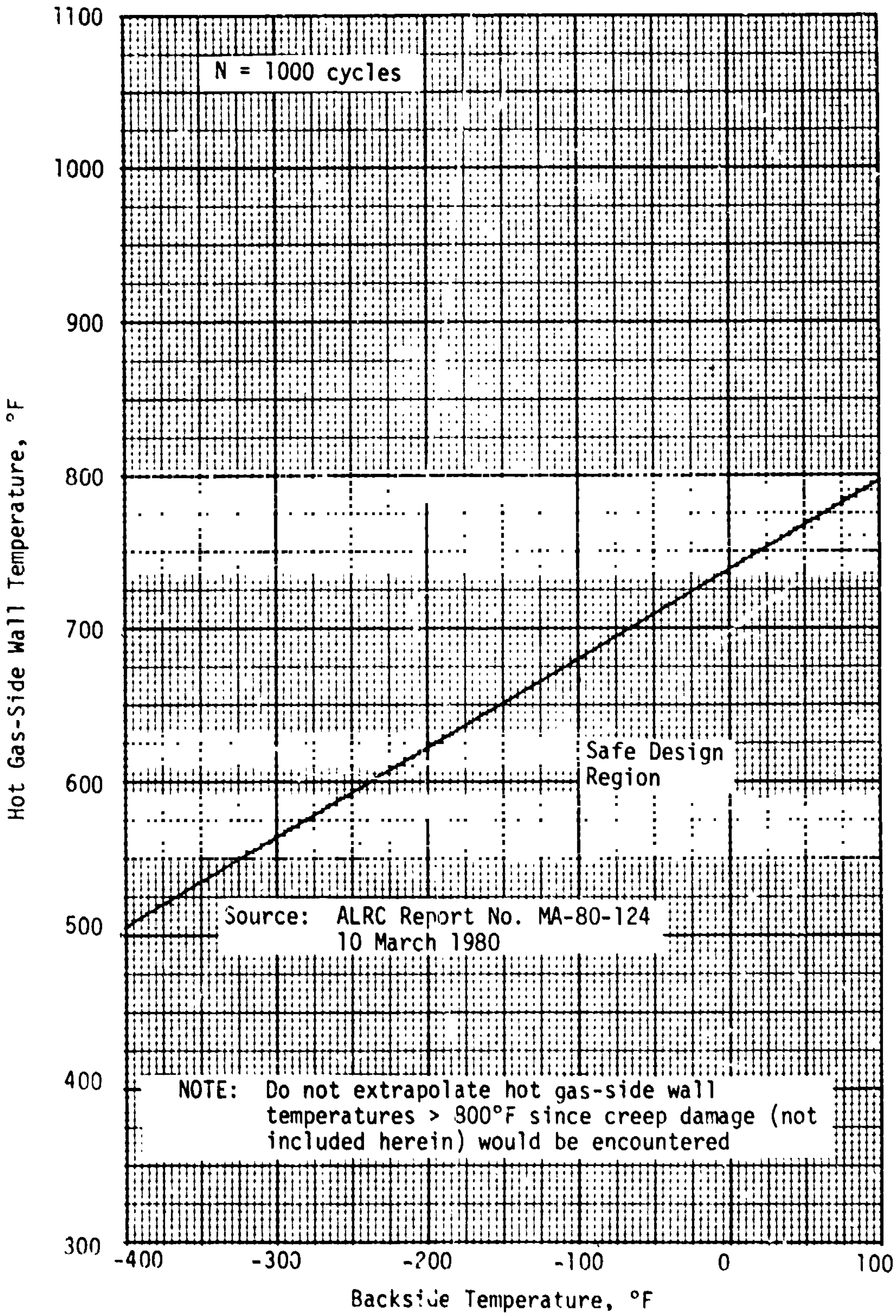


Figure II-12. 304L Stainless Steel Envelope

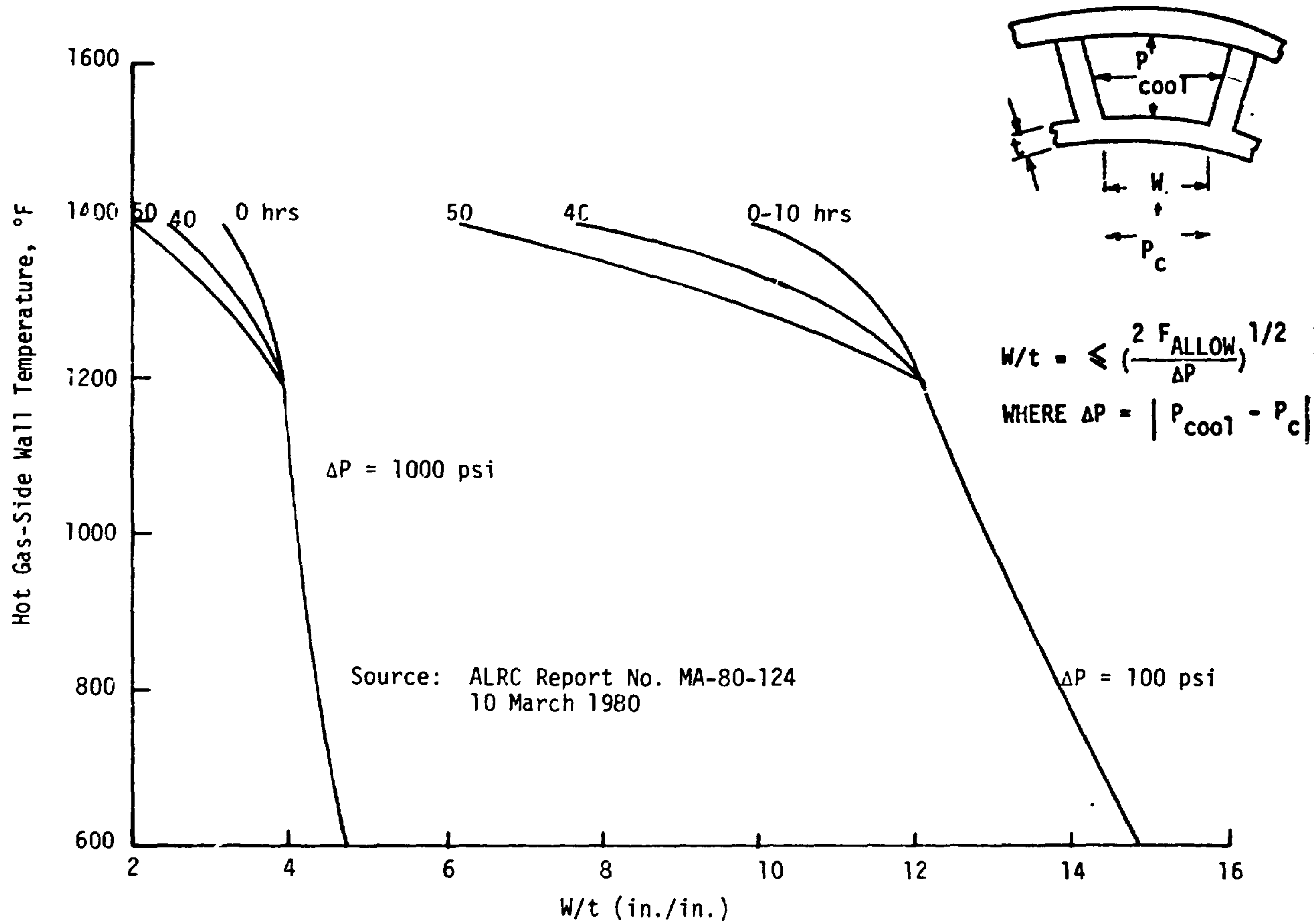


Figure II-13. 304L Stainless Steel Wall Thickness Requirements

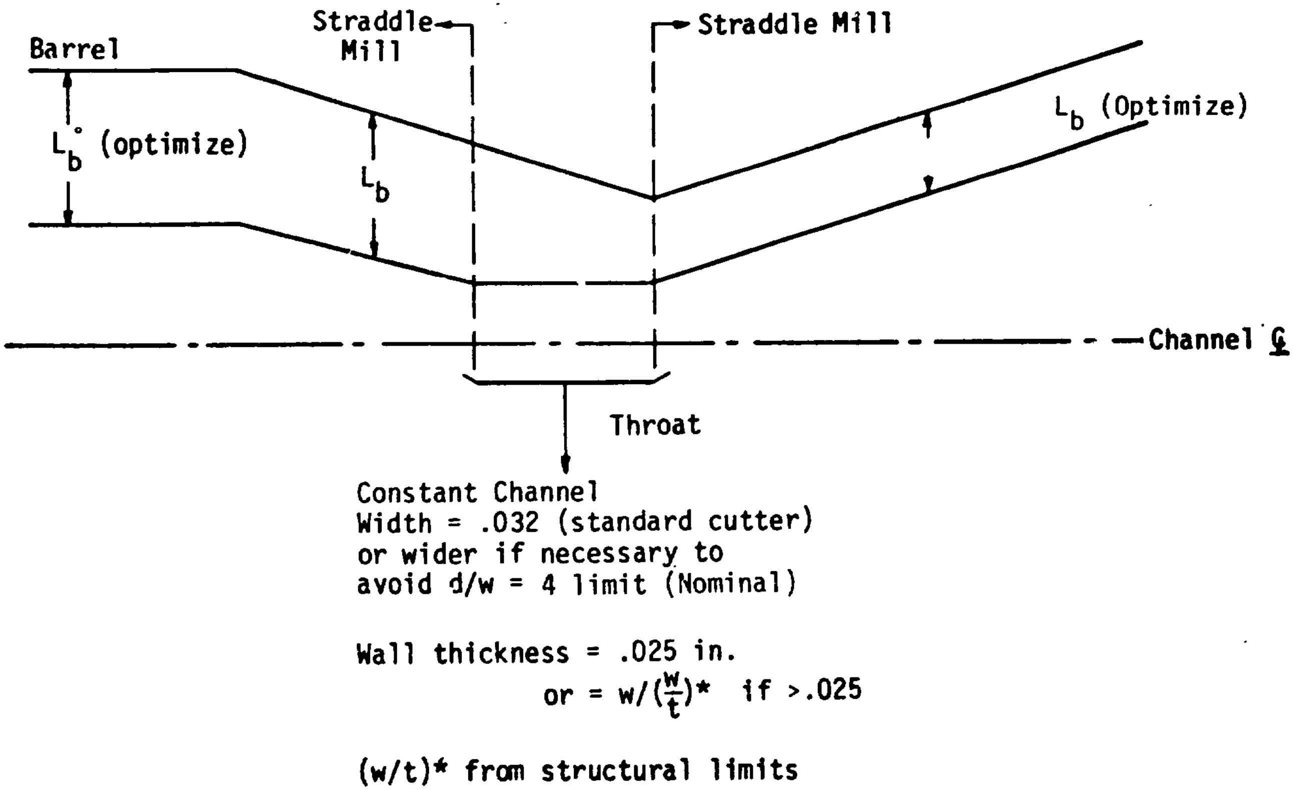


Figure II-14. Channel Layout

coolant state, etc.) requires an iterative optimization of station channel and land dimensions to minimize pressure drop and provide the most effective cooling. Although such an optimization was beyond the scope of this parametric study, several channel designs (to be discussed later) were utilized as approximations for the needs of a broad categorization of heat transfer regimes and coolant states (e.g., dense single-phase supercritical superheated vapor, etc.).

In order to minimize maldistribution of flow resulting from typical dimensional tolerances, a channel depth of 0.030 in. was selected as the minimum representative of a feasible channel design. Channel depths ranging from 0.020 to 0.030 in. were considered marginal in that it was considered possible that channel optimization could result in obtaining a minimum channel depth of 0.030 in. Calculated channel depths of less than 0.020 in. were considered beyond the probability of significant improvement.

b. Nozzle Extension

FS-85 columbium with a silicide coating was selected because of its high temperature capability. This material was found to be suitable for use in nozzles with low pressure levels.

6. <u>Coolant Properties</u>

Data requirements for the SCALER and BOSCALE thermal analysis programs consist of the following criteria: 1) coolant thermodynamic (density, enthalpy, specific heat, and sonic velocity); 2) transport (thermal conductivity and viscosity); and 3) saturation pressures and temperatures.

a. RP-1

Density, specific heat, thermal conductivity, and viscosity data were an integral part of the SCALER program data bank at the inception of the study. Data for saturated liquid are utilized under 340 psia and 800°F; above the critical pressure, the data have been extended to 1800 psia and 1280°F.

b. Methane

Similarly, density, specific heat, enthalpy, sonic velocity, thermal conductivity, and viscosity data for methane were available at the start of analysis. Pressures range from 100 to 10,000 psia, while the data temperature range is from -290 to 1340°F.

c. Propane

A very limited data file for propane required that more extensive property data be obtained and included in the program data bank. The density, enthalpy, specific heat, and sonic velocity data of Ref. 4 were input for a pressure range of 1.45 to 2030 psia and a temperature range of -298 to 800°F. The transport properties of thermal conductivity and viscosity were obtained from the data of Ref. 5. It was necessary to graphically extrapolate both the low and high ends of the temperature spectrum, with pressures ranging from 145 to 2176 psia and temperatures ranging from -298 to 800°F.

d. Ammonia

No data for ammonia were available to the design programs at the start of the analysis. Thermodynamic data (density and enthalpy) were obtained from Ref. 6. An extensive effort was required to extend these data to include sonic velocity, thermal conductivity, and viscosity data for pressures up to 2000 psia and temperatures between -60 and 1040°F as per the approaches of Refs. 7, 8 and 9. In the absence of specific heat data the program logic was modified to accept a pressure-temperature-enthalpy relationship in calculating bulk temperature rise and pressure drop.

C. ANALYSIS CRITERIA

A point design analysis at a given thrust and chamber pressure was considered acceptable when the following criteria were met.

1. Channel Gas-Side Wall Temperature

The coolant channel design program limits the gas-side channel wall temperature and the temperature difference between the gas-side and channel closure as set by creep and cycle life considerations. These criteria are shown in Figure II-10 for zirconium-copper and in Figure II-12 for 304L stainless steel. Where these criteria could not be met and were the limiting factor in the analysis, cycle life limit was reported.

2. Channel Coolant-Side Wall Temperature

For the hydrocarbon coolants, the limit on the coolant-side wall temperature was the reported coking temperature:

Propane	800°F (750°F in some analyses)
Methane	1300°F
RP-1	550°F

The coking limit of 1300°F for methane was not a practical limit in that maximum gas-side wall temperatures were limited to 1000°F. Where the coolant-side temperature become limited by the coking temperatures, a coking limit was reported.

3. Coolant Pressure Drop

For this study, a maximum pressure ratio (P_{inlet}: Pc) of 1.8 was allowed. The pressure in excess of the chamber pressure would normally be distributed 20/60 between injector and regeneratively cooled jacket. The design program requires input of a specific coolant inlet pressure, and this parameter was normally input as 1.8 times Pc. A lower ratio, 1.3, was used in selected subcritical analyses where regen jacket ΔP was not limiting and where ratios in excess of the coolant critical pressure may involve phase change.

4. Burnout Safety Factor

The burnout safety factor (BOSF) criterion constrains the ratio of the burnout heat flux to the maximum coolant-side heat flux iterating on channel depth to provide the necessary coolant flow velocity. Burnout heat fluxes employed relationships of the following form:

$$\phi_{BO} = K_1 + K_2 \; V \; (T_{sat} - T_b)$$

The value of the BOSF was initially set at 1.6. For propane, this conservative estimate could not be met, and convergence failures, in all cases, precluded a complete description of the limiting factors. As a result, the BOSF was changed to 1.0 for all subsequent analyses, and the burnout safety margin was estimated from the excess available pressure drop.

D. COOLANT CORRELATIONS

A number of coolant heat transfer correlations for design predictions are available. However, since these are semi-empirical, the usual caveat relative to their use beyond the operating ranges for which they were developed should be observed.

The table below presents the critical points, normal boiling points, and typical inlet temperatures for the four fuels under consideration:

	PROPANE	METHANE	RP-1	AMMONIA
Critical Pressure, psia	615	667	315	1636
Critical Temperature, °F	206	-117	758	270
Normal Boiling Point, °F	-44	-259	422	-28
Typical Inlet Temperature, °F	-44 295*	-259	60	-28

*Subcooled Propane

1. Propane

To avoid the uncertainties of designing in the near-critical region, analyses were performed at the following pressures:

Pressure Regime	Chamber Pressures	Channel Inlet Pressures
Supercritical	1000	1800
	800	1440
	650	1170
Subcritical	400	- , 520
	300	540, 390
	200	360, 260
	100	180, 130

Carbon deposits on the chamber gas-side walls from the combustion of propane are postulated to result in a significant reduction in local heat transfer rates. This reduction was accounted for in calculating heat loads, i.e., coolant bulk temperature rise, but not in defining local heat fluxes in the channel design procedure. For propane, with a H:C ratio of 2.67, a heat input reduction factor of 0.42 was employed on the basis of previous data (see Ref. 10). While this procedure does provide a reasonable estimate for coolant enthalpy change and, therefore, bulk temperature rise, it allows for startup with a clean engine, with intermittent loss of coating deposits due to flaking or spalling during engine operation.

a. Supercritical Pressures

No data are known for heat transfer to propane in the reduced pressure range where $1.9 \leq P_{red} \leq 2.9$ (study inlet pressures). Finn, as noted by Hendricks in Ref. 11, developed the following correlation for tests at low fluxes (0.02 - 0.23 Btu/in^2-sec) at 695 psia (P_{red} = 1.13):

$$Nu_b = 0.026\, Re_b^{0.8}\, Pr_b^{0.4} \left(\frac{\mu_w}{\mu_b}\right)^{-0.02} \left(\frac{k_w}{k_b}\right)^{0.2} \left(\frac{\rho_w}{\rho_b}\right)^{-0.27} \left(\frac{\bar{C}_p}{C_{p,b}}\right)^{0.54}$$

Since wall temperature effects due to temperature-dependent properties must be accounted for in this regime, a correlation of this type was selected. The recently concluded heated-tube test program on heat transfer to oxygen (Ref. 12) utilized both ALRC and other data for a reduced pressure range of 0.39 to 5.76, with heat fluxes ranging from 1.2 to 55 Btu/in^2-sec. The following correlation predicted over 95% of the experimental data within ± 30%:

$$Nu_b = Nu_{ref} \left(\frac{\rho_b}{\rho_w}\right)^{-0.5} \left(\frac{k_b}{k_w}\right)^{0.5} \left(\frac{\bar{C}_p}{C_{p_b}}\right)^{0.67} \left(\frac{P}{P_{crit}}\right)^{-0.2} \left(1 + \frac{2}{\ell/D}\right)$$

where $Nu_{ref} = 0.0025\ Re_b\ Pr_b^{0.4}$

This correlation (generally termed the "LOX" correlation) was used in preference to the Finn correlation to predict coolant-side coefficients for propane because the pressure and flux ranges are consistant with those required in this study.

b. Subcritical Pressures

Two types of analyses for propane at subcritical pressures were performed. In the first, it was assumed that a "vaporizer" section of the nozzle extending aft from an area ratio of 6:1 had vaporized the inlet liquid propane and added ten degrees of superheat. Heat transfer on the coolant-side could thus be characterized as forced convection cooling with a gas. The Hines equation of Ref. 13, i.e.,

$$Nu_b = 0.005\ Re_b^{0.95}\ Pr_b^{0.4}$$

was used in this regime to provide a common correlation for comparison of coolant characteristics.

The second analysis considered the inlet coolant to be either at its normal boiling point (i.e., essentially a saturated liquid) or in a subcooled state. Thus analyses for propane considered a liquid phase at inlet temperatures of -44 or -295°F. For forced convection heat transfer, the Hines relationship was employed.

The wall superheat for nucleate boiling was conservatively estimated, i.e., the nucleate boiling mechanism was initiated when the local wall temperature exceeded the fluid saturation temperature at the local pressure by 25°F. Nucleate boiling heat transfer coefficients (defined as the slope of the curve relating boiling heat fluxes to wall temperature) ranging from 0.05 to 3 Btu/in^2-sec-°F were evaluated since no forced-flow boiling data were available.

Burnout heat flux correlations for propane, based on the work reported in Ref. 14, were derived at ALRC as:

a. Where $V\ \Delta T_{sub} \leq 1000$

$$\phi_{B.O.} = 0.3 + 0.0004\ V\ \Delta T_{sub}$$

b. Where $V\ \Delta T_{sub} > 1000$

$$\phi_{B.O.} = 0.58 + 0.00012\ V\ \Delta T_{sub}$$

where:

V = Coolant velocity, ft/sec

ΔT_{sub} = Coolant subcooling, °F

$\phi_{B.O.}$ = Burnout heat flux, Btu/in^2-sec

The correlations are supported by test data to a $V\ \Delta T_{sub}$ value of about 3500 ft °F/sec, with a data spread of ± 25%.

2. Methane

The proximity of the boiling and freezing point of methane precludes any significant improvement in subcooling. Since the burnout correlation given above for propane is also applicable to methane, heat transfer by nucleate boiling of methane in the nozzle high heat flux region was considered impractical. The methane investigation was therefore limited to the supercritical pressure range and as a superheated vapor at subcritical pressure.

a. Supercritical Pressures

No data on the heat transfer characteristics of methane at supercritical pressures are known to be published. Following the rationale discussed above for propane, the "LOX" correlation was selected. For methane, however, the data of Ref. 10 suggest a wall carbon factor of 0.765. A coking temperature of 1300°F was employed.

b. Subcritical Pressures

The Hines correlation, given above, was used to predict the heat transfer coefficients for methane, assumed to be a vapor with ten degrees of superheat. This analysis thus paralleled the one performed for propane.

3. RP-1

Only limited analyses with RP-1 as the coolant were performed. While offering many advantages, the low coking temperature of 550°F and large bulk temperature rise in the relatively long chambers characteristic of O_2/RP-1 engines present severe design problems. Attention in this study was directed primarily to the use of RP-1 as a coolant at supercritical pressures ($P > 315$ psia). A review of published correlations indicates that the Hines correlation adequately represents the heat transfer characteristics of RP-1 at supercritical pressures when the wall temperatures are less than the critical temperature of 758°F (true for these analyses, since the lower coking temperature limit of 550°F constrains the maximum coolant-side temperature to this lower value). A wall carbon factor of 0.25 (Ref. 10) was used.

4. Ammonia

The high critical pressure of ammonia (1636 psia) eliminated analyses of this fuel at supercritical pressures. Effort was thus directed toward analysis of (a) superheated vapor at subcritical pressures and (b) forced convection and nucleate boiling. The Hines correlation was again selected for the superheated vapor state as adequately characterizing the heat transfer characteristics based on bulk temperature.

The non-boiling forced convection analyses were performed by using the Hines correlation. The burnout heat flux correlation for ammonia is of the same form as the one discussed earlier for propane. Based on test data of JPL and RMI (Refs. 15 and 16), the equations derived by ALRC, with notation as employed earlier, are

a. Where $V \, \Delta T_{sub} \leq 4000$ ft °F/sec

$$\phi_{B.O.} = 2.15 + 0.00036 \; V \, \Delta T_{sub}$$

b. Where $V \, \Delta T_{sub} > 4000$

$$\phi_{B.O.} = 3.3 + 0.000587 \; V \, \Delta T_{sub}$$

These equations are supported by test data to a $V \, \Delta T_{sub}$ value of about 14,000 ft °F/sec, with a data spread of ± 30%.

E. RESULTS OF COOLING COMPARISON ANALYSES

A preliminary finding drawn from the analyses of the four coolants considered in this study, with heat transferred either by forced convection or nucleate boiling mechanisms, is that cooling characteristics are highly sensitive to channel layout (channel and land width profiles). Ideally, channel design varies with thrust level and coolant pressure, In essence, each coolant-thrust-pressure combination requires a tailor-made channel configuration; conversely, any specific channel layout satisfies the thermal and hydraulic requirements of a relatively narrow range of input parameters. This makes a meaningful comparison of four coolants over a wide range of thrusts and pressures more difficult in that time constraints preclude optimization iterations on channel layout at each specific point. The results reported herein are thus based on several channel geometries considered relatively crude approximations of the channel layout most appropriate to a broad categorization of cases.

The five channel layouts used in this study are given in Table II-II. The channel width and land width input to the program at the throat (Station 18) determines the number of coolant channels for each specific engine design case. For all other stations, the dimension input either as channel width or land width specifies that dimension for each station while the alternate parameter is automatically varied to accommodate the appropriate nozzle chamber dimensions. For example, for the C channel design, the channel width is held constant at 0.174 in. for the first 13 stations whereas the land width varies, giving the widest land width at Station 1 and the narrowest at Station 13.

Channel nomenclature, as used in Tables II-III through II-IX, is depicted in Figure II-15.

TABLE II-II
CHANNEL DESIGN LAYOUT

Station	A/A_t	A Channel Controlling Dimensions		A′ Channel Controlling Dimensions		A" Channel Controlling Dimensions		C Channel Controlling Dimensions		D Channel Controlling Dimensions	
		Channel Width, in.	Land Width, in.	Channel Width, in.	Land Width, in.	Channel Width, in.	Land Width, in.	Channel Width, in.	Land Width, in.	Channel Width, in.	Land Width, in.
1	208.7	.174		.174		.130		.174			.120
2	189.6										
3	161.0										
4	133.0										
5	105.1										
6	88.1										
7	69.2										
8	52.6										
9	41.8										
10	30.9										
11	22.8										
12	16.1										
13	11.0										
14	6.73		.030		.030		.030		.080		
15	3.77										
16	2.21										
17	1.16										
18	1.00	.0324		.0325		.0325		.070		.040	
19	1.07										
20	1.29										
21	1.71		.040				.040		.080	.060	
22	2.20									.088	
23	2.65									.166	
24	3.00										.150
25	3.30										
26	3.30										
27	3.30										
28	3.30										
29	3.30										
30	3.30										
31	3.30										
32	3.30										
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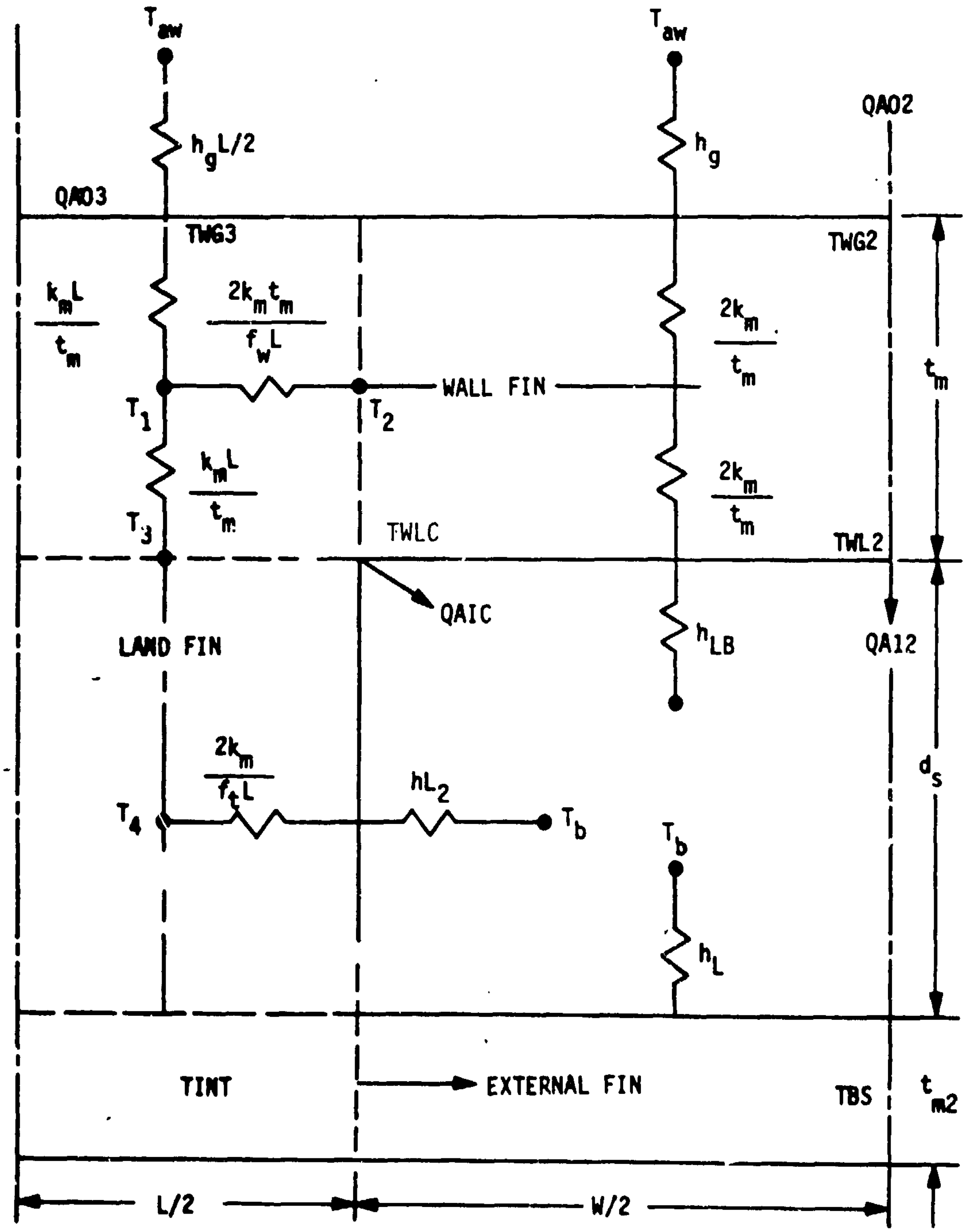


Figure II-15. Schematic of Wall Conduction Model

1. Propane

a. Supercritical Pressures

Analyses were performed primarily at thrust levels of 6 and 10K and at chamber pressures of 650, 800, and 1000 psia. In all cases, the coolant inlet pressure was 180% of the chamber pressure. Coolant inlet temperatures were -44°F (normal boiling point) and -295°F. In the majority of cases, a reduction in the gas-side heat flux to 42% of the "clean wall" flux was employed in calculating the bulk temperature rise; channel design, however, was based on the "clean wall" flux. Coking temperature limits were either 750 or 800°F, reflecting the range of temperatures for which decomposition can be expected.

Input data for the analysis are given in Part A of Table II-III. Selected SCALER-calculated nozzle parameters are presented in Part B, while local fluxes and temperatures are given in Part C for the station with the calculated maximum coolant-side heat flux.

Cases 7A-1 through 7A-4 in Table II-III consider propane at an inlet temperature of -44°F (normal boiling point). Parameters of interest are plotted Figure II-16 as a function of thrust for the OMS application, with Pc as the independent variable. Coolant pressure drop, velocity and temperature at the throat, Mach number, maximum coolant-side heat flux, and the radiation-cooled attachment area ratio increase with increasing chamber pressure. The effect of changes in thrust level is most significant for pressure drop and bulk temperature rise. Minimum channel depths are satisfactory for all chamber pressures at a thrust of 10K but become increasingly marginal as thrust decreases to 6K.

TABLE II-III

PROPANE AT SUPERCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor	T_{coke} °F	Corre-lation	ε -	Engine Basis	Channel Design	Computer Run Ident.
7A-1.1	10K	1000	1.8	1800	-44	.42	750	LOX	Rad.Attach.	OMS	A	7A/2-11/1
-1.2		800		1440		1.0	800					7A/2-13/1
-1.3		650		1170		.42	750					7A/2-11/1
-2.1	8K	800		1440		.42	800					7A/2-13/1
-2.2		650		1170		1.0	750					7A/2-12/1
-3.1	6K	1000		1800		.42	750					7A/2-11/1
-3.1A		1000		1800			800				A′	7A/2-14/1
-3.2		650		1170			750				A	7A/2-11/1
-3.2A		650		1170			800					7A/2-13/1
-3.3		500		900			800					7A/2-13/1
-4.1	4K	1000		1800			750		155			7A/2-11/1
-10.1	10K	1000		1800	-295				Rad.Attach.			7A/2-12/1
-11.1	6K	1000		1800		1.0						7A/2-12/2
-11.1A		1000		1800		.42						7A/2-12/2
-11.2		800		1440								7A/2-12/2
-11.3		650		1170			800					7A/2-13/1

TABLE II-III

PROPANE AT SUPERCRITICAL PRESSURES

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loca. ε	Design Limit Type -	Design Limit Loca. -	Rad. Attach ε	T @ Throat °F	V @ Throat ft/sec
7A-1.1	1000	1.262	6.85	129	-10.78	.385	234	136	.08	L'	.032	1.0	Coking	TWL2	33.1	27	133
-1.2	800	1.410		144	-10.96	.410	415	37[illegible]	.26		.030	-1.97			26.5	98	108
-1.3	650	1.565		160	-11.14	.245	200	157	.05		.035	-2.18			21.2	11	66
-2.1	800	1.262	5.48	129	-10.78	.348	232	189	.07		.028	-2.15			27.1	20	94
-2.2	650	1.400		143	-10.94	.552	406	362	.32		.025	-1.95			21.7	83	80
-3.1	1000	.977	4.11	01	-10.45	.803	272	229	.22		.019	-3.3			35.0	30	140
-3.1A	1000	.977		101	(-7.73)	(1.104)	(230)	(187)	(.25)		.025	L'			35.0	30	140
-3.2	650	.212		124	-10.72	.540	235	191	.10		.022	L'			22.2	14	80
-3.2A	650	1.212		124	-10.72	.449	236	192	.09		.023	-2.65			22.2	14	76
-3.3	500	1.382		[illegible]	-10.92	.398	222	179	.07		.025	-2.65			17.1	15	60
-4.1	1000	.798	2.74	83	(-.49)	(.467)	(153)	(110)	(.13)	ε = -1.37	.015	-1.37			N/A	94	175
-10.1	1000	1.262	6.85	129	-10.78	.372	291	-3	.03	ε = 1.0	.029	-1.39			33.1	-212	169
-11.1	1000	.977	4.11	101	-10.45	.961	656	362	.56	L'	.020	-5.01			35.0	-93	117
-11.1A	1000	.977		101	-10.45	.661	350	55	.04	L'	.018	-0.78			35.0	-208	165
-11.2	800	1.093		112	(.04)	.398	(76)	(-218)	(.04)	ε = 1.03	.017	1.03			28.0	-221	86
-11.3	650	1.212		124	(.05)	.454	(66)	(-229)	(.03)	L'	.016	1.06			22.2	-231	101

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

TABLE II-III

PROPANE AT SUPERCRITICAL PRESSURES

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	Coolant-Side QAI2 Btu/in²-sec	Coolant-Side TWL2 °F	Coolant-Side $QAIC_2$ Btu/in²-sec	Coolant-Side TWLC °F	Coolant-Side TBS °F	Gas-Side QAO2 Btu/in²-sec	Gas-Side TWG2 °F	Gas-Side QAO3 Btu/in²-sec	Gas-Side TWG3 °F	P psia	T_c °F	V ft/sec	M -
7A-1.1	-1.07	12.41	585	12.18	575	348	22.39	673	22.43	662	1686	33	157	.05
-1.2	-1.07	8.91	681	8.76	671	453	18.05	749	18.08	740	1366	111	133	.06
-1.3	-1.07	5.87	554	5.78	644	402	15.09	707	15.12	697	1139	17	80	.02
-2.1	-1.07	9.16	685	9.02	676	462	18.43	756	18.47	746	1379	27	115	.04
-2.2	-1.29	7.76	749	7.68	742	592	14.30	805	14.32	798	1100	112	121	.05
-3.1	-1.07	14.34	688	14.14	680	495	23.06	784	23.11	774	1667	37	172	.05
-3.1A	-1.07	14.34	688	14.14	680	495	23.06	784	23.11	774	1668	37	172	.05
-3.2	-1.07	8.28	750	8.19	742	584	15.57	811	15.60	803	1116	26	109	.03
-3.2A	-1.29	8.40	799	8.33	792	657	14.57	858	14.59	851	1107	27	110	.04
-3.3	-1.29	6.34	799	6.29	793	679	11.53	844	11.55	839	856	29	92	.03
-4.1	-1.29	17.93	749	17.81	745	634	22.38	852	22.40	847	1514	106	245	.10
-10.1	-1.07	12.02	659	11.87	649	445	22.08	746	22.12	735	1577	-204	164	.03
-11.1	-1.07	13.69	652	13.51	642	443	23.24	746	23.28	735	1682	-75	145	.03
-11.1A	-1.29	15.47	751	15.37	745	617	21.52	845	21.55	839	1440	-192	201	.04
-11.2	(1.03)	(10.62)	(750)	(10.56)	(745)	(655)	(15.40)	(817)	(15.42)	(811)	(1121)	(-218)	(217)	(.04)
-11.3	(1.06)	(7.45)	(800)	(7.42)	(797)	(733)	(10.79)	(847)	(10.80)	(843)	(875)	(-229)	(203)	(.03)

( ) Solution did not converge. Data in parentheses are for maximum coolant-side heat flux at the area ratio shown.

Column notation depicted in Figure II-15.

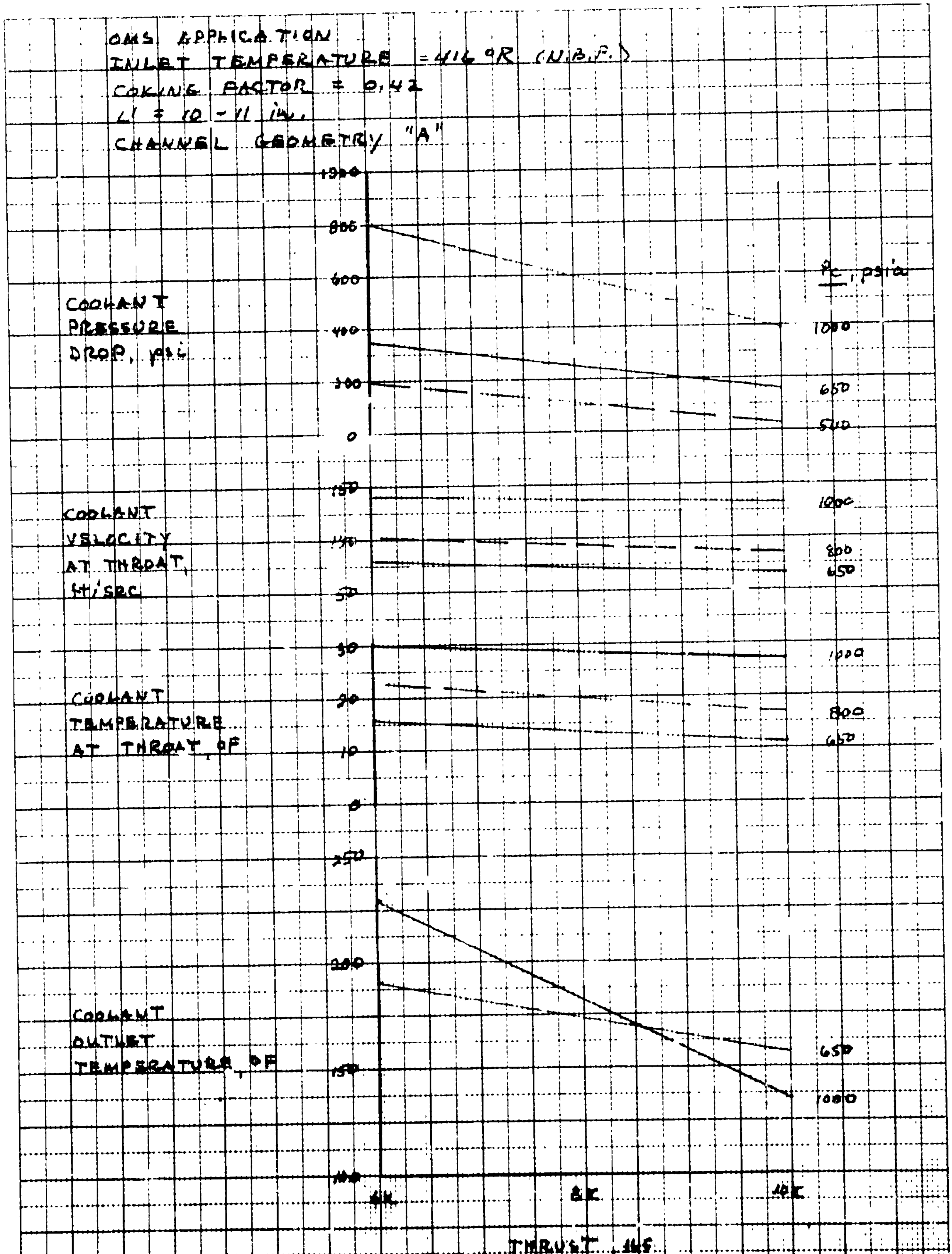


Figure II-16. Cooling Parameters for Propane at Supercritical Pressures, N.B.P. Inlet Temperature and Wall Carbon - OMS (Sheet 1 of 2)

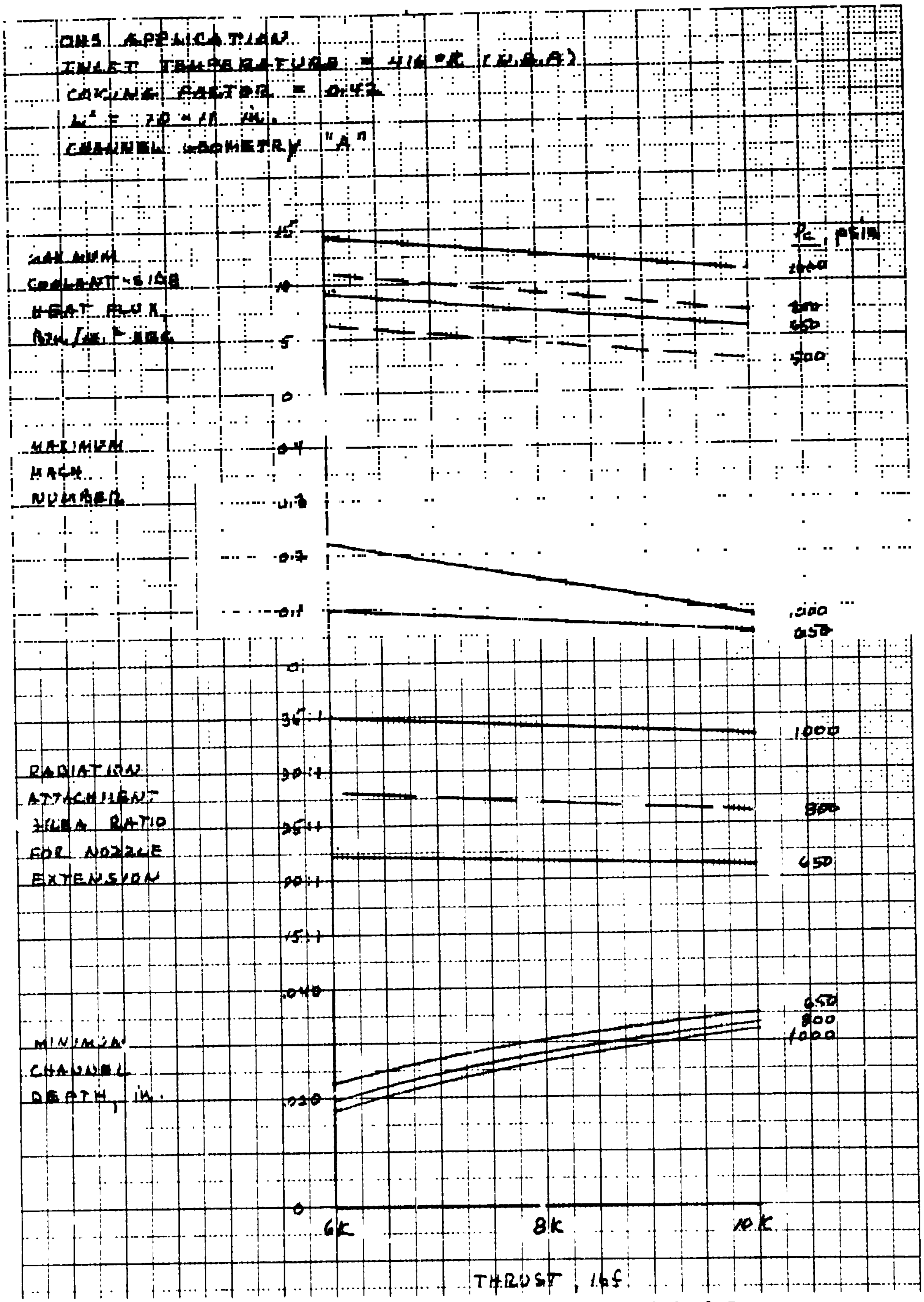


Figure II-16. Cooling Parameters for Propane at Supercritical Pressures, N.B.P. Inlet Temperature and Wall Carbon - OMS (Sheet 2 of 2)

Cases 7A-10 and 7A-11 provide analyses in which the inlet temperature was assumed to -295°F. Results are similar, as indicated by a comparison of the data plotted in Figures II-16 and II-17.

The effect of a less effective gas-side carbon layer with trends as anticipated, is shown in Figure II-18. Velocity and the associated coolant pressure drops increase significantly as the heat reduction effect decreases. The formation and adherence of the carbon layer is significant to the design of a propane-cooled engine.

b. Superheated Vapor at Subcritical Pressures

Data for superheated propane vapor at subcritical pressures are presented in Table II-IV. Thrust levels again were 6K and 10K lbF for the OMS application, while chamber pressures ranged from 100 to 500 psia. Inlet temperature were 10° above the saturation temperature at the inlet pressure which, respectively, was 1.8 and 1.3 times the chamber pressure. No carbon factor variation was studied, and the coking temperature was held constant at 800°F. The C channel design, which has larger land and channel widths in the throat and a wider land width upstream of the throat, was used, providing a larger channel flow cross section to reduce flow velocities for the less dense gas.

Parameters of interest are plotted as a function of thrust for the chamber pressures analyzed in Figures II-19 and II-20 for P_{in}/P_c values of 1.8 and 1.3, respectively. As was to be expected, coolant throat and outlet temperatures are greater. Coolant throat velocities for $P_{in}/P_c = 1.8$ approximate those for supercritical propane; at the lower pressure ratio, throat velocities are higher. Coolant pressure drops are low for $P_{in}/P_c = 1.8$ and

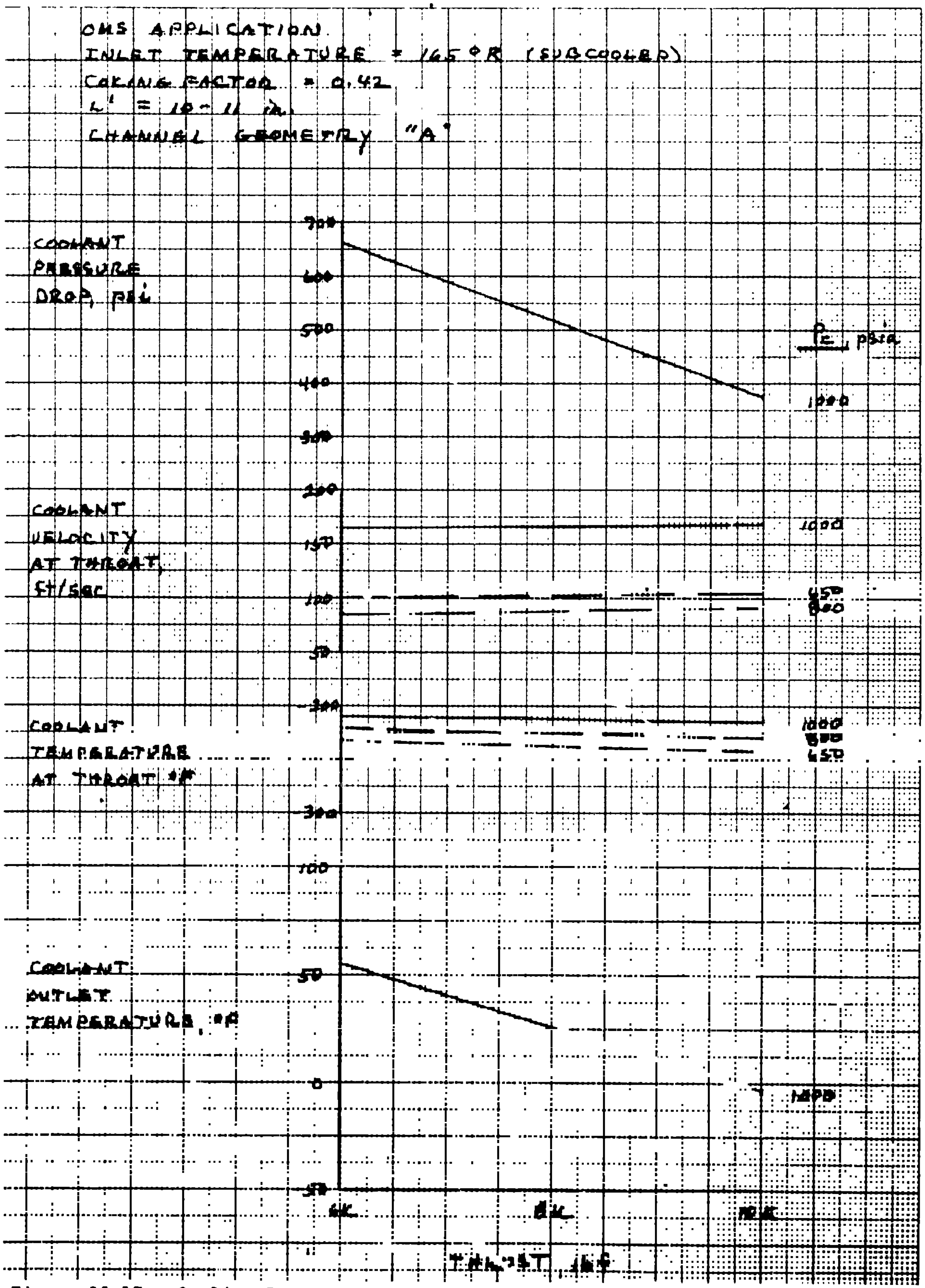


Figure II-17. Cooling Parameters for Propane at Supercritical Pressures, Subcooled Inlet Temperature and Wall Carbon - OMS (Sheet 1 of 2)

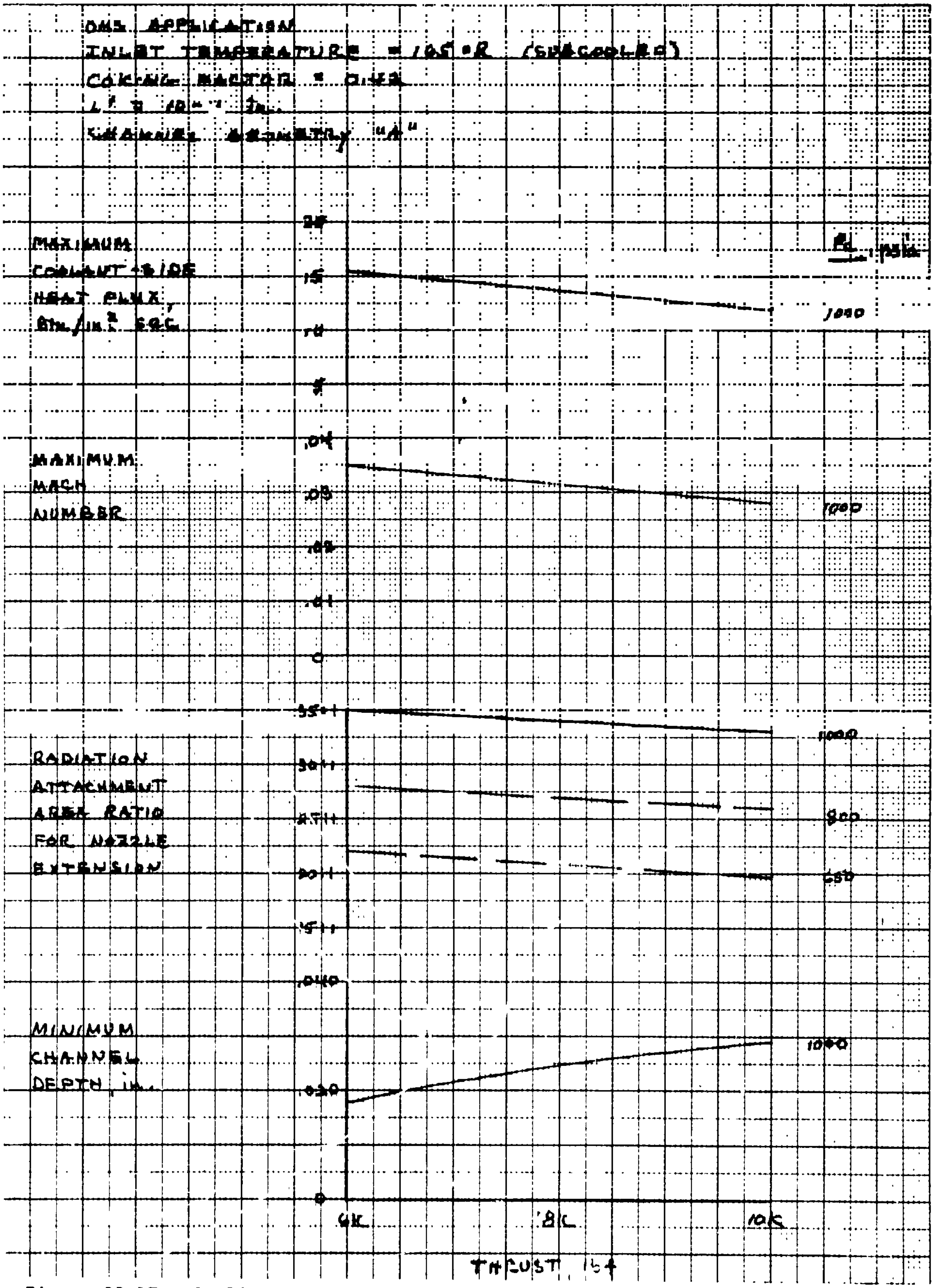


Figure II-17. Cooling Parameters for Propane at Supercritical Pressures, Subcooled Inlet Temperature and Wall Carbon - OMS (Sheet 2 of 2)

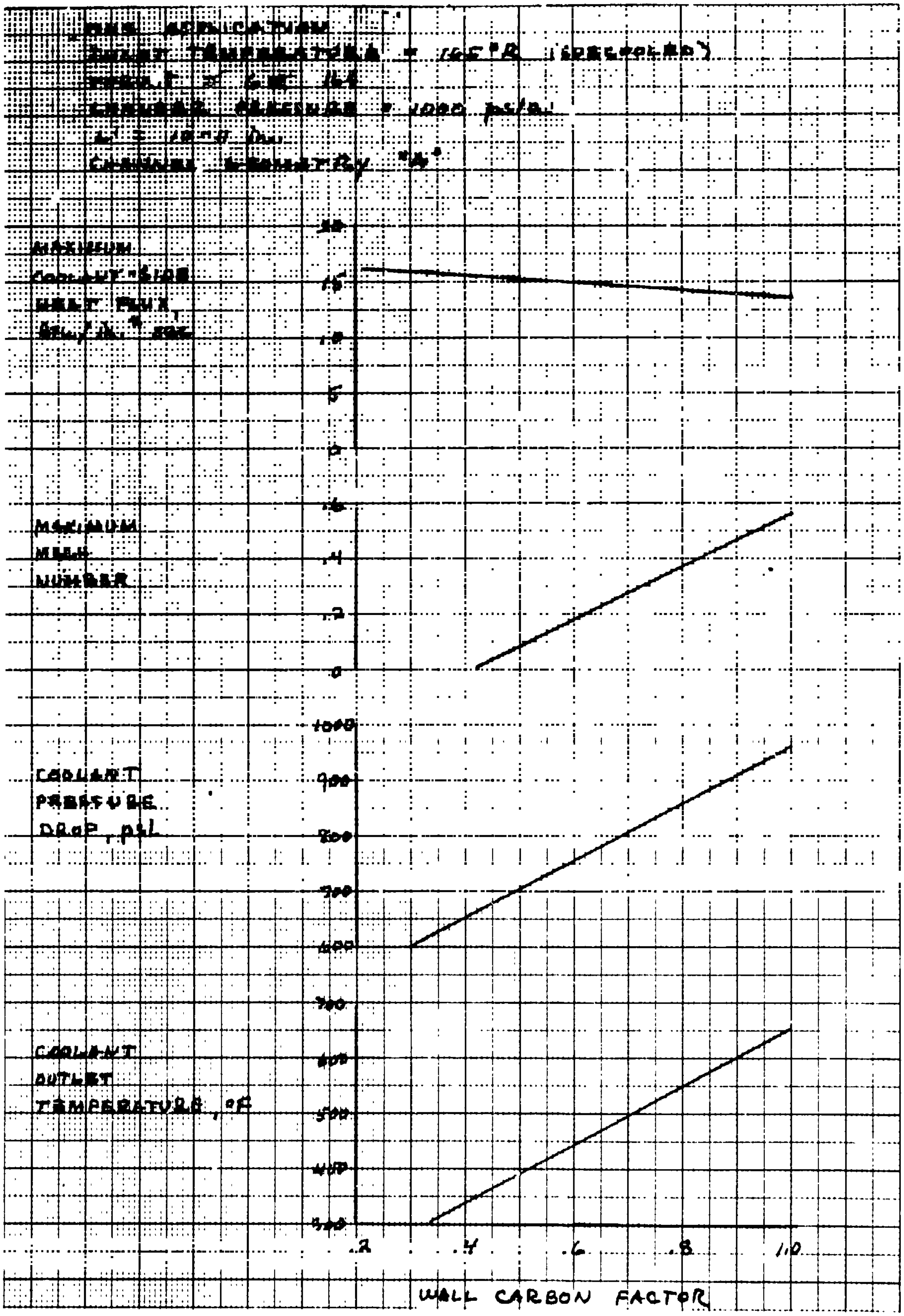


Figure II-18. Selected Cooling Parameters for Propane at Supercritical Pressures as Function of Wall Carbon - OMS

TABLE II-IV

PROPANE AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc Psia	P_{in}/P_c -	P_{in} psia	T_{in}^* °F	Carbon Factor -	T_{coke} °F	Corre-lation -	ε -	Engine Basis	Channel Design	Computer Run Ident.
7B-1.1	10K	300	1.8	540	203	0.42	800	Hines	6:1	OMS	C	7B/2-19/2
-1.2		200		360	165							7B/2-19/2
-1.3		100		180	110							7B/2-19/1
-2.1		400	1.3	520	200							7B/2-19/3
-2.2		300		390	171							7B/2-19/3
-2.3		200		260	135							7B/2-19/3
-2.4		100		138	82							7B/2-19/3
-3.1	6K	300	1.8	540	203							7B/2-19/4
-3.2		200		360	165							7B/2-13/4
-3.3		100		180	110							7B/2-19/4
-4.1		500	1.3	650	260							7B/2-20/1
-4.2		400		520	200							7B/2-19/4
-4.3		300		390	171							7B/2-19/4
-4.4		200		260	135							7B/2-19/4
-4.5		100		130	82							7B/2-19/4
-5.1	2K	400		520	200					RCS		7B/2-20/1
-5.2		100		130	82							7B/2-20/1
-6.1	1K	400		520	200							7B/2-20/1
-6.2		100		130	82							7B/2-20/1
-7.1	6K	300	1.8	540	203					OMS		7B/3-12/1 (1),(5)
-7.2												7B/3-12/2 (2),(5)
-7.3												7B/3-12/2 (4),(5)
-8.1												7B/3-13/1 (1)
-8.2												7B/3-13/1 (3)

NOTES: $^*T_{in} = T_{sat} + 10°R$

(1) 50% of Coolant in Bypass
(2) 35% of Coolant in Bypass
(3) 25% of Coolant in Bypass
(4) 20% of Coolant in Bypass
(5) Hot-Gas Wall 0.250 in. thick (0.025 in. nominal)

TABLE II-IV

PROPANE AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ (lbm/sec)	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Location	Channel Min. Depth in.	Channel Loca. ε	Design Limit Type -	Design Limit Loca. -	Attach ε	T @ Throat °F	V @ Throat ft/sec
7B-1.1	300	2.303	6.85	98	-10.91	11.7	118	320	.16	ε = -1.71	.137	-2.65	Coking	TWL2	6:1	210	99
-1.2	200	2.821		119	-10.62	7.1	124	289	.20	ε = -1.29	.207	-3.30				190	140
-1.3	100	3.989		168	-10.92	6.7	127	237	.30	ε = -1.29	.280	Throat				144	218
-2.1	400	1.995		85	-10.49	34	130	330	.29	ε = -1.71	.095	-2.65				217	151
-2.2	300	2.303		98	-10.91	18	137	308	.24	ε = -1.71	.138	-2.65				194	154
-2.3	200	2.821		119	-10.62	10	136	271	.29	ε = -1.29	.206	Throat				164	205
-2.4	100	3.989		168	-10.92	9	135	216	.44	ε = -1.29	.280	Throat				118	314
-3.1	300	1.784	4.11	76	-11.40	17	161	364	.16	ε = -1.71	.097	-2.49				220	85
-3.2	200	2.185		93	-10.75	8	159	323	.15	ε = -1.29	.134	-2.65				191	107
-3.3	100	3.090		130	-11.04	4	152	262	.22	ε = -1.29	.277	-3.00				143	164
-4.1	500	1.382		59	-10.92	130	190	450	.39	L'	.053	-2.65				282	213
-4.2	400	1.524		66	-11.12	49	179	379	.28	ε = -1.71	.073	-2.65				218	144
-4.3	300	1.784		76	-11.40	27	183	354	.24	ε = -1.71	.093	-2.65				195	134
-4.4	200	2.185		93	-10.75	12	172	307	.22	ε = -1.29	.133	-2.65				165	155
-4.5	100	3.090		130	-11.04	5	161	404	.31	ε = -1.29	.280	Throat				118	230
-5.1	400	.892	1.37	38	(-9.52)	(299)	(282)	(382)	(.94)	(ε= -3.30)	(.026)	-3.30				221	130
-5.2	100	1.784		76	-11.40	8	228	310	.22	ε = -2.65	.096	-2.65				102	121
-6.1	400	.631	.68	27	(6.05)	(250)	(251)	(451)	(.78)		(.019)					214	50
-6.2	100	1.262		54	10.78	21	316	398	.36	L'	.049	L'				106	85
-7.1	300	1.784	2.05	85	~Throat	(73)	(36)	(239)	(.56)	~Throat	(.032)		Conv. Failure	ε= 1.06		-	-
-7.2			2.67		~Throat	(81)	(26)	(229)	(.59)	~Throat	(.038)			ε= 1.06		-	-
-7.3			3.29		~Throat	(93)	(20)	(223)	(.64)	~Throat	(.044)			ε= 1.06		-	-
-8.1			2.05	76	-11.40	113	331	534	.39	L'	.024		Coking	TWL2		242	77
-8.2			3.08		-11.40	32	219	422	.20	L'	.059					227	77

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

TABLE II-IV

PROPANE AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	OAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
7B-1.1	-1.07	3.84	628	3.67	610	331	7.60	657	7.63	638	532	224	106	.16
-1.2	-1.07	2.39	554	2.29	540	321	5.36	574	5.37	559	351	197	144	.20
-1.3	-1.07	1.12	426	1.08	417	284	2.94	436	2.95	426	169	153	227	.29
-2.1	-1.07	5.98	626	5.70	607	341	9.83	666	9.86	646	500	222	184	.27
-2.2	-1.07	3.78	625	3.61	606	326	7.60	654	7.63	634	378	200	168	.24
-2.3	-1.07	2.34	545	2.25	530	308	5.37	565	5.38	549	247	172	212	.28
-2.4	-1.07	1.10	411	1.07	402	268	2.95	422	2.96	412	114	128	333	.42
-3.1	-1.07	4.09	671	3.92	652	388	7.93	701	7.96	681	534	225	100	.15
-3.2	-1.07	2.31	634	2.22	618	378	5.55	654	5.57	637	355	198	110	.15
-3.3	-1.07	1.03	470	1.00	461	326	2.88	480	2.89	470	174	152	169	.22
-4.1	-1.07	9.04	705	8.69	689	461	12.42	760	12.46	742	612	288	257	.34
-4.2	-1.07	6.38	670	6.11	651	400	10.25	712	10.29	692	503	224	175	.26
-4.3	-1.07	4.03	672	3.87	653	390	7.93	703	7.96	683	380	201	158	.22
-4.4	-1.07	2.27	629	2.19	613	370	5.56	649	5.58	632	253	174	160	.22
-4.5	-1.07	1.02	457	.99	448	312	2.89	467	2.90	458	122	128	239	.31
-5.1	-1.29	7.80	800	7.61	786	603	8.93	847	10.56	[illegible]2	503	234	172	.25
-5.2	-2.65	.84	799	.80	772	668	1.85	806	1.86	778	126	141	172	.22
-6.1	-3.30	4.74	800	4.40	775	500	5.64	836	5.67	809	270	451	781	.78
-6.2	-2.65	1.06	800	1.02	775	682	1.98	808	1.99	782	124	150	221	.28
-7.1	(1.06)	(5.35)	(437)	(5.35)	(437)	(395)	(5.53)	(712)	(5.53)	(712)	(467)	(239)	(403)	(.56)
-7.[illegible]	(1.06)	(5.20)	(412)	(5.20)	(411)	(358)	(5.56)	(683)	(5.56)	(683)	(459)	(229)	(422)	(.59)
-7.3	(1.06)	(5.15)	(394)	(5.14)	(394)	(335)	(5.58)	(665)	(5.58)	(664)	(447)	(223)	(454)	(.64)
-8.1	-1.29	4.94	800	4.83	788	647	7.30	831	7.32	818	530	267	133	.18
-8.2	-1.07	4.02	737	3.87	718	476	7.83	767	7.86	748	535	234	93	.14

Column notation depicted in Figure II-15.

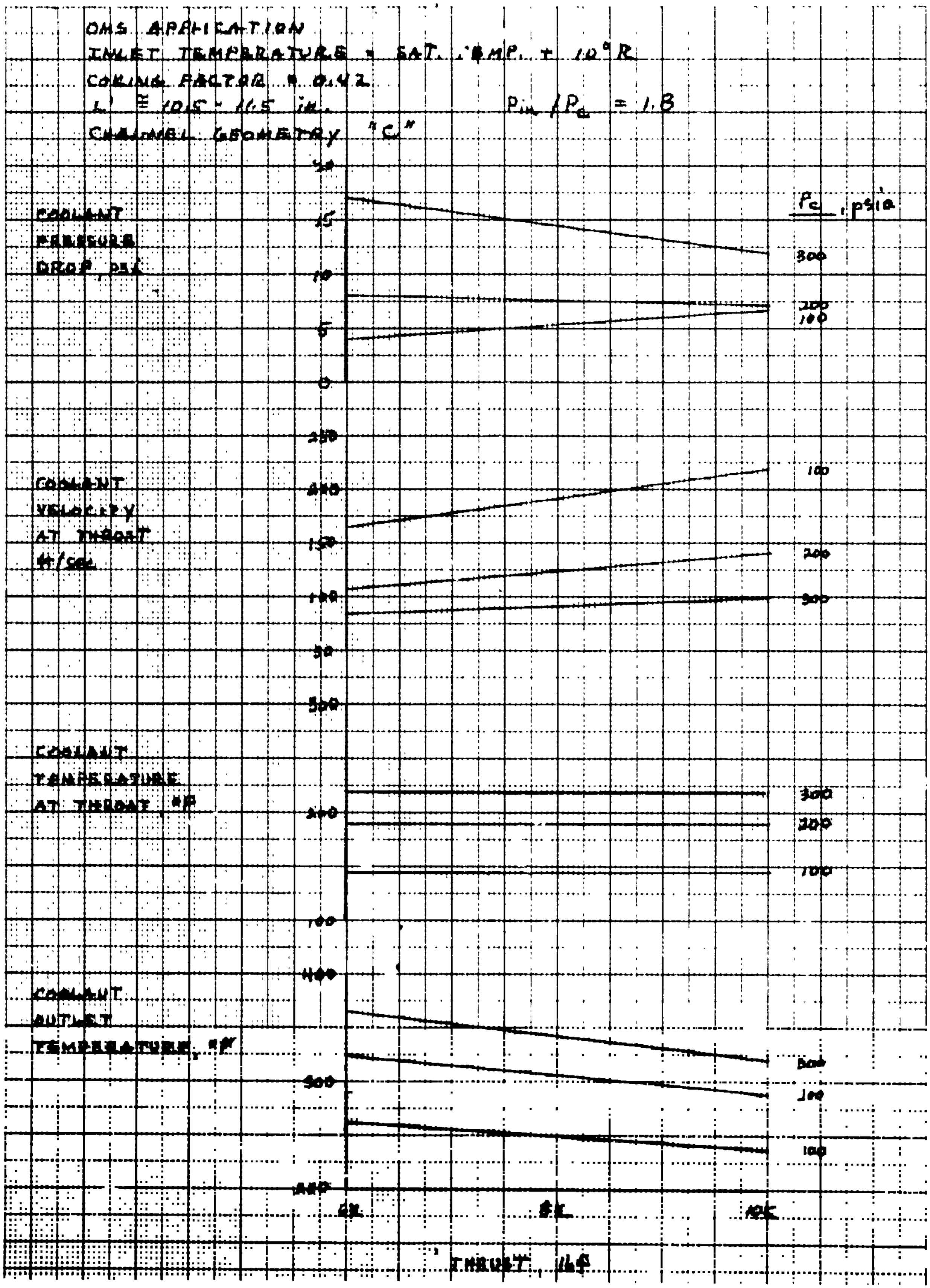


Figure II-19. Cooling Parameters for Superheated Propane at Subcritical Pressures and Wall Carbon - OMS (Sheet 1 of 2)

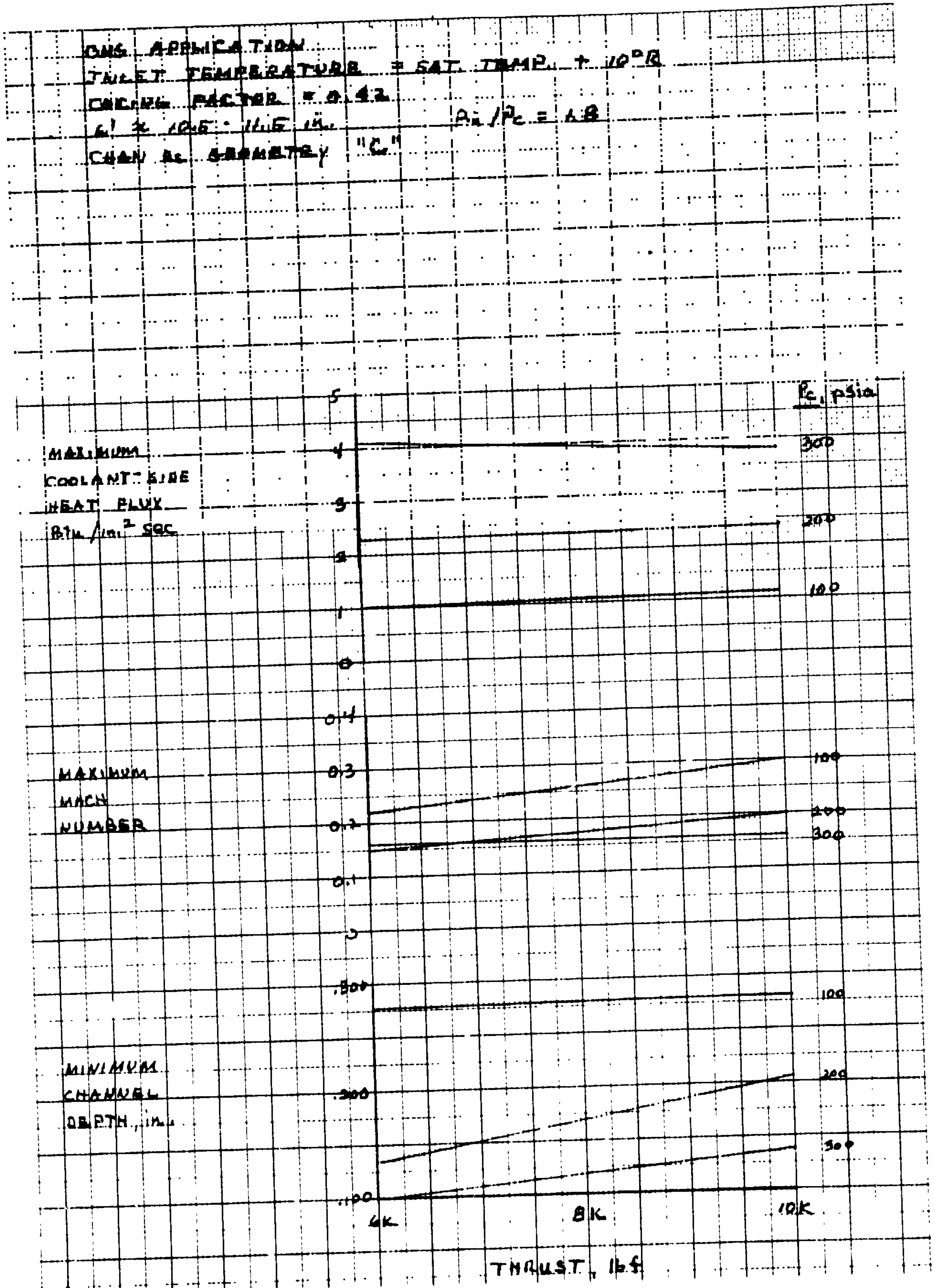


Figure II-19. Cooling Parameters for Superheated Propane at Subcritical Pressures and Wall Carbon - OMS (Sheet 2 of 2)

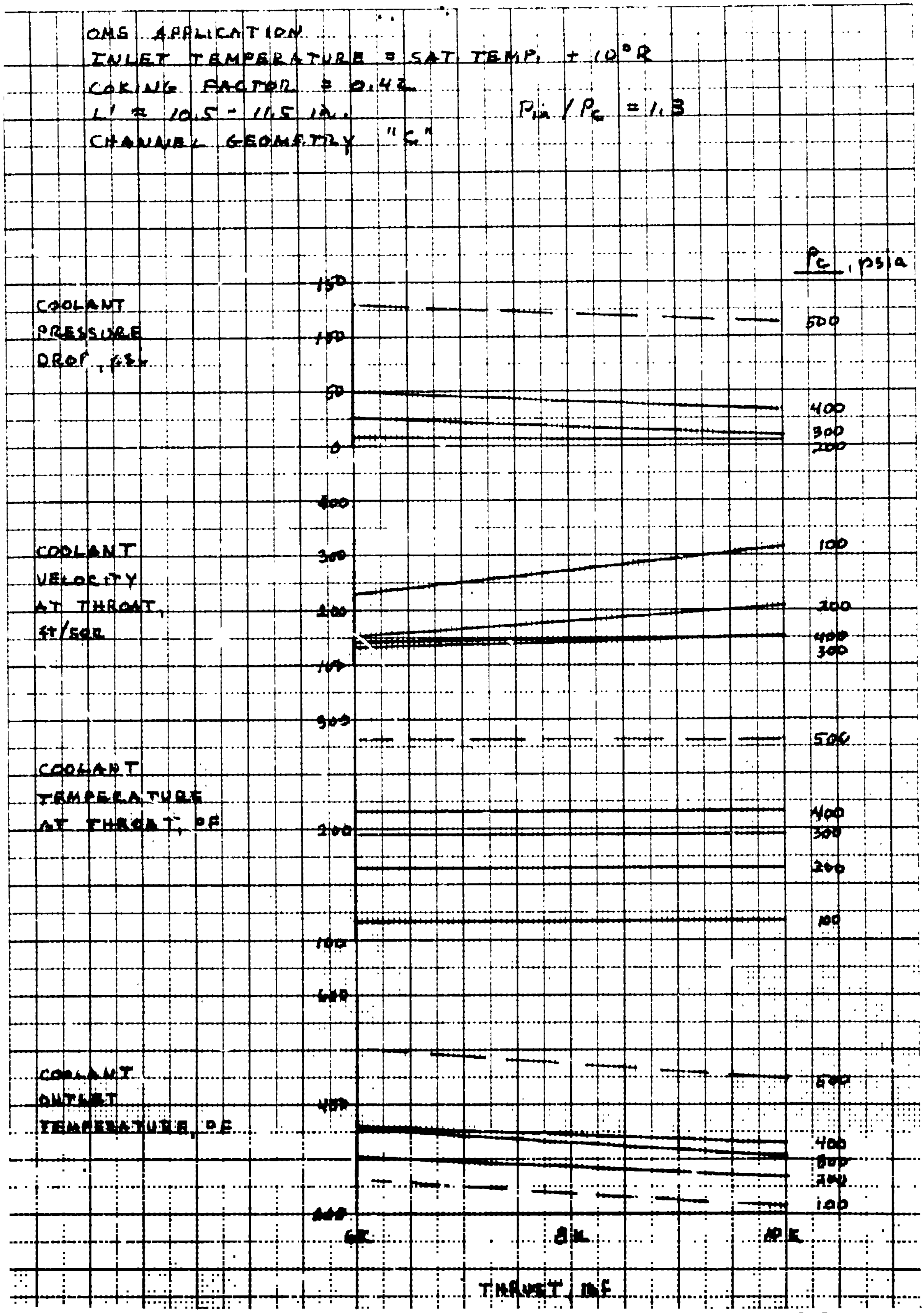


Figure II-20. Cooling Parameters for Superheated Propane at Subcritical Pressures and Wall Carbon - OMS (Sheet 1 of 2)

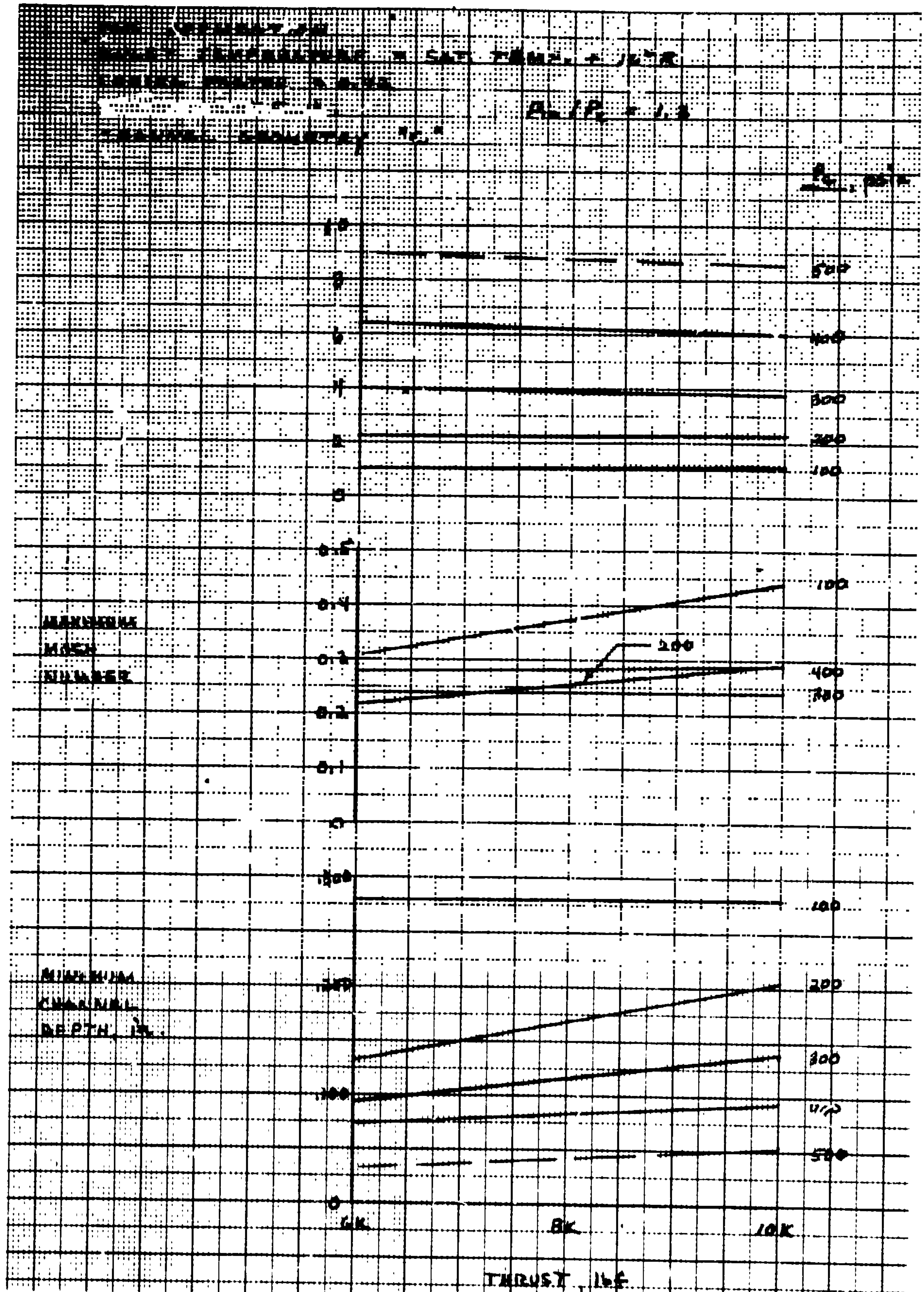


Figure II-20. Cooling Parameters for Superheated Propane at Subcritical Pressures and Wall Carbon - OMS (Sheet 2 of 2)

generally somewhat higher for P_{in}/P_c = 1.3, with all subcritical ΔP values being significantly less than those calculated for supercritical propane. Coolant-side heat fluxes are also lower, reflecting the lower gas-side fluxes at lower chamber pressures. All calculated maximum Mach number values were less than the 0.3 criteria, except for Pc = 100 psia and P_{in}/P_c = 1.3.

The cases analyzed for the RCS application showed an acceptable Mach number at Pc = 100 psia at thrust levels down to approximately 1400 lbF. Channel depths were satisfactory, as shown in Figure II-21.

c. Forced Convection and Nucleate Boiling at Subcritical Pressures

As shown in Table II-V, the majority of analyses in this heat transfer regime were conducted for an engine designed for 10K lb thrust and a chamber pressure of 300 psia. Part A indicates the primary parameter variations utilized to develop a configuration and operating state capable of meeting the analysis criteria.

In all cases, the low burnout heat fluxes predicted by the burnout correlations controlled the analysis. Channel design considerations centered on maximizing the coolant velocity to provide the V ΔT_{sub} product required for maintaining the coolant-side heat flux at 62.1% of the burnout flux. These high velocities resulted in severe overcooling, as indicated by the maximum coolant-side wall temperatures (given in Part B of Table II V) which ranged from 83 to 348°F - far below the desired limits set by the coking (800°F) or cycle life/creep considerations.

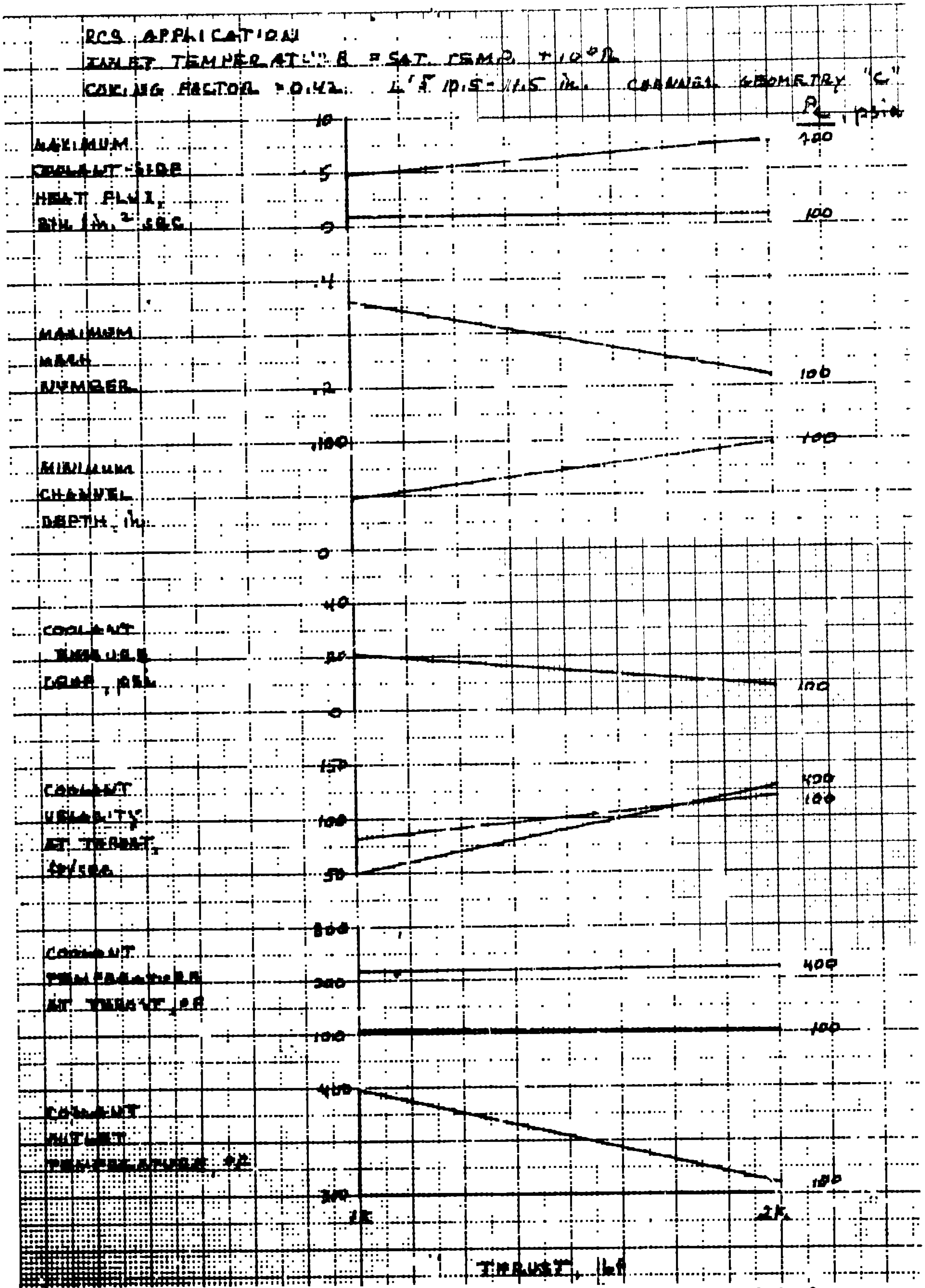


Figure II-21. Cooling Parameters for Superheated Propane at Subcritical pressures and Wall Carbon - RCS

TABLE II-V

PROPANE AT SUBCRITICAL PRESSURES WITH NUCLEATE BOILING

PART A. ANALYSIS INPUT

Case Code	F lbF	P_c psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{coke} °F	Correlation (F.C.)	ε	Engine Basis	Channel Design	BOSF -	Boiling Coeff. Btu/in^2-sec °F	Wall Thick. in.	Computer Run Ident.
7C-1.1	10K	300	.8	540	-295	0.42	900	Hines	Rad.Attach.	OMS	D	1.6	2.0	.025	7C/2-28/2
-1.2													.05		7C/2-28/4
-1.3					-44										7C/2-29/1
-1.4					-295						A	1.0			7C/2-29/3
-1.5														.250	7C/3-3/1
-1.6											C				7C/3-3/1
-1.7											D				7C/3-3/1
-2.1		100		180							C	1.6	2.0	.025	7C/2-27/2
-2.2															7C/2-29/2
-3.1	6K	300		540							A				7C/2-27/1
-3.2															7C/2-27/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	ε_f (last calc.)	ΔP/Pc to ε_f	ΔT to ε_f °F	T @ ε_f °F	M_{max} -	M_{max} Loc.	Channel Min Depth in.	Channel Loc. ε	Design Type -	Limit Loc.	V ΔT_{sub} @ ε_f f °F/sec	Rad. Attach ε_A	Max. Coolant Flux Btu/in^2-sec	Max. Coolant-Side Wall Temp. °F
7C-1.1	2.303	6.85	91	1.16	76	42	207	.01	ε=1.16	.039	3.77	BOSF	ε_f	37,000	9.25	3.13	196
-1.2				1.09	177	44	209	.03	ε=1.09	.030	1.09			70,000		5.56	280
-1.3				2.21	135	28	444	.04	ε=2.21	.018	2.21			25,900		2.27	196
-1.4			234	-3.30	310(1)	189(1)	354(1)	.02	(1)	.015	(1)		(1)	20,100		5.77	314
-1.5			257	-3.30	386(2)	147(2)	312(2)	.02	(2)	.016	(2)		(2)	20,600		6.33	324
-1.6			107	1.29	328	65	230	.03	ε=1.29	.017	1.29		ε_f	71,600		7.70	339
-1.7			100	-1.05	290	55	220	.03	ε=-1.05	.027	-1.05			74,800		8.89	348
-2.1	3.989		168	1.06	41	13	176	.01	ε=1.06	.023	1.06			28,460	2.14	2.38	83
-2.2			158	1.03	102.5	14	179	.02	ε=1.03	.026	1.03			42,600		3.50	147
-3.1	1.784	4.11	182	1.09	99	47	212	.02	ε=1.09	.018	1.09			49,700	9.89	4.08	184
-3.2				1.09	100	47	341	.02	ε=1.09	.016	1.09			49,900		4.13	184

(1) L' = -10.91 in.
(2) L = -7.75 in.

Negative values of ε refer to area ratios between throat and injector.

It was noted the burnout correlation was supported by data to V ΔT_{sub} products of about 3500 ft °F/sec. The calculation values of the product at the last station analyzed range from 20,000 to nearly 75,000. The applicability of the burnout equation at these very high V ΔT_{sub} values is questionable.

The effect of arbitrarily forcing the coolant to operate at the burnout limit was studied in Cases 7C-1.4 through 7C-1.7. Case 1.4 ran to completion, but the minimum channel depth was only 0.015 in. The wall thickness was increased in Case 1.5 to improve the circumferential fin effect; however, the maximum flux and pressure drop increased with no effect on channel depth. No benefit was gained by enlarging the channel cross section in Cases 1.6 and 1.7.

2. Methane

a. Supercritical Pressures

Analyses were performed at thrust levels of 6 and 10K for chamber pressures of 700 and 1000 psia, with inlet pressures 1.8 times the chamber pressure. The inlet temperature was -259°F (normal boiling point) with a constant wall carbon factor of 0.765, i.e., the bulk temperature rise calculated was based on a flux at 76.5% of the "clean wall" flux. The coking temperature was 1300°F.

Input data are given in Part A of Table II-VI as Cases 11A-1 and 11A-2 for the OMS application and as Cases 11A-3 and 11A-4 for the RCS application. Calculated data are given in Parts B and C of the table.

<u>TABLE II-VI</u>

METHANE AT SUPERCRITICAL AND SUBCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	State	F lbF	Pc psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{Coke} °F	Corre-lation	ε -	Engine Basis	Channel Design	Computer Run Ident.
11A-1.1	$P > P_{crit}$	10K	1000	1.8	1800	-259	.765	1300	Lox	Red. Attach.	OMS	A	11A/3-21/1
-1.2			700		1260								
-2.1		6K	1000		1800								11A/2-21/1
-2.2			700		1260								
-3.1		2K	800		1440						RCS		
-4.1		1K	400		720								11A/2-21/2
11B-1.1	$P < P_{crit}$	10K	400		720	-107			Hines	6:1	OMS	C	11B/2-21/1
-1.2			200		360	-151							
-2.1		6K	400		720	-107							
-2.2			200		360	-151							
-3.1		3K	300		540	-119					RCS		
-4.1		1K											11B/3-31/1
-4.2							1.0						

TABLE II-VI

METHANE AT SUPERCRITICAL AND SUBCRITICAL PRESSURES

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Pc Psia	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels	L' in.	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loc	Design Type -	Limit Loc. -	Rad. Attach ε	T @ Throat °F	V @ Throat ft/sec
11A-1.1	1000	1.262	5.86	129	-10.78	.283	302	43	.20	L'	.040	ε=-2.65	Cycle Life	TWL2-TBS	32.1	-162	123
-1.2	700	1.508	5.86	154	-11.07	.159	289	-30	.14	L'	.051	Barrel	Cycle Life	TWL2-TBS	22.4	-185	61
-2.1	1000	.977	3.52	101	-10.45	.464	401	-142	.27	L'	.027	ε=-2.65	Cycle Life	TWL2-TBS	34.0	-157	132
-2.2	700	1.168	3.52	120	-10.67	.324	325	66	.19	L'	.028	Barrel	Cycle Life	TWL2-TBS	24.0	-169	76
-3.1	800	.631	1.17	66	(.31)	(.149)	(118)	(-141)	(.08)	L'	.019	L'	Cycle Life	TWG3	30.5	-160	134
-4.1	400	.631	.59	66	(-.76)	(.06)	(87)	(-172)	(.03)	L'	.015	L'	Cycle Life	TWG3	11.7	-208	10
11B-1.1	400	1.995	5.86	85	-10.49	.068	243	136	.14	L'	.120	ε=-2.65	Cycle Life	TWL2-TBS	N/A	-89	110
-1.2	200	2.821	5.86	119	-10.62	.045	230	79	.17	ε=-1.29	.266	ε=-2.65	Cycle Life	TWL2-TBS	N/A	-121	150
-2.1	400	1.545	3.52	66	-11.12	.090	347	240	.17	L'	.091	Barrel	Cycle Life	TWL2-TBS	N/A	-88	96
-2.2	200	2.185	3.52	93	.75	.040	304	142	.13	ε=-1.29	.205	ε=-3.00	Cycle Life	TWL2-TBS	N/A	-119	117
-3.1	300	1.262	1.76	54	-10.78	.090	493	307	.17	L'	.083	ε=-2.65	Cycle Life	TWG3	N/A	-80	104
4.1	↓	.728	.59	32	-10.16	.400	737	619	~.3	L'	.027	Barrel	Cycle Life	TWG3	N/A	-98	43
4.2	↓	.728	.59	32	(7.6)	.337	732	514	~.3	L'	.027	Barrel	Cycle Life	TWG3	N/A	-90	46

TABLE II-VI

METHANE AT SUPERCRITICAL AND SUBCRITICAL PRESSURES

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{C,\ max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
11A-1.1	-1.07	11.14	342	10.87	330	27	23.48	429	23.54	416	1737	-154	148	.05
-1.2	-1.07	5.45	353	5.33	340	-1	17.10	409	17.14	396	1242	-176	74	.02
-2.1	-1.07	12.82	491	12.59	479	229	24.01	583	24.07	571	1725	-148	165	.06
-2.2	-1.29	7.30	715	7.22	706	492	15.87	774	15.90	765	1228	-152	100	.04
-3.1	-1.29	15.21	908	15.15	904	808	19.10	997	19.12	993	1321	-141	201	.08
-4.1	-1.29	4.47	964	4.46	962	913	6.78	994	6.78	991	709	-191	60	.02
11B-1.1	-1.07	5.66	389	5.39	367	26	10.29	429	10.34	406	711	-82	125	.12
-1.2	1.00	2.58	200	2.47	186	-25	5.46	220	5.47	206	353	-121	150	.15
-2.1	-1.07	5.99	437	5.73	414	92	10.73	479	10.78	455	712	-80	122	.12
-2.2	1.00	2.47	277	2.37	268	27	5.66	297	5.68	281	356	-119	117	.11
-3.1	-1.07	4.16	579	4.02	557	268	8.66	611	8.70	588	535	-67	128	.11
4.1	-3.3	3.32	973	3.08	948	796	4.23	1000	4.25	974	420	619	900	~.3
4.2	-3.3	3.32	973	3.08	948	796	4.23	1000	4.25	974	439	614	830	~.3

The parameters for the supercritical pressure analyses for the OMS cases are shown as solid curves in Figure II-22. Data trends are similar to those shown in Figure II-21 for propane. Using the same channel geometry, coolant pressure drops are less for methane than for propane.

These limited data indicate the feasibility of using methane at supercritical pressures as a coolant for the OMS application. When applied to the RCS case, however, with thrust and Pc combinations of 2K and 800 psia and 1K and 400 psia, the design program for this channel layout provides unacceptable minimum channel depths as flow area is reduced in order to generate the velocity necessary for maintaining the gas-side wall temperature below 1000°F. Iteration on channel layout may provide a configuration within analysis criteria.

b. Subcritical Pressures

Chamber pressures of 400 and 200 psia were evaluated at the 6 and 10K thrust levels by applying the input parameters in Part A of Table II-VI. Inlet temperatures represent the saturation temperature plus the 10 degrees of superheat. The design limit constraint is the temperature differential between the channel gas-side wall temperature and the nickel closeout temperature (Figure II-10). Pressure drops were low and channel depths satisfactory. These data are plotted as the dashed curves in Figure II-22.

Analyses for the RCS application were performed at 1 and 3K lb thrust at Pc = 300 psia. Channel depths in the chamber were satisfactory at the 3K thrust level but only marginal at 1K. Associated with the shallow channel depths were high pressure drops and Mach numbers.

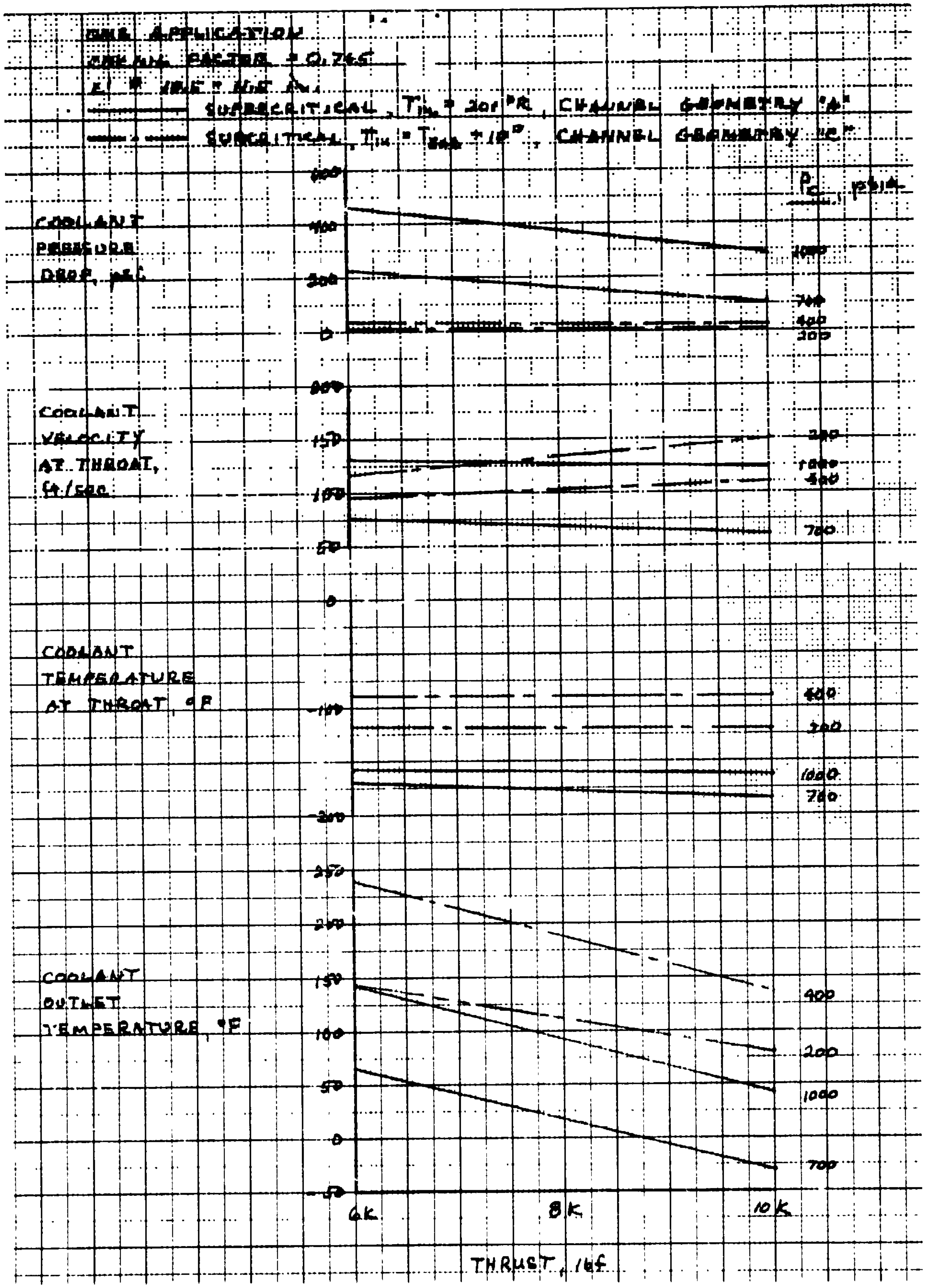


Figure II-22. Cooling Parameters for Methane with Wall Carbon - OMS(Sheet 1 of 2)

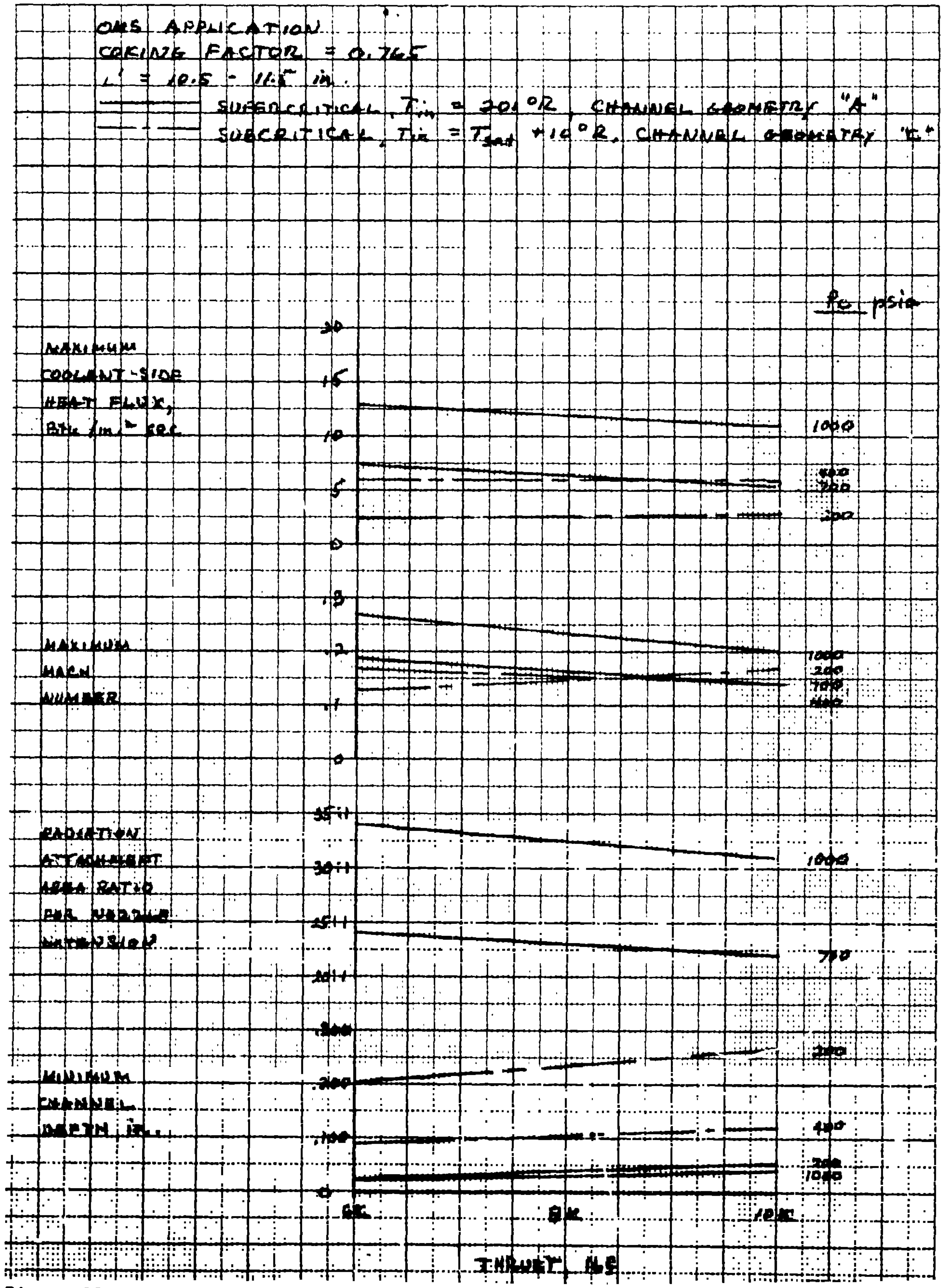


Figure II-22. Cooling Parameters for Methane with Wall Carbon - OMS (Sheet 2 of 2)

3. RP-1

Analysis input and computed results for nozzle design analyses of RP-1 at supercritical pressures are given in Table II-VII. For the two cases in which complete solutions were obtained (F = 10K lbF and Pc = 500 and 315 psia), the first (Case 6A-1.2) resulted in an unacceptable pressure drop and a maximum liquid velocity just under the limiting criterion of 200 ft/sec. A channel geometry modification, a decrease in chamber pressure, and an increase in the coking temperature to 800°F (Case 6A-4.2) resolved these problem areas and gave satisfactory results. In all cases, wall temperatures specified by the coking temperature controlled the solution. Bulk temperature increases were moderate as a result of the flux reduction obtained with a wall carbon factor of 0.25. The ΔT_b for Case 6A-1.1 (Factor of 0.25) from ε = 33:1 to the throat was 36.5°F, compared to 138.5°F for Case 6A-3.1 (Factor = 1.0).

Analyses at subcritical pressures were not successful due to solution convergence problems encountered at the first station. A typical analysis input attempted is shown in Table II-VII as Case 6C-1.1. Time constraints precluded resolving the nature of the computational problems, thus preventing achievement of analytical solutions.

4. Ammonia

Analysis input and selected nozzle design parameters are given in Table II-VIII for superheated ammonia vapor at subcritical pressures. Note that these results are for ammonia in Zr-Cu chambers; computer solutions could not be accomplished with stainless steel as the material of construction. The inlet temperatures for ammonia incorporate more superheating than was the case for propane and methane. These higher superheats were necessary to prevent the generation of erroneous property data caused by interpolations between liquid and gas phase data values.

TABLE II-VII

RP-1 AT SUPERCRITICAL PRESSURES

PART A. ANALYSIS INPUT

Case Code	State	F lbF	P_c psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Carbon Factor -	T_{coke} °F	Corre-lation	Engine Basis	Channel Design	Computer Run Ident.
6A-1.1	$P > P_{crit}$	10K	1000	1.8	1800	70	0.25	550	Hines	OMS	A	6A/2-26/1
-1.2			500		900							6A/2-27/1
-2.1		6K	1000		1800							
-2.2			500		900							
-3.1		10K	1000		1800		1.0					
-4.1		10K	315		567	60	0.25	550			A'	6A.4-2/1
-4.2			315		567			800				6A/4-2/2
6C-1.1	$P < P_{crit}$	10K	100		180			550			A	6C/4-9/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in.	$\dot{W}_c$ lbm/sec	No. of Channels -	L' in.	$\Delta P/Pc$ @ L'	ΔT to L' °F	T @ L' °F	V_{max} ft/sec	V_{max} Loc.	Channel Min. Depth in.	Channel Loc.	Design Type -	Limit Loc. -	Rad Attach. ϵ	T @ Throat °F	V @ Throat ft/sec
6A-1.1	1.262	7.30	129	(Throat)	(.707)	(37)	(107)	(335)	Throat	(.015)	Throat	Coking	TWL2	31.0	107	335
-1.2	1.784	7.30	182	-10.44	1.78	110	180	197	ϵ=-.9	.017	ϵ=-1.71			15.3	98	157
-2.1	.977	4.38	101	(ϵ=1.09)	(.271)	(43)	(113)	(191)	ϵ=1.09	(.019)	ϵ=1.09			33.3	-	-
-2.2	1.382	4.38	141	(Throat)	.440	(30)	(100)	(185)	Throat	(.015)	Throat			16.2	100	185
-3.1	1.262	7.30	129	(ϵ=-1.15)	(1.090)	(158)	(228)	(361)	ϵ=-1.15	(.015)	ϵ=-1.07			31.0	209	293
-4.1	2.248	7.30	114	(-.80)	1.63	(30)	(91)	(232)	ϵ=-1.15	.032	ϵ=-1.11			9.33	84	168
-4.2	2.248	7.30	114	-10.83	.260	98	158	82	ϵ=-1.80	.035	ϵ=-2.20			9.33	84	32
6C-1.1	No Design Available															

TABLE II-VII (cont.)

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max.}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec
6A-1.1	(1.00)	(16.39)	(550)	(16.25)	(647)	(460)	(20.27)	(643)	(20.28)	(639)	(1093)	(107)	(335)
-1.2	-1.29	8.40	550	8.35	548	493	10.89	599	10.90	596	445	106	157
-2.1	(1.09)	(9.59)	(550)	(9.49)	(546)	(471)	(13.07)	(607)	(13.08)	(603)	(1529)	(113)	(191)
-2.2	(1.00)	(8.83)	(552)	(8.78)	(548)	(495)	(11.52)	(603)	(11.52)	(600)	(680)	(100)	(185)
-3.1	(-1.15)	(17.98)	(552)	(17.83)	(549)	(469)	(20.83)	(650)	(20.84)	(646)	(710)	(228)	(361)
4.1	Throat	(9.4)	(549)	(9.4)	(550)	(520)	(7.4)	(591)	(7.44)	(593)	(<140)	(90)	(230)
4.2	-1.8	5.02	800	5.00	797	730	5.84	828	5.84	824	505	99	82
6C-1.1	No Design Available												

* Case 6A - Analyses at supercritical pressures

Case 6C - Analyses at subcritical pressures with forced convection and nucleate boiling

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by notation in L' column. Column nomenclature of Part C depicted in Figure II-15.

TABLE II-VIII

AMMONIA AS SUPERHEATED VAPOR AT SUBCRITICAL PRESSURES (in Zr-Cu)

PART A. ANALYSIS INPUT

Case Code	F lbF	Pc psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Correlation	ε -	Engine Basis	Channel Design	Computer Run Ident.
12B-1.1	10K	900	1.8	1620	280	Hines	6.0	OMS	C	12B/4-9/1
-2.1	6K	900	1.8	1620	280	Hines	6.0	OMS	C	12B/4-10/1
-3.1	1K	400	1.8	720	260	Hines	6.0	RCS	C	12B/4-10/1
-4.1	1K	100	1.8	180	240	Hines	6.0	RCS	C	12B/4-10/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius	$\dot{W}_c$ lbm/sec	No. of Channels	L' in	ΔP/Pc @ L'	ΔT to L' °F	T @ L' °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loc.	Design Limit Type	Design Limit Loc.	T @ Throat °F	V @ Throat ft/sec
12B-1.1	1.330	12.00	57	-10.86	.200	80	360	.40	ε=-0.66	.100	Inj.	Cycle Life	TWG2-TBS	286	476
-2.1	1.030	7.20	44	-10.51	.331	112	392	.40	ε=-0.51	.064	Inj.	↓	↓	286	452
-3.1	.631	1.20	27	(-8.62)	.520	(393)	(653)	.55	L'	.041	Inj.	↓	TWG2	282	467
-4.1	1.262	1.20	54	-10.78	.080	334	(574)	.21	L'	.142	Inj.	↓	TWG2	264	214

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ε @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °F	QAIC Btu/in^2-sec	TWLC °F	TBS °F	QAO2 Btu/in^2-sec	TWG2 °F	QAO3 Btu/in^2-sec	TWG3 °F	P psia	Tc °F	V ft/sec	M -
12B-1.1	-1.07	15.74	538	15.14	528	283	17.96	623	18.01	612	1562	274	303	.26
-2.1	-1.07	16.67	541	16.67	531	290	18.79	630	18.84	619	1571	274	290	.25
-3.1	-1.07	6.27	801	6.02	781	570	9.68	844	10.37	823	665	286	529	.34
-4.1	-1.07	.61	807	.60	795	546	2.99	816	3.00	804	177	276	241	.15

( ) Solution did not converge. Data in parentheses are those for last station converged as indicated by value of axial distance from throat given in L' column.

Negative values in L' column refer to axial distance from throat to injector. Negative values for ε also refer to area ratios between throat and injector.

Column notation for Part C depicted in Figure II-15.

Solutions in three of the four analyses performed gave maximum Mach numbers greater than the 0.3 limiting criterion. These high values for the Mach modulus are due largely to the low density of ammonia at the relatively high gas temperatures. However, an RCS application (Case 12B-4.1), at a thrust of 1K lbF and a chamber pressure of 100 psia, gave a satisfactory solution with an outlet ammonia temperature of 574°F. The heat flux for this case was quite low, however, as is shown in Part C of Table II-VIII.

A limited number of representative analyses on forced convection and nucleate boiling of liquid ammonia were performed, with data given in Table II-IX. The burnout safety factor, set equal to unity for the most favorable analysis, controlled the channel depth at each station, resulting in a highly overcooled channel. In one analysis (Case 12C-1.1), a computer solution was achieved for each station; in the other three cases evaluated, solution convergence problems were encountered for the nozzle between the throat and the cylindrical chamber section. Unlike the case for propane, the $V\ \Delta T_{sub}$ values calculated for ammonia were within the data range of the burnout correlating equations, providing a higher degree of confidence in the burnout criterion.

TABLE II-IX

AMMONIA AT SUBCRITICAL PRESSURES WITH NUCLEATE BOILING (in Zr-Cu)

PART A. ANALYSIS INPUT

Case Code	F lbF	P_c psia	P_{in}/P_c -	P_{in} psia	T_{in} °F	Correlation (F.C.)	ϵ -	Engine Basis	Channel Design	BOSF -	Boiling Coeff. Btu/in^2-sec-°F	Computer Run Ident.
12C-1.1	10K	300	1.8	540	-28	Hines	5.89	OMS	A	1.0	0.05	12C/4-2/1
-2.1	6K	800	1.2	1440	↓	↓	18.98	OMS	A	↓	↓	12C/4-2/2
-3.1	2K	800	1.8	1440			21.29	RCS	A"			12C/4-14/1
-3.2	↓	500	1.8	900			12.90	RCS	A"			12C/4-14/1

PART B. NOZZLE DESIGN PARAMETERS

Case Code	Throat Radius in	$\dot{W}_c$ lbm/sec	No. of Channels	ϵ_f (last calc.)	$\Delta P/P_c$ @ ϵ_f	ΔT to ϵ_f °F	T @ ϵ_f °F	M_{max} -	M_{max} Loc.	Channel Min. Depth in.	Channel Loc ϵ	Design Limit Type -	Design Limit Loc	T @ Throat °F
12C-1.1	2.303	12.00	234	-3.30	.015	136	109	.005	Inj.	.145	Inj.	BOSF	Ea.Sta.	-10
-2.1	1.093	7.20	112	-1.37	.025	50	22	.010	ϵ -1.37	.127	Throat	BOSF	Ea.Sta.	5
-3.1	.631	2.40	66	-2.37	.029	69	41	.012	ϵ=-1.07	.049	ϵ=-2.37	BOSF	Ea.Sta.	10
-3.2	.798	2.40	83	-1.01	.018	38	11	.008	ϵ=-1.01	.076	ϵ=-1.01	BOSF	Ea.Sta.	5

PART C. PARAMETERS AT MAXIMUM COOLANT-SIDE HEAT FLUX STATION

Case Code	ϵ @ $Q/A_{c,max}$	QAI2 Btu/in^2-sec	TWL2 °R	QAIC Btu/in^2-sec	TWLC °R	TBS °F	QA02 Btu/in^2-sec	TWG2 °F	QA03 Btu/in^2-sec	TWG3 °F	P psia	T_c °F	V ft/sec	M -
12C-1.1	-1.07	5.80	110	5.73	109	-1.4	7.42	143	7.43	141	536	-6	25	.004
-2.1	1.00	11.24	231	10.95	225	18	17.31	302	17.33	295	1423	6	54	.009
-3.1	-1.07	12.71	534	12.41	528	356	9.02	614	19.05	607	1414	15	67	.012
-3.2	1.00	8.42	179	8.21	169	45	12.99	233	12.88	222	891	5	43	.007

Column notation for Part C depicted in Figure II-15.

III. TASK I.2 HEATED TUBE TESTING

A. OBJECTIVES AND SUMMARY

The objectives of the experimental heat transfer investigation were (1) to measure the forced convection heat transfer coefficient of propane at subcritical and supercritical pressures; (2) to measure the nucleate boiling and burnout heat flux characteristics of subcritical propane; (3) to investigate propane coking characteristics at elevated wall temperatures; and (4) to correlate these data in a manner meaningful to the design of regeneratively cooled thrust chambers.

Data generated from the cooling comparison effort (Task I.1) of this contract was used to identify propane cooling regimes and the associated parameters of particular interest to the OMS/RCS Engine application.

A total of 12 individual heat transfer tests were conducted during this effort. These are summarized in Table III-I.

Forced convection heat transfer coefficients were measured over the following range of nominal test conditions:

Pressure:	450 to 1800 psia
Bulk Temperature:	-250 to 250°F
Velocity:	50 to 150 ft/sec
Wall Temperatures:	Ambient to 1200°F
Heat Flux:	0.2 to 10 Btu/in^2 sec

Subsequent analysis of the data led to a correlation predicting 95% of the data within ± 24%.

TABLE III-I

HEATED TUBE TEST SUMMARY

Test Number HTRS-797-	Nominal Test Conditions** Inlet Pressure psia	Inlet Temp °F	Inlet Vel ft/sec	Heat Flux (Max) BTU/in^2-sec	Test Objectives*
101	1000	Ambient	50	4	SC-FC: Evaluate heat transfer coefficient
102	1000	Ambient	150	10	SC-FC: Velocity effects
103	750-1800	Ambient	100	10	SC-FC: Velocity and pressure effects
104	750-1800	-44 (NBP)	50	6	SC-FC: Bulk temperature effects
105	750-1800	-44 (NBP)	100	10	SC-FC: Bulk temperature effects
106	500	-44 (NBP)	100	7	Sub-FC: NUB: FB: Evaluate heat transfer coefficients and determine $\phi_{B.O.}$
107	1800	Ambient	50	6	SC-FC: Evaluate coking @ low velocity
108	1800	Ambient	150	10	SC-FC: Evaluate coking @ high velocity
109	500	-175	125	12	Sub-FC: NUB: FB: Bulk temperature effects
110	500	-250	100	6	Sub-FC: Bulk temperature effects
111	500	-250	100	11	Sub-FC: NUB: FB: Bulk temperature effects
112	1800	Ambient	50	6	SC-FC: Evaluate coking with instrument grade (99.5% purity) propane

*Heat Transfer Modes

Supercritical Forced Convection (SC-FC)
Subcritical Forced Convection (Sub-FC)
Nucleate Boiling (NUB)
Film Boiling (FB)

**Propane Grade

Tests: 101-111 (Natural)
Test: 112 (Instrument)

Nucleate boiling coefficients and effective critical heat flux (transition from nucleate to film boiling) were measured over the following test conditions:

Pressure:	450 to 500 psia
Bulk Temperature:	-240 to -12°F
V ΔT:	20,000 to 40,000 Ft-°F/sec

The number of data points over the above range are few compared to those for forced convection. Nucleate boiling data, plotted versus wall superheat, show property dependence. Correlation techniques for these data have not been thoroughly evaluated due to limited data range and quantity. The critical heat flux measured for propane was considerably higher (80-100%) than had been originally predicted on the basis of the limited low flux data. This fact considerably enhances the prospect of regenerative thrust chambers cooled with subcritical propane.

Coking data were measured over the following range of test conditions:

Pressure:	1800 psia
Bulk Temperature:	Ambient to 230°F
Wall Temperature:	350 to 1000°F
Velocities:	50 and 150 ft/sec
Propane grade:	Instrument (99.5%)
	Natural (96%)

Coking was observed at low wall temperatures $\sim$ 500°F. Coking rates appeared comparable to those rates published for RP-1. The level of purity did not appear to affect the wall temperature at which coking was initiated; however, measured rates were generally lower with instrument grade.

B. TEST FACILITY

1. ALRC Heat Transfer Test System

The heat transfer test facility, shown schematically in Figure III-1, consists of the following: 1) a 150 gallon 5500 psi, vacuum-jacketed, propane-run tank with a high-pressure helium pressurization system; 2) a jacketed run line; 3) an enclosed, electrically heated test section; 4) a 225 Kw DC power supply; and 5) all necessary controls and instrumentation.

The test section apparatus was enclosed in a 1/2 in. thick aluminum box. The test section enclosure was covered with an acrylic window and purged with dry nitrogen to maintain an inert atmosphere. During testing, the test section was monitored continuously with a closed circuit television.

The test section was clamped into electrical connections cantilever-mounted in the test section enclosure. The upper connection was supported with flexures to permit axial movement of the heated test section tube due to thermal expansion. To ensure free axial movement, a tension force was applied to the outlet end of the test section. The inlet of the test section was maintained at ground polarity, and the outlet mixer incorporated electrical insulation to isolate the test section from downstream plumbing.

Flow control was accomplished using a 1/2 in. control valve at the test section outlet.

Bulk temperature control of the propane was provided by an LN_2 driven heat exchanger and recirculation pump system.

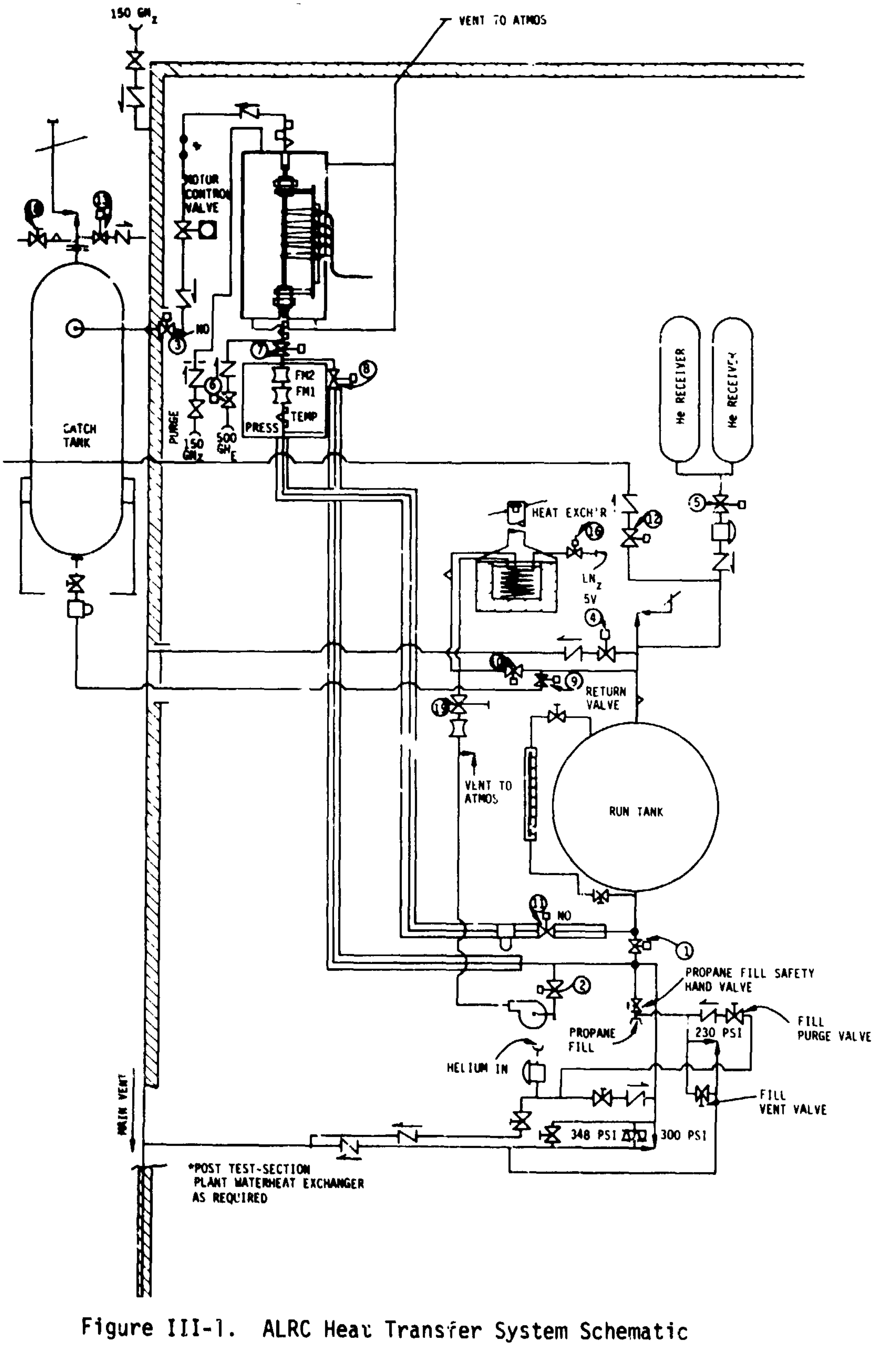


Figure III-1. ALRC Heat Transfer System Schematic

2. Test Sections

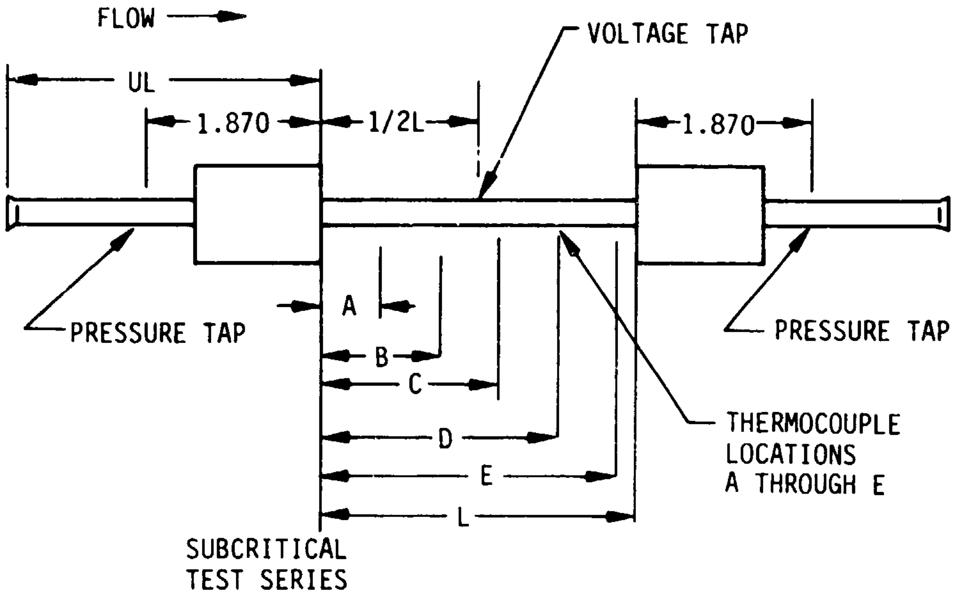
Electrically heated test sections were designed to give the greatest range of test conditions and data points without exceeding the strength of the tube or the capacity of the test facility.

The test section configuration, together with instrumentation locations for all tests, is shown in Figure III-2. With the exception of Test 111, where the test section from the previous test was used, new test sections were used for each test.

The installation of instrumentation in the test sections is shown in Figures III-3 and III-4. Pressure taps were located immediately upstream and downstream of the test section and were connected to pressure transducers with 1/8 in. dia. CRES tubing. Temperature was measured at five stations, spaced at even increments of L/ID along the outside wall of the heated section. Two measurements, located 180° apart, were taken at each station and averaged. The thermocouples were electrically insulated from the tube with a thin strip of Mica to prevent voltage from the tube interfering with thermocouple readings. To ensure good heat transfer between the tube wall and the thermocouple, the thermocouples were spring-loaded against the test section. Because the thermocouples are not directly attached to the heated tube, the measured temperature is somewhat lower than the actual wall temperature. Calibration tests for these configurations, conducted as a part of Contract NAS 3-20384, "Supercritical Oxygen Heat Transfer" (Ref. 12), allow correlation of measured data with actual wall temperature.

3. Instrumentation

The measured parameters, together with instrument type, are listed in Table III-II. In addition to the standard low frequency measurements,



TEST NO. HTB6-797-	OD in.	Wall in.	UL in.	L in.	A in.	B in.	C in.	D in.	E in.	Mat'l MONEL
101	.1875	.015	4.87	10.50	2.50	4.38	6.27	8.15	10.04	K500
102										
103										
104										
105										
106				5.00	1.57	2.36	3.14	3.93	4.71	
109										
110										
111										
107	.125			5.97	[illegible]3	2.50	3.58	4.66	5.73	
108										
112										

Figure III-2. Test Section Dimensions

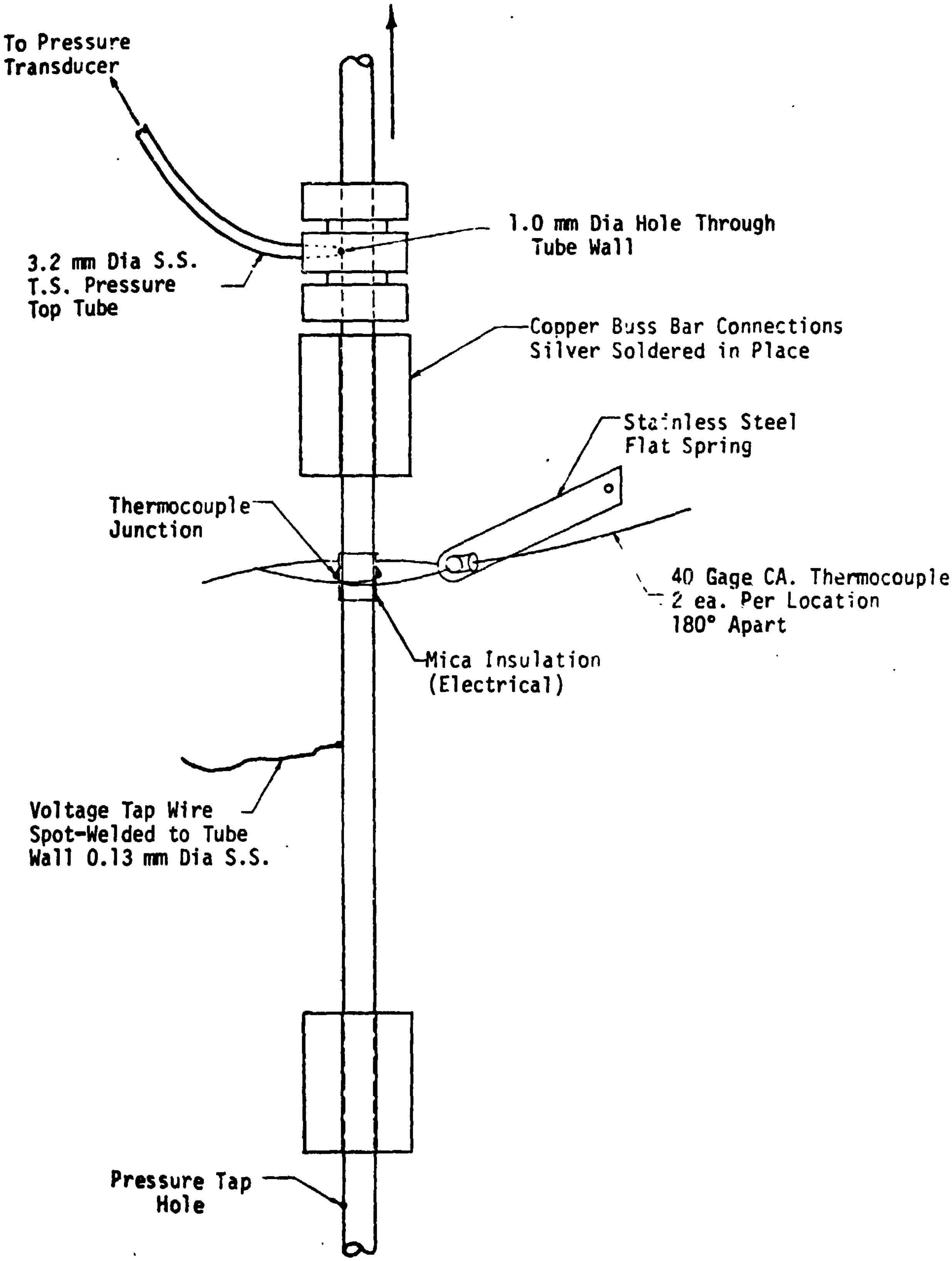


Figure III-3. Heat Transfer Test Section

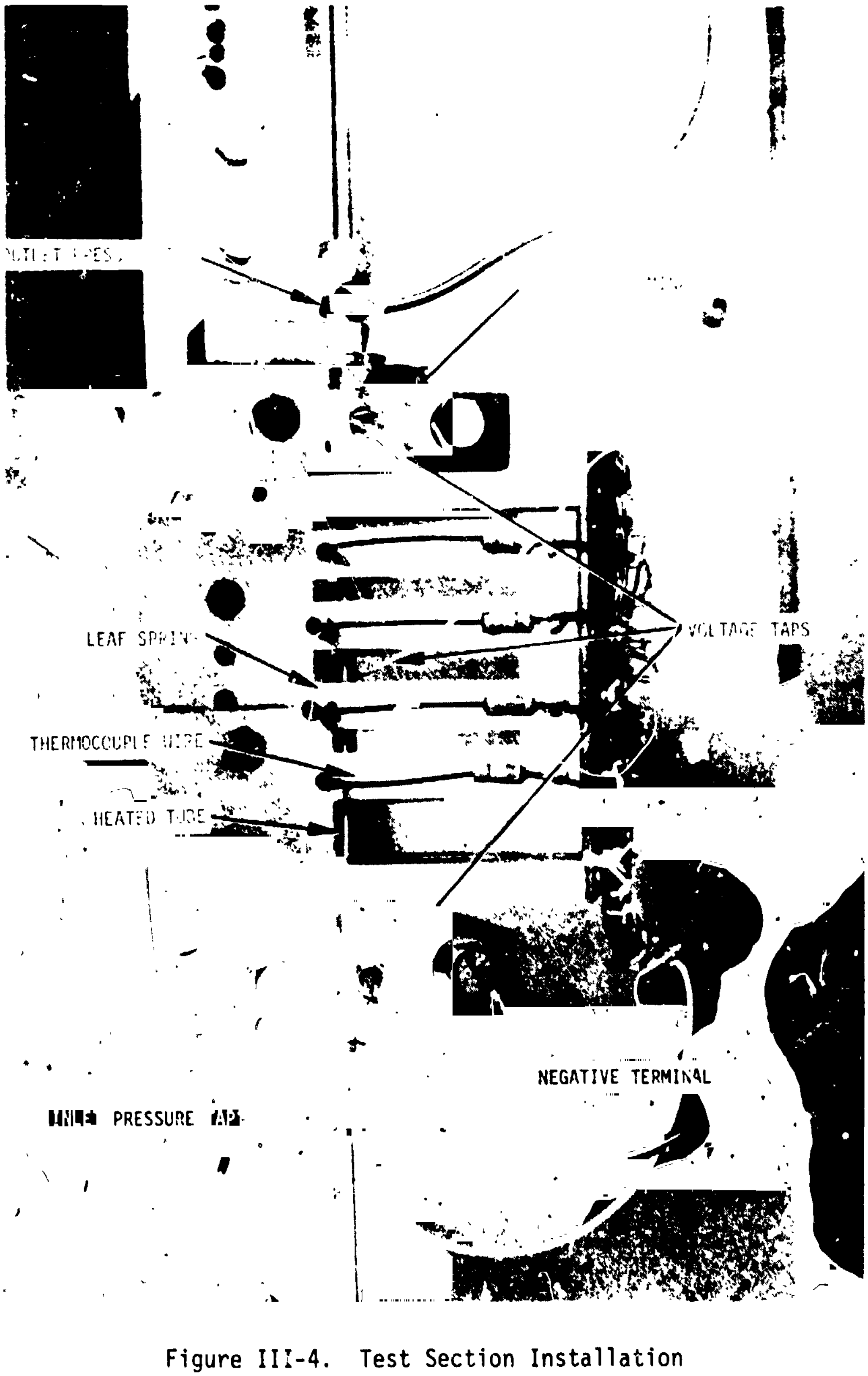


Figure III-4. Test Section Installation

TABLE III-II

PROPANE HEAT TRANSFER
INSTRUMENTATION LIST

PARAMETER	SYMBOL	TRANSDUCER TYPE	RANGE	ACCURACY ±% READING	RECORDING DEVICE TAPE	VISUAL	GRAPH	DISC	MALFUNCTION DETECTION	COMMENTS
Inlet Mixer Pressure	P_{Mi}	Strain Gauge	0-2000 psi	0.25				X		Optimize
Test Section Inlet Pressure	P_{in}	" "	0-2000 psi	0.25		X	X	X		"
Test Section Outlet Pressure	P_{out}	" "	0-2000 psi	0.25		X	X	X		"
Outlet Mixer Pressure	P_{MO}	" "	0-2000 psi	0.25				X		"
Fuel Tank Pressure	P_{FT}	" "	0-2000 psi	0.5		X		X		
Flowmeter Inlet Pressure	P_{FM}	" "	0-2000 psi	0.25				X		"
High Freq. Inlet Pressure	P_{HF1}	Piezio Electric	500 p-p psi	5	X	X	X			
High Freq. Outlet Pressure	P_{HF2}	" "	500 p-p psi	5	X	X	X			
Flowmeter Temperature	T_{FM}	RTT	165-600°R	(± .5°R)				X		
Test Section Inlet Temp.	T_{IN}	RTT	"	(± .5°R)		X	X	X		
Test Section Inlet Temp.	T_{IN-R}	Thermocouple	"	(± .5°R)				X		Redundant
Test Section Wall Temp.	T_{W1-A}	"	165-1260°R	"		X	X	X		
"	T_{W1-B}	"	"	"			X	X		
"	T_{W2-A}	"	"	"		X	X	X		
"	T_{W2-B}	"	"	"			X	X		
"	T_{W3-A}	"	"	"		X	X	X		
"	T_{W3-B}	"	"	"			X	X		
"	T_{W4-A}	"	"	"		X	X	X		
"	T_{W4-B}	"	"	"			X	X		
"	T_{W5-A}	"	"	"		X	X	X		
"	T_{W5-B}	"	"	"			X	X		
Test Section Outlet Temp.	T_{out}	RTT	165-600°R			X	X	X		
Test Section Outlet Temp.	T_{out-R}	Thermocouple						X		Redundant
Test Section Voltage	V_{TS}	Voltmeter	100 VDC	.25		X	X	X		
Center Tap Voltage	V_{CT}	"	100 VDC	.25				X		
Test Section Current	I_{TS}	Shunt	3000A	.5		X	X	X	"0"after Power Up	
Test Section Current	I_{TS-R}	"	3000A	.5				X	"0" after Power Up	Redundant
Propane Flowrate	W_{F1}		.1-1.7 #/sec	.5		X	X	X	Overspin	
Propane Flowrate	W_{F2}		.1-1.7 #/sec	.5				X	Overspin	

high frequency pressure transducers, installed in both inlet and outlet mixer sections, were used to measure pressure oscillation resulting from abnormal flow or heat transfer modes.

C. HEAT TRANSFER TESTS

The propane heated tube test program consisted of a total of twelve individual tests. Each test was designed to cover as wide a range of test conditions and variables as coolant flow time would permit.

A detailed summary of all test conditions is presented in Table III-III. At each data point, five wall temperatrue measurements along the length of the tube have been recorded; these correspond to the thermocouple positions shown in Figure III-2. Internal wall temperatures, calculated from the measured external wall temperatures, are listed in Table III-IV in conjunction with the calculated local coolant parameters. The data points listed in Table III-III are keyed to the test section local coolant parameters, shown in Table III-IV, through the ID#.

1. Supercritical Pressure Tests

Tests 101-105 were all conducted at supercritical pressure, covering a wide range of coolant bulk temperature and velocity. Wall temperature trends versus input heat flux for each test are plotted in Figures III-5 through III-9. Tests 101 and 102 were conducted at constant pressure, while special experimental techniques, developed after Test 102, allowed multiple pressure level data to be gathered during the same test. This considerably enhanced the range of parametrics and data points available for the forced convection correlation. Data trends are similar in all tests, with the heat transfer coefficient degrading at increased wall temperatures in all cases.

TABLE III-III

HEATED TUBE TEST CONDITION SUMMARY

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
HTB6-797-101	3-26-80	1-5	1	13	.0039	.216	1019.2	52.3	48.6	1010.6	53.3	-			
		6-10	2	101	.236	.216	1022.0	52.3	48.6	1011.6	62.6	-3.9			
		11-15	3	187	.590	.216	1022.0	52.4	48.6	1012.6	76.0	0.2			
		16-20	4	232	.656	.216	1022.0	52.5	48.6	1013.0	78.7	-0.5			
		21-25	5	322	1.34	.216	1023.1	52.6	48.6	1013.1	104.0	1.3			
		26-30	6	375	1.79	.215	1025.2	52.6	48.4	1012.7	119.7	2.4			
		31-35	7	453	2.43	.214	1025.3	52.6	48.2	1013.6	142.5	2.3			
		36-40	8	544	2.81	.21[illegible]	1025.6	52.7	48.2	1014.8	155.6	1.9			
		41-45	9	586	3.11	.214	1025.9	52.7	48.2	1014.9	165.4	1.8			
		46-50	10	641	3.39	.215	1031.6	52.8	48.4	1003.1	175.8	0.6	15	15	505
		51-55	11	750	3.54	.214	1031.7	52.8	48.2	1002.8	180.4	0.4	10	6	480
		56-60	12	796	3.82	.215	1034.2	52.8	48.4	1010.7	188.5	0.3	22	8	150
102	3-31-80	61-65	1	801	4.17	.639	1034.0	60.4	145.2	926.3	144.6	-0.9			
		66-70	2	871	7.13	.629	1045.5	60.4	142.9	932.7	151.0	-0.7			
		71-75	3	921	8.76	.624	1050.7	60.5	141.8	938.8	170.0	-0.8			
		76-80	4	990	9.27	.622	1054.4	60.5	141.3	943.5	176.6	-1.8			
		81-85	5	1033	9.92	.619	1056.7	60.6	140.6	948.2	183.9	-1.5			
		86-90	6	1104	10.4	.617	1060.9	60.6	140.2	949.9	189.8	-1.7	4	4	420
103	4-1-80	91-95	1	257	3.03	.449	1840.3	62.1	100.2	1785.1	118.7	1.1			
		96-100	2	316	5.15	.445	1846.8	62.1	99.3	1788.7	157.3	0.4			
		101-105	3	371	7.19	.442	1852.4	62.1	98.6	1791.9	192.4	0.05			
		106-110	4	426	8.66	.439	1857.2	62.1	98.0	1796.3	217.3	-0.3			
		111-115	5	479	9.91	.438	1860.6	62.1	97.9	1797.1	237.3	-0.6			
		116-120	6	640	5.30	.432	1019.3	57.9	97.9	961.4	155.1	-0.06			
		121-125	7	688	6.44	.441	1018.5	57.9	99.9	958.1	172.2	-1.0			
		126-130	8	726	6.97	.439	1025.7	57.9	99.5	961.0	180.7	-1.1	7	11	460
		131-135	9	783	7.16	.440	1027.9	58.0	99.7	962.6	183.6	-1.4	20	16	450
		136-140	10	998	3.14	.442	786.3	57.0	100.7	728.5	114.9	-0.2			
		141-145	11	1052	5.24	.434	786.1	57.2	98.9	727.5	151.3	+0.2			
		146-150	12	1086	5.86	.446	785.9	57.4	101.7	730.7	158.6	0.1	26	23	460

TABLE III-III (cont.)

Test Data Point Identification					Test Section Parameters								Auxiliary Parameters			
													Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
104	4-9-80	151-155	1	358	2.41	.247	1839.9	-39.6	49.4	1827.1	52.0	-0.8			
		156-160	2	418	3.60	.246	1842.8	-40.2	49.2	1827.8	94.0	-0.3			
		161-165	3	454	4.62	.246	1844.7	-40.4	49.2	1829.3	128.3	-0.8			
		166-170	4	505	5.30	.245	1846.2	-40.8	49.0	1830.4	149.6	0.2			
		171-175	5	572	5.84	.245	1849.4	-41.1	48.9	1832.4	157.0	-0.3			
		176-180	6	739	1.32	.251	1036.1	-43.6	50.5	1024.1	6.6	-1.8			
		181-185	7	804	2.56	.248	1036.1	-49.9	49.9	1023.1	50.2	0.8			
		186-190	8	898	3.75	.241	1040.2	-43.7	48.5	1030.6	93.5	1.7	7	6	>10K
		191-195	9	945	3.77	.241	1042.8	-43.4	48.5	1023.1	97.8	-0.7	7	6	>10K
		196-200	10	1014	4.49	.240	1040.0	-43.6	48.3	1032.8	121.2	-0.3	7	6	>10K
		201-205	11	1072	5.08	.255	1039.4	-43.9	51.3	1025.4	130.9	-0.5	7	6	>10K
		206-210	12	1096	5.52	.291	1035.0	-43.9	58.5	1012.4	121.7	-4.6	69	29	600
		211-215	13	1287	1.32	.245	753.7	-44.7	49.4	742.7	6.4	-1.8			
		216-220	14	1380	2.73	.241	751.9	-44.8	48.6	742.9	58.6	0.3			
		221-225	15	1410	2.89	.244	757.6	-44.8	49.2	741.7	64.1	-0.8	49	39	765
		226-230	16	1553	3.26	.241	759.4	-44.8	48.6	741.8	78.7	-1.4	35	34	705
		231-235	17	1601	3.39	.264	770.9	-44.7	53.2	729.5	90.1	-17.6	105	42	545
105	4-9-80	236-240	1	274	4.19	.493	1842.4	-47.7	97.9	1784.1	35.1	-2.9			
		241-245	2	319	6.19	.485	1848.5	-48.0	96.3	1787.1	72.6	-1.5			
		246-250	3	370	8.18	.480	1852.0	-48.1	95.3	1791.0	109.3	-1.4			
		251-255	4	407	9.55	.478	1853.9	-48.1	94.9	1791.1	133.4	-1.3			
		256-260	5	471	10.5	.465	1862.7	-47.9	92.3	1804.5	155.1	-1.9			
		261-265	6	667	4.12	.490	1044.6	-49.9	98.0	987.1	31.1	-3.1			
		266-270	7	728	6.77	.479	1048.4	-49.5	95.8	988.9	80.9	-1.2			
		271-275	8	789	8.87	.473	1051.8	-49.0	94.7	990.5	119.2	-1.4			
		276-280	9	877	10.0	.487	1070.6	-48.3	97.5	958.4	134.3	-1.8	90	80	1070/530
		281-285	10	1003	2.45	.513	805.3	-48.4	103.1	744.4	-1.0	-4.3			
		286-290	11	1042	4.38	.508	808.3	-48.2	102.1	744.0	33.6	-2.1			
		291-295	12	1077	7.06	.497	848.7	-47.9	99.8	738.9	82.5	-1.6	28	60	700
		296-300	13	1117	5.68	.498	812.0	-47.9	100.1	747.1	60.5	-3.2			

TABLE III-III (cont.)

Test Data Point Identification					Test Section Parameters								Auxiliary Parameters			
													Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
106	4-10-80	301-305	1	211	.512	.493	471.9	-68.5	97.5	439.5	-60.7	-44.0			
		306-310	2	273	.893	.508	462.7	-68.9	100.4	429.[illegible]	-58.1	-20.5			
		311-315	3	319	1.54	.507	[illegible]3.7	-68.9	100.2	429.	-52.2	-10.8			
		316-320	4	356	1.95	.507	465.3	-68.9	100.2	429.[illegible]	-48.7	-6.5			
		321-325	5	394	2.34	.506	466.8	-68.8	100.0	430.[illegible]	-44.9	-5.6			
		326-330	6	430	2.60	.505	466.9	-68.7	99.8	430.8	-42.3	-4.9			
		331-335	7	497	3.11	.504	467.2	-63.3	99.7	431.8	-37.0	-4.3			
		336-340	8	544	3.46	.503	468.6	-68.1	99.5	432.7	-33.7	-3.1			
		341-345	9	582	3.73	.502	469.2	-67.8	99.3	433.2	-31.0	-2.1			
		346-350	10	644	4.32	.500	470.4	-67.6	98.9	434.0	-25.1	-2.5			
		351-355	11	676	4.99	.499	471.4	-67.5	98.7	434.8	-18.8	-3.2			
		356-360	12	713	5.68 B.O.	.497	473.8	-67.2	98.4	436.3	-12.4	-3.1			
		361-365	13	751	6.13	.495	474.7	-67.1	98.0	443.8	-7.9	-3.5	40	30	910
		366-370	14	817	6.80	.492	482.1	-66.6	97.4	446.3	-.9	-4.0	40	30	910
		371-375	15	868	6.93	.439	486.7	-66.3	96.9	446.5	1.2	-4.4	42	53	600
		376-380	16	921	7.48	.489	465.4	-66.0	96.9	411.7	6.5	-4.5	64	66	480
107	4-18-80	381-385	1	0	5.77	.082	1842.9	51.3	49.7	1825.4	234.5	2.7			
		386-390	2	300	5.75	.080	1856.3	50.7	48.4	1837.7	246.3	-2.8			
		391-395	3	660	5.60	.078	1849.6	51.0	47.2	1831.4	245.9	-2.5			
		396-400	4	780	5.59	.077	1851.4	5[illegible]	46.6	1833.6	246.2	-1.5			
		401-405	5	865	5.49	.078	1852.3	51.1	47.2	1834.8	243.1	-2.7			
		406-410	6	980	4.35	.078	1854.7	51.1	47.2	1837.2	209.8	-3.9			
		411-415	7	1290	4.35	.078	1859.7	51.2	47.2	1843.[illegible]	207.6	-2.3			
		416-420	8	1620	4.35	.079	1865.7	51.3	47.9	1849.5	207.7	-3.5			
		421-425	9	1765	4.36	.077	1865.6	51.5	46.[illegible]	1849.1	209.2	-1.67			
		426-430	10	1850	4.38	.079	1853.9	51.7	47.9	1846.9	208.8	-3.4			
		431-4[illegible]	11	2040	3.75	.073	1864.6	51.7	47.2	1848.1	189.4	-2.9			
		43[illegible]	12	2085	3.71	.077	1865.5	51.6	46.6	1849.4	188.6	-1.8			
		441-445	13	2225	3.75	.079	1871.[illegible]	51.6	47.9	1854.8	189.8	-4.4			

TABLE III-III (cont.)

Test Data Point Identification					Test Section Parameters								Auxiliary Parameters			
												Energy	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	Balance %	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
108	6-4-80	446-450	1	0	7.06	.256	1817.6	65.3	157.8	1645.5	147.6	-4.8			
		451-455	2	55	7.09	.260	1813.3	65.3	160.3	1634.6	147.6	-6.1			
		456-460	3	125	6.86	.261	1813.5	65.2	160.9	1634.6	145.9	-7.6			
		461-465	4	195	6.95	.261	1815.6	65.1	160.9	1636.8	146.6	-7.5			
		466-470	5	290	7.01	.261	1819.6	65.0	160.9	1639.1	147.1	-7.4			
		471-475	6	410	7.04	.262	1823.1	64.8	161.4	1641.8	147.6	-7.4			
		476-480	7	530	7.03	.262	1826.2	64.7	161.4	1645.1	147.6	-8.5			
		481-485	8	665	7.03	.262	1828.4	64.6	161.4	1647.5	147.6	-8.6			
		486-490	9	755	8.50	.261	1831.6	64.6	160.9	1647.1	162.3	-7.1			
		491-495	10	890	8.47	.261	1833.7	64.6	160.9	1649.9	161.9	-6.9			
		996-500	11	1010	8.45	.262	1836.9	64.6	161.4	1652.2	161.8	-7.4			
		501-505	12	1130	8.47	.262	1839.2	64.6	161.4	1654.7	162.0	-7.5			
		506-510	13	1250	8.48	.262	1840.4	64.6	161.4	1658.2	162.2	-7.5			
		511-515	14	1265	8.48	.262	1840.5	64.6	161.4	1658.2	162.3	-7.6			
		516-520	15	1275	8.48	.262	1840.5	64.7	161.4	1658.3	162.5	-7.7			
		521-525	16	1350	10.4	.261	1843.2	64.8	160.9	1657.8	180.7	-6.3			
		526-530	17	1375	10.3	.261	1843.7	64.9	160.9	1658.4	180.8	-6.4			
		531-535	18	1385	10.4	.261	1843.8	64.9	160.9	1658.2	180.8	-6.4			
		536-540	19	1490	10.3	.261	1846.7	65.2	160.9	1658.9	180.9	-6.3			
		541-545	20	1610	10.3	.261	1847.2	65.7	160.9	1660.6	181.3	-6.5			
		546-550	21	1735	10.3	.262	1850.4	66.2	161.4	1662 [illegible]	181.7	-6.9			
		551-555	22	1850	10.2	.262	1850.4	66.9	161.4	1663.5	181.3	-7.1			
		556-560	23	1940	10.3	.259	1856.7	67.6	160.0	1674.8	183.6	-6.7			

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TABLE III-III (cont.)

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
109	6-5-80	561-565	1	251	4.0	.741	543.7	-178.7	132.2	475.0	-146.3	-11.7			
		566-570	2	292	5.74	.739	545.6	-179.1	131.8	474.0	-135.3	-6.5			
		571-575	3	331	7.30	.738	546.0	-179.0	131.7	474.3	-125.0	-3.9			
		576-580	4	382	8.24	.737	548.6	-179.0	131.5	475.0	-118.1	-4.0			
		581-585	5	414	9.07	.735	549.3	-178.1	131.2	475.2	-111.9	-3.2			
		586-590	6	452	10.1	.733	551.0	-177.7	130.9	476.5	-104.3	-3.6			
		591-595	7	479	11.1	.731	553.0	-177.0	130.6	498.5	-96.8	-3.3			
		596-600	8	525	12.1	.728	559.6	-175.9	130.2	505.0	-89.2	-3.1			
		601-605	9	572	12.1	728	564.9	-174.8	130.3	450.9	-86.4	-4.7			
		606-610	10	628	9.92	.730	552.5	-172.7	130.9	501.5	-100.7	-3.4			
		611-615	11	639	10.1	.729	553.1	-172.2	130.8	502.3	-99.4	-2.6			
		616-620	12	656	11.1	.726	556.7	-171.3	130.4	502.7	-91.1	-3.4			
		621-625	13	675	11.5	.726	556.3	-170.5	130.5	522.3	-87.3	-3.6			
110	6-26-80	626-630	1	287	3.45	.602	489.4	-242.5	102.0	461.3	-207.1	-12.0			
		631-635	2	335	4.10	.604	489.3	-243.2	102.3	460.9	-202.7	-9.5			
		636-640	3	370	4.76	.604	489.3	-243.3	102.3	460.4	-197.6	-7.3			
		641-645	4	402	5.47	.605	489.4	-243.2	102.4	459.9	-191.6	-6.2			
		646-650	5	432	6.15	.605	489.7	-243.1	102.4	459.3	-186.1	-5.0			
		651-655	6	472	6.44	.605	490.3	-242.9	102.5	459.6	-183.3	-5.0			
111	6-30-80	656-660	1	215	4.01	.597	492.0	-238.8	101.4	463.5	-197.2	-14.5			
		661-665	2	260	6.13	.596	492.5	-240.6	101.1	463.1	-182.1	-6.8			
		666-670	3	300	7.79	.594	497.1	-241.3	100.7	463.7	-168.4	-5.3			
		671-675	4	340	8.73	.593	502.2	-241.6	100.5	464.2	-160.7	-4.5			
		676-680	5	375	9.18	.592	502.1	-241.6	100.4	466.1	-156.3	-4.7	89	70	1.6K
		681-685	6	409	9.54	.591	515.8	-241.6	100.2	465.3	-152.8	-4.8	>350	157	1.6K
		686-690	7	451	10.1	.590	518.9	-241.6	100.0	468.9	-148.1	-4.6	>350	150	1.5K
		691-695	8	504	10.6	.587	520.3	-241.1	99.5	477.6	-142.1	-4.4	>350	150	1.5K
		696-700	9	525	10.6	.593	495.2	-240.8	100.6	418.8	-142.0	-5.7	>350	>300	950
		701-705	10	549	9.68	.589	527.7	-240.7	99.9	407.6	-148.8	-6.7	310	>300	950
		706-710	11	568	9.30	.589	506.2	-240.2	100.0	469.3	-151.7	-6.9	56	105	>10K
		711-715	12	598	4.00	.591	501.6	-239.4	100.4	473.1	-196.5	-17.2			

TABLE III-III (cont.)

Test Data Point Identification					Test Section Parameters							Auxiliary Parameters			
												Energy Balance	Flow Oscillation		
Test #	Date	ID #	Data Pt	Time Secs	ϕ Btu/in.^{2}-sec	$\dot{w}$ lb/sec	P_{IN} psia	T_{IN} °F	V_{IN} ft/sec	P_{OUT} psia	T_{OUT} °F	%	Inlet psi (P-P)	Outlet psi (P-P)	Freq Hz
112		716-720	1	0	4.35	.091	1776.7	32.4	54.1	1752.8	162.6	5.8			
		721-725	2	355	4.32	.088	1791.3	30.8	52.2	1768.9	168.5	2.9			
		726-730	3	630	4.31	.088	1798.1	30.6	52.1	1776.5	169.8	1.5			
		731-735	4	940	4.31	.087	1804.3	30.2	51.5	1783.2	170.4	1.9			
		736-740	5	985	4.74		1804.7	30.2		1783.2	182.0	2.4			
		741-745	6	1375	4.73		1808.8	30.1		1787.8	183.0	1.4			
		746-750	7	1660	4.73		1813.3	29.8		1791.7	183.0	1.2			
		751-755	8	1870	4.73		1816.7	30.2		1796.4	183.9	0.9			
		756-760	9	1940	5.28		1817.9	30.2		1796.5	198.2	1.7			
		761.765	10	2360	5.27		1821.6	30.2		1798.9	199.0	1.0			
		766-770	11	2595	5.26		1823.1	30.2		1801.5	199.0	.9			
		771-775	12	2840	5.27		1825.1	30.7		1803.7	199.2	1.1			
		776-780	13	2915	5.74		1825.5	30.6		1803.5	211.4	1.6			
		781-785	14	3215	5.74		1828.0	30.8		1805.6	212.5	1.0			
		786-790	15	3505	5.73		1831.7	30.7		1807.0	212.5	0.8			
		791-795	16	3820	5.72		1833.8	30.8		1810.2	212.4	0.8			
		796-800	17	3920	6.20		1835.0	30.8		1810.2	223.7	1.8			
		801-805	18	4210	6.20		1835.5	31.0		1812.4	224.8	1.2			
		806-810	19	4595	6.20		1838.5	31.7		1814.4	224.9	1.4			
		811-815	20	4805	6.20		1840.4	30.9		1816.8	224.7	1.2			
		816-820	21	5115	6.19		1843.1	31.0		1818.7	224.6	1.3			
		821-825	22	5390	6.18		184[illegible].3	31.0		1820.3	224.0	1.4			
		826-830	23	5705	6.17		1838.6	32.0		1814.1	224.9	1.1			
		831-835	24	5740	4.68		1838.4	32.1		1813.0	187.4	1.5			
		836-840	25	6005	4.68	.083	1831.7	31.9	49.2	1810.1	188.6	2.2			

TABLE III-IV

HEATED TUBE STATION SUMMARY

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/ $Pr^{.4}$	Re/ 1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
101	1	67.8	1017.0	52.6	15.9	2.0	251.0	1.021	1.082	1.039	.989	2.983
	2	67.2	1016.0	52.8	27.8	2.0	252.0	1.019	1.076	1.037	.987	2.982
	3	67.[illegible]	1014.0	52.9	39.8	2.0	252.0	1.020	1.078	1.037	.988	2.982
	4	[illegible]	1013.0	53.1	51.8	2.0	252.0	1.017	1.070	1.033	.982	2.981
	5	67.5	1011.0	53.5	63.7	2.0	253.0	1.019	1.076	1.037	.988	2.980
	6	106.7	1020.0	54.8	15.9	33[illegible]	254.0	1.062	1.306	1.139	1.038	2.974
	7	108.7	1018.0	56.8	27.8	355.0	257.0	1.083	1.310	1.140	1.041	2.966
	8	111.1	1016.0	58.5	39.8	334.0	259.0	1.085	1.314	1.141	1.044	2.958
	9	111.9	1014.0	60.3	51.8	[illegible]	262.0	1.084	1.307	1.138	1.046	2.950
	10	116.4	1012.0	62.2	63.7	327.0	265.0	1.091	1.329	1.147	1.051	2.941
	11	162.5	102[illegible]	56.[illegible]	15.9	421.0	259.0	1.207	1.763	1.305	1.096	2.960
	12	166.8	1018.0	62.2	27.8	425.0	265.0	1.215	1.774	1.306	1.102	2.941
	13	172.4	1016.0	66.5	39.8	425.0	270.0	1.226	1.801	1.312	1.105	2.931
	14	175.5	1015.0	70.7	51.8	434.0	276.0	1.230	1.799	1.309	1.105	2.920
	15	163.6	1013.0	74.9	63.7	424.0	262.0	1.252	1.862	1.324	1.114	2.909
	16	172.9	1020.0	58.7	15.9	424.0	260.0	1.246	1.878	1.339	1.110	2.957
	17	177.5	1018.0	63.4	27.8	435.0	266.0	1.250	1.891	1.340	1.117	2.938
	18	183.6	1017.0	68.1	39.8	435.0	273.0	1.265	1.928	1.347	1.121	2.927
	19	187.5	1015.0	72.8	51.8	444.0	279.0	1.271	1.934	1.345	1.121	2.915
	20	166.4	1013.0	77.6	63.7	435.0	286.0	1.304	2.020	1.357	1.135	2.901
	21	277.8	1021.0	64.8	15.9	477.0	268.0	2.624	5.144	1.645	1.416	2.935
	22	265.4	1019.0	74.0	27.8	494.0	281.0	2.753	5.256	1.863	1.422	2.911
	23	290.8	1017.0	83.2	39.8	5[illegible]6.0	295.0	2.926	5.492	1.899	1.429	2.885
	24	300.3	1015.0	92.5	51.8	529.0	309.0	3.025	5.407	1.884	1.432	2.864
	25	313.4	1014.0	101.7	63.7	533.0	324.0	3.350	5.345	1.878	1.437	2.840
	26	337.2	1022.0	68.6	15.9	512.0	272.0	3.919	6.670	2.091	1.444	2.925
	27	343.3	1020.0	80.6	27.8	543.0	290.0	3.987	6.307	2.030	1.432	2.890
	28	353.5	1018.0	92.7	39.8	565.0	308.0	4.114	6.016	1.975	1.418	2.863
	29	358.9	1016.0	104.7	51.8	600.0	328.0	4.105	5.687	1.918	1.400	2.834
	30	379.1	1013.0	116.8	63.7	614.0	351.0	4.202	5.380	1.853	1.368	2.802
	31	410.4	1023.0	74.0	15.9	563.0	278.0	4.961	6.775	2.009	1.392	2.910
	32	422.7	1020.0	90.1	27.8	596.0	302.0	5.051	6.246	1.908	1.366	2.869
	33	439.9	1018.0	106.2	39.8	622.0	329.0	5.227	5.745	1.803	1.332	2.830
	34	454.1	1016.0	122.4	51.8	656.0	359.0	5.222	5.253	1.703	1.294	2.792
	35	476.7	1014.0	138.5	63.7	666.0	392.0	5.314	4.790	1.589	1.247	2.755
	36	462.1	1023.0	77.2	15.9	575.0	283.0	5.667	6.634	1.889	1.359	2.900
	37	481.6	1021.0	95.7	27.8	604.0	311.0	5.722	6.033	1.767	1.324	2.854
	38	507.5	1019.0	114.1	39.8	625.0	343.0	5.832	5.443	1.641	1.276	2.810
	39	530.9	1017.0	132.6	51.8	651.0	379.0	5.918	4.912	1.528	1.231	2.768
	40	570.2	1015.0	151.1	63.7	653.0	423.0	6.096	4.382	1.398	1.171	2.724
	41	500.3	1023.0	79.5	15.9	575.0	287.0	6.167	6.506	1.784	1.333	2.892
	42	537.9	1021.0	99.8	27.8	596.0	318.0	6.345	5.858	1.649	1.291	2.843
	43	574.1	1019.0	120.0	39.8	610.0	354.0	6.499	5.222	1.510	1.237	2.797
	44	612.9	1017.0	140.2	51.8	621.0	396.0	6.631	4.647	1.381	1.183	2.752
	45	670.2	1015.0	160.4	63.7	611.0	447.0	6.797	3.968	1.237	1.118	2.708
	46	568.2	1025.0	81.3	15.9	556.0	292.0	6.832	6.374	1.670	1.309	2.886
	47	623.5	1020.0	103.7	27.8	553.0	326.0	7.191	5.658	1.501	1.257	2.836
	48	690.6	1015.0	125.6	39.8	542.0	367.0	7.517	4.790	1.329	1.200	2.785
	49	708.9	1010.0	147.5	51.8	543.0	416.0	7.731	4.062	1.189	1.142	2.735
	50	708.9	1004.0	169.4	63.7	646.0	477.0	7.037	3.645	1.164	1.084	2.689
	51	592.7	1025.0	83.2	15.9	557.0	292.0	7.064	6.311	1.626	1.300	2.883
	52	664.7	1020.0	106.1	27.8	560.0	328.0	7.354	5.493	1.458	1.248	2.831
	53	715.5	1014.0	129.0	39.8	552.0	372.0	7.706	4.624	1.287	1.190	2.777
	54	783.0	1009.0	151.9	51.8	549.0	426.0	7.932	3.866	1.139	1.129	2.723
	55	762.1	1004.0	174.7	63.7	631.0	491.0	7.349	3.394	1.093	1.059	2.683
	56	635.4	1029.0	85.1	15.9	560.0	297.0	7.442	6.158	1.552	1.288	2.878
	57	698.7	1024.0	109.5	27.8	559.0	336.0	7.745	5.199	1.374	1.233	2.822
	58	789.7	1020.0	133.8	39.8	539.0	384.0	8.220	4.288	1.189	1.175	2.764
	59	895.0	1016.0	158.2	51.8	516.0	443.0	8.792	3.475	1.022	1.106	2.712
	60	959.9	1012.0	182.5	63.7	525.0	519.0	8.939	2.853	.910	1.023	2.667

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp	Pressure Psia	Bulk Temp °F	L/D	Nu/ $Pr^{.4}$	Re/ 1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
102	61	282.7	1008.0	73.3	15.9	1552.0	629.0	2.755	5.229	1.456	1.427	2.913
	62	263.6	989.0	83.0	27.8	1666.0	674.0	3.052	5.604	1.426	1.446	2.866
	63	302.3	970.0	92.4	39.8	1644.0	620.0	3.323	5.643	1.930	1.450	2.863
	64	313.2	950.0	102.5	51.8	1663.0	671.0	3.608	5.575	1.934	1.465	2.839
	65	317.7	931.0	112.2	63.7	1779.0	1128.	3.846	5.403	1.612	1.459	2.818
	66	412.0	1013.0	82.0	15.9	1733.0	854.0	4.926	6.506	1.970	1.343	2.868
	67	427.6	998.0	98.2	27.8	1810.0	928.0	5.205	6.026	1.866	1.356	2.847
	68	462.5	978.0	114.5	39.8	1908.0	1018.0	5.422	5.522	1.769	1.317	2.810
	69	460.3	958.0	130.7	51.8	1994.0	1115.0	5.553	5.046	1.662	1.276	2.776
	70	483.6	938.0	147.0	63.7	2052.0	1232.0	5.720	4.569	1.55	1.221	2.745
	71	466.6	1024.0	86.6	15.9	1771.0	866.0	5.837	6.302	1.766	1.334	2.876
	72	513.9	1004.0	106.2	27.8	1811.0	960.0	6.161	5.665	1.654	1.266	2.831
	73	556.2	984.0	125.9	39.8	1846.0	1072.0	6.503	5.075	1.515	1.231	2.786
	74	568.8	964.0	145.5	51.8	1860.0	1205.0	6.774	4.489	1.377	1.169	2.745
	75	671.5	943.0	165.1	63.7	1766.0	1368.0	7.209	3.796	1.213	1.090	2.711
	76	521.1	1028.0	88.2	15.9	1739.0	671.0	6.199	6.215	1.765	1.316	2.871
	77	566.4	1008.0	109.0	27.8	1746.0	971.0	6.635	5.555	1.566	1.262	2.824
	78	618.9	988.0	129.6	39.8	1738.0	1091.0	7.035	4.906	1.409	1.203	2.777
	79	676.0	966.0	150.7	51.8	1716.0	1239.0	7.360	4.153	1.255	1.138	2.732
	80	761.8	948.0	171.5	63.7	1581.0	1421.0	7.976	3.377	1.076	1.057	2.698
	81	583.6	1031.0	89.9	15.9	1710.0	874.0	6.662	6.123	1.644	1.297	2.866
	82	629.1	1011.0	112.0	27.8	1655.0	983.0	7.148	5.406	1.468	1.230	2.816
	83	701.3	992.0	134.2	39.8	1625.0	1112.0	7.663	4.524	1.265	1.180	2.765
	84	794.9	972.0	156.3	51.8	1564.0	1275.0	8.226	3.710	1.111	1.109	2.721
	85	964.1	953.0	178.4	63.7	1340.0	1482.0	9.574	2.876	.910	1.019	2.694
	86	604.2	1034.0	91.4	15.9	1667.0	878.0	7.028	6.044	1.575	1.284	2.862
	87	682.0	1015.0	114.5	27.8	1630.0	993.0	7.591	5.111	1.376	1.225	2.809
	88	736.6	995.0	137.7	39.8	1488.0	1131.0	8.357	4.167	1.170	1.163	2.758
	89	913.3	975.0	160.9	51.8	1385.0	1306.0	9.522	3.346	.941	1.066	2.714
	90	1125.5	9[illegible].0	184.0	63.7	1195.0	1538.0	11.819	2.522	.767	.992	2.886
103	91	298.8	1827.0	75.6	15.9	1031.0	555.0	1.637	3.060	1.523	1.199	2.901
	92	311.6	1817.0	85.7	27.8	1051.0	585.0	1.703	3.123	1.519	1.206	2.861
	93	315.9	1807.0	95.9	39.8	1101.0	608.0	1.715	3.096	1.506	1.205	2.844
	94	333.5	1797.0	106.0	51.8	1066.0	633.0	1.823	3.284	1.528	1.215	2.827
	95	350.7	1788.0	116.2	63.7	1078.0	660.0	1.947	3.385	1.535	1.222	2.808
	96	443.2	1833.0	84.8	15.9	1123.0	577.0	2.772	4.821	1.684	1.260	2.864
	97	464.9	1823.0	101.9	27.8	1147.0	616.0	2.857	4.621	1.622	1.265	2.835
	98	468.9	1812.0	118.9	39.8	1235.0	660.0	2.828	4.343	1.571	1.245	2.803
	99	495.4	1802.0	136.0	51.8	1257.0	715.0	2.950	4.115	1.499	1.225	2.756
	100	523.0	1791.0	153.1	63.7	1280.0	780.0	3.089	3.877	1.427	1.202	2.698
	101	572.6	1838.0	93.1	15.9	1189.0	591.0	3.683	5.223	1.576	1.275	2.851
	102	606.4	1827.0	116.5	27.8	1221.0	647.0	3.806	4.934	1.493	1.243	2.809
	103	617.4	1816.0	139.8	39.8	1330.0	722.0	3.769	4.485	1.413	1.212	2.745
	104	660.7	1805.0	163.2	51.8	1359.0	810.0	3.865	3.993	1.295	1.177	2.670
	105	702.3	1795.0	186.6	63.7	1397.0	913.0	3.940	3.524	1.188	1.142	2.583
	106	677.7	1843.0	99.0	15.9	1202.0	600.0	4.296	5.294	1.457	1.268	2.840
	107	733.5	1832.0	126.9	27.8	1220.0	673.0	4.491	4.685	1.317	1.228	2.783
	108	767.0	1821.0	154.7	39.8	1302.0	772.0	4.485	4.073	1.206	1.169	2.695
	109	840.7	1810.0	182.6	51.8	1303.0	885.0	4.682	3.509	1.073	1.148	2.600
	110	900.2	1799.0	210.5	63.7	1332.0	1022.0	4.795	3.008	.973	1.093	2.509
	111	792.6	1846.0	103.8	15.9	1165.0	609.0	4.942	5.112	1.314	1.265	2.833
	112	877.6	1834.0	135.2	27.8	1164.0	698.0	5.283	4.407	1.157	1.222	2.759
	113	930.3	1823.0	166.7	39.8	1229.0	814.0	5.415	3.750	1.040	1.173	2.659
	114	1028.3	1811.0	198.1	51.8	1228.0	954.0	5.949	3.143	.912	1.120	2.550
	115	1107.9	1800.0	229.6	63.7	1253.0	1131.0	6.398	2.611	.817	1.053	2.435
	116	440.5	1005.0	81.0	15.9	1175.0	584.0	5.535	6.556	1.922	1.368	2.890
	117	465.3	995.0	98.5	27.8	1211.0	638.0	5.694	5.989	1.791	1.331	2.847
	118	469.9	985.0	115.9	39.8	1321.0	704.0	5.630	5.441	1.704	1.295	2.806
	119	502.4	974.0	133.3	51.8	1334.0	775.0	5.851	4.923	1.573	1.244	2.768
	120	531.2	964.0	150.8	63.7	1364.0	862.0	6.023	4.410	1.455	1.184	2.732

TABLE III-IV (cont.)

Pg. 3 of 14

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
103	121	516.0	1004.0	85.1	15.9	1222.0	668.0	6.335	6.346	1.750	1.323	2.682
	122	558.3	993.0	105.6	27.8	1215.0	677.0	6.711	5.667	1.591	1.271	2.633
	123	580.5	982.0	126.1	39.8	1275.0	759.0	6.774	5.039	1.471	1.220	2.766
	124	651.3	972.0	146.6	51.8	1234.0	856.0	7.161	4.347	1.305	1.154	2.742
	125	722.2	961.0	167.1	63.7	1178.0	975.0	7.556	3.610	1.145	1.078	[illegible]
	126	531.0	1013.0	87.1	15.9	1114.0	611.0	7.141	6.203	1.610	1.293	2.877
	127	626.7	999.0	109.2	27.8	1156.0	687.0	7.324	5.461	1.471	1.244	2.824
	128	682.2	987.0	131.2	39.8	[illegible]	776.0	7.566	4.659	1.318	1.186	2.773
	129	768.2	975.0	153.2	51.8	1066.0	887.0	8.205	3.770	1.117	1.119	2.724
	130	828.2	964.0	175.2	63.7	973.0	1024.0	9.157	3.013	.945	1.037	2.693
	131	566.6	1012.0	87.9	15.9	1164.0	615.0	7.135	6.176	1.605	1.292	2.675
	132	670.3	1001.0	110.4	27.8	1118.0	693.0	7.645	5.266	1.408	1.234	2.821
	133	743.9	989.0	133.0	39.8	1065.0	786.0	8.094	4.422	1.239	1.177	2.765
	134	880.4	977.0	155.5	51.8	974.0	901.0	9.057	3.526	1.033	1.107	2.722
	135	1018.5	966.0	178.1	63.7	902.0	1047.0	10.188	2.804	.876	1.022	2.691
	136	301.9	773.0	70.7	15.9	1066.0	581.0	5.090	7.377	2.295	1.572	2.915
	137	305.1	762.0	81.1	27.8	1088.0	616.0	5.467	7.049	2.237	1.551	2.888
	138	313.1	752.0	91.5	39.8	1184.0	651.0	5.435	6.715	2.190	1.554	2.865
	139	321.6	741.0	101.9	51.8	1232.0	690.0	5.606	6.389	2.132	1.533	2.843
	140	320.7	731.0	112.3	63.7	1285.0	730.0	5.745	6.082	2.072	1.503	2.826
	141	435.9	772.0	79.6	15.9	1185.0	599.0	7.442	6.893	1.984	1.393	2.802
	142	456.6	762.0	96.5	27.8	1232.0	656.0	7.631	6.250	1.851	1.353	2.852
	143	470.4	751.0	113.4	39.8	1307.0	723.0	7.665	5.644	1.738	1.303	2.823
	144	493.7	741.0	130.3	51.8	1355.0	800.0	7.810	5.056	1.610	1.247	2.792
	145	522.6	730.0	147.2	63.7	1381.0	892.0	7.989	4.472	1.480	1.173	2.773
	146	406.0	773.0	81.5	15.9	1163.0	622.0	8.115	6.650	1.843	1.351	2.887
	147	542.6	763.0	99.5	27.8	1131.0	685.0	6.741	5.895	1.650	1.290	2.845
	148	595.4	753.0	117.8	39.8	1108.0	763.0	9.182	5.171	1.478	1.222	2.813
	149	[illegible]	743.0	135.9	51.8	975.0	850.0	10.240	4.291	1.246	1.147	2.786
	150	837.9	733.0	154.1	63.7	867.0	961.0	11.291	3.478	1.049	1.069	2.764
104	15	356.5	1837.0	-17.8	15.9	368.0	166.0	2.236	6.422	2.096	1.309	3.349
	152	360.3	1835.0	-1.4	27.8	395.0	203.0	2.268	6.128	2.035	1.303	3.261
	153	349.9	1832.0	15.1	39.8	461.0	221.0	2.074	5.209	1.907	1.276	3.180
	154	350.7	1830.0	31.5	51.8	455.0	240.0	2.128	4.987	1.855	1.275	3.105
	155	359.2	1828.0	48.0	63.7	533.0	261.0	2.148	4.765	1.802	1.273	3.034
	156	507.9	1839.0	-8.2	15.9	465.0	195.0	3.570	8.304	2.086	1.365	3.294
	157	520.4	1837.0	15.8	27.8	447.0	221.0	3.596	7.417	1.954	1.345	3.177
	158	494.3	1834.0	39.9	39.8	534.0	250.0	3.286	6.430	1.862	1.322	3.068
	159	507.7	1831.0	64.0	51.8	598.0	281.0	3.309	5.774	1.746	1.306	2.965
	160	524.9	1828.0	88.1	63.7	648.0	323.0	3.356	5.110	1.621	1.280	2.858
	161	[illegible]	1841.0	[illegible]	15.9	433.0	203.0	4.555	8.803	1.932	1.371	3.255
	162	655.2	1838.0	30.2	27.8	483.0	238.0	4.538	7.512	1.759	1.343	3.110
	163	621.3	1836.0	60.6	39.8	589.0	276.0	4.200	6.510	1.685	1.314	2.981
	164	650.1	1833.0	91.0	51.8	653.0	326.0	4.201	5.486	1.513	1.277	2.854
	165	683.1	1830.0	121.3	63.7	693.0	368.0	4.217	4.843	1.391	1.236	2.797
	166	733.5	1842.0	4.5	15.9	439.0	208.0	5.205	8.460	1.754	1.376	3.230
	167	775.5	1840.0	38.7	27.8	482.0	247.0	5.268	7.076	1.559	1.344	3.074
	168	750.7	1837.0	72.9	39.8	586.0	297.0	4.925	5.911	1.452	1.304	2.917
	169	810.6	1834.0	107.0	51.8	615.0	345.0	5.057	5.034	1.288	1.261	2.827
	170	857.3	1831.0	141.2	63.7	656.0	402.0	5.101	4.295	1.159	1.212	2.741
	171	827.1	1845.0	8.4	15.9	436.0	212.0	5.782	8.170	1.613	1.382	3.209
	172	895.3	1842.0	45.8	27.8	470.0	256.0	6.077	6.710	1.399	1.346	3.042
	173	877.3	1839.0	83.1	39.8	572.0	316.0	5.675	5.450	1.277	1.298	2.866
	174	985.1	1836.0	120.5	51.8	567.0	365.0	6.302	4.642	1.107	1.246	2.800
	175	1086.2	1833.0	157.8	63.7	582.0	436.0	7.057	3.827	.955	1.189	2.687
	176	168.8	1033.0	-31.6	15.9	368.0	185.0	1.364	2.970	1.675	1.161	3.384
	177	180.8	1031.0	-22.6	27.8	374.0	195.0	1.399	3.053	1.689	1.172	3.326
	178	165.3	1029.0	-13.6	39.8	438.0	205.0	1.376	2.625	1.582	1.142	3.278
	179	177.9	1027.0	-4.6	51.8	442.0	216.0	1.359	2.709	1.597	1.151	3.234
	180	198.1	1025.0	4.4	63.7	420.0	227.0	1.439	2.992	1.641	1.175	3.191

TABLE III-IV (cont.)

Test Number HT86-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
104	181	385.5	1035.	-21.5	15.9	[illegible]	194.0	4.496	10.784	2.633	1.485	3.320
	182	355.4	1051.0	-4.[illegible]	27.8	628.0	213.0	4.665	9.987	2.522	1.468	3.234
	183	424.4	1028.0	12.[illegible]	39.8	527.0	234.0	3.920	8.657	2.380	1.461	3.155
	184	383.7	1028.0	24.2	51.8	55[illegible].0	256.0	4.236	8.215	2.310	1.454	3.080
	185	376.0	1024.	46.[illegible]	63.7	55[illegible].0	279.0	4.638	7.752	2.204	1.433	3.009
	186	469.[illegible]	1038.0	-11.[illegible]	15.9	46[illegible].0	200.0	6.302	10.525	2.350	1.441	3.264
	187	492.4	1036.0	13.0	27.8	50[illegible].0	228.0	6.414	9.191	2.148	1.408	3.150
	188	440.1	1034.0	38.2	39.8	621.0	260.0	5.871	8.112	2.089	1.397	3.044
	189	500.4	1033.0	62.8	51.8	64[illegible].0	296.0	6.149	7.102	1.879	1.362	2.940
	190	[illegible]	1031.0	87.4	63.7	725.0	336.0	6.008	6.243	1.753	1.323	2.872
	191	472.8	104[illegible].	-9.8	15.9	449.0	201.0	6.326	10.439	2.332	1.438	3.257
	192	467.9	1037.0	15.0	27.8	5[illegible]9.0	231.0	6.455	9.090	2.126	1.404	3.141
	193	478.5	1035.0	40.9	39.8	617.0	266.0	6.050	7.979	2.033	1.388	3.032
	194	497.1	1032.0	66.2	51.8	667.0	301.0	6.083	6.981	1.869	1.358	2.931
	195	470.3	1030.0	91.6	63.7	7[illegible]7.0	343.0	5.678	6.143	1.787	1.330	2.863
	196	[illegible]	1041.	-4.4	15.9	443.0	206.0	7.877	9.993	2.020	1.405	3.233
	197	638.2	1035.0	25.2	27.8	432.0	242.0	8.005	8.397	1.804	1.366	3.097
	198	461.4	1037.	54.0	39.8	615.0	282.0	7.251	7.325	1.750	1.342	2.975
	199	610.5	1035.[illegible]	84.3	51.8	675.0	330.0	7.267	6.240	1.578	1.292	2.878
	200	593.0	1033.0	113.9	63.7	619.0	384.0	6.66[illegible]	5.381	1.506	1.244	2.810
	201	464.7	1036.0	-2.3	15.9	683.0	222.0	8.356	9.691	1.926	1.399	3.224
	202	[illegible]	1034.[illegible]	29.1	27.8	514.0	263.0	8.636	7.875	1.680	1.357	3.081
	203	669.0	1031.	60.4	39.8	625.0	309.0	8.008	6.843	1.599	1.325	2.950
	204	695.3	1029.0	91.5	51.8	697.0	363.0	7.464	5.733	1.447	1.270	2.862
	205	670.0	1026.0	123.2	63.7	827.0	429.0	7.318	4.912	1.359	1.208	2.790
	206	604.1	1030.0	-4.5	15.9	527.0	250.0	7.999	9.998	2.015	1.4[illegible]5	3.233
	207	774.3	1026.0	25.2	27.8	471.0	294.0	9.486	7.648	1.587	1.360	3.096
	208	778.2	1021.	55.[illegible]	39.8	535.0	343.0	9.219	6.541	1.466	1.324	2.974
	209	752.2	1017.0	84.7	51.8	632.0	400.0	8.635	5.705	1.392	1.276	2.882
	210	637.8	1013.0	114.4	63.7	678.0	468.0	7.216	5.277	1.439	1.232	2.809
	211	167.5	751.0	-32.5	15.9	372.0	184.0	1.401	3.155	1.720	1.177	3.373
	212	181.3	749.0	-23.4	27.8	375.0	194.0	1.461	3.350	1.750	1.199	3.312
	213	170.1	747.0	-14.2	39.8	430.0	204.0	1.383	2.900	1.649	1.167	3.266
	214	181.6	745.0	-5.0	51.8	437.0	215.0	1.432	3.032	1.667	1.182	3.222
	215	177.8	743.0	4.1	63.7	484.0	226.0	1.396	2.793	1.608	1.166	3.180
	216	358.2	759.0	-20.2	15.9	425.0	194.0	7.312	12.261	2.849	1.550	3.297
	217	344.5	748.0	-1.6	27.8	494.0	216.0	6.908	11.103	2.747	1.546	3.207
	218	291.9	747.0	16.9	39.8	660.0	239.0	5.509	9.919	2.674	1.590	3.125
	219	326.6	745.0	35.5	51.8	661.0	264.0	6.250	9.107	2.531	1.550	3.044
	220	327.7	743.0	54.0	63.7	746.0	291.0	6.142	8.259	2.411	1.549	2.967
	221	396.0	754.0	-18.9	15.9	411.0	198.0	7.891	12.015	2.716	1.519	3.291
	222	511.0	751.0	.7	27.8	356.0	221.0	9.673	10.174	2.222	1.436	3.197
	223	548.8	748.0	20.2	39.8	367.0	246.0	10.113	8.981	2.017	1.398	3.110
	224	578.9	745.0	39.7	51.8	382.0	273.0	10.293	7.970	1.853	1.367	3.024
	225	470.8	742.0	59.3	63.7	533.0	303.0	8.514	7.585	2.006	1.400	2.946
	226	461.5	755.0	-15.4	15.9	408.0	199.0	9.037	11.405	2.471	1.478	3.273
	227	577.8	752.0	6.8	27.8	367.0	226.0	10.610	9.517	2.021	1.407	3.167
	228	614.9	749.0	28.9	39.8	384.0	255.0	10.892	8.295	1.829	1.370	3.071
	229	711.5	746.0	51.1	51.8	365.0	286.0	11.854	6.876	1.564	1.329	2.978
	230	621.4	743.0	73.2	63.7	471.0	322.0	10.437	6.530	1.617	1.309	2.909
	231	559.2	751.0	-12.6	15.9	357.0	222.0	10.474	10.690	2.174	1.436	3.258
	232	757.8	754.0	11.6	27.8	296.0	254.0	12.942	8.222	1.659	1.378	3.146
	233	743.1	746.0	35.8	39.8	337.0	289.0	12.500	7.296	1.579	1.345	3.043
	234	695.8	739.0	60.0	51.8	406.0	329.0	11.617	6.628	1.551	1.321	2.943
	235	581.2	731.0	84.1	63.7	558.0	375.0	9.878	6.279	1.643	1.301	2.882
105	236	282.8	1829.0	-28.0	15.9	734.0	351.0	1.732	4.847	1.937	1.245	3.405
	237	288.1	1818.0	-13.1	27.8	796.0	381.0	1.742	4.632	1.883	1.240	3.321
	238	306.4	1808.0	1.7	39.8	825.0	413.0	1.844	4.761	1.873	1.251	3.243
	239	318.5	1797.0	16.6	51.8	872.0	446.0	1.912	4.717	1.847	1.255	3.171
	240	339.6	1787.0	31.4	63.7	895.0	481.0	2.063	4.881	1.845	1.270	3.103

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr^.4	Re/1000	ρb/ρw	μb/μw	kb/kw	C̄p/Cpb	Pr
105	241	424.3	1634.0	-19.5	15.9	777.0	362.0	2.924	8.113	2.205	1.356	3.357
	242	430.0	1623.0	2.4	27.8	869.0	407.0	2.918	7.307	2.040	1.339	3.241
	243	457.7	1812.0	24.0	39.8	916.0	455.0	3.111	6.706	1.969	1.331	3.137
	244	470.8	1801.0	45.6	51.8	966.0	508.0	3.146	6.191	1.860	1.316	3.041
	245	499.6	1790.0	67.3	63.7	1052.0	569.0	3.305	5.684	1.739	1.305	2.948
	246	553.6	1638.0	-10.6	15.9	835.0	376.0	4.023	6.760	2.062	1.374	3.306
	247	558.2	1627.0	17.6	27.8	953.0	436.0	3.955	7.621	1.918	1.348	3.168
	248	600.0	1616.0	45.9	39.8	1013.0	503.0	4.149	6.667	1.761	1.326	3.041
	249	622.7	1605.0	74.1	51.8	1126.0	588.0	4.294	6.015	1.613	1.298	2.909
	250	662.5	1794.0	102.5	63.7	1184.0	668.0	4.295	5.274	1.466	1.263	2.835
	251	643.6	1639.0	-4.9	15.9	863.0	386.0	4.640	9.016	1.940	1.377	3.278
	252	657.0	1628.0	27.7	27.8	965.0	457.0	4.588	7.617	1.767	1.345	3.120
	253	721.9	1816.0	60.2	39.8	1032.0	536.0	4.882	6.432	1.545	1.319	2.982
	254	767.4	1805.0	92.8	51.8	1125.0	640.0	4.972	5.353	1.365	1.279	2.850
	255	833.6	1794.0	125.4	63.7	1150.0	732.0	5.166	4.634	1.219	1.233	2.766
	256	751.2	1849.0	.4	15.9	835.0	325.0	5.316	8.621	1.747	1.382	3.252
	257	763.3	1836.0	36.9	27.8	937.0	464.0	5.332	7.133	1.556	1.347	3.082
	258	874.1	1828.0	73.5	39.8	964.0	565.0	5.755	5.782	1.318	1.312	2.915
	259	953.0	1818.0	109.7	51.8	1022.0	684.0	6.152	4.862	1.154	1.261	2.822
	260	1039.9	1807.0	146.1	63.7	1058.0	765.0	6.708	4.048	1.007	1.206	2.724
	261	281.6	1031.0	-30.6	15.9	739.0	364.0	2.983	8.735	2.390	1.439	3.375
	262	283.4	1021.0	-16.1	27.8	809.0	395.0	3.026	8.301	2.330	1.440	3.291
	263	306.6	1010.0	-1.5	39.8	825.0	429.0	3.639	9.017	2.424	1.466	3.219
	264	317.9	1000.0	13.0	51.8	874.0	464.0	3.964	8.655	2.383	1.472	3.151
	265	331.3	990.0	27.5	63.7	919.0	503.0	4.211	8.309	2.347	1.468	3.085
	266	448.0	1034.0	-16.5	15.9	847.0	381.0	6.148	11.021	2.455	1.455	3.305
	267	439.3	1024.0	4.9	27.8	982.0	434.0	5.954	9.722	2.332	1.435	3.188
	268	448.6	1013.0	28.3	39.8	1044.0	492.0	5.971	8.593	2.175	1.412	3.083
	269	461.2	1002.0	51.7	51.8	1208.0	556.0	6.003	7.613	2.022	1.390	2.966
	270	-248.2	992.0	75.1	63.7	1641.0	629.0	.724	.029	.434	.841	2.908
	271	548.1	1037.0	-9.0	15.9	959.0	347.0	7.356	10.303	2.153	1.419	3.253
	272	543.9	1026.0	21.2	27.8	1126.0	467.0	7.117	8.782	1.999	1.386	3.116
	273	582.7	1015.0	51.4	39.8	1217.0	548.0	7.354	7.467	1.781	1.348	2.988
	274	600.9	1004.0	81.6	51.8	1266.0	641.0	7.717	6.252	1.558	1.293	2.889
	275	-342.4	993.0	111.8	63.7	1761.0	752.0	.636	.009	.327	.782	2.817
	276	709.0	1044.0	-4.8	15.9	856.0	418.0	8.991	9.393	1.822	1.399	3.235
	277	801.3	1024.0	27.9	27.8	876.0	499.0	9.746	7.408	1.539	1.357	3.085
	278	973.2	1004.0	60.7	39.8	823.0	593.0	11.679	5.622	1.232	1.314	2.948
	279	1085.8	983.0	93.5	51.8	832.0	702.0	13.274	4.454	1.045	1.250	2.861
	280	-393.3	963.0	126.2	63.7	1751.0	842.0	.596	.006	.288	.756	2.786
	281	136.6	791.0	-37.1	15.9	779.0	373.0	1.289	2.404	1.587	1.134	3.411
	282	136.4	780.0	-28.6	27.8	847.0	393.0	1.278	2.474	1.550	1.134	3.342
	283	148.4	769.0	-20.1	39.8	853.0	413.0	1.305	2.553	1.570	1.141	3.298
	284	161.0	758.0	-11.6	51.8	858.0	434.0	1.340	2.660	1.593	1.150	3.253
	285	-71.6	747.0	-3.1	63.7	2222.0	455.0	.929	.664	.829	.964	3.214
	286	276.6	793.0	-28.7	15.9	819.0	389.0	4.839	11.794	2.839	1.587	3.344
	287	276.1	781.0	-14.0	27.8	906.0	423.0	4.866	10.993	2.757	1.588	3.267
	288	295.7	770.0	.6	39.8	935.0	459.0	5.434	10.715	2.764	1.579	3.198
	289	310.1	758.0	15.3	51.8	962.0	498.0	5.877	10.031	2.668	1.568	3.132
	290	-145.1	747.0	30.0	63.7	1734.0	540.0	.833	.315	.619	.909	3.067
	291	389.1	823.0	-16.9	15.9	1031.0	406.0	6.934	11.681	2.689	1.509	3.284
	292	557.2	803.0	6.5	27.8	822.0	463.0	9.643	9.606	2.067	1.410	3.170
	293	654.7	783.0	29.9	39.8	781.0	526.0	10.863	8.033	1.750	1.362	3.069
	294	738.4	763.0	53.3	51.8	767.0	597.0	11.889	6.674	1.516	1.324	2.971
	295	-261.6	744.0	76.7	63.7	1671.0	678.0	.710	.023	.417	.829	2.900
	296	339.2	797.0	-22.1	15.9	917.0	395.0	6.381	12.205	2.872	1.554	3.309
	297	341.9	785.0	-2.6	27.8	1026.0	442.0	6.423	10.996	2.729	1.540	3.213
	298	366.0	773.0	16.8	39.8	1079.0	491.0	6.831	9.911	2.547	1.509	3.126
	299	380.3	762.0	36.3	51.8	1151.0	546.0	7.084	8.907	2.377	1.482	3.041
	300	-199.1	750.0	55.7	63.7	1673.0	606.0	.770	.149	.508	.869	2.961

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
106	301	-38.3	462.0	-66.1	10.0	931.0	308.0	1.029	1.187	1.080	.992	3.641
	302	-37.2	457.0	-64.6	15.0	937.0	311.0	1.029	1.185	1.080	.991	3.627
	303	-36.8	452.0	-63.6	19.9	973.0	313.0	1.028	1.178	1.077	.990	3.613
	304	[illegible]	[illegible]	-62.[illegible]	24.9	1055.0	316.0	1.026	1.164	1.072	.989	3.602
	305	-34.6	441.0	-61.2	29.9	984.0	314.0	1.026	1.178	1.077	.988	3.591
	306	-10.3	452.0	-65.5	10.0	819.0	319.0	1.062	1.394	1.166	1.029	3.635
	307	-8.5	447.0	-63.6	15.0	821.0	322.0	1.063	1.393	1.166	1.031	3.615
	308	-7.6	442.0	-62.1	19.9	843.0	326.0	1.062	1.383	1.163	1.032	3.599
	309	-5.5	436.0	-60.4	24.9	838.0	329.0	1.064	1.387	1.165	1.035	3.585
	310	-3.3	431.0	-58.7	29.9	836.0	333.0	1.065	1.390	1.166	1.036	3.570
	311	36.1	453.0	-63.7	10.0	765.0	322.0	1.126	1.780	1.315	1.066	3.614
	312	39.3	447.0	-61.[illegible]	15.0	769.0	327.0	1.126	1.783	1.317	1.067	3.591
	313	40.6	442.0	-58.4	19.9	806.0	333.0	1.127	1.770	1.313	1.067	3.568
	314	47.[illegible]	437.0	-55.6	24.9	779.0	338.0	1.135	1.812	1.329	1.069	3.545
	315	[illegible]	431.0	-53.2	29.9	799.0	[illegible]	1.134	1.792	1.323	1.070	3.522
	316	[illegible]	454.0	-62.6	10.0	773.0	324.0	1.173	2.096	1.424	1.080	3.604
	317	67.4	449.0	-59.4	15.0	796.0	331.0	1.172	2.062	1.415	1.080	3.577
	318	72.5	443.0	-55.2	19.9	794.0	337.0	1.176	2.061	1.423	1.065	3.549
	319	70.6	437.0	-53.3	24.9	780.0	344.0	1.189	2.126	1.439	1.091	3.521
	320	80.2	432.0	-49.4	29.9	805.0	351.0	1.187	2.092	1.429	1.091	3.491
	321	96.6	455.0	-61.3	10.0	759.0	326.0	1.235	2.462	1.544	1.107	3.594
	322	100.6	453.0	-57.5	15.0	769.0	334.0	1.241	2.465	1.546	1.110	3.561
	323	103.6	444.0	-53.6	19.9	786.0	342.0	1.243	2.448	1.542	1.113	3.528
	324	111.2	438.0	-50.0	24.9	777.0	350.0	1.261	2.513	1.562	1.123	3.493
	325	113.1	432.0	-46.3	29.9	798.0	359.0	1.262	2.483	1.554	1.125	3.457
	326	115.1	456.0	-60.4	10.0	764.0	327.0	1.284	2.742	1.625	1.129	3.586
	327	119.0	450.0	-56.3	15.0	777.0	336.0	1.291	2.745	1.626	1.133	3.550
	328	122.4	444.0	-52.1	19.9	793.0	345.0	1.296	2.737	1.626	1.136	3.513
	329	140.6	439.0	-48.0	24.9	787.0	354.0	1.317	2.824	1.651	1.144	3.474
	330	132.5	433.0	-43.8	29.9	810.0	363.0	1.317	2.789	1.642	1.146	3.438
	331	152.5	456.0	-58.5	10.0	766.0	330.0	1.417	3.539	1.826	1.177	3.570
	332	156.9	451.0	-53.6	15.0	782.0	341.0	1.501	3.808	1.931	1.232	3.526
	333	161.0	445.0	-48.6	19.9	800.0	352.0	1.657	4.123	2.049	1.323	3.481
	334	170.4	439.0	-43.7	24.9	790.0	363.0	2.304	5.420	2.442	1.555	3.438
	335	174.4	434.0	-38.8	29.9	817.0	373.0	3.072	6.205	2.651	1.714	3.401
	336	176.0	457.0	-57.3	10.0	773.0	332.0	2.211	7.393	2.830	1.489	3.560
	337	181.2	452.0	-51.9	15.0	790.0	343.0	3.355	9.468	3.201	1.698	3.512
	338	186.3	446.0	-46.5	19.9	808.0	356.0	5.879	13.573	3.718	1.868	3.460
	339	195.5	440.0	-41.1	24.9	811.0	367.0	8.572	16.728	3.997	1.924	3.419
	340	200.2	435.0	-35.7	29.9	830.0	380.0	8.969	16.292	3.970	1.931	3.377
	341	195.9	458.0	-56.2	10.0	775.0	333.0	8.158	17.977	4.018	1.875	3.551
	342	201.1	452.0	-50.5	15.0	795.0	346.0	8.573	17.464	4.002	1.882	3.498
	343	205.9	447.0	-44.7	19.9	816.0	359.0	8.986	16.933	3.974	1.888	3.445
	344	216.0	441.0	-38.9	24.9	819.0	371.0	9.552	16.440	3.929	1.878	3.402
	345	221.9	435.0	-33.1	29.9	837.0	365.0	9.946	15.922	3.874	1.878	3.357
	346	237.4	459.0	-54.3	10.0	781.0	336.0	10.034	17.722	3.968	1.797	3.533
	347	242.4	453.0	-47.6	15.0	807.0	351.0	10.340	16.985	3.884	1.797	3.471
	348	247.2	448.0	-40.9	19.9	833.0	365.0	10.610	16.316	3.802	1.798	3.418
	349	257.1	442.0	-34.2	24.9	844.0	380.0	11.070	15.627	3.695	1.786	3.366
	350	260.2	436.0	-27.6	29.9	877.0	397.0	11.296	15.001	3.620	1.790	3.311
	351	269.1	460.0	-52.2	10.0	826.0	340.0	11.113	17.162	3.788	1.738	3.515
	352	271.0	454.0	-44.6	15.0	866.0	357.0	11.265	16.356	3.705	1.743	3.444
	353	271.8	448.0	-36.9	19.9	911.0	373.0	11.383	15.667	3.632	1.750	3.388
	354	280.1	443.0	-29.3	24.9	935.0	391.0	11.751	14.887	3.517	1.743	3.326
	355	292.6	437.0	-21.6	29.9	945.0	409.0	12.196	14.132	3.385	1.718	3.286
	356	309.2	462.0	-50.0	10.0	847.0	343.0	12.262	16.406	3.543	1.674	3.495
	357	325.0	456.0	-41.4	15.0	858.0	362.0	12.794	15.384	3.378	1.656	3.422
	358	339.6	450.0	-32.8	19.9	872.0	381.0	13.281	14.461	3.227	1.640	3.355
	359	363.8	444.0	-24.2	24.9	863.0	401.0	13.975	13.481	3.032	1.608	3.297
	360	378.7	438.0	-15.6	29.9	874.0	422.0	14.386	12.687	2.893	1.582	3.258

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
106	361	410.3	465.0	-48.5	10.0	714.0	345.0	14.872	14.913	2.983	1.560	3.481
	362	446.2	460.0	-39.2	15.0	705.0	365.0	15.762	13.745	2.767	1.534	3.406
	363	482.4	455.0	-29.9	19.9	691.0	386.0	16.560	12.627	2.557	1.511	3.332
	364	526.7	450.0	-20.6	24.9	668.0	458.0	17.620	11.563	2.344	1.478	3.282
	365	559.4	446.0	-11.3	29.9	661.0	431.0	18.409	10.681	2.187	1.449	3.236
	366	474.9	471.0	-46.0	10.0	710.0	349.0	16.079	13.959	2.699	1.519	3.457
	367	517.4	465.0	-35.7	15.0	695.0	370.0	17.095	12.716	2.472	1.495	3.379
	368	569.2	460.0	-25.3	19.9	672.0	394.0	18.341	11.495	2.244	1.468	3.303
	369	634.2	454.0	-15.0	24.9	636.0	418.0	19.747	10.325	2.016	1.434	3.256
	370	697.2	446.0	-4.7	29.9	609.0	444.0	21.054	9.268	1.830	1.408	3.208
	371	641.8	474.0	-45.1	10.0	551.0	348.0	19.661	12.247	2.172	1.464	3.450
	372	736.3	468.0	-34.5	15.0	511.0	371.0	21.760	10.711	1.910	1.447	3.370
	373	810.7	461.0	-23.9	19.9	490.0	345.0	23.335	9.533	1.725	1.434	3.297
	374	869.8	455.0	-13.3	24.9	480.0	420.0	24.735	8.612	1.588	1.414	3.247
	375	918.9	449.0	-2.7	29.9	476.0	446.0	26.032	7.851	1.478	1.394	3.200
	376	845.9	449.0	-43.2	10.0	463.0	353.0	25.369	10.427	1.762	1.452	3.435
	377	1067.0	440.0	-31.9	15.0	391.0	376.0	32.618	8.464	1.421	1.439	3.347
	378	1149.1	432.0	-20.5	19.9	382.0	404.0	36.511	7.553	1.297	1.421	3.284
	379	1152.7	423.0	-9.1	24.9	400.0	432.0	36.894	7.045	1.253	1.399	3.223
	380	1170.4	415.0	2.3	29.9	413.0	460.0	38.037	6.544	1.199	1.378	3.177
107	381	827.1	1839.0	95.2	15.1	379.0	163.0	5.236	5.254	1.299	1.279	2.840
	382	955.6	1836.0	128.0	26.3	360.0	210.0	5.959	4.506	1.111	1.234	2.770
	383	1015.9	1832.0	161.2	37.7	360.0	246.0	6.209	3.807	.993	1.[illegible]	2.670
	384	1049.0	1829.0	194.3	49.1	415.0	290.0	6.167	3.211	.907	1.[illegible]	2.560
	385	1170.4	1826.0	227.1	60.3	407.0	344.0	7.252	2.651	.791	1.061	2.450
	386	857.5	1852.0	97.6	15.1	365.0	180.0	5.391	5.189	1.265	1.278	0.000
	387	949.7	1845.0	132.6	26.3	367.0	208.0	5.830	4.425	1.106	1.228	0.000
	388	974.6	1845.0	168.0	37.7	408.0	247.0	5.712	3.720	1.008	1.174	0.000
	389	1012.1	1842.0	203.4	49.1	445.0	295.0	5.656	3.100	.915	1.112	0.000
	390	1127.1	1838.0	238.4	60.3	440.0	355.0	6.404	2.531	.799	1.040	0.000
	391	839.6	1845.0	97.7	15.1	364.0	176.0	5.284	5.197	1.282	1.277	0.000
	392	911.8	1842.0	132.6	26.3	375.0	203.0	5.538	4.444	1.135	1.227	0.000
	393	943.1	1839.0	167.9	37.7	414.0	241.0	5.464	3.733	1.030	1.173	0.000
	394	972.4	1835.0	203.1	49.1	456.0	267.0	5.329	3.116	.940	1.112	0.000
	395	1165.1	1832.0	238.1	60.3	411.0	346.0	6.955	2.514	.781	1.040	0.000
	396	849.0	1847.0	97.8	15.1	359.0	173.0	5.343	5.190	1.272	1.277	0.000
	397	911.1	1844.0	132.7	26.3	375.0	201.0	5.526	4.443	1.136	1.226	0.000
	398	944.0	1841.0	168.1	37.7	413.0	238.0	5.465	3.731	1.029	1.173	0.000
	399	976.8	1838.0	203.4	49.1	453.0	284.0	5.358	3.112	.937	1.112	0.000
	400	1218.4	1834.0	238.4	60.3	388.0	342.0	7.852	2.493	.756	1.039	0.000
	401	835.1	1848.0	97.1	15.1	359.0	175.0	5.251	5.213	1.287	1.277	0.000
	402	887.0	1845.0	131.5	26.3	378.0	202.0	5.352	4.484	1.159	1.228	0.000
	403	919.3	1842.0	166.2	37.7	415.0	239.0	5.288	3.778	1.051	1.175	0.000
	404	949.3	1839.0	201.0	49.1	457.0	284.0	5.164	3.163	.959	1.117	0.000
	405	1220.6	1836.0	235.4	60.3	377.0	341.0	7.954	2.534	.759	1.046	0.000
	406	665.9	1850.0	89.1	15.1	358.0	170.0	4.264	5.496	1.497	1.280	0.000
	407	689.6	1847.0	117.6	26.3	382.0	190.0	4.242	4.911	1.395	1.241	0.000
	408	703.4	1844.0	146.3	37.7	422.0	217.0	4.146	4.287	1.296	1.201	0.000
	409	717.3	1841.0	175.0	49.1	468.0	249.0	4.029	3.729	1.206	1.160	0.000
	410	942.8	1858.0	20[illegible].4	60.3	368.0	288.0	5.089	3.127	.959	1.112	0.000
	411	700.4	1856.0	88.7	15.1	337.0	170.0	4.468	5.476	1.455	1.281	0.000
	412	714.2	1853.0	116.7	26.3	365.0	189.0	4.391	4.910	1.369	1.243	0.000
	413	732.9	1850.0	145.0	37.7	399.0	216.0	4.323	4.295	1.268	1.203	0.000
	414	751.5	1847.0	173.3	49.1	436.0	247.0	4.203	3.741	1.177	1.163	0.000
	415	982.7	1844.0	201.3	60.3	346.0	284.0	5.415	3.147	.937	1.117	0.000
	416	735.6	1862.0	88.8	15.1	319.0	172.0	4.682	5.446	1.413	1.282	0.000
	417	740.1	1859.0	116.8	26.3	350.0	191.0	4.531	4.890	1.340	1.243	0.000
	418	758.2	1856.0	145.1	37.7	383.0	212.0	4.435	4.278	1.242	1.204	0.000
	419	780.9	1853.0	173.4	49.1	4[illegible]5.0	250.0	4.340	3.725	1.150	1.164	0.000
	420	1017.0	1850.0	201.4	60.3	332.0	288.0	5.706	3.137	.916	1.117	0.000

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psi.	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
107	421	748.9	1862.0	69.3	15.1	313.0	168.0	4.750	5.427	1.397	1.283	0.000
	422	754.4	1859.0	117.5	26.3	344.0	187.0	[illegible].601	4.865	1.322	1.243	0.000
	423	771.5	1856.0	146.1	37.7	377.0	214.0	4.498	4.250	1.226	1.203	0.000
	424	755.3	1853.0	174.6	49.1	409.0	245.0	4.407	3.696	1.134	1.162	0.000
	425	1035.4	1850.0	202.9	60.3	327.0	283.0	5.867	3.106	.903	1.114	0.000
	426	747.8	1860.0	89.3	15.1	315.0	172.0	4.748	5.427	1.398	1.282	0.000
	427	756.5	1857.0	117.5	26.3	341.0	192.0	4.617	4.865	1.320	1.243	0.000
	428	774.4	1854.0	145.9	37.7	376.0	219.0	4.518	4.251	1.224	1.203	0.000
	429	700.5	1851.0	174.3	49.1	407.0	251.0	4.435	3.698	1.131	1.162	0.000
	430	1039.9	1848.0	202.5	60.3	326.0	289.0	5.922	3.108	.900	1.115	0.000
	431	657.2	1861.0	84.7	15.1	308.0	167.0	4.215	5.583	1.521	1.285	0.000
	432	666.0	1858.0	109.4	26.3	332.0	184.0	4.131	5.086	1.445	1.253	0.000
	433	678.4	1855.0	134.3	37.7	361.0	205.0	4.057	4.556	1.359	1.219	0.000
	434	695.0	1852.0	159.2	49.1	391.0	231.0	3.992	4.032	1.270	1.183	0.000
	435	900.8	1849.0	183.9	60.3	312.0	261.0	4.969	3.474	1.027	1.150	0.000
	436	653.7	1862.0	84.4	15.1	306.0	165.0	4.194	5.590	1.526	1.285	0.000
	437	662.3	1859.0	109.0	26.3	331.0	181.0	4.110	5.096	1.451	1.253	0.000
	438	675.0	1856.0	133.8	37.7	359.0	202.0	4.039	4.569	1.365	1.220	0.000
	439	691.1	1853.0	158.5	49.1	389.0	227.0	3.972	4.046	1.276	1.184	0.000
	440	895.5	1850.0	183.1	60.3	310.0	256.0	4.938	3.491	1.072	1.151	0.000
	441	668.8	1867.0	84.7	15.1	[illegible]2.0	169.0	4.268	5.569	1.506	1.285	0.000
	442	680.2	1864.0	109.5	26.3	325.0	186.0	4.199	5.071	1.4[illegible]	1.253	0.000
	443	694.0	1861.0	134.5	37.7	351.0	207.0	4.133	4.540	1.[illegible]1	1.219	0.000
	444	711.2	1858.0	159.5	49.1	381.0	234.0	4.072	4.017	1.252	1.183	0.000
	445	919.1	1855.0	184.2	60.3	305.0	264.0	5.078	3.463	1.013	1.150	0.000
108	446	360.2	1776.0	85.0	15.1	1175.0	554.0	2.169	4.133	1.663	1.258	2.861
	447	403.5	1746.0	99.8	26.3	1131.0	588.0	2.448	4.378	1.662	1.263	2.835
	448	427.2	1714.0	114.7	37.7	1139.0	625.0	2.672	4.354	1.624	1.256	2.809
	449	441.7	1683.0	129.5	49.1	1165.0	671.0	2.830	4.218	1.577	1.245	2.772
	450	478.8	1652.0	144.3	60.3	1153.0	725.0	3.057	4.066	1.499	1.223	2.729
	451	366.9	1770.0	85.0	15.1	1169.0	563.0	2.159	4.108	1.660	1.258	2.860
	452	401.8	1738.0	99.8	26.3	1145.0	597.0	2.433	4.357	1.661	1.263	2.835
	453	424.2	1706.0	114.7	37.7	1154.0	636.0	2.653	4.343	1.626	1.256	2.809
	454	438.5	1674.0	129.5	49.1	1202.0	683.0	2.815	4.212	1.580	1.246	2.772
	455	475.3	1642.0	144.3	60.3	1170.0	737.0	3.054	4.069	1.504	1.224	2.729
	456	357.7	1771.0	84.5	15.1	1168.0	565.0	2.096	3.961	1.642	1.254	2.861
	457	392.0	1739.0	99.0	26.3	1142.0	598.0	2.348	4.250	1.654	1.261	2.836
	458	413.1	1706.0	113.6	37.7	1153.0	635.0	2.540	4.277	1.630	1.255	2.811
	459	427.4	1674.0	128.2	49.1	1199.0	681.0	2.689	4.158	1.586	1.246	2.776
	460	463.6	1642.0	142.7	60.3	1164.0	734.0	2.983	4.070	1.519	1.228	2.734
	461	361.0	1773.0	84.6	15.1	1188.0	565.0	2.116	4.009	1.648	1.255	2.861
	462	395.6	1741.0	99.2	26.3	1143.0	598.0	2.376	4.286	1.656	1.262	2.835
	463	417.4	1708.0	114.0	37.7	1153.0	636.0	2.579	4.300	1.628	1.255	2.810
	464	431.7	1676.0	128.7	49.1	1199.0	682.0	2.732	4.176	1.583	1.246	2.775
	465	468.1	1644.0	143.3	60.3	1166.0	736.0	3.005	4.066	1.513	1.226	2.732
	466	363.0	1776.0	84.7	15.1	1190.0	564.0	2.127	4.035	1.651	1.256	2.861
	467	398.3	1744.0	99.4	26.3	1143.0	598.0	2.396	4.311	1.658	1.262	2.835
	468	408.6	1711.0	114.2	37.7	1199.0	637.0	2.485	4.224	1.627	1.253	2.810
	469	435.0	1679.0	129.1	49.1	1199.0	683.0	2.765	4.189	1.581	1.246	2.774
	470	471.4	1646.0	143.8	60.3	1167.0	738.0	3.020	4.062	1.508	1.225	2.730
	471	365.2	1730.0	84.6	15.1	1186.0	566.0	2.139	4.067	1.655	1.256	2.861
	472	400.4	1747.0	99.5	26.3	1141.0	601.0	2.410	4.329	1.658	1.262	2.835
	473	410.9	1714.0	114.5	37.7	1197.0	639.0	2.502	4.233	1.626	1.253	2.809
	474	437.4	1682.0	129.4	49.1	1198.0	687.0	2.787	4.195	1.579	1.245	2.773
	475	475.1	1649.0	144.3	60.3	1163.0	742.0	3.038	4.060	1.503	[illegible]	2.729
	476	363.4	1783.0	84.6	15.1	1190.0	566.0	2.124	4.032	1.651	[illegible]	2.862
	477	399.7	1750.0	99.4	26.3	1141.0	600.0	2.400	4.315	1.657	[illegible]	2.836
	478	410.4	1718.0	114.4	37.7	1196.0	639.0	2.492	4.224	1.625	[illegible]	2.810
	479	437.3	1685.0	129.4	49.1	1195.0	687.0	2.780	4.190	1.578	[illegible]	2.773
	480	474.7	1652.0	144.3	60.3	1162.0	742.0	3.029	4.055	1.503	[illegible]24	2.729

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
108	481	363.8	1785.0	84.5	15.1	1188.0	566.0	2.124	4.036	1.651	1.255	2.862
	482	399.9	1753.0	99.4	26.3	1140.0	600.0	2.399	4.315	1.657	1.262	2.836
	483	410.7	1720.0	114.4	37.7	1194.0	639.0	2.492	4.223	1.625	1.252	2.810
	484	437.5	1687.0	129.4	49.1	1194.0	686.0	2.779	4.189	1.578	1.245	2.773
	485	475.3	1655.0	144.3	60.3	1160.0	742.0	3.028	4.054	1.502	1.223	2.729
	486	423.4	1787.0	88.0	15.1	1204.0	571.0	2.620	4.664	1.686	1.276	2.857
	487	464.2	1754.0	105.5	26.3	1169.0	612.0	2.949	4.650	1.623	1.265	2.827
	488	490.5	1721.0	123.2	37.7	1190.0	661.0	3.114	4.452	1.554	1.244	2.790
	489	509.1	1688.0	140.9	49.1	1246.0	723.0	3.233	4.188	1.483	1.221	2.739
	490	553.7	1655.0	158.4	60.3	1219.0	793.0	3.572	3.998	1.395	1.191	2.684
	491	421.6	1790.0	87.9	15.1	1206.0	570.0	2.598	4.645	1.686	1.275	2.857
	492	464.7	1757.0	105.3	26.3	1162.0	611.0	2.949	4.652	1.623	1.265	2.827
	493	491.3	1723.0	122.9	37.7	1182.0	661.0	3.116	4.456	1.553	1.244	2.790
	494	510.2	1690.0	140.5	49.1	1236.0	721.0	3.238	4.195	1.483	1.222	2.740
	495	555.2	1657.0	158.0	60.3	1208.0	791.0	3.578	4.007	1.395	1.191	2.685
	496	420.9	1793.0	87.9	15.1	1206.0	572.0	2.587	4.635	1.685	1.274	2.857
	497	465.0	1760.0	105.3	26.3	1158.0	613.0	2.947	4.649	1.622	1.265	2.827
	498	492.1	1726.0	122.9	37.7	1176.0	663.0	3.117	4.457	1.553	1.244	2.790
	499	511.2	1693.0	140.5	49.1	1229.0	724.0	3.241	4.197	1.483	1.222	2.741
	500	556.5	1660.0	157.9	60.3	1201.0	794.0	3.581	4.011	1.395	1.191	2.686
	501	423.4	1795.0	87.9	15.1	1199.0	572.0	2.610	4.653	1.684	1.275	2.857
	502	467.1	1762.0	105.4	26.3	1154.0	613.0	2.956	.652	1.620	1.264	2.827
	503	495.1	1729.0	123.0	37.7	1169.0	663.0	3.135	4.461	1.550	1.243	2.790
	504	514.6	1695.0	140.6	49.1	1220.0	724.0	3.264	4.202	1.479	1.221	2.740
	505	561.1	1662.0	158.1	60.3	1190.0	794.0	3.602	4.019	1.391	1.190	2.685
	506	425.5	1797.0	88.0	15.1	1194.0	572.0	2.630	4.668	1.684	1.275	2.857
	507	469.0	1764.0	105.5	26.3	1151.0	613.0	2.965	4.654	1.618	1.264	2.827
	508	497.8	1731.0	123.1	37.7	1163.0	663.0	3.150	4.465	1.547	1.243	2.790
	509	517.4	1698.0	140.8	49.1	1215.0	724.0	3.280	4.204	1.477	1.220	2.740
	510	564.8	1666.0	158.3	60.3	1183.0	794.0	3.616	4.024	1.388	1.189	2.684
	511	425.4	1797.0	88.0	15.1	1195.0	572.0	2.628	4.666	1.684	1.275	2.857
	512	469.0	1764.0	105.5	26.3	1151.0	614.0	2.965	4.653	1.618	1.264	2.827
	513	497.7	1731.0	123.2	37.7	1164.0	663.0	3.149	4.464	1.547	1.243	2.790
	514	517.4	1698.0	140.9	49.1	1215.0	725.0	3.279	4.203	1.476	1.220	2.739
	515	565.0	1666.0	158.4	60.3	1183.0	795.0	3.617	4.023	1.387	1.189	2.684
	516	424.9	1797.0	88.1	15.1	1197.0	573.0	2.622	4.660	1.683	1.275	2.857
	517	469.3	1764.0	105.7	26.3	1150.0	614.0	2.966	4.652	1.617	1.264	2.827
	518	498.1	1731.0	123.3	37.7	1164.0	664.0	3.151	4.462	1.546	1.243	2.789
	519	518.2	1698.0	141.0	49.1	1214.0	725.0	3.285	4.201	1.475	1.220	2.739
	520	565.3	1666.0	158.6	60.3	1183.0	795.0	3.616	4.020	1.386	1.189	2.684
	521	497.6	1799.0	92.6	15.1	1225.0	580.0	3.166	4.951	1.630	1.276	2.850
	522	550.1	1766.0	113.3	26.3	1187.0	630.0	3.584	4.817	1.538	1.251	2.813
	523	586.4	1732.0	134.3	37.7	1211.0	696.0	3.764	4.551	1.448	1.222	2.759
	524	613.3	1698.0	155.3	49.1	1268.0	776.0	3.884	4.216	1.364	1.188	2.692
	525	675.8	1665.0	176.0	60.3	1230.0	865.0	4.146	3.773	1.235	1.150	2.627
	526	497.3	1799.0	92.7	15.1	1226.0	580.0	3.162	4.947	1.630	1.276	2.850
	527	551.0	1766.0	113.4	26.3	1185.0	631.0	3.587	4.818	1.537	1.251	2.813
	528	587.5	1733.0	134.4	37.7	1208.0	696.0	3.769	4.552	1.447	1.222	2.758
	529	615.0	1699.0	155.4	49.1	1263.0	777.0	3.893	4.220	1.362	1.188	2.692
	530	677.8	1666.0	176.1	60.3	1225.0	865.0	4.155	3.768	1.232	1.149	2.627
	531	498.5	1799.0	92.7	15.1	1222.0	580.0	3.172	4.952	1.629	1.276	2.850
	532	551.8	1766.0	113.4	26.3	1183.0	631.0	3.592	4.821	1.536	1.251	2.813
	533	588.7	1733.0	134.4	37.7	1205.0	696.0	3.777	4.557	1.446	1.222	2.758
	534	616.4	1699.0	155.4	49.1	1260.0	777.0	3.904	4.225	1.361	1.188	2.692
	535	679.4	1666.0	176.1	60.3	1222.0	865.0	4.165	3.766	1.231	1.149	2.627
	536	499.2	1802.0	92.9	15.1	1221.0	580.0	3.171	4.947	1.627	1.276	2.849
	537	554.9	1768.0	113.7	26.3	1175.0	631.0	3.606	4.827	1.534	1.251	2.812
	538	593.5	1734.0	134.6	37.7	1193.0	697.0	3.805	4.570	1.442	1.221	2.758
	539	622.6	1700.0	155.5	49.1	1243.0	777.0	3.940	4.233	1.356	1.187	2.691
	540	687.6	1666.0	176.2	60.3	1202.0	866.0	4.209	3.754	1.222	1.148	2.627

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr.4	Re/1000	ρb/ρw	μb/μw	kb/kw	Cp/Cpb	Pr
108	541	501.6	1802.0	93.4	15.1	1214.0	581.0	3.187	4.947	1.624	1.275	2.848
	542	557.8	1769.0	114.1	26.3	1167.0	632.0	3.619	4.829	1.530	1.250	2.811
	543	598.0	1735.0	135.0	37.7	1181.0	698.0	3.830	4.576	1.438	1.220	2.757
	544	629.9	1702.0	155.9	49.1	1224.0	778.0	3.972	4.215	1.346	1.186	2.690
	545	696.5	1668.0	176.7	60.3	1181.0	867.0	4.255	3.734	1.211	1.147	2.625
	546	503.7	1805.0	93.9	15.1	1209.0	564.0	3.197	4.944	1.621	1.275	2.848
	547	561.5	1772.0	114.6	26.3	1159.0	636.0	3.634	4.833	1.526	1.249	2.811
	548	603.4	1737.0	135.5	37.7	1169.0	702.0	3.860	4.586	1.433	1.219	2.755
	549	637.7	1703.0	156.4	49.1	1206.0	783.0	4.006	4.195	1.335	1.185	2.689
	550	705.7	1670.0	177.1	60.3	1162.0	672.0	4.304	3.714	1.201	1.146	2.623
	551	501.2	1806.0	94.3	15.1	1204.0	585.0	3.174	4.924	1.622	1.274	2.847
	552	560.4	1772.0	114.8	26.3	1149.0	636.0	3.624	4.822	1.526	1.249	2.810
	553	603.5	1738.0	135.5	37.7	1155.0	702.0	3.858	4.585	1.433	1.219	2.755
	554	638.6	1705.0	156.2	49.1	1188.0	782.0	4.008	4.197	1.334	1.185	2.689
	555	705.6	1671.0	176.7	60.3	1146.0	870.0	4.304	3.721	1.202	1.147	2.625
	556	510.1	1813.0	95.4	15.1	1193.0	580.0	3.227	4.931	1.612	1.273	2.845
	557	571.9	1781.0	116.2	26.3	1135.0	632.0	3.672	[illegible]	1.515	1.246	2.808
	558	619.0	1748.0	137.2	37.7	1135.0	699.0	3.939	4.602	1.418	1.215	2.751
	559	658.6	1715.0	158.1	49.1	1159.0	779.0	4.080	4.129	1.306	1.181	2.684
	560	732.1	1682.0	176.9	60.3	1111.0	869.0	4.421	3.646	1.170	1.143	2.616
109	561	-129.4	522.0	-168.5	10.0	3207.0	199.0	1.035	1.449	1.109	1.001	5.868
	562	-129.3	511.0	-163.4	15.0	3776.0	210.0	1.030	1.379	1.095	.998	5.668
	563	-129.3	501.0	-158.4	19.9	4561.0	222.0	1.026	1.308	1.081	.995	5.460
	564	-129.5	490.0	-153.3	24.9	5747.0	234.0	1.021	1.235	1.066	.992	5.247
	565	39.0	479.0	-148.2	29.9	749.0	245.0	1.225	3.463	1.678	1.095	5.103
	566	-87.5	523.0	-165.3	10.0	2348.0	205.0	1.074	1.936	1.237	1.027	5.745
	567	-200.0	512.0	-158.5	15.0	4573.0	221.0	.965	.609	.907	.995	5.466
	568	-200.0	501.0	-151.6	19.9	4080.0	237.0	.959	.568	.891	.991	5.202
	569	-200.5	489.0	-144.7	24.9	3664.0	252.0	.953	.530	.874	.987	5.005
	570	106.8	478.0	-137.8	29.9	865.0	269.0	1.357	4.605	1.967	1.144	4.797
	571	-87.1	523.0	-162.0	10.0	3159.0	212.0	1.071	1.877	1.228	1.027	5.614
	572	100.5	512.0	-153.6	15.0	978.0	232.0	1.355	5.097	2.011	1.137	5.261
	573	-268.8	501.0	-145.1	19.9	2094.0	251.0	.903	.084	.749	.966	5.017
	574	-269.9	490.0	-136.6	24.9	2032.0	272.0	.896	.076	.730	.963	4.760
	575	159.6	478.0	-128.1	29.9	980.0	292.0	1.558	6.928	2.473	1.212	4.565
	576	82.6	526.0	-159.9	10.0	1115.0	216.0	1.319	4.934	1.944	1.124	5.526
	577	133.5	514.0	-150.3	15.0	1004.0	239.0	1.453	6.104	2.200	1.170	5.168
	578	-310.3	502.0	-140.8	19.9	1764.0	261.0	.872	.051	.680	.959	4.888
	579	-312.0	491.0	-131.2	24.9	1735.0	284.0	.863	.047	.661	.955	4.633
	580	184.6	479.0	-121.6	29.9	1073.0	308.0	3.112	19.080	4.076	1.569	4.419
	581	160.5	526.0	-157.3	10.0	951.0	222.0	1.590	8.798	2.610	1.209	5.421
	582	166.6	514.0	-146.9	15.0	1018.0	245.0	1.618	9.607	2.826	1.220	5.072
	583	165.0	503.0	-136.5	19.9	1117.0	271.0	1.597	8.551	2.733	1.219	4.759
	584	174.4	491.0	-126.1	24.9	1177.0	295.0	1.809	11.077	3.194	1.303	4.522
	585	178.8	479.0	-115.7	29.9	1263.0	322.0	2.241	12.582	3.462	1.436	4.295
	586	166.8	528.0	-154.7	10.0	1062.0	228.0	1.626	9.845	2.796	1.219	5.309
	587	171.3	516.0	-143.1	15.0	1150.0	253.0	1.652	10.681	3.004	1.231	4.961
	588	171.4	504.0	-131.6	19.9	1266.0	281.0	1.651	10.180	3.017	1.238	4.644
	589	189.2	492.0	-120.1	24.9	1311.0	310.0	3.061	26.842	4.433	1.552	4.384
	590	202.1	481.0	-108.5	29.9	1373.0	339.0	6.604	25.179	4.483	1.751	4.185
	591	183.2	536.0	-151.8	10.0	1139.0	233.0	1.784	14.429	5.323	1.259	5.213
	592	190.5	527.0	-139.2	15.0	1233.0	262.0	1.994	18.914	3.774	1.323	4.845
	593	200.5	519.0	-126.6	19.9	1321.0	292.0	3.743	22.352	4.132	1.592	4.537
	594	227.3	510.0	-114.0	24.9	1343.0	324.0	8.634	26.155	4.582	1.739	4.273
	595	244.6	502.0	-101.4	29.9	1400.0	357.0	9.489	23.760	4.388	1.730	4.070
	596	214.4	542.0	-148.7	10.0	1158.0	239.0	7.155	25.463	4.323	1.682	5.126
	597	240.0	534.0	-135.1	15.0	1202.0	271.0	8.698	30.380	4.707	1.695	4.721
	598	257.0	525.0	-121.5	19.9	1270.0	303.0	9.503	27.320	4.532	1.698	4.420
	599	284.5	517.0	-107.8	24.9	1302.0	338.0	10.533	24.352	4.248	1.677	4.177
	600	320.8	508.0	-94.2	29.9	1306.0	374.0	11.723	21.545	3.898	1.641	3.973

TABLE III-IV (cont.)

Test Number F736-737-	Run Number	Wall Temp	Pressure psia	Bulk Temp	L/D	Nu	Re ×10⁻³	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
I	601	357.7	529.0	-147.0	11.0	857.0	241.0	12.591	32.242	4.261	1.615	5.177
	602	434.0	511.0	-133.2	15.0	814.0	274.0	15.185	24.702	3.651	1.585	4.674
	603	515.2	493.0	-124.3	19.9	772.0	311.0	17.394	22.454	3.131	1.539	4.366
	604	615.6	475.0	-115.4	24.9	722.0	345.0	21.246	18.736	2.651	1.511	4.133
	605	721.3	458.0	-91.5	29.9	681.0	382.0	23.224	15.669	2.274	1.491	4.435
	606	169.5	537.0	-151.0	11.0	1177.0	237.0	1.624	9.853	2.751	1.227	5.167
	607	182.9	529.0	-138.4	15.0	1133.1	263.0	1.784	13.881	5.352	1.251	4.672
	608	193.5	521.0	-127.5	19.9	1211.0	289.0	2.221	21.155	3.921	1.391	4.556
	609	218.1	513.0	-115.2	24.9	1212.0	318.0	8.111	15.534	4.439	1.743	4.365
	610	212.2	514.0	-114.9	29.9	1334.0	347.0	7.442	24.148	4.375	1.757	4.127
	611	[illegible]	537.0	-149.1	11.0	1144.0	239.0	1.639	9.776	1.794	1.223	5.144
	612	186.1	529.0	-137.9	15.0	1148.0	264.0	1.817	13.763	3.517	1.276	4.815
	613	219.4	521.0	-126.5	19.9	1212.0	291.0	3.641	21.357	4.565	1.583	4.534
	614	234.5	513.0	-115.1	24.9	1187.0	321.0	8.899	26.233	4.555	1.736	4.288
	615	222.4	505.0	-111.6	29.9	1338.0	357.0	9.445	26.212	4.456	1.751	4.117
	616	193.1	541.0	-146.1	11.0	1154.0	244.0	2.251	16.899	3.557	1.341	5.152
	617	219.3	531.0	-133.5	15.0	1214.0	274.0	7.219	22.514	4.178	1.718	4.688
	618	232.6	523.0	-121.9	19.9	1253.0	314.0	8.579	27.314	4.592	1.721	[illegible]
	619	261.3	514.0	-118.3	24.9	1268.0	335.0	9.644	24.703	4.384	1.703	[illegible]
	620	266.5	516.0	-95.7	29.9	1367.0	369.0	11.116	22.574	4.221	1.713	3.991
	621	216.0	546.0	-144.4	11.0	1169.0	248.0	6.115	19.567	3.856	1.667	5.192
	622	261.0	541.0	-131.3	15.0	1117.0	277.0	9.313	29.617	4.611	1.691	4.642
	623	293.7	535.0	-118.3	19.9	1159.0	311.0	11.127	26.133	4.343	1.671	4.346
	624	281.3	533.0	-115.2	24.9	1275.0	341.0	11.173	23.799	4.219	1.678	4.135
	625	328.6	524.0	-92.1	29.9	1238.0	378.0	11.469	21.022	3.816	1.631	3.948
II	626	87.6	481.0	-231.4	11.0	171.0	35.0	1.415	25.193	2.332	1.138	23.164
	627	79.9	476.0	-225.8	15.0	191.0	41.0	1.391	21.225	2.254	1.133	19.866
	628	73.3	472.0	-221.3	19.9	217.0	51.0	1.366	16.697	2.179	1.127	16.571
	629	74.6	467.0	-214.7	24.9	244.0	63.0	1.365	13.229	2.163	1.123	13.171
	630	81.5	463.0	-219.1	29.9	279.0	89.0	1.376	9.355	2.177	1.135	9.642
	631	119.5	481.0	-231.5	11.0	186.0	36.0	1.511	31.874	2.553	1.157	22.553
	632	159.4	476.0	-224.1	15.0	213.0	43.0	1.468	23.801	2.449	1.158	18.865
	633	163.4	472.0	-217.8	19.9	246.0	55.0	1.442	17.991	2.363	1.152	15.053
	634	156.5	467.0	-211.4	24.9	275.0	76.0	1.445	13.295	2.349	1.155	11.182
	635	112.6	463.0	-215.0	29.9	301.0	113.0	1.457	10.219	2.357	1.162	[illegible]
	636	145.8	481.0	-229.0	11.0	[illegible]	37.0	1.614	35.464	2.767	1.195	[illegible]
	637	134.8	476.0	-221.8	15.0	240.0	47.0	1.554	25.900	2.626	1.182	17.475
	638	128.8	471.0	-214.6	19.9	284.0	64.0	1.523	18.273	2.532	1.177	13.115
	639	131.5	467.0	-237.4	24.9	348.0	100.0	1.525	11.924	2.512	1.181	8.556
	640	138.5	462.0	-231.2	29.9	364.0	110.0	1.545	11.423	2.533	1.187	7.943
	641	165.0	481.0	-227.0	11.0	231.0	39.0	1.753	55.725	3.711	1.231	21.551
	642	158.6	476.0	-218.9	15.0	273.0	53.0	1.675	37.511	3.033	1.215	15.744
	643	153.8	471.0	-210.8	19.9	338.0	79.0	1.629	17.780	2.730	1.207	10.716
	644	156.5	466.5	-202.7	24.9	388.0	107.0	1.643	14.396	2.835	1.213	8.151
	645	164.1	462.8	-194.6	29.9	410.0	119.0	1.723	15.844	3.177	1.239	7.454
	646	182.4	485.0	-225.2	11.0	257.0	42.0	2.950	99.035	4.946	1.459	19.505
	647	173.5	475.5	-219.3	15.0	312.0	59.0	1.929	43.129	3.965	1.287	14.129
	648	169.9	471.0	-207.3	19.9	414.0	100.0	1.745	22.667	3.623	1.236	8.533
	649	178.5	466.0	-199.4	24.9	437.0	113.0	1.739	28.693	3.617	1.236	7.783
	650	177.8	461.0	-189.4	29.9	467.0	129.0	2.638	24.939	4.195	1.451	6.995
	651	183.6	481.5	-224.2	10.0	274.0	43.0	3.125	6.866	5.161	1.478	18.908
	652	174.1	476.1	-214.8	15.0	338.0	63.0	2.016	42.212	4.004	1.311	13.249
	653	176.4	471.0	-215.5	19.9	430.0	103.0	1.746	22.542	3.645	1.237	9.345
	654	172.6	466.0	-196.1	24.9	465.0	116.0	1.901	21.722	3.759	1.289	7.590
	655	186.7	461.8	-186.7	29.9	496.0	132.0	3.234	28.537	4.489	1.525	6.651
III	656	418.8	483.0	-225.7	16.0	197.0	41.0	1.500	26.581	2.515	1.166	19.421
	657	112.8	479.0	-219.2	15.0	227.0	51.0	1.474	26.256	2.436	1.161	15.934
	658	166.2	474.0	-212.7	19.9	269.0	70.0	1.445	14.268	2.353	1.155	11.904
	659	188.6	470.0	-206.1	24.9	318.0	111.0	1.445	10.082	2.333	1.158	8.438
	660	114.1	465.0	-199.6	29.9	332.0	109.0	1.456	9.665	2.341	1.162	7.890

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ρb/ρw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
111	661	187.3	483.0	-222.2	10.0	267.0	46.0	3.743	0.000	5.596	1.529	17.753
	662	181.1	479.0	-213.0	15.0	330.0	66.0	2.758	54.712	4.670	1.447	12.139
	663	176.9	474.0	-203.9	19.9	407.0	103.0	2.294	29.076	4.169	1.380	8.250
	664	178.3	462.0	-194.7	24.9	441.0	117.0	2.524	27.540	4.245	1.427	7.466
	665	184.7	465.0	-185.5	29.9	472.0	132.0	4.494	36.717	4.958	1.614	6.782
	666	191.1	487.0	-216.4	10.0	361.0	53.0	4.228	0.000	5.755	1.559	15.456
	667	190.8	481.0	-207.0	15.0	486.0	99.0	4.586	69.242	5.652	1.592	8.508
	668	192.4	476.0	-195.5	19.9	536.0	115.0	5.557	59.998	5.594	1.639	7.541
	669	204.2	471.0	-184.1	24.9	575.0	134.0	8.751	52.312	5.576	1.707	[illegible]
	670	225.0	466.0	-172.6	29.9	601.0	154.0	10.478	46.134	5.544	1.711	6.042
	671	221.1	490.0	-216.2	10.0	296.0	58.0	9.719	0.000	5.978	1.671	14.104
	672	249.5	484.0	-203.5	15.0	488.0	103.0	11.127	67.121	5.725	1.668	8.222
	673	233.4	478.0	-190.6	19.9	567.0	123.0	10.511	56.760	5.687	1.687	7.124
	674	228.6	472.0	-178.1	24.9	637.0	143.0	10.400	49.142	5.572	1.702	6.366
	675	276.5	466.0	-165.4	29.9	631.0	165.0	12.421	41.589	5.110	1.670	5.737
	676	232.9	491.0	-214.8	10.0	419.0	62.0	10.273	0.000	5.947	1.667	13.249
	677	277.1	485.0	-201.4	15.0	493.0	106.0	12.168	64.317	5.509	1.649	8.069
	678	252.5	480.0	-188.0	19.9	585.0	128.0	11.268	54.255	5.538	1.674	6.925
	679	247.0	474.0	-174.6	24.9	661.0	149.0	11.115	46.651	5.412	1.688	6.164
	680	310.5	468.0	-161.2	29.9	636.0	172.0	13.454	38.845	4.803	1.642	5.573
	681	265.8	500.0	-213.7	10.0	415.0	65.0	11.372	0.000	5.718	1.646	12.570
	682	286.8	492.0	-199.8	15.0	508.0	108.0	12.240	62.380	5.405	1.641	7.911
	683	295.1	484.0	-185.8	19.9	563.0	130.0	12.627	51.492	5.200	1.641	6.805
	684	328.5	477.0	-171.9	24.9	588.0	154.0	13.839	42.542	4.791	1.624	6.000
	685	364.5	469.0	-157.9	29.9	608.0	178.0	14.996	35.925	4.375	1.605	5.438
	686	287.7	503.0	-212.2	10.0	435.0	71.0	12.047	94.587	5.529	1.632	11.644
	687	310.4	495.0	-197.6	15.0	521.0	111.0	12.928	59.475	5.196	1.626	7.722
	688	323.5	488.0	-182.9	19.9	574.0	135.0	13.438	48.708	4.943	1.622	6.641
	689	358.5	480.0	-168.2	24.9	602.0	160.0	14.577	40.010	4.525	1.605	5.849
	690	393.3	472.0	-153.5	29.9	628.0	187.0	15.578	33.402	4.128	1.589	5.253
	691	328.1	507.0	-210.0	10.0	452.0	81.0	13.246	80.204	5.186	1.610	10.232
	692	357.1	500.0	-194.5	15.0	518.0	115.0	14.157	58.902	4.805	1.599	7.454
	693	370.9	493.0	-178.9	19.9	571.0	140.0	14.536	44.786	4.545	1.594	6.417
	694	412.1	487.0	-163.4	24.9	597.0	167.0	15.687	36.507	4.104	1.576	5.662
	695	445.1	480.0	-147.8	29.9	629.0	195.0	16.691	30.453	3.746	1.563	5.093
	696	419.2	471.0	-209.8	10.0	389.0	83.0	17.150	73.975	4.520	1.576	10.068
	697	485.1	459.0	-194.3	15.0	420.0	117.0	19.231	49.708	3.965	1.557	7.427
	698	525.7	447.0	-178.8	19.9	446.0	142.0	20.659	39.713	3.620	1.546	6.399
	699	592.1	435.0	-163.2	24.9	454.0	169.0	22.781	31.790	3.196	1.533	5.648
	700	630.5	423.0	-147.7	29.9	479.0	198.0	24.160	26.433	2.930	1.576	5.083
	701	383.5	490.0	-211.8	10.0	355.0	72.0	15.401	86.314	4.794	1.586	11.387
	702	449.3	471.0	-197.4	15.0	394.0	111.0	17.877	53.428	4.202	1.565	7.704
	703	486.4	452.0	-183.0	19.9	418.0	135.0	19.393	43.025	3.861	1.556	6.641
	704	530.6	433.0	-168.6	24.9	436.0	159.0	21.314	35.130	3.510	1.544	5.856
	705	546.6	415.0	-154.1	29.9	471.0	186.0	22.578	29.856	3.313	1.539	5.271
	706	251.4	495.0	-212.4	10.0	432.0	70.0	10.951	97.725	5.801	1.657	11.767
	707	285.7	489.0	-198.5	15.0	502.0	109.0	12.302	61.437	5.405	1.643	7.803
	708	237.7	483.0	-184.6	19.9	629.0	132.0	10.493	52.500	5.566	1.685	[illegible]
	709	309.9	477.0	-170.7	24.9	601.0	156.0	13.221	42.605	4.913	1.637	5.985
	710	284.5	471.0	-156.8	29.9	705.0	179.0	12.416	37.758	4.932	1.665	5.392
	711	120.9	493.0	-225.9	10.0	195.0	40.0	1.507	27.141	2.534	1.168	19.982
	712	120.4	488.0	-219.2	15.0	221.0	51.0	1.498	21.229	2.491	1.168	15.933
	713	113.5	484.0	-212.5	19.9	259.0	70.0	1.487	15.322	2.445	1.168	11.772
	714	113.7	479.0	-205.7	24.9	313.0	100.0	1.461	10.354	2.366	1.163	8.460
	715	111.9	475.0	-199.0	29.9	336.0	109.0	1.487	9.378	2.321	1.159	7.039
112	716	391.8	1771.0	63.4	15.1	579.0	173.0	2.419	5.030	1.799	1.209	2.905
	717	402.2	1767.0	86.6	26.3	654.0	198.0	2.444	4.528	1.693	1.272	[illegible]
	718	422.9	1762.0	110.1	37.7	652.0	217.0	2.569	4.323	1.627	1.255	2.819
	719	452.7	1758.0	133.5	49.1	713.0	241.0	2.750	4.075	1.542	1.234	2.762
	720	478.9	1754.0	156.7	60.3	757.0	270.0	2.812	3.714	1.447	1.203	2.688

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall Temp °F	Pressure Psia	Bulk Temp °F	L/D	Nu/Pr	Re/1000	cb/cw	μb/μw	kb/kw	$\bar{C}p/Cpb$	Pr
112	721	400.0	1786.0	63.6	15.1	561.0	147.0	2.473	5.112	1.802	1.291	2.965
	722	412.5	1782.0	88.2	26.3	634.0	193.0	2.517	4.575	1.666	1.272	2.886
	723	434.6	1774.0	113.0	37.7	672.0	212.0	2.663	4.347	1.615	1.254	2.814
	724	466.0	1774.0	137.7	49.1	700.0	237.0	2.749	4.016	1.516	1.227	2.75[illegible]
	725	500.4	1770.0	162.3	60.3	726.0	268.0	2.904	3.665	1.415	1.193	2.672
	726	406.4	1793.0	63.8	15.1	550.0	167.0	2.523	5.179	1.804	1.292	2.965
	727	419.9	1789.0	88.6	26.3	621.0	193.0	2.570	4.612	1.684	1.273	2.856
	728	442.1	1785.0	113.7	37.7	657.0	212.0	2.727	4.382	1.610	1.254	2.813
	729	470.5	1781.0	138.7	49.1	684.0	238.0	2.829	4.017	1.506	1.225	2.747
	730	516.9	1778.0	163.5	60.3	695.0	269.0	3.007	3.687	1.401	1.189	2.668
	731	409.2	1799.0	63.6	15.1	544.0	145.0	2.543	5.199	1.803	1.293	2.966
	732	423.3	1795.0	88.5	26.3	612.0	191.0	2.605	4.639	1.682	1.274	2.856
	733	446.1	1792.0	113.9	37.7	649.0	210.0	2.740	4.384	1.606	1.253	2.813
	734	481.9	1788.0	139.1	49.1	670.0	236.0	2.864	4.025	1.499	1.223	2.746
	735	524.1	1784.0	164.1	60.3	682.0	266.0	3.059	3.694	1.394	1.188	2.667
	736	448.4	1800.0	66.4	15.1	548.	168.0	2.924	5.467	1.782	1.302	2.951
	737	465.5	1796.0	93.4	26.3	612.0	194.0	2.939	4.812	1.650	1.275	2.846
	738	494.6	1792.0	120.8	37.7	645.	216.0	3.030	4.425	1.550	1.243	2.797
	739	538.3	1788.0	148.1	49.1	664.0	246.0	3.250	4.033	1.433	1.207	2.716
	740	591.0	1784.0	175.2	60.3	669.0	281.0	3.431	3.706	1.324	1.165	2.629
	741	452.1	1804.0	66.5	15.1	542.0	168.0	2.940	5.470	1.777	1.302	2.951
	742	468.6	1800.0	93.6	26.3	606.0	194.0	2.951	4.811	1.646	1.275	2.848
	743	496.8	1796.0	121.3	37.7	641.0	217.0	3.056	4.417	1.547	1.242	2.796
	744	541.7	1792.0	146.9	49.1	659.0	247.0	3.268	4.025	1.429	1.206	2.714
	745	597.1	1789.0	176.1	60.3	660.0	282.0	3.454	3.705	1.318	1.163	2.625
	746	455.0	1808.0	66.3	15.1	536.0	168.0	2.953	5.483	1.775	1.302	2.952
	747	471.6	1804.0	93.6	26.3	600.0	194.0	2.964	4.819	1.644	1.275	2.848
	748	500.5	1800.0	121.2	37.7	634.0	216.0	3.057	4.428	1.544	1.242	2.797
	749	546.7	1797.0	148.8	49.1	650.0	247.0	3.307	4.040	1.426	1.206	2.714
	750	603.8	1793.0	176.1	60.3	649.0	282.0	3.489	3.724	1.314	1.163	2.625
	751	457.4	1812.0	66.8	15.1	535.0	168.0	2.961	5.459	1.770	1.301	2.950
	752	474.2	1808.0	94.2	26.3	598.0	[illegible]	2.973	4.817	1.640	1.274	2.847
	753	504.1	1805.0	121.9	37.7	631.0	217.0	3.073	4.42[illegible]	1.539	1.241	2.795
	754	551.7	1801.0	149.6	49.1	645.0	248.0	3.329	4.038	1.420	1.204	2.711
	755	610.2	1797.0	177.0	60.3	643.0	283.0	3.515	3.729	1.309	1.161	2.622
	756	516.9	1813.0	70.2	15.1	536.0	172.0	3.343	5.590	1.711	1.300	2.931
	757	533.9	1809.0	100.2	26.3	592.0	199.0	3.418	4.948	1.583	1.268	2.837
	758	573.7	1805.0	130.4	37.7	620.0	226.0	3.557	4.516	1.468	1.227	2.772
	759	635.1	1801.0	160.7	49.1	627.0	261.0	3.759	4.063	1.331	1.182	2.678
	760	710.4	1797.0	190.6	60.3	620.0	304.0	3.908	3.447	1.170	1.134	2.569
	761	513.5	1816.0	70.4	15.1	533.0	172.0	3.358	5.590	1.708	1.300	2.930
	762	535.9	1812.0	100.5	26.3	589.0	199.0	3.42[illegible]	4.946	1.580	1.267	2.837
	763	577.9	1808.0	130.9	37.7	614.0	226.0	3.574	4.520	1.464	1.226	2.771
	764	638.3	1804.0	161.3	49.1	624.0	262.0	3.765	4.047	1.326	1.181	2.676
	765	713.7	1800.0	191.4	60.3	617.0	305.0	3.956	3.432	1.166	1.133	2.568
	766	515.8	1818.0	70.4	15.1	529.0	172.0	3.374	5.598	1.706	1.300	2.930
	767	538.7	1814.0	100.5	26.3	584.0	199.0	3.450	4.955	1.572	1.267	2.837
	768	581.6	1810.0	130.9	37.7	608.0	226.0	3.594	4.533	1.462	1.226	2.771
	769	640.9	1806.0	161.3	49.1	619.0	262.0	3.774	4.044	1.323	1.181	2.676
	770	718.6	1802.0	191.4	60.3	610.0	305.0	3.980	3.429	1.161	1.133	2.568
	771	517.2	1820.0	70.9	15.1	530.0	173.0	3.380	5.586	1.702	1.299	2.928
	772	540.8	1816.0	100.9	26.3	583.0	199.0	3.464	4.955	1.576	1.267	2.836
	773	584.2	1812.0	131.2	37.7	606.0	226.0	3.604	4.535	1.459	1.226	2.770
	774	643.2	1808.0	161.6	49.1	618.0	262.0	3.779	4.036	1.319	1.180	2.675
	775	722.7	1805.0	191.6	60.3	607.0	305.0	3.999	3.423	1.157	1.132	2.567
	776	567.8	1820.0	73.7	15.1	527.0	176.0	3.782	5.730	1.652	1.298	2.912
	777	599.6	1816.0	105.9	26.3	572.0	203.0	3.839	5.123	1.525	1.258	2.828
	778	653.9	1812.0	138.5	37.7	592.0	234.0	3.981	4.504	1.374	1.213	2.749
	779	726.9	1808.0	171.0	49.1	598.0	274.0	4.184	3.798	1.204	1.163	2.644
112	780	827.6	1804.0	203.3	60.3	578.0	323.0	4.422	3.168	1.041	1.109	2.534

TABLE III-IV (cont.)

Test Number HTB6-797-	ID Number	Wall T Temp °F	Pressure Psia	Bulk Temp °F	L/D	$Nu/Pr^{.4}$	Re/1000	ϵb/ϵw	μb/μw	kb/kw	Cp/Cpb	Pr
112	781	571.8	1823.0	74.1	15.1	525.0	176.0	3.801	5.732	1.647	1.297	2.909
	782	603.7	1819.0	106.5	26.3	564.0	203.0	3.860	5.129	1.521	1.257	2.827
	783	656.4	1815.0	139.2	37.7	591.0	235.0	3.984	4.485	1.369	1.212	2.747
	784	732.4	1811.0	171.9	49.1	594.0	275.0	4.201	3.777	1.196	1.163	2.641
	785	838.7	1807.0	204.3	60.3	570.0	325.0	4.469	3.146	1.031	1.107	2.530
	786	574.0	1826.0	74.0	15.1	521.0	176.0	3.809	5.742	1.646	1.297	2.910
	787	606.0	1821.0	106.4	26.3	564.0	203.0	3.871	5.138	1.520	1.257	2.828
	788	657.5	1817.0	139.2	37.7	588.0	235.0	3.986	4.483	1.368	1.212	2.747
	789	732.7	1812.0	171.9	49.1	593.0	275.0	4.199	3.778	1.196	1.163	2.642
	790	849.7	1808.0	204.3	60.3	559.0	324.0	4.529	3.140	1.022	1.107	2.530
	791	572.1	1828.0	74.1	15.1	523.0	176.0	3.792	5.727	1.647	1.297	2.910
	792	604.3	1824.0	106.5	26.3	566.0	203.0	3.853	5.127	1.521	1.257	2.828
	793	657.1	1820.0	139.2	37.7	588.0	235.0	3.978	4.483	1.368	1.212	2.747
	794	735.5	1815.0	171.8	49.1	594.0	275.0	4.183	3.780	1.199	1.163	2.642
	795	862.2	1811.0	204.2	60.3	548.0	324.0	4.598	3.137	1.013	1.107	2.531
	796	629.0	1829.0	76.8	15.1	516.0	180.0	4.169	5.872	1.590	1.294	2.894
	797	669.6	1825.0	111.2	26.3	552.0	207.0	4.212	5.068	1.435	1.250	2.819
	798	735.4	1820.0	145.9	37.7	570.0	243.0	4.393	4.278	1.261	1.201	2.725
	799	825.0	1816.0	180.5	49.1	571.0	288.0	4.596	3.558	1.091	1.151	2.609
	800	986.8	1811.0	215.0	60.3	517.0	343.0	5.381	2.898	.907	1.085	2.494
	801	632.2	1830.0	77.2	15.1	514.0	180.0	4.182	5.852	1.583	1.294	2.891
	802	672.3	1826.0	111.7	26.3	550.0	207.0	4.222	5.054	1.430	1.249	2.818
	803	730.1	1822.0	146.6	37.7	568.0	244.0	4.492	4.260	1.256	1.200	2.723
	804	821.4	1818.0	181.5	49.1	576.0	289.0	4.564	3.544	1.092	1.150	2.605
	805	1034.3	1813.0	216.1	60.3	491.0	345.0	5.765	2.862	.878	1.083	2.490
	806	633.2	1833.0	77.7	15.1	515.0	181.0	4.179	5.825	1.579	1.293	2.888
	807	673.0	1828.0	112.2	26.3	550.0	208.0	4.217	5.043	1.428	1.249	2.817
	808	733.7	1824.0	147.0	37.7	574.0	244.0	4.368	4.256	1.260	1.199	2.721
	809	818.7	1820.0	181.8	49.1	579.0	289.0	4.542	3.542	1.094	1.150	2.604
	810	1076.4	1815.0	216.2	60.3	466.0	345.0	6.200	2.842	.854	1.083	2.489
	811	631.1	1835.0	77.1	15.1	515.0	180.0	4.166	5.852	1.585	1.294	2.892
	812	674.1	1831.0	111.6	26.3	547.0	207.0	4.223	5.051	1.428	1.250	2.818
	813	730.5	1826.0	146.5	37.7	576.0	243.0	4.351	4.267	1.265	1.200	2.723
	814	828.7	1822.0	181.4	49.1	569.0	288.0	4.597	3.543	1.087	1.150	2.606
	815	1107.3	1818.0	216.0	60.3	450.0	344.0	6.566	2.834	.838	1.083	2.490
	816	632.9	1837.0	77.1	15.1	514.0	180.0	4.165	5.846	1.584	1.294	2.892
	817	677.4	1833.0	111.7	26.3	544.0	207.0	4.237	5.047	1.424	1.250	2.819
	818	734.8	1829.0	146.5	37.7	571.0	243.0	4.367	4.264	1.261	1.200	2.723
	819	842.1	1824.0	181.4	49.1	557.0	288.0	4.671	3.537	1.076	1.151	2.606
	820	1136.5	1820.0	215.9	60.3	435.0	344.0	6.952	2.825	.824	1.084	2.491
	821	630.7	1839.0	77.0	15.1	513.0	180.0	4.154	5.851	[illegible]	1.294	2.893
	822	678.5	1835.0	111.4	26.3	541.0	207.0	4.241	5.050	[illegible]	1.250	2.819
	823	738.5	1830.0	[illegible]	37.7	565.0	243.0	4.384	4.269	[illegible]	1.201	2.724
	824	854.2	1826.0	180.9	49.1	545.0	287.0	[illegible]	3.540	1.068	1.152	2.608
	825	1149.8	1821.0	215.3	60.3	427.0	343.0	7.152	2.830	.818	1.085	2.493
	826	634.9	1833.0	78.0	15.1	510.0	181.0	4.198	5.813	1.572	1.293	2.886
	827	682.9	1828.0	112.4	26.3	538.0	208.0	4.276	5.031	1.415	1.249	2.817
	828	747.6	1824.0	147.1	37.7	558.0	244.0	4.436	4.243	1.246	1.200	2.721
	829	876.5	1820.0	181.8	49.1	529.0	289.0	4.891	3.507	1.047	1.150	2.604
	830	1164.5	1815.0	216.2	60.3	421.0	345.0	7.380	2.801	.809	1.082	2.489
	831	478.5	1832.0	69.1	15.1	510.0	171.0	3.061	5.447	1.738	1.298	2.938
	832	503.5	1828.0	96.8	26.3	555.0	196.0	3.143	4.858	1.610	1.271	2.843
	833	539.5	1824.0	124.8	37.7	579.0	219.0	3.320	4.479	1.506	1.236	2.789
	834	622.2	1819.0	152.7	49.1	551.0	251.0	3.714	4.214	1.370	1.194	2.700
	835	842.3	1815.0	180.4	60.3	420.0	287.0	4.701	3.551	1.077	1.152	2.609
	836	475.1	1827.0	69.2	15.1	479.0	163.0	3.273	5.577	1.719	1.300	2.937
	837	537.5	1823.0	97.2	26.3	514.0	187.0	3.439	5.003	[illegible]	[illegible]	2.883
	838	575.7	1819.0	125.4	37.7	534.0	210.0	3.570	4.617	[illegible]	1.233	2.787
	839	658.1	1815.0	153.6	49.1	514.0	241.0	3.899	4.173	1.324	1.191	2.698
	840	904.1	1811.0	181.5	60.3	386.0	276.0	5.101	3.490	1.026	1.150	2.605

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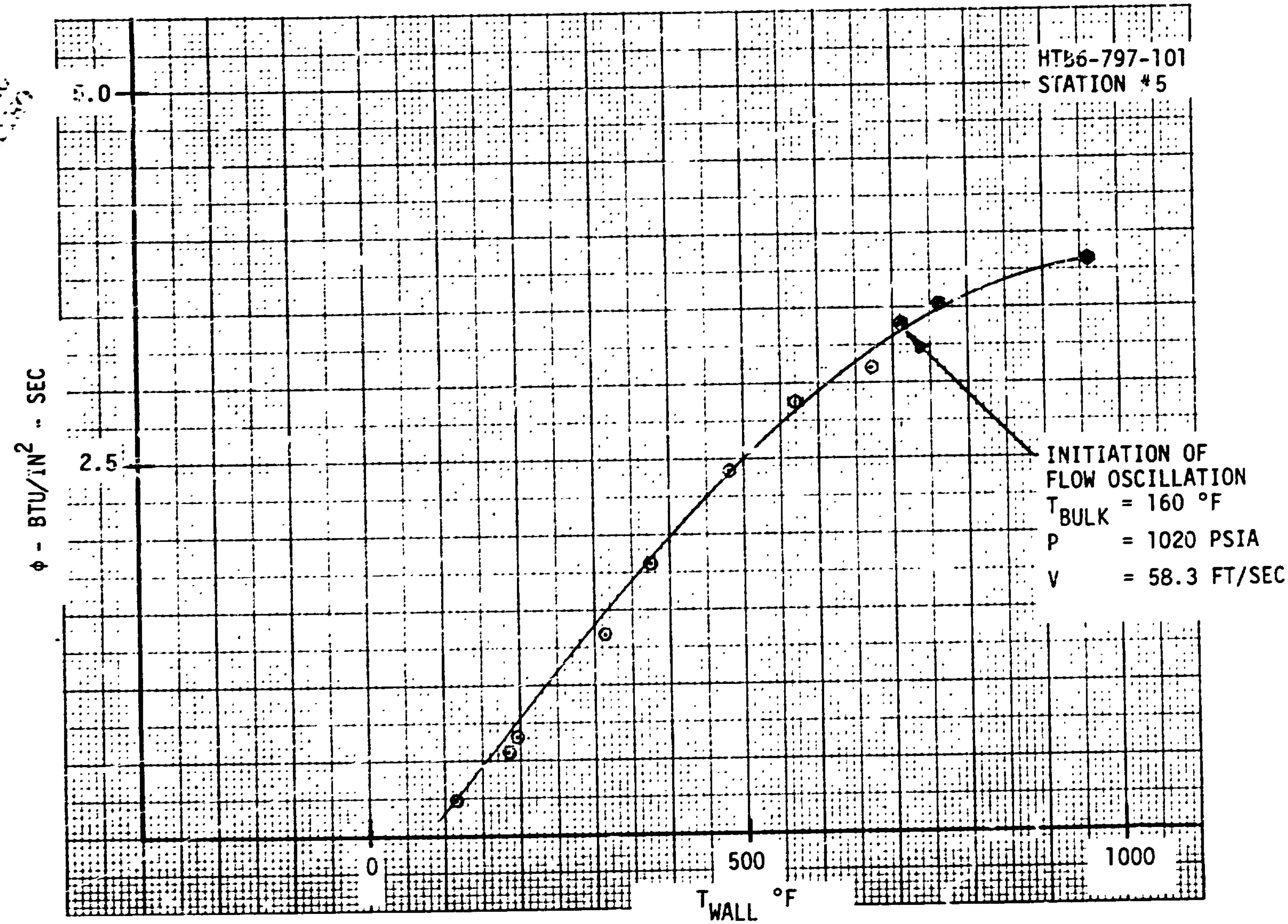


Figure III-5. Test HTB6-797-101 - Wall Temperature Trends

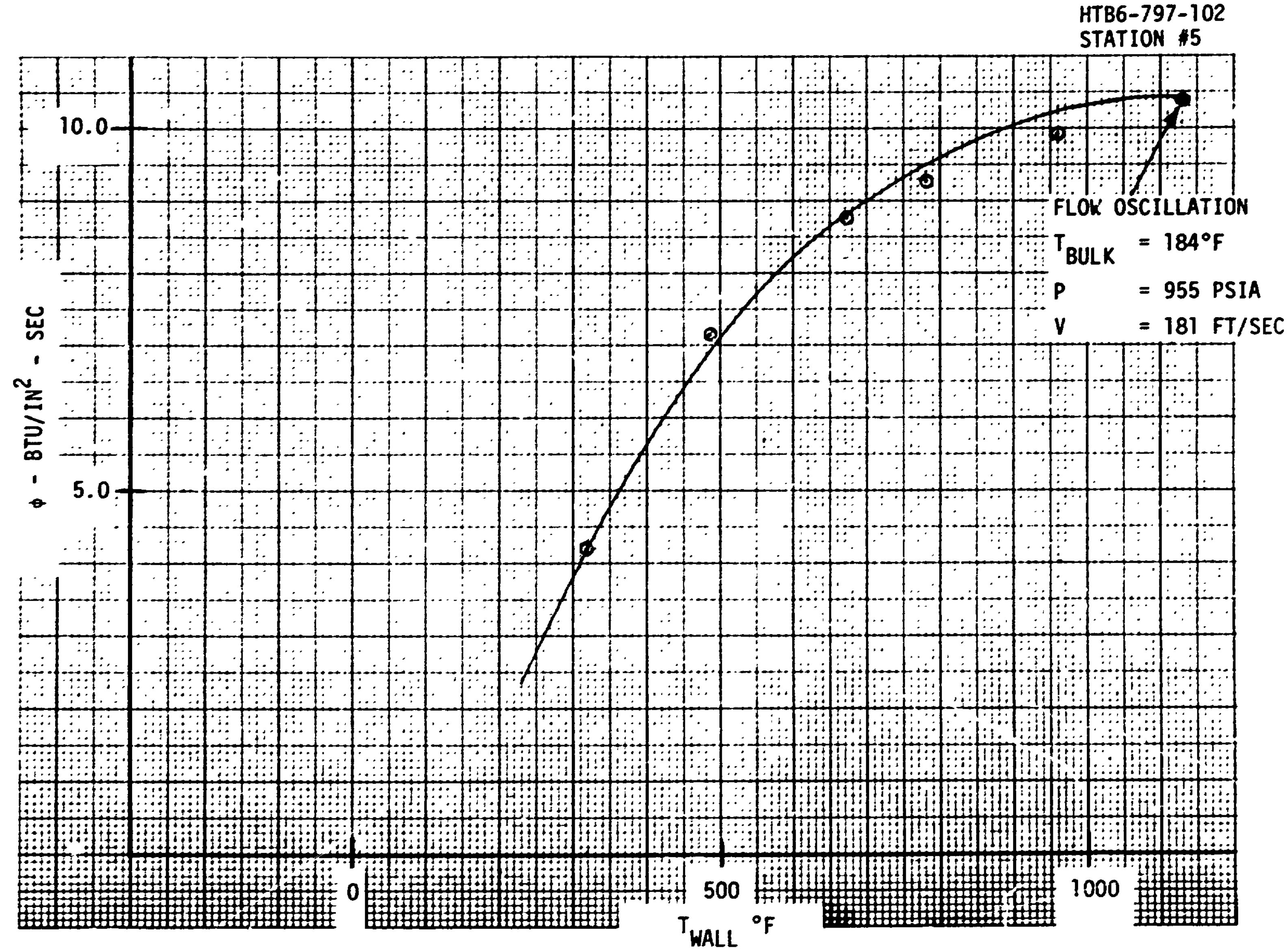


Figure III-6. Test HTB6-797-102 - Wall Temperature Trends

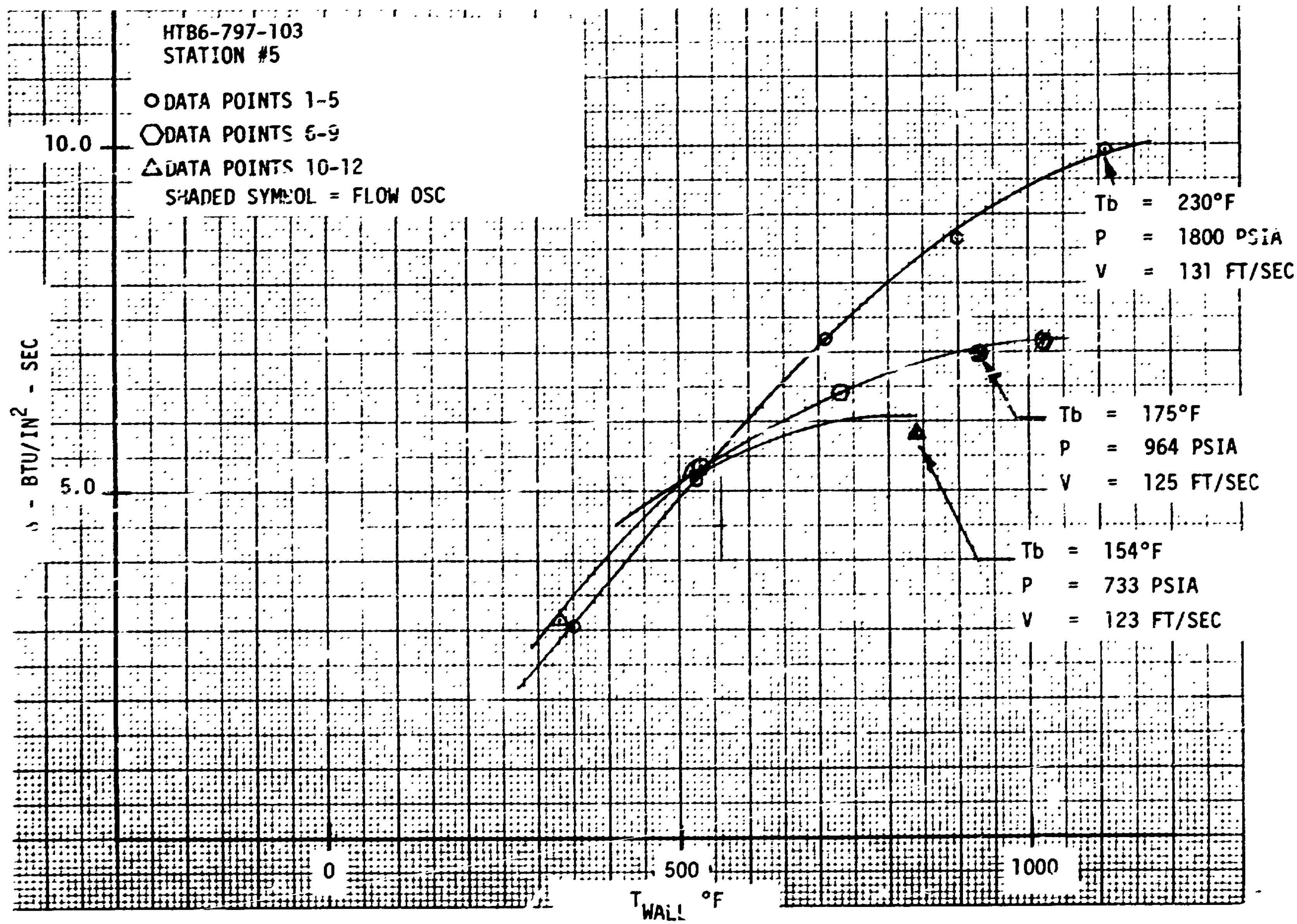


Figure III-7. Test HTB6-797-103 - Wall Temperature Trends

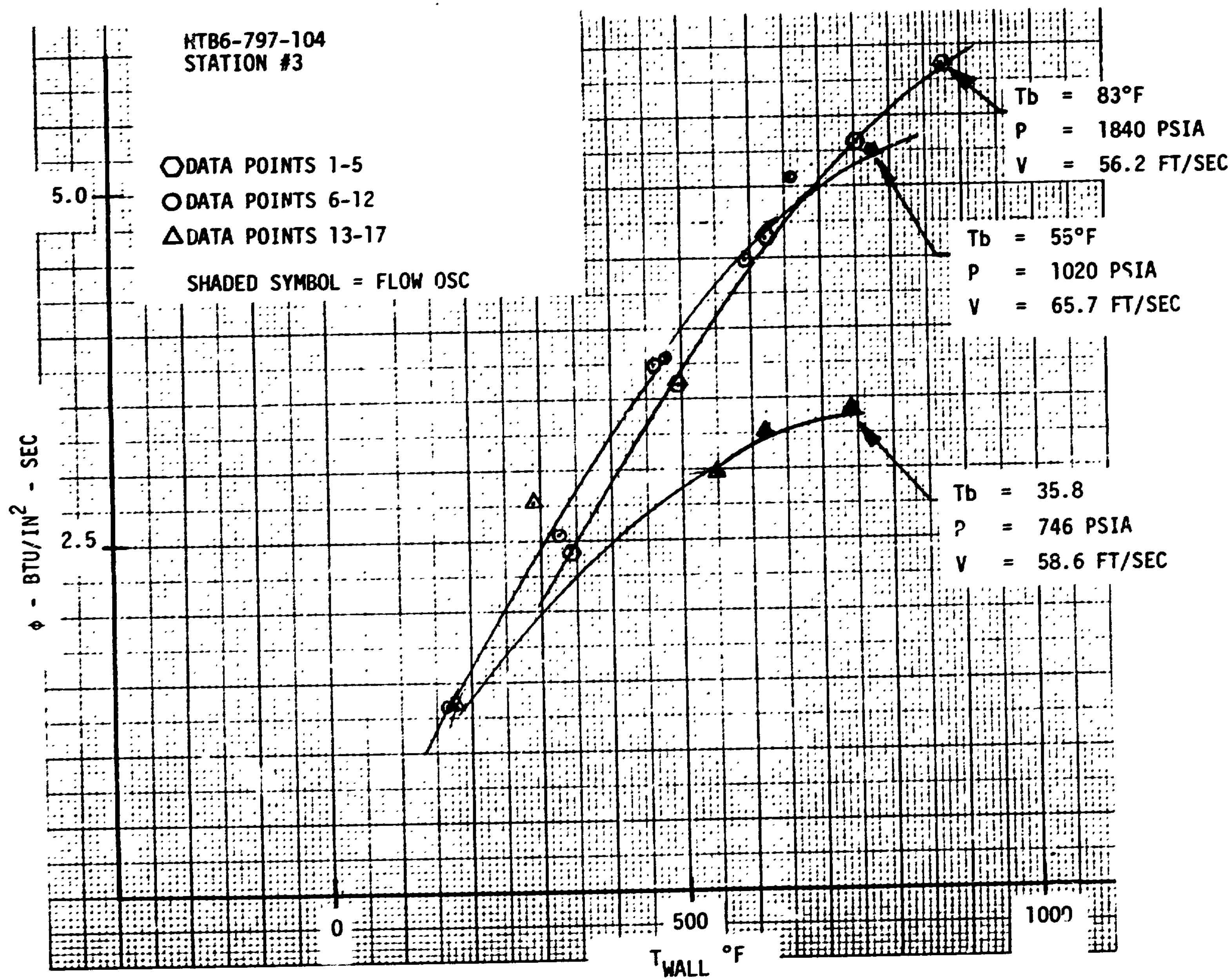


Figure III-8. Test HTB6-797-104 - Wall Temperature Trends

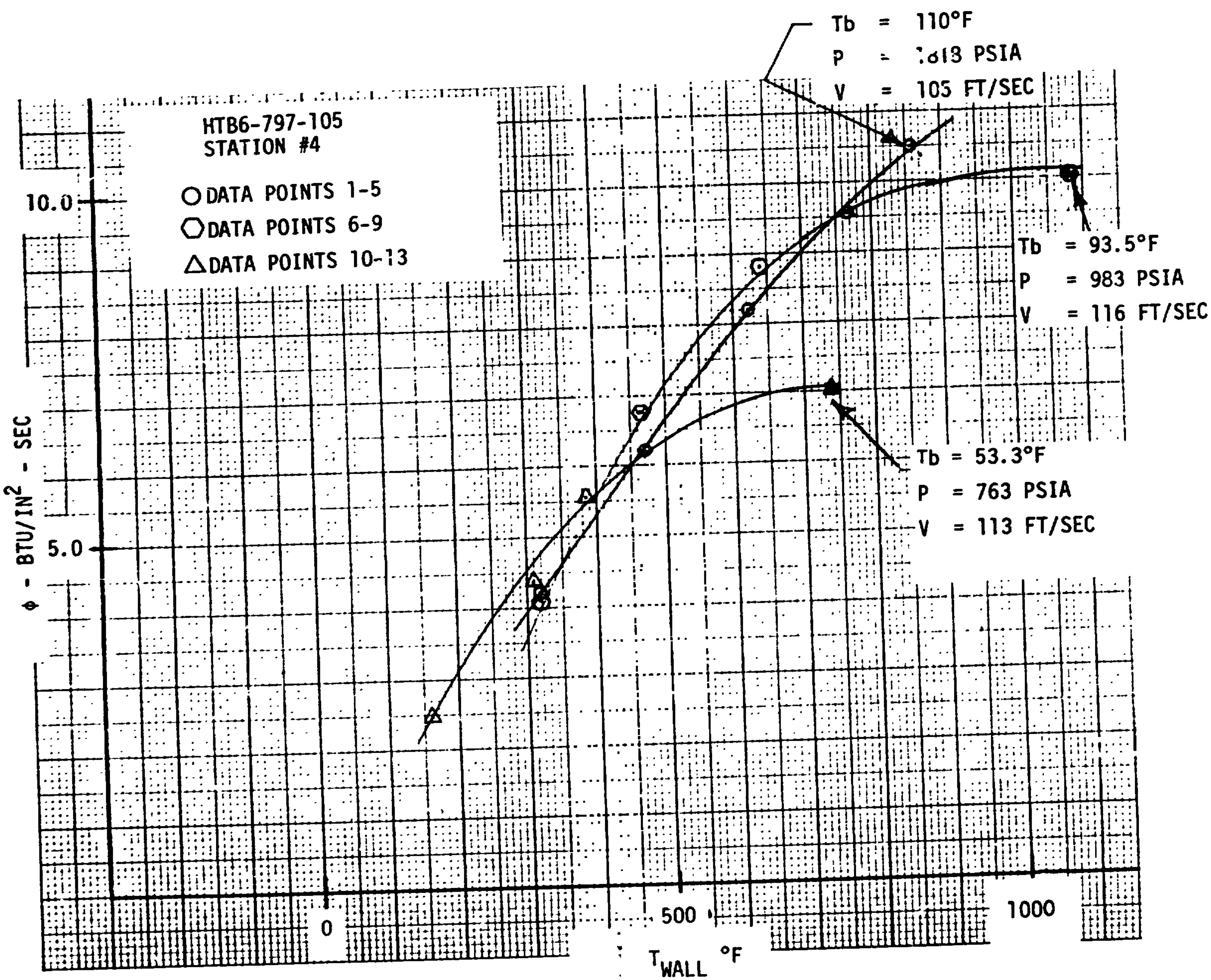


Figure III-9. Test HTB6-797-105 - Wall Temperature Trends

Flow oscillations, shown shaded in the plots, often accompanied the higher wall temperature data, particularly at lower pressures.

2. Subcritical Pressure Tests

Test 106 and Tests 109 through 111 were all conducted at subcritical pressure. Wall temperature versus heat flux for these tests are plotted in Figures III-10 through III-12. Test 110 and Test 111 share the same plot since the latter is an extension of the data generated in Test 110. Data trends are all similar and can be separated into the various cooling regimes: (1) forced convection at wall temperatures below the saturation temperature; (2) forced convection with nucleate boiling from T_{sat} to a wall temperature corresponding to the critical heat flux; and (3) film boiling.

Whereas Test 106 exhibited a smooth transition to the film boiling regime, Tests 109 and 111 encountered a distinct jump in wall temperature at the critical heat flux. The flagged data points shown in Figure III-12 (Test 111) were measured as power was slowly reduced after encountering the wall temperature jump.

3. Coking Tests

Tests 107, 108 and 112 were conducted at supercritical pressure with the express purpose of defining coking rate versus wall temperature.

Wall temperatures versus time for these tests are plotted in Figures III-13 through III-15. In Test 107, an optimistic estimate of coking temperature was assumed. Wall temperatures had to be quickly lowered to preclude tube burnout because of the rapid coking at the hottest tube station.

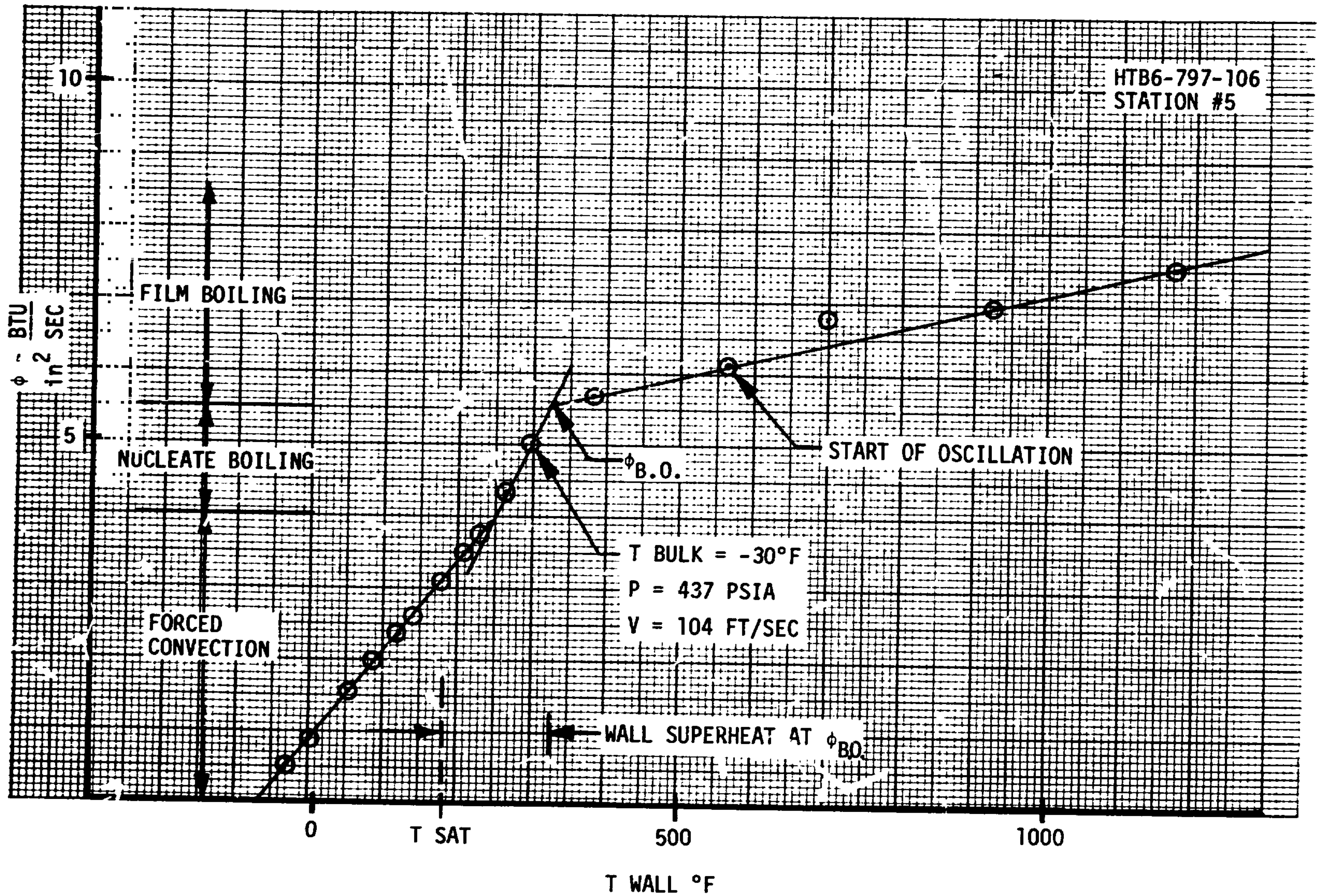


Figure III-10. Test HTB6-797-106 - Wall Temperature Trends

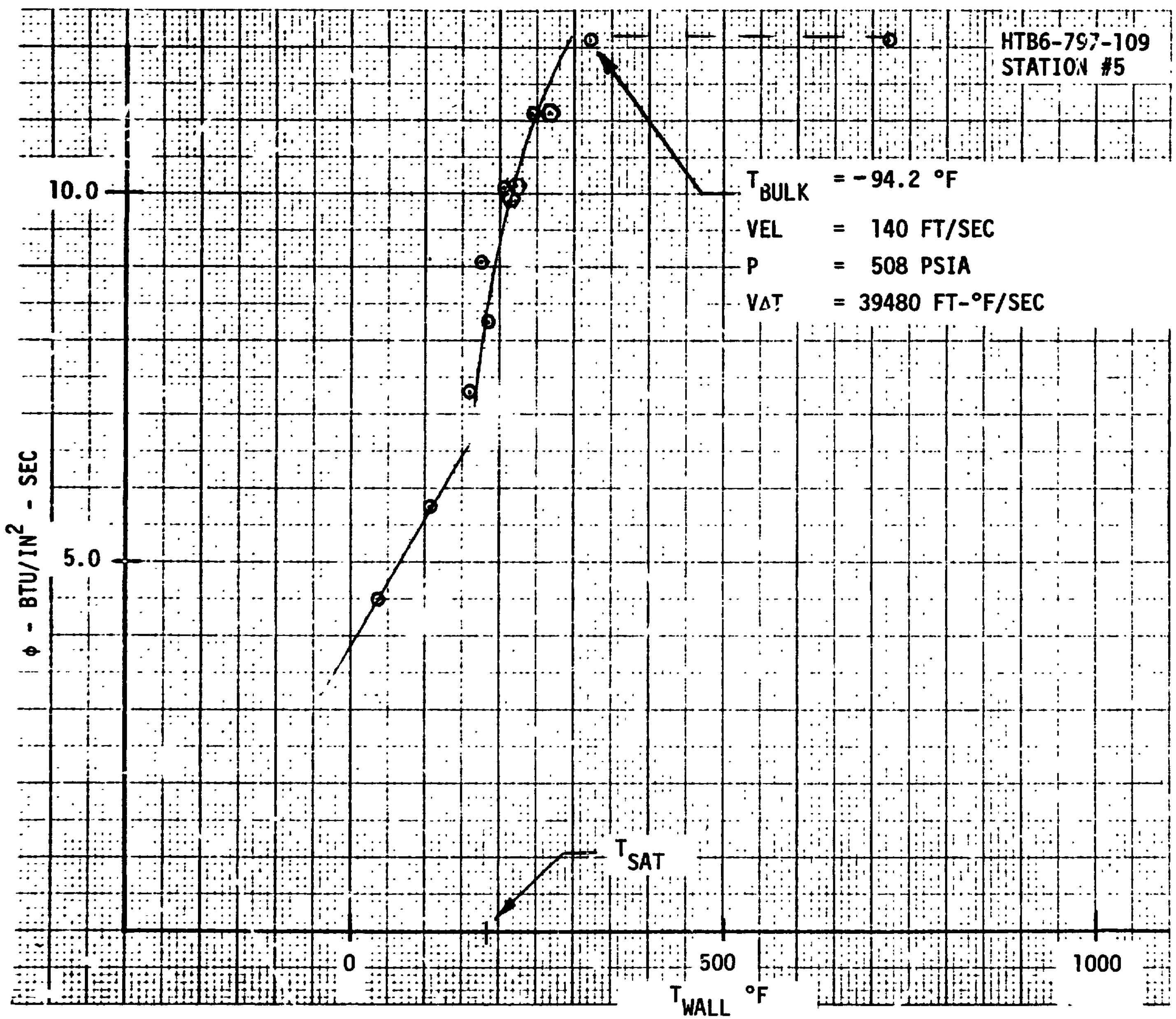


Figure III-11. Test HTB6-797-109 - Wall Temperature Trends

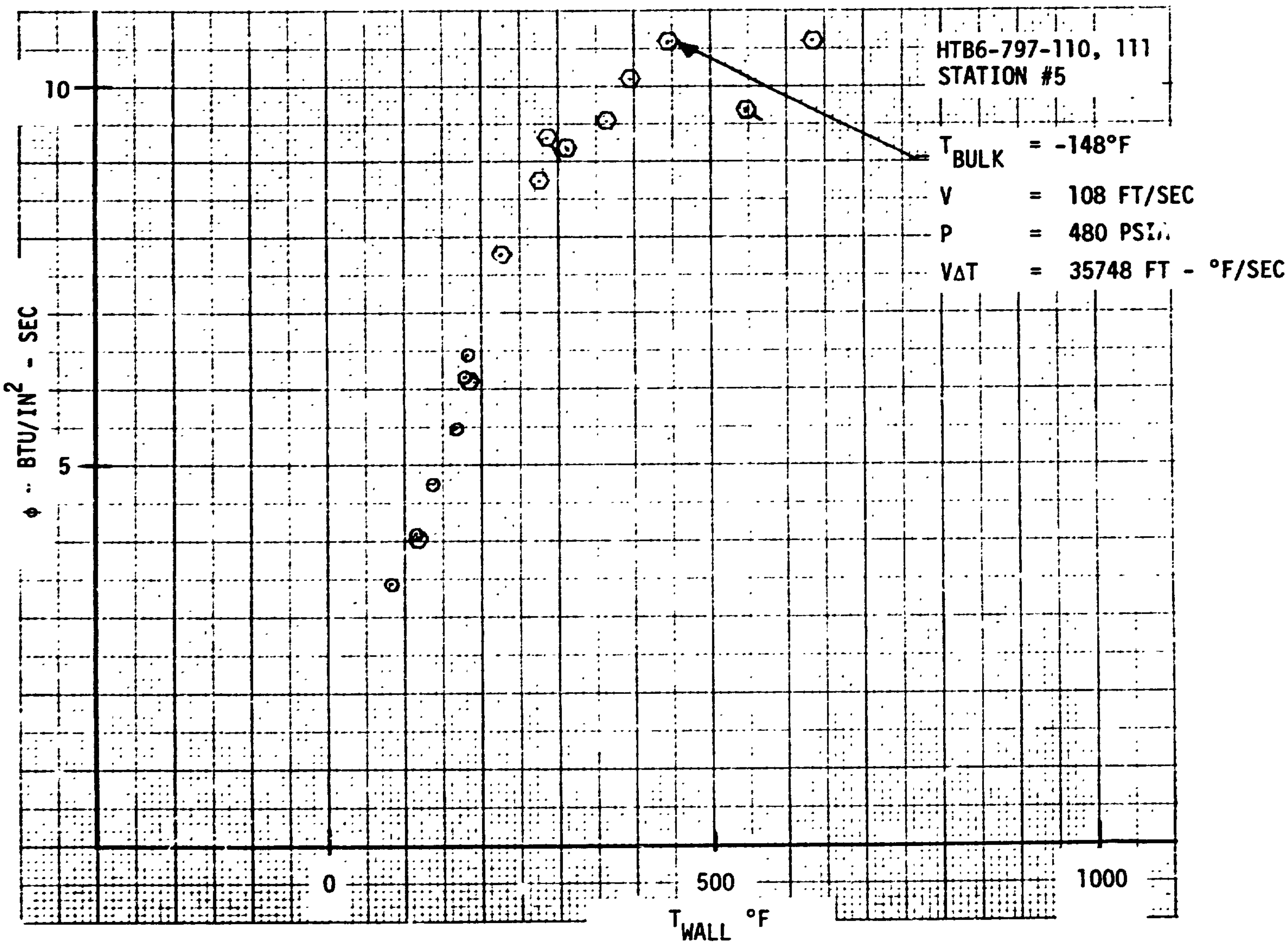


Figure III-12. Tests HTB6-797-110/111 - Wall Temperature Trends

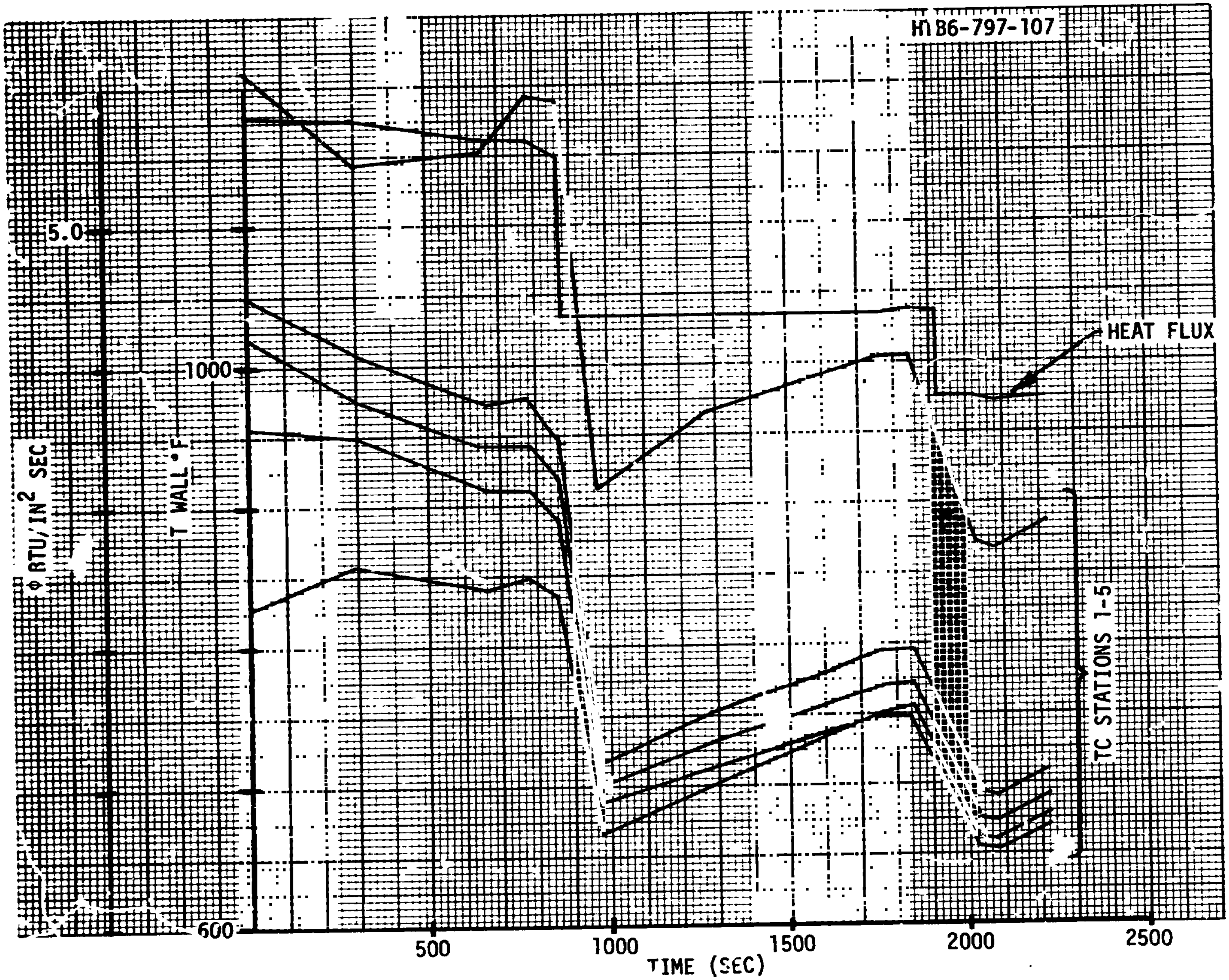


Figure III-13. Test HTB6-797-107 - Wall Temperature Trends

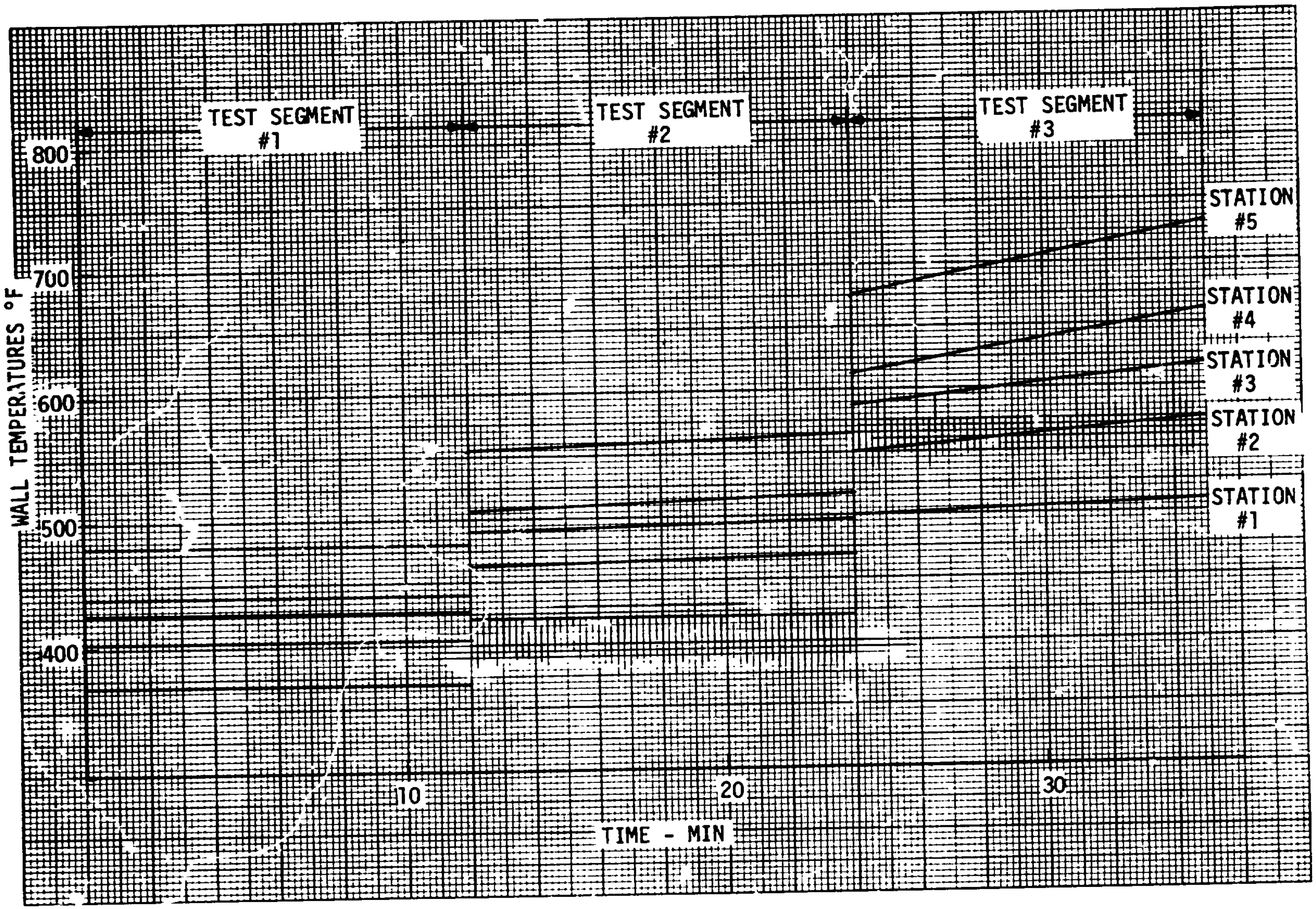


Figure III-14. Test HTB6-797-108 - Wall Temperature Trends

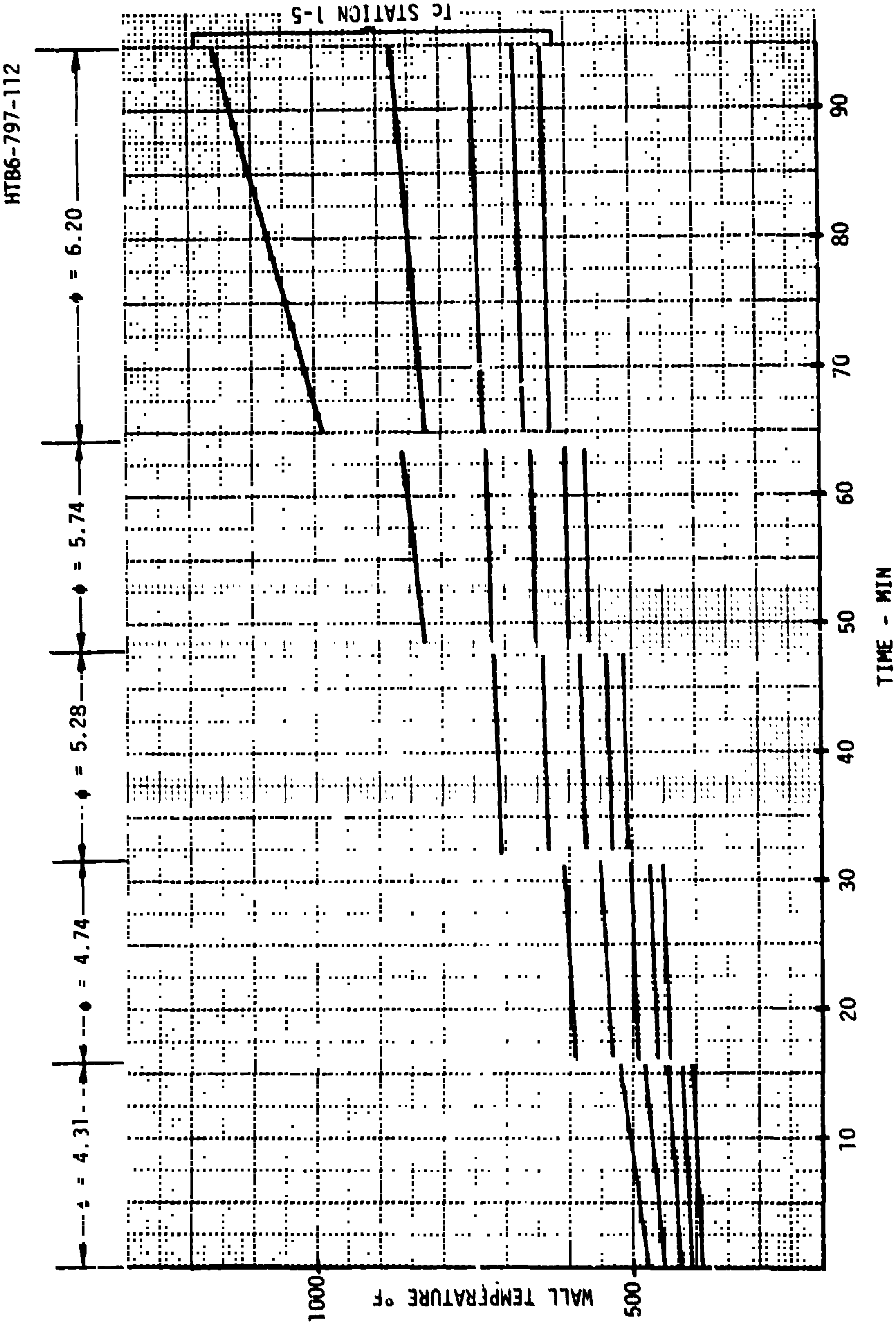


Figure III-15. Test HTB6-797-112 - Wall Temperature Trends

D. DATA CORRELATION

1. Forced Convection

Forced convection heat transfer data were correlated by using the following equation:

$$Nu_b = (K)\,(Re_b)^a\,(Pr)^c\,\left(\frac{\rho_b}{\rho_w}\right)^d\,\left(\frac{\mu_b}{\mu_w}\right)^e\,\left(\frac{k_b}{k_w}\right)^f\,\left(\frac{\bar{C}p}{Cp_b}\right)^g\,\left(\frac{P}{P_{crit}}\right)^h\,\left(1 + \frac{2}{L/D}\right)$$

Where:

Nu	=	Nusselt number
Re	=	Reynolds number
Pr	=	Prandtl number
ρ	=	Density
μ	=	Viscosity
k	=	Thermal conductivity
Cp	=	Specific heat
K	=	Experimental determined constant
P	=	Pressure
P_{crit}	=	Critical pressure
L/D	=	Length/diameter from initiation of heating

and subscripts:

b	-	denotes property evaluated at bulk temperature
w	-	denotes property evaluated at wall temperature

The constants k, a, c, d, e, f, g, and h were determined from the forced convection data by using a multiple regression anlaysis computer program.

Several cases were run; these are summarized in Table III-V. Table III-VI lists the specific data base used in each correlation case. Data points influenced by oscillations or poor energy balance were not used in the correlation.

Figures III-16 and 17, respectively, are a plot of the recommended forced convection correlations based on all data and on $P > P_{crit}$ (Cases 3 and 5).

2. Nucleate Boiling and Burnout Heat Flux

Burnout heat flux versus the product of the local velocity times saturation minus bulk temperature ($V \Delta T$) is plotted in Figure III-18.

The correlation derived from the data is:

$$\phi_{B.O.} = 2.71\text{ E-4 } (V \Delta T) + .5$$

where:

$\phi_{B.O.}$ = Burnout heat flux - Btu/in^{2}sec

V = fluid velocity - ft/sec

ΔT = (T saturation - T bulk) -°F

Nucleate boiling data were correlated in the following manner:

$$\phi_T = \phi_{F.C.} + \phi_{N.b.}$$

where:

ϕ_T = Total measured heat flux - Btu/in^{2}sec

$\phi_{F.C.}$ = Assumed forced convection component when $T_{wall} > T_{sat}$ - Btu/in^{2}sec

$\phi_{N.b.}$ = Residual attributed to nucleate boiling mechanism - Btu/in^{2}sec

TABLE III-V

PROPANE FORCED CONVECTION CORRELATION SUMMARY

Correlation Form: $Nu = \left(1 + \frac{2}{L/D}\right) (K) (Re_b)^a (Pr_b)^c (\rho_b/\rho_w)^d (\mu_b/\mu_w)^e (k_b/k_w)^f (\overline{Cp}/Cp_b)^g (P/P_{crit})^h$

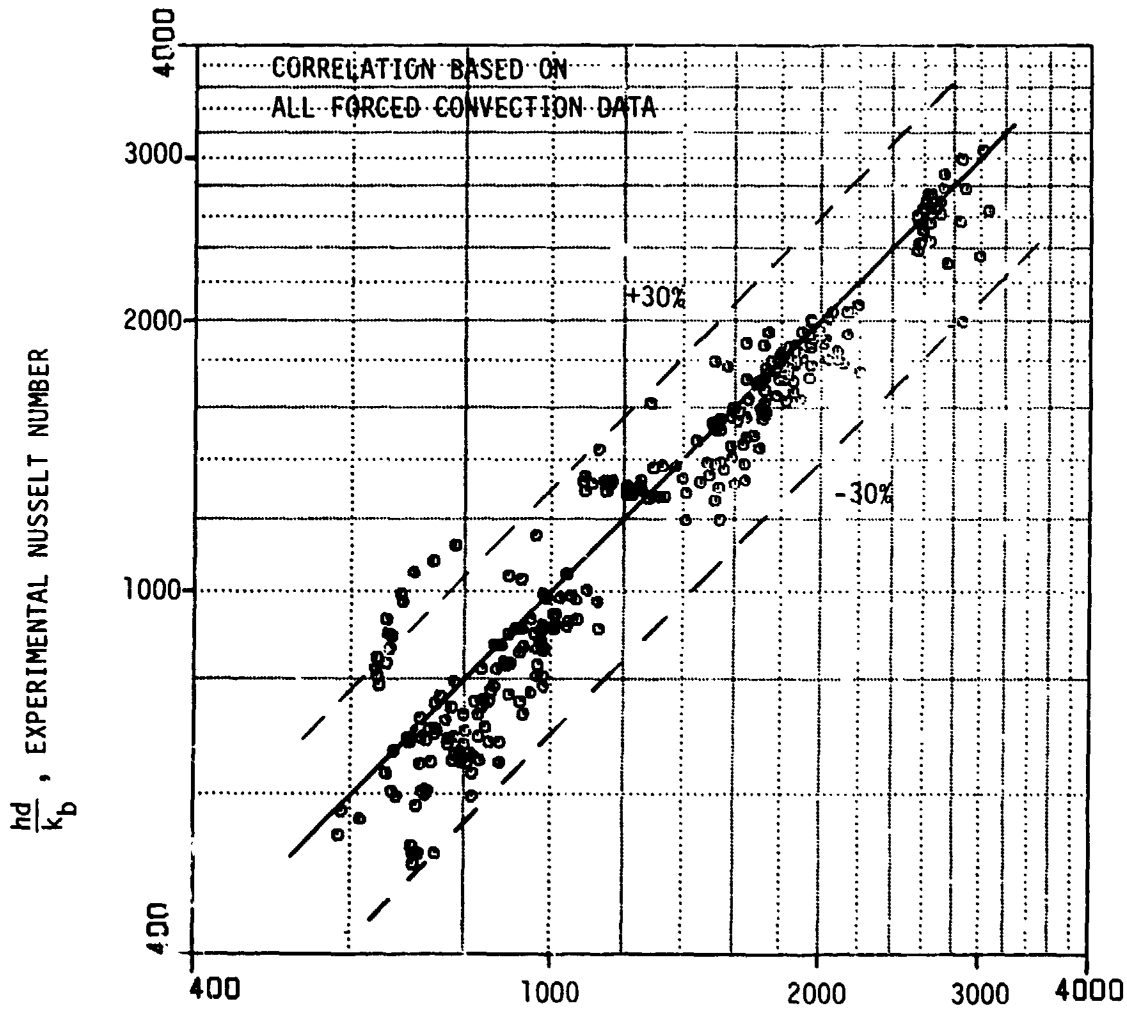
Case Number	Coefficients / Exponents								STD Deviation	Comments
	K	a	c	d	e	f	g	h		
1	.00538	.90	.4*	-.125	.242	.193	-.395	-.024	.130	All forced convection data
2	.00145	1.0*	.4*	-.227	.357	.069	-.299	-.037	.136	All forced convection data Reynolds number fixed
3	.00545	.898	.4*	-.114	.228	.267	-.526	0*	.130	All forced convection data (P/P_{crit}) removed
4	.00532	.889	.4*	-.129	.351	.0995	-.432	0*	.127	Supercritical data (P/P_{crit}) removed
5	.00568	.876	.4*	.120	-.142	.828	-.368	.254	.121	Supercritical data with (ρ/P_{crit}) term

*Denotes exponent held constant in analysis

TABLE III-VI

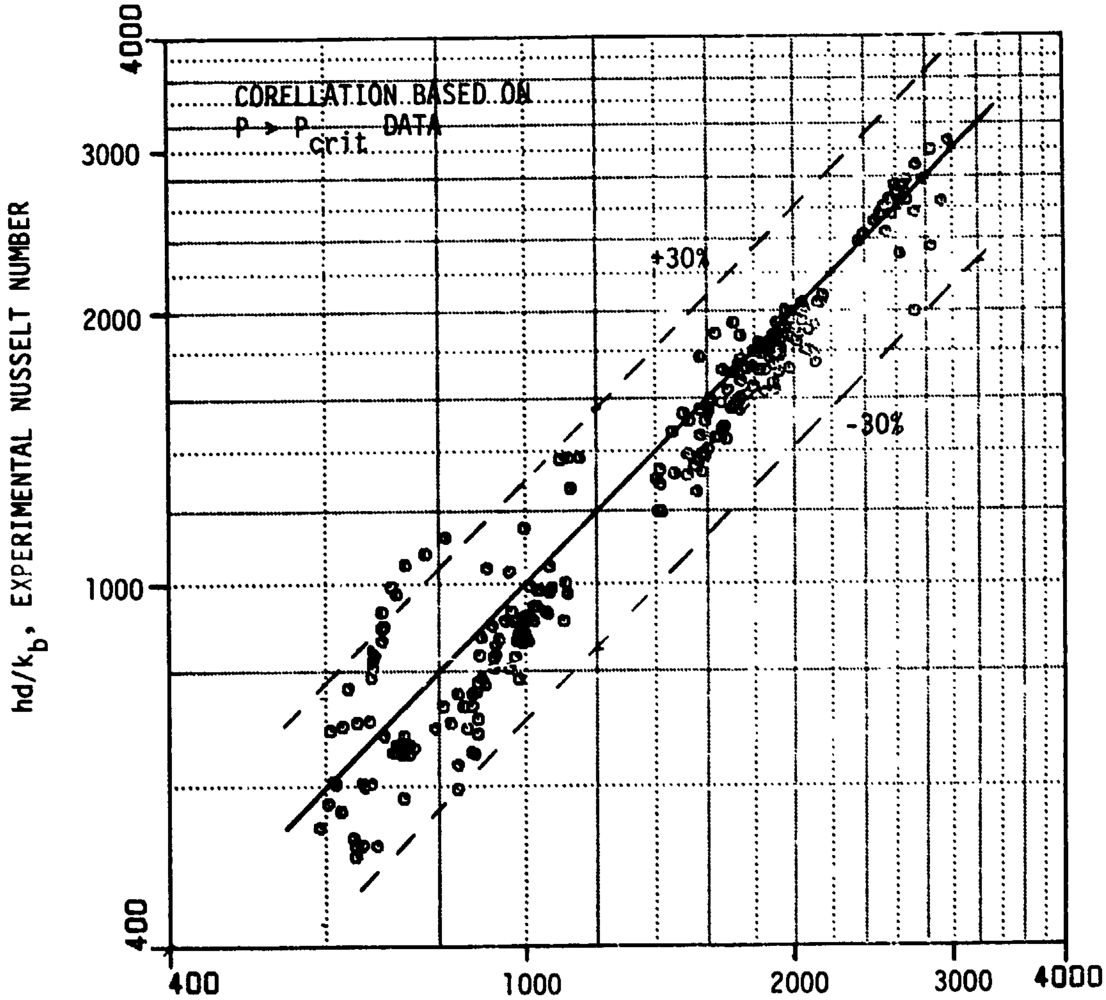
FORCED CONVECTION DATA BASE

Test No. HTB6-797-	Data ID NO.	Correlation Case 1-3	Correlation Case 4-5
101	6-45	Use	
102	61-85		
103	91-125		
	136-145		
104	151-185		
	211-220		
105	236-269		
	271-274		
	281-284		
	286-289		
	296-299		
106	311-330		Delete
107	381-385		Use
108	446-450		
	486-490		
	521-525		
109	565, 570, 575		Delete
110	626-645		Delete
111	656-660		Delete
112	716-720		Use
	736-738		
	756-757		
	776-777		
	796-797		



$$.00545\ Re^{.90}\ Pr^{.4}\left(\frac{\rho b}{\rho w}\right)^{-.11}\left(\frac{\mu b}{\mu w}\right)^{.23}\left(\frac{kb}{kw}\right)^{.27}\left(\frac{\overline{Cp}}{Cp_b}\right)^{.53}\left(1+\frac{2}{L/D}\right)$$

Figure III-16. Forced Convection Correlation Based on All Data



$$.00569\ Re_b^{.88}\ Pr_b^{.4} \left(\frac{\rho b}{\rho w}\right)^{.12} \left(\frac{\mu b}{\mu w}\right)^{-.14} \left(\frac{kb}{kw}\right)^{.83} \left(\frac{\overline{Cp}}{Cp_b}\right)^{-.37} \left(\frac{P}{Pcr}\right)^{.25} \left(1 + \frac{2}{L/D}\right)$$

Figure III-17. Forced Convection Corrleation Based on $P > P_{crit}$ Data

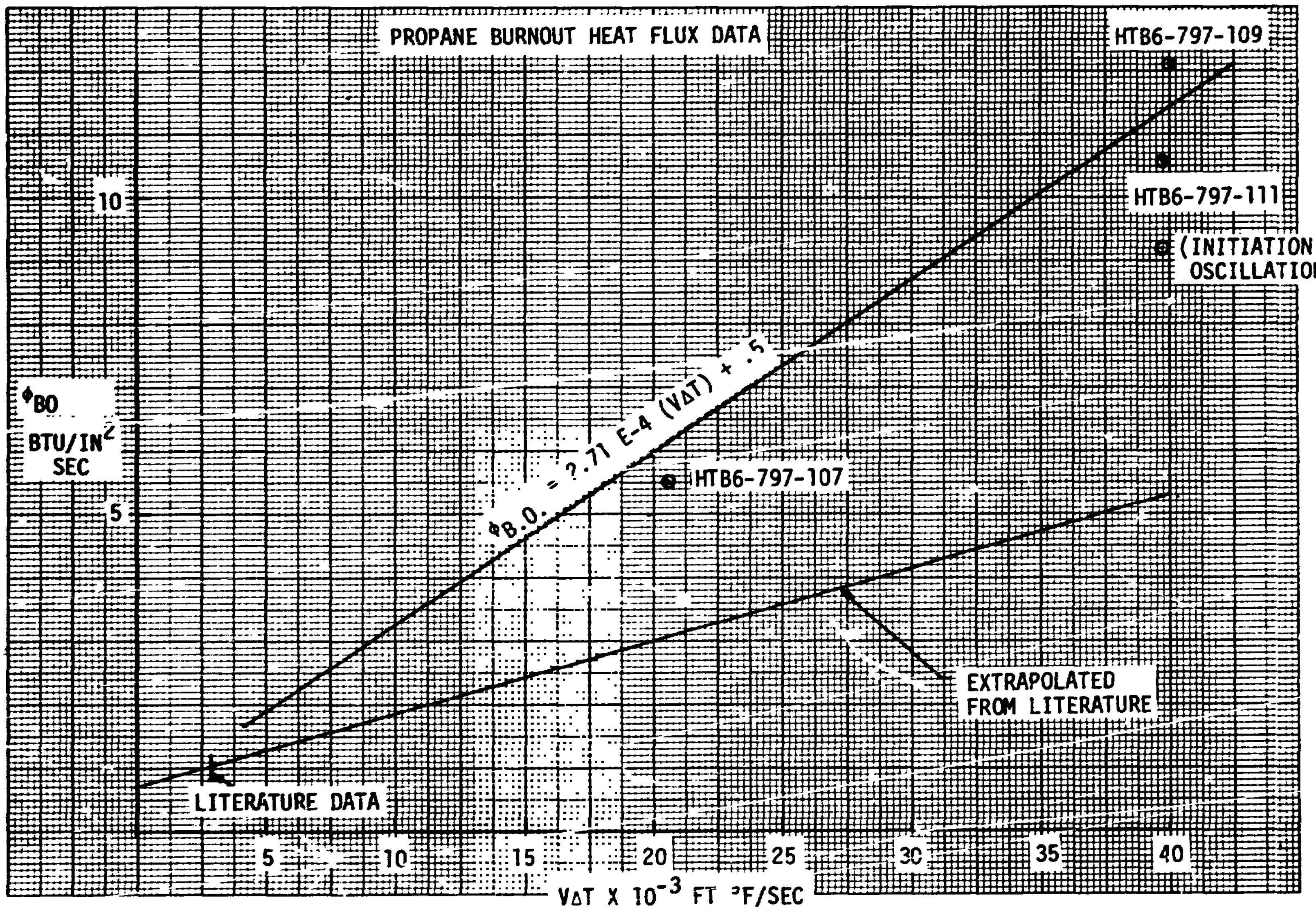


Figure III-18. $\phi B.O.$ Correlation

The forced convection effect was calculated from

$$\phi_{Fc} = h_{F.C.} (T_{sat} - T_{bulk})$$

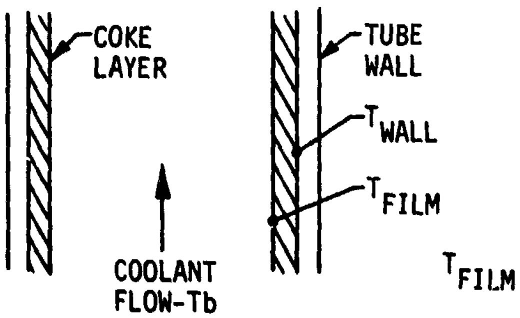
The forced convection coefficient $h_{F.C.}$ was calculated @ $T_{wall} = T_{sat}$ and was then taken to be constant.

ϕ_{NUB} was then plotted versus wall superheat ($T_{wall} - T_{sat}$). The results are shown in Figure III-19.

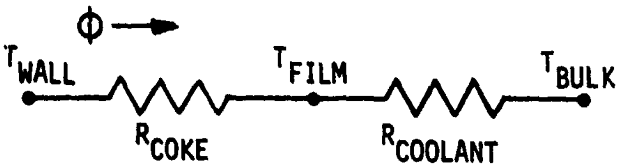
3. Coking Correlation

Coking data are plotted in Figure III-20 in the form of coking rate versus the reciprocal of absolute temperature. A dashed line representing RP-1 rates (Ref. 17) is shown as a comparison.

Coking rates were calculated from the test data using the following model:



TEST SECTION



HEAT MODEL

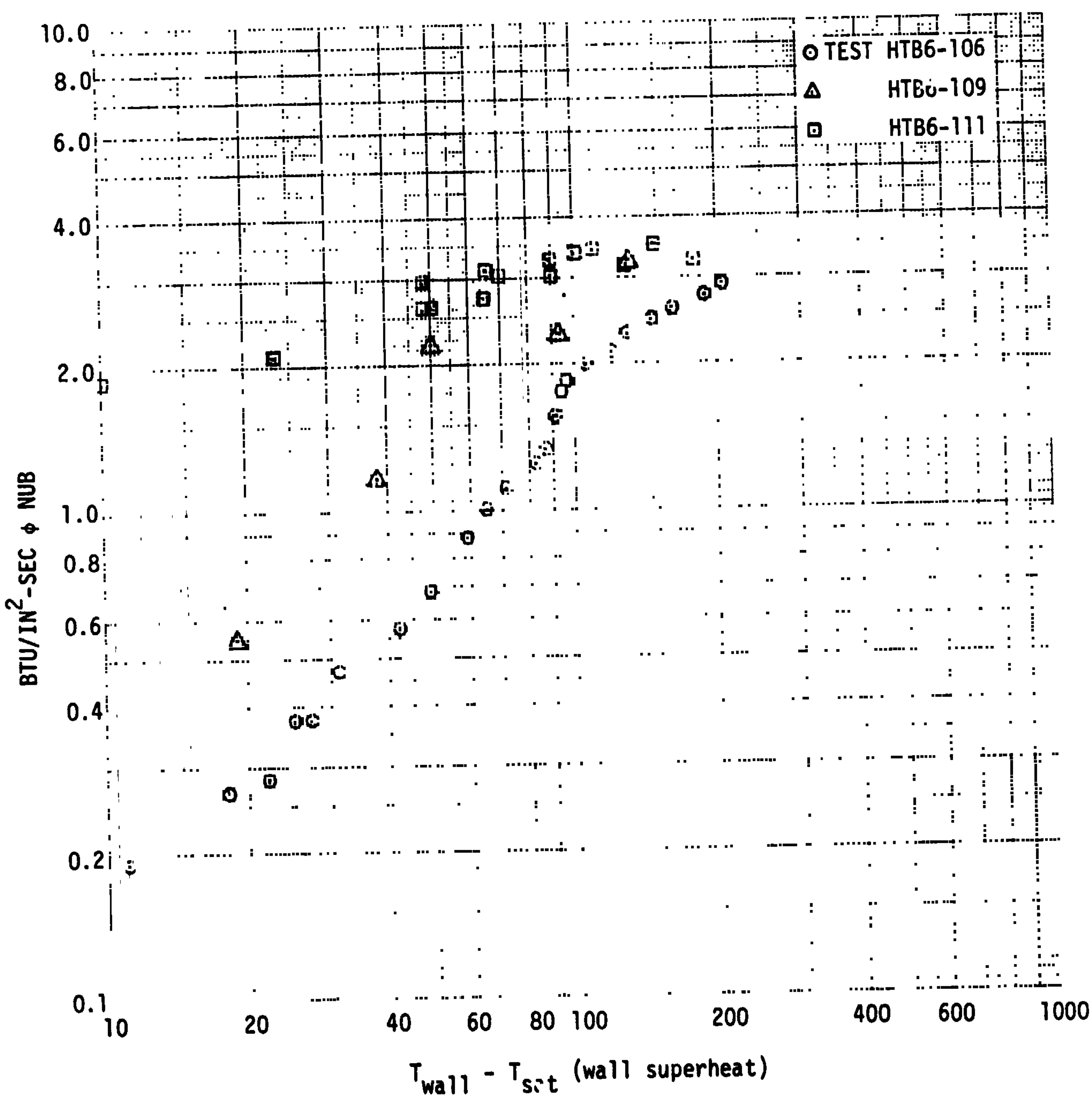


Figure III-19. Nucleate Boiling Data

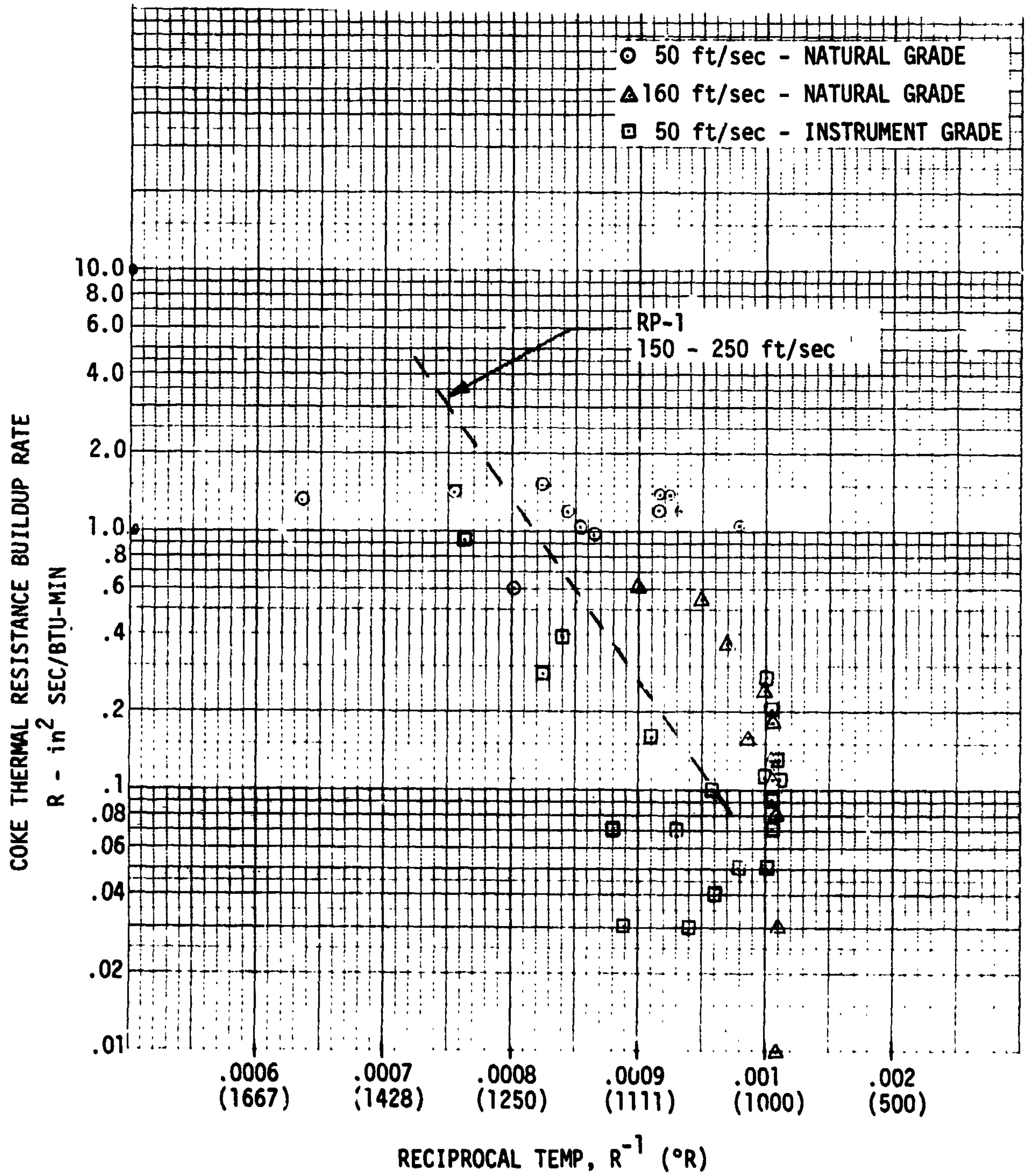


Figure III-20. Propane Ccking Rates

where:

T_{wall} = Calculated inside tube wall temperature (from test data)

T_{film} = Effective coolant film temperature

T_{bulk} = Bulk temperature of coolant (from test data)

$\emptyset$ = Heat flux (from test data)

$R_{coolant}$ = 1/h, where h is the measured heat transfer coefficient

R_{coke} = Thermal resistance of coke layer

T_{film} is assumed to be the reference temperature at which the coking is occurring. It is calculated as

$$T_{film} = T_{wall} - (R_{coke}\ \emptyset)$$

or

$$T_{film} = T_b + (R_{coolant}\ \emptyset)$$

Initially $R_{coke} = 0$ and $T_{film} = T_{wall}$.

As coke develops on the tube wall, T_{film} is calculated as:

$$T_{film} = T_b + (R\ coolant\ \emptyset)$$

At constant $\emptyset$, T_b and $R_{coolant}$ are also assumed constant, therefore T_{film} remains constant and R_{coke} is calculated from $R_{coke} = (T_{wall} - T_{film})/\emptyset$

R_{coke} is measured as a function of time and a coking rate defined as

$$\frac{\Delta\ R_{coke}}{\Delta\ T}$$

at the effective temperature, T_{film}.

Upon change of power level, Ø, a new T_{film} is calculated as

$$T_{film} = T_{wall} - (R_{coke} \text{ [current value] } \emptyset)$$

whereupon the procedure is repeated.

F. TEST SECTION INSPECTION

Test sections used for the supercritical and coking test series were split into two halves, as shown in Figures III-21 and III-22.

Small amounts of coke can be seen in some of the supercritical test sections (short duration exposure), while blackend tubes were characteristic of the low velocity coking tests.

F. PROPANE PURITY

Two grades of propane were purchased for this program - natural and instrument grade. Nine cylinders (20 gallons each) of natural grade have been used. Five of the nine were purchased from Matheson, the remainder from Liquid Carbonics.

The initial run tank fill consisted of 5 Matheson and 2 Liquid Carbonics cylinders. An additional cylinder was added on 16 April 1980. A sample of the run tank contents was taken on 23 May 1980 after completion of heat transfer Test #107. Propane purity was near nominal, 95.4%.

Prior to initiating heat transfer Test #108, an additional cylinder was added, and Tests 108 through 111 were completed. On 1 July 1980, a sample was again taken prior to purging the system for addition of instrument grade.

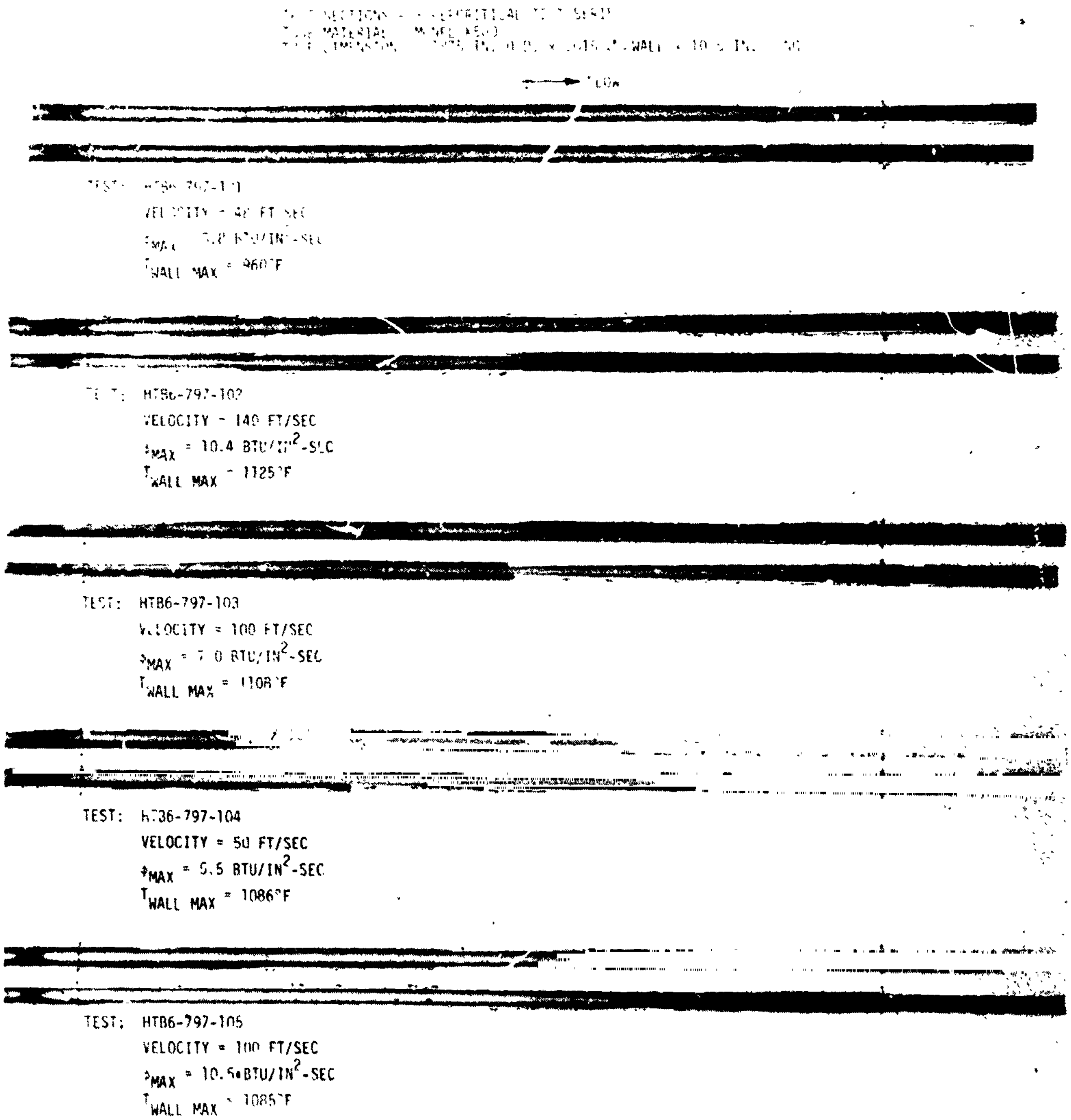


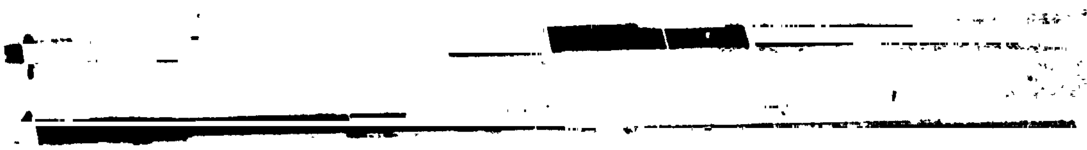
Figure III-21. Test Sections - Supercritical Test Series

TEST SECTIONS - COKING SERIES

TUBE MATERIAL: MONEL K500

TUBE DIMENSION: .125 IN. O.D. x .015 IN. WALL x 5.97 IN.

→ FLOW



TEST: HTB6-797-107

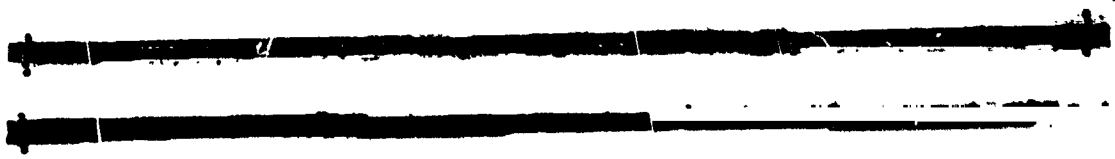
VELOCITY = 48 FT/SEC

PRESSURE = 1800 PSIA

$T_{WALL\ MAX}$ = 1220°F

ϕ_{MAX} = 5.8 BTU/IN^2-SEC

PROPANE GRADE: NATURAL



TEST: HTB6-797-108

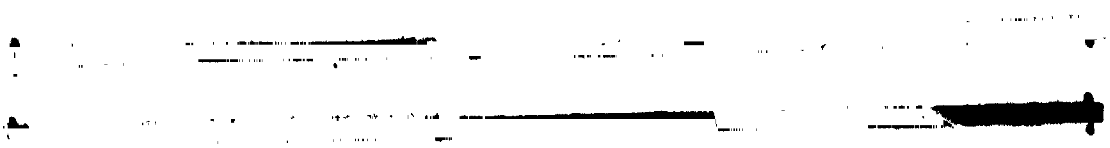
VELOCITY = 160 FT/SEC

PRESSURE = 1800 PSIA

$T_{WALL\ MAX}$ = 732°F

ϕ_{MAX} = 10.4 BTU/IN^2-SEC

PROPANE GRADE: NATURAL



TEST: HTB6-797-112

VELOCITY = 50 FT/SEC

PRESSURE = 1800 PSIA

$T_{WALL\ MAX}$ = 1164°F

ϕ_{MAX} = 6.20 BTU/IN^2-SEC

PROPANE GRADE: INSTRUMENT

Figure III-22. Test Sections - Coking Series

The analysis showed an unusually low propane content, 87%, while ethylene and butane components were each up to 5%.

On 18 July 1980, following Test 112, the run tank was sampled together with unused cylinders of product. The results are tabulated in Table III-VII.

TABLE III-VII

PROPANE SAMPLE ANALYSIS

Sample	Component, Volume %				
	Ethane	Ethylene[1]	Propane	Butane	Unknown[2]
23 May 1980 (Run Tank)	1.32	-	95.4	3.03	0.25
1 July 1980 (Run Tank)	0.56	5.14	87.36	5.48	1.46
18 July 1980 (Run Tank)	0.10		99.00	0.42	0.48
Liquid Carbonic Instrument Grade, as received	0.04		99.95		0.01
Liquid Carbonic Natural Grade, as received	1.08	5.23	90.85	2.82	0.02

1 Tentative assignment; retention time is consistent.

2 Peak shape is similar to butane. One speculative assignment is butylene, but no standards were available.

IV. TASK I - CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The Task I analytic study has demonstrated the relative cooling capabilities of methane, propane, ammonia, and RP-1. The sensitivity of these fuels to the various operating conditions has been determined.

There are three significant factors influencing the analysis:

1) The assumed forced convection and nucleate boiling heat transfer correlations employed.

2) The assumed coolant-side coking characteristics of the fuel.

3) The gas-side carbon deposition.

Each of these factors, particularly for methane, propane, and RP-1, has influenced the projected cooling ranges and should be verified experimentally.

The Task I experimental study of the heat transfer characteristics of propane had the following unexpected results:

1) Forced convection heat transfer coefficients were 30 to 50% higher than predicted by the "LOX" correlation used in the analytic study.

2) Burnout heat flux measurements were signficantly higher than had been predicted on the basis of limited low flux data.

3) Coolant-side coking occurred at relatively low wall temperatures $\sim$ 500°F.

IV, A, Conclusions (cont.)

The higher forced convection and burnout flux characteristics of propane should show significant improvement in the predicted operating range. However, the unexpected low coking temperature may severely penalize propane in forced convection cooling modes.

B. RECOMMENDATIONS

1. Investigate causes of propane coking, i.e., impurities, catalytic effects, etc.

2. Verify predicted methane coking limits and forced convection correlations.

3. Investigate gas-side carbon deposition for methane and propane.

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