Rockwell International

Rocketdyne Division

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METHANE HEAT TRANSFER INVESTIGATION
TECHNICAL PROGRESS NARRATIVE
PERIOD OF PERFORMANCE: 15 AUGUST THRU OCTOBER 31

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Prepared for:

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Huntsville, Alabama 35812

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Advanced Booster Propulsion Systems

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FOREWORD

This is a 12-month program being conducted for NASA-MSFC. The NASA-MSFC Program Monitor is Dale Blount. The major efforts of this program are being conducted by the Rocketdyne Engineering Aerothermal, and Materials Departments. Testing is being conducted at the Rockwell North American Aviation Operations (NAAO) Aerothermal Laboratory. The responsible Engineers in these areas are:

Ron Morinishi	Heat Transfer, Testing, Data Analysis
Dennis Lim	Task I Thrust Chamber Thermal Analysis
Frank Wimmer	Materials & Processes
Bob Scherer	Test (NAAO)

The Project Engineer is Ron Cook, Advanced Programs, and the Program Manager is Frank Kirby.

INTRODUCTION

This program is a 12-month experimental investigation to determine the coking thresholds and cooling capability (convective correlations) of methane. Economical exploitation of space in the future will require reusable, high-performance, liquid rocket booster engines. The high propellant bulk density and relatively high-performance LOX/hydrocarbon liquid engines look extremely attractive. LOX/methane is of particular interest because it has a higher chamber pressure cooling limit, higher specific impulse, higher coolant coking temperature, cleaner exhaust products, and lower potential for carbon deposition at low mixture ratio preburner operation than other hydrocarbon fuels.

Future high chamber pressure LOX/hydrocarbon booster engines will require copper-base alloy main combustion chamber coolant channels similar to the SSME to provide adequate cooling and reusable engine life. Therefore, it is of vital importance to evaluate the heat transfer characteristics and coking thresholds for LNG (94% methane) cooling, with a copper-base alloy material adjacent to the fuel coolant.

High-pressure methane cooling and coking characteristics have recently been evaluated at Rocketdyne using stainless-steel heated tubes at methane bulk temperatures and coolant wall temperatures typical of advanced engine operation except at lower heat fluxes as limited by the tube material. As expected, there was no coking observed. However, coking evaluations need be conducted with a copper-base surface exposed to the methane coolant at higher heat fluxes approaching those of future high chamber pressure engines.

This program consists of five working tasks and a reporting task.

TASK 1: Test Matrix Definition consists of (1) design and analysis of a 600K LOX/CH_4 Main Combustion Chamber (MCC) at 3000 psia chamber pressure and (2) definition of the test matrix to cover the ranges of methane coolant conditions described in the MCC design analysis. The MCC design will utilize a high strength copper base channel configuration coolant liner, typical of the Space Shuttle Main Engine (SSME). The test matrix will provide for definition of coking thresholds and convective cooling heat transfer correlations.

TASK 2: Design and Procurement of Test Sections consist of designing electrically heated tubular test specimens and procuring associated test specimen hardware. The test specimens will utilize a bimetallic tube assembly to allow testing at a heat flux of 50 Btu/in^2-sec and 5000 psia CH_4 coolant pressure, which is typical of a 3000 psia chamber pressure MCC throat region coolant wall heat flux. The inner tube material will be copper to simulate any coking phenomena associated with the MCC liner material and surface conditions.

TASK 3: Preparation of Detail Test Plan consists of preparing a document that completely describes the test instrumentation, data acquisition, data correlation approach, heated tube specimen configuration control, and test procedures. The detailed test plan will include test section drawings, tube specimen operational maps, facility schematics, and data analysis processing procedures.

TASK 4: Heated Tube Testing will be conducted at the Rockwell North American Aviation Operations (NAAO) thermodynamics laboratory. Testing will be conducted to define the coking thresholds of methane at purities between 85% and 95% for LNG and near 100% pure methane. Coolant convective heat transfer characteristics will be evaluated at a purity between 94% and 100%.

TASK 5: Data Analysis and Correlation will be performed to define any coking thresholds and define convective cooling correlations for the complete range of operating conditions applicable for a high chamber pressure MCC design. A number of convective heat transfer correlating formats will be satistically evaluated to obtain the best data-fit.

SUMMARY

(1) The program effort has been completed. The final report and briefing are being prepared for presentation at the end of November.

(2) A preliminary program overview briefing was completed for NASA-MSFC presentation to OAST.

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METHANE HEAT TRANSFER INVESTIGATION

PROGRAM OVERVIEW

ROCKETDYNE DIVISION

METHANE HEAT TRANSFER INVESTIGATION
INTRODUCTION

- LOX-HYDROCARBON LIQUID ROCKET ENGINES ARE ATTRACTIVE CANDIDATES FOR HIGH PERFORMANCE, REUSABLE BOOSTER APPLICATIONS
    - HIGH PROPELLANT BULK DENSITY
    - RELATIVELY HIGH PERFORMANCE
- LOX-METHANE IS OF PARTICULAR INTEREST
    - HIGH CHAMBER PRESSURE COOLING LIMIT
    - HIGH SPECIFIC IMPULSE
    - HIGH COOLANT COKING LIMIT
- COOLING CAPABILITIES OF METHANE ARE NOT YET FULLY DESCRIBED
    - EXPERIMENTAL HEAT TRANSFER DATA USUALLY LIMITED TO LOW HEAT FLUXES
    - THERMAL DECOMPOSITION AND COPPER WALL INTERACTION NOT FULLY UNDERSTOOD

METHANE HEAT TRANSFER INVESTIGATION
PROGRAM OBJECTIVES

- TO DEMONSTRATE THE COOLING CAPABILITIES OF METHANE AND LNG (94% PURITY) IN COPPER COOLING CHANNELS
  - HEATED TUBE CONCEPT PROVIDES HEAT TRANSFER DATA UNDER SIMULATED ENGINE OPERATING CONDITIONS OF:
    - COOLANT MASS FLUX (0-100 LBM/IN^2-S)
    - HEAT FLUX (0-85 BTU/IN^2-S)
    - WALL TEMPERATURE (600-900°F)
    - FLUID PRESSURE (4500 PSIA)
- TO INVESTIGATE THERMAL DECOMPOSITION OF METHANE AND CHARACTERIZE TUBE WALL DEPOSITION
- TO EVALUATE COMPATIBILITY OF FLUID WITH COPPER WALL MATERIAL

METHANE HEAT TRANSFER INVESTIGATION
SUMMARY OF RESULTS

- BIMETALLIC TUBE PROVIDED ACCURATE DATA TO UNPRECEDENTED HEAT FLUX LEVELS (85 BTU/IN2-SEC) FOR THIS TYPE OF EXPERIMENT
- ESTABLISHED HEAT TRANSFER CORRELATIONS FOR BOTH SMOOTH AND ROUGH COOLING CHANNELS
- DEMONSTRATED A CORROSIVE TYPE OF REACTION BETWEEN METHANE AND COPPER WHICH ROUGHENED THE TUBE WALLS
- ROUGHENING WAS FOUND TO BE A FUNCTION OF WALL TEMPERATURE, HEAT FLUX, FLUID MASS FLUX, AND EXPOSURE TIME

EXPERIMENTAL HARDWARE
BIMETALLIC TUBE AND BUS BAR DESIGN

- BIMETALLIC TUBE ALLOWS HIGH HEAT INPUT AND THIN TUBE WALLS
  - COPPER INNER WALL GENERATED 90% OF HEAT
  - K-MONEL OUTER WALL BEARS LOAD OF 5000 PSIA FLUID PRESSURE
  - WALL THICKNESS OF 0.015 INCH ALLOWS ACCURATE PREDICTION OF INNER WALL TEMPERATURE
- BUS BAR DESIGNED TO DELIVER 50 KW AND ALLOW FOR TUBE THERMAL EXPANSION
  - PERMANENT BUS BARS CARRY POWER CABLES
  - MODULAR TUBE TEST SPECIMENS HAVE CU DISKS FURNACE BRAZED TO TUBES
  - ONE BUS BAR IS ON SLIDING MECHANISM TO ALLOW FOR 0.1 INCH EXPANSION

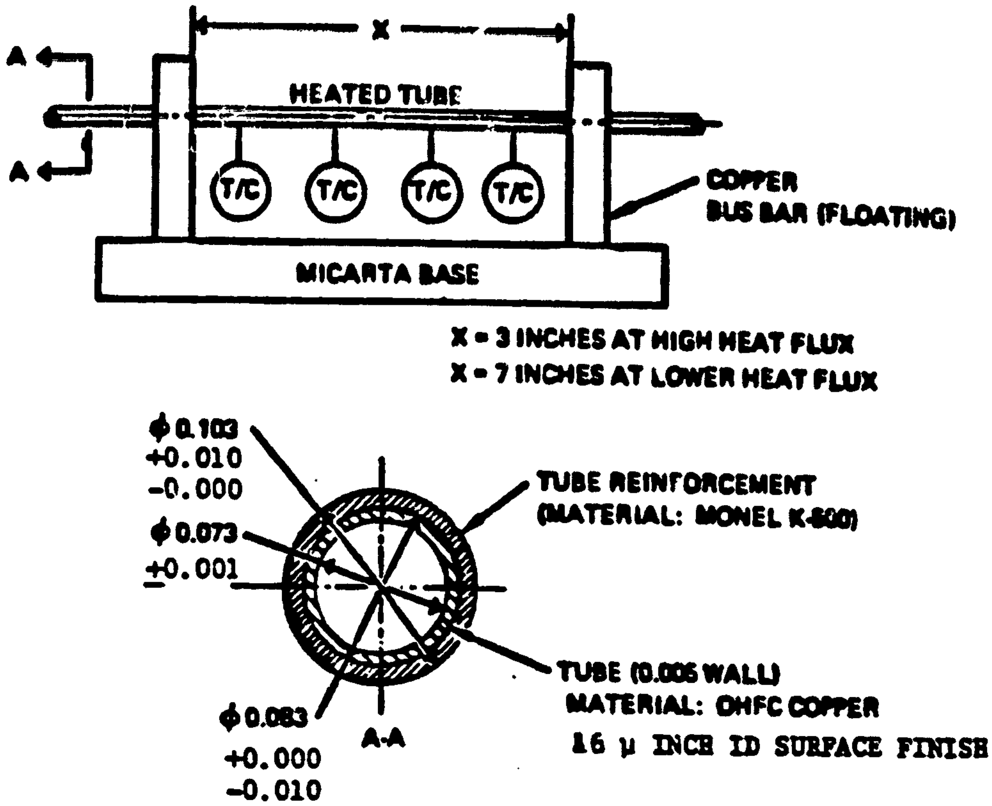


Figure 1. Heated Tube Test Section Design

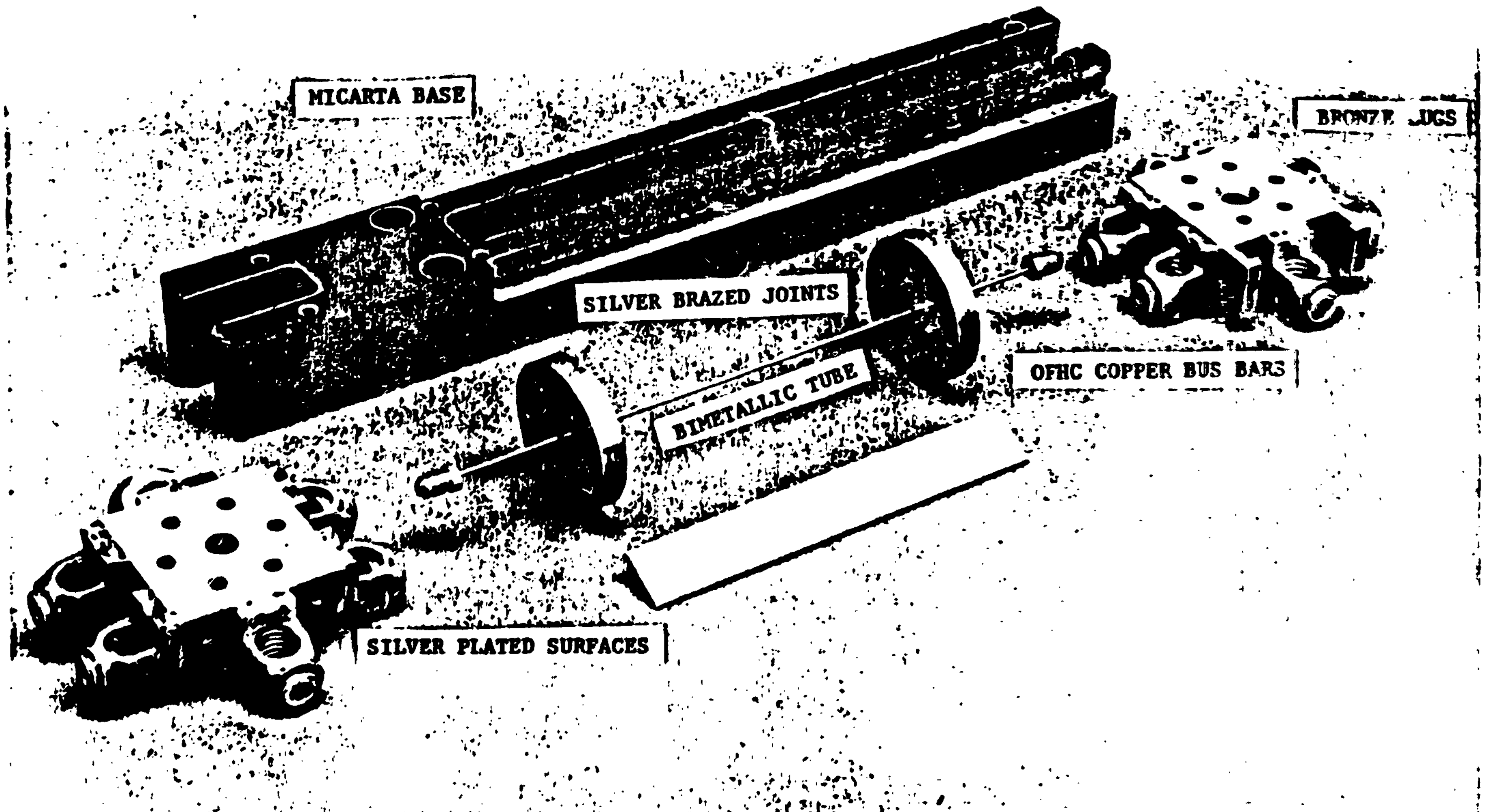


Figure 2. Exploded View of the Bus Bar/Bimetallic Tube Assembly. The Circular Bus, Tube, and AN Fittings, Comprise a Test Specimen Unit.

EXPERIMENTAL HARDWARE
TEST FACILITY

- ELECTRICAL POWER PROVIDED BY THREE AC REACTORS RATED AT 2000 AMPS EACH
    - POWER MEASURED BY INTEGRATING WATTMETER (IxV)
- 35 GALLON METHANE RUN TANK MAINTAINED CONSTANT PRESSURE (UP TO 6000 PSIA)
- ELECTRICAL PREHEATERS ALLOWED VARIATION IN FLUID INLET TEMPERATURE
- TURBINE FLOW METER PROVIDED FLOW MEASUREMENT
- FLUID PRESSURES AND TEMPERATURES MEASURED AT INLET AND OUTLET
- TUBE OUTER WALL TEMPERATURE MEASURED USING NOVEL TC ATTACHMENT TECHNIQUE
- FLOW RATE CONTROLLED BY TANK PRESSURE AND DOWNSTREAM VALVE
- SAFETY DEVICES
    - AUTOMATIC SHUTDOWN FOR TUBE OVER TEMPERATURE
    - NITROGEN PURGED CONTAINMENT BOX

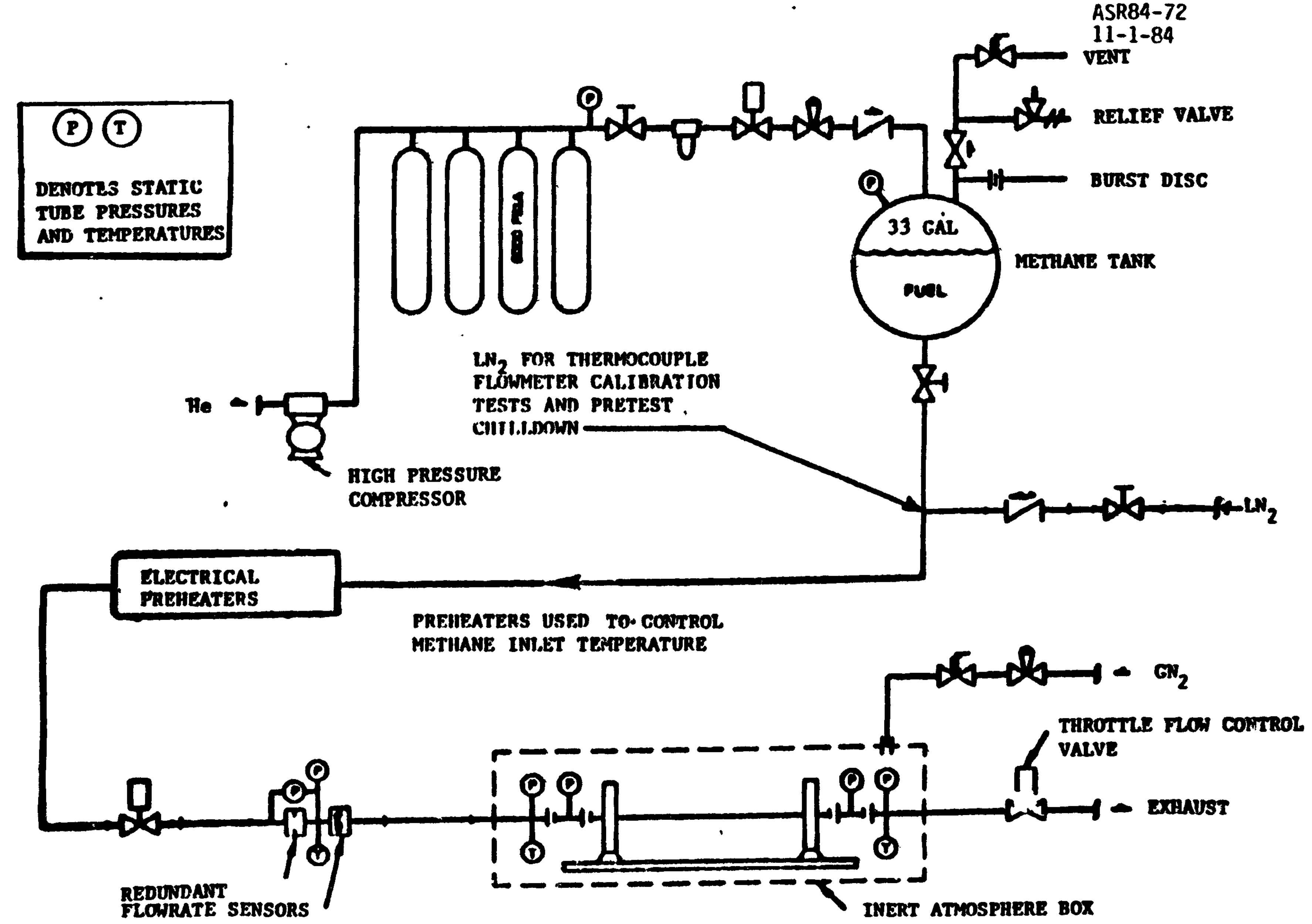


Figure 4. Test Facility Flow Schematic

DATA ANALYSIS

- NUMERICAL SOLUTION PERFORMED ON IBM PERSONAL COMPUTER
- PERFORMED SIMULTANEOUS SOLUTION FOR HEAT TRANSFER AND FLOW PROPERTIES
- CALCULATIONS MADE ON SMALL TUBE SEGMENTS, BEGINNING AT ENTRANCE
- LOCAL HEAT TRANSFER COEFFICIENT h FOUND BY SATISFYING HEAT BALANCE

$$Q_{ABSORBED} = Q_{GENERATED} + Q_{DISSIPATION}$$

WHERE,

$$Q_{ABSORBED} = hA\,(T_{WALL} - T_{FLUID})$$

$$Q_{GENERATED} = I^2R$$

$$Q_{DISSIPATION} = c\,(v\ \ \Delta P)$$

- FULL METHANE PROPERTIES TABLES (FROM NBS DATA)
- PROGRAM OUTPUTS NONDIMENSIONAL PARAMETERS NU, RE, PR, ST, f

- RANGE OF TEST CONDITIONS ACHIEVED IN THE BIMETALLIC TUBE TEST SERIES FOR LNG

TOTAL NUMBER OF TESTS	37
NUMBER OF STEADY-STATE POINTS	64
TOTAL NUMBER OF DATA POINTS	450
NUSSLET NUMBER	1067 TO 5844
REYNOLDS NUMBER	8.2 E5 TO 3.8 E6
HEAT FLUX	1.6 TO 85.0 (BTU/S-IN^2)
MASS FLUX	16.8 TO 96.0 (LBM/S-IN^2)
INLET FLUID TEMPERATURE	-197 TO 36 (°F)
OUTLET FLUID TEMPERATURE	-135 TO 489 (°F)
INLET FLUID PRESSURE	3914 TO 4966 (PSIA)
FLUID VELOCITY	181 TO 781 (FT/S)

TEST MATRIX FOR LIQUIFIED NATURAL GAS TESTS

HEAT FLUX (BTU/IN^2-SEC)	10	20	30	40	50	60	70	80	90	100	110
0 - 5		X		X	X						
6 - 10	X	X		X	X	X					
11 - 15	X	X			X	X					
16 - 20		X	X		X	X			0		
21 - 25		X	X		X	X	0		0		
26 - 30		X	X				0		0		
31 - 35			X		0	0	0		0		
36 - 40			0		0	0	0		0		
41 - 45					0	0	0		0		
46 - 50						0	0	0			
51 - 55						0	0	0			
56 - 60						0		0	0	0	
61 - 65						0			0	0	0
66 - 70						0					0
71 - 75						0				0	
76 - 80						0				0	
81 - 85										0	

X - LONG TUBE
0 - SHORT TUBE

TEST RESULTS

- HEAT TRANSFER RESULTS WERE CONSISTENT WITHIN EXPERIMENTAL ERROR ($\pm$ 10%)

- THE DATA CORRESPONDING TO SMOOTH TUBES CORRELATED WELL TO

$$NU = 0.022\ Re^{0.8}\ Pr^{0.4} \left(\frac{T_b}{T_w}\right)^{0.45}$$

  FOR BOTH METHANE AND LNG

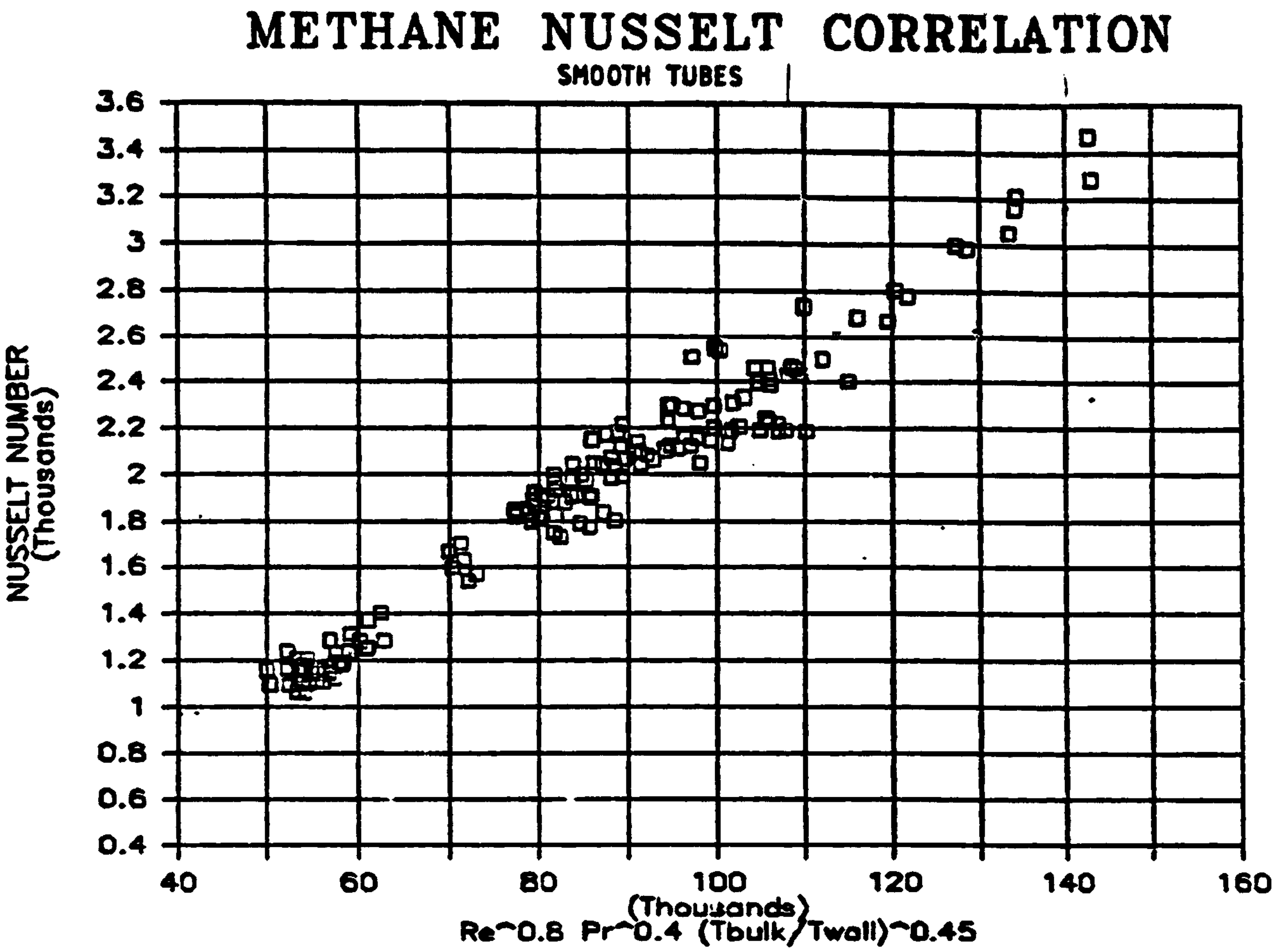
- AT MORE SEVERE CONDITIONS (HIGHER WALL TEMPERATURE AND HEAT FLUX) CHEMICAL CORROSION OF THE COPPER WALL BECAME SIGNIFICANT

  - HIGH TUBE WALL ROUGHNESS PRODUCED LARGE INCREASES IN PRESSURE DROP AND HEAT TRANSFER

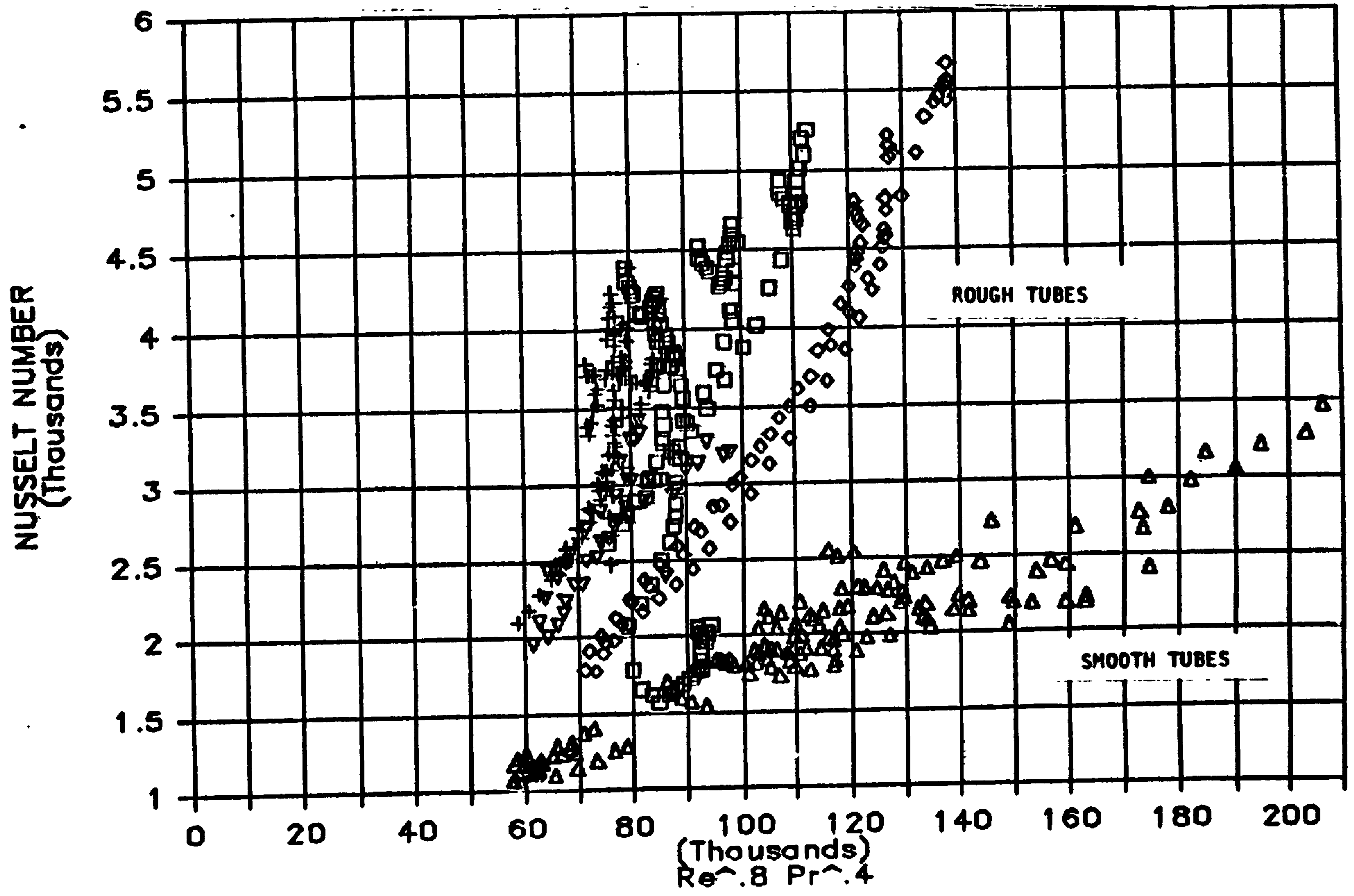
  - INCORPORATION OF THE WALL ROUGHNESS INTO HEAT TRANSFER EQUATION GAVE THE FOLLOWING FOR BOTH METHANE AND LNG

$$NU = \frac{0.4\ (f/8)\ Re\ Pr}{1 + \sqrt{f/8}\left[5.19\ (\varepsilon_s^+)^{0.2}\ Pr^{0.44} - 8.5\right]}$$

WHERE, f = FRICTION FACTOR
ε_{s+} = EQUIVALENT SAND GRAIN ROUGHNESS

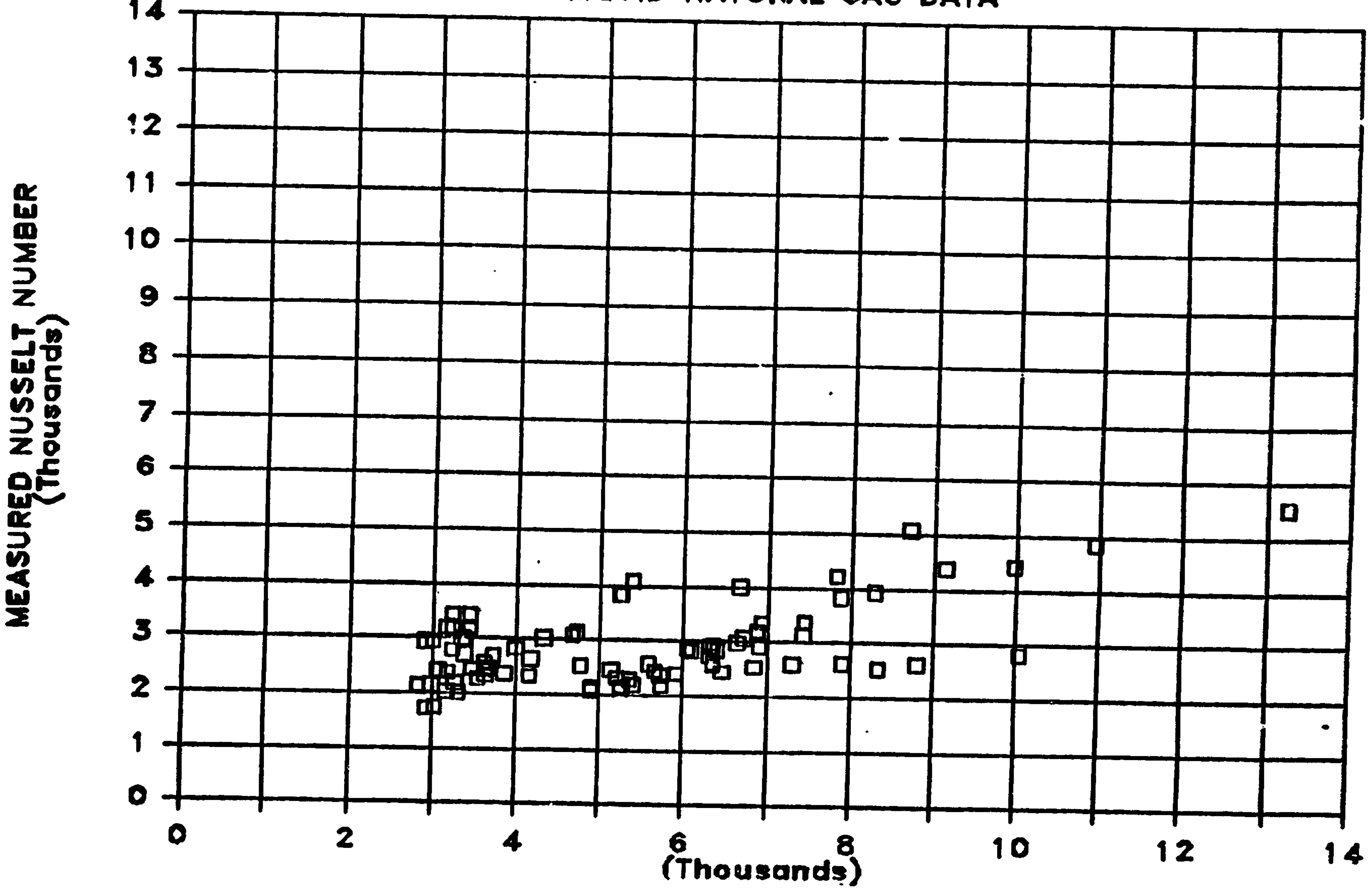

METHANE NUSSELT CORRELATION
SMOOTH TUBES
NUSSELT NUMBER (Thousands)
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
40
60
80
100
120
140
160
(Thousands)
Re^0.8 Pr^0.4 (Tbulk/Twall)^0.45

METHANE NUSSELT CORRELATION



FRICTION FACTOR EFFECT ON NUSSELT NO.

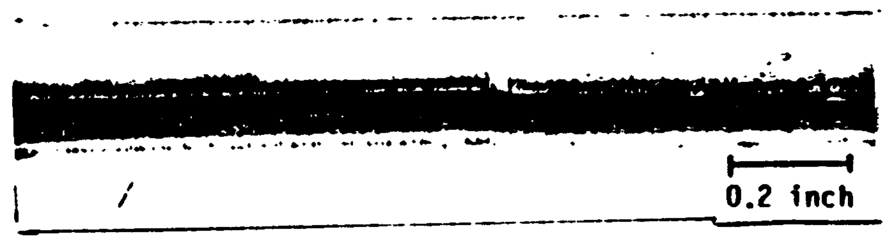
LIQUID NATURAL GAS DATA



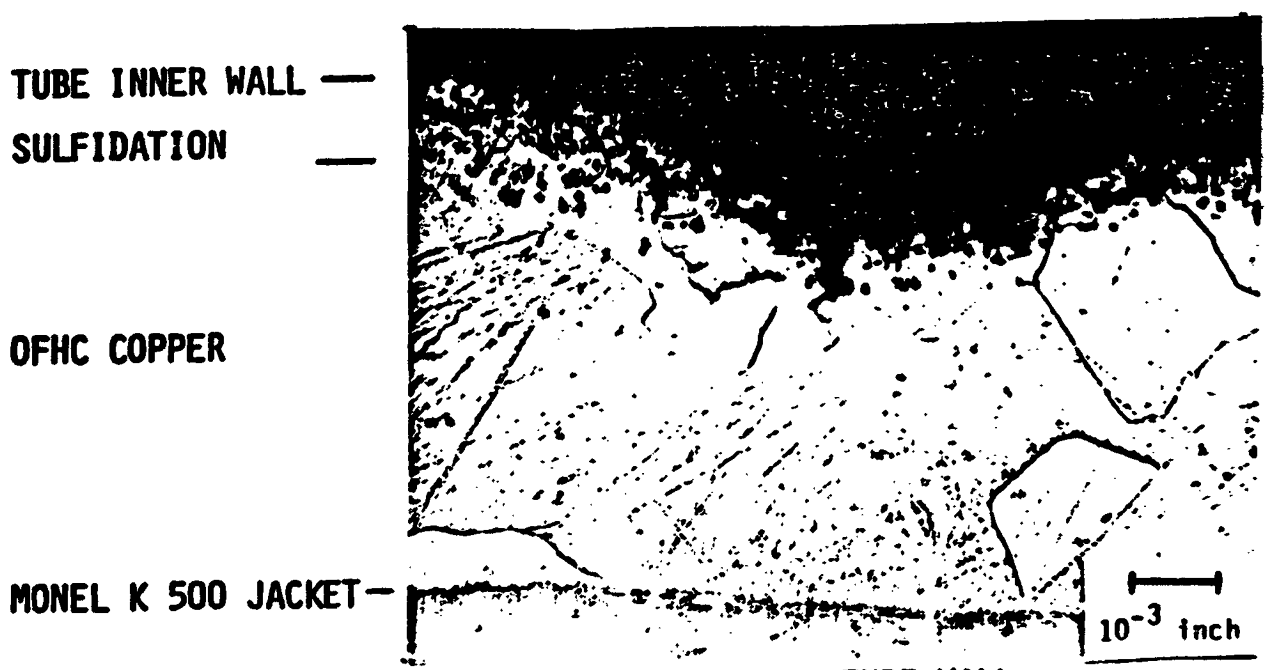
$$Nu = \frac{(f/8)\, Re\, Pr}{1 + \sqrt{f/8}\,(5.19\, e_s^{+}\, Pr^{0.44} - 8.5)}$$

ROUGHENING AND DISCOLORATION OF TUBE WALLS

- DISPLAYED BY ALL TUBES RUN WITH LNG
- METALLOGRAPHY AND ELECTRON MICROPROBE REVEAL SIGNIFICANT SULFIDATION
- NO SIGNIFICANT COKING DETECTED



BIMETALLIC TUBE SECTIONED AFTER TEST



DETERIORATION OF TUBE WALL