WCAP-14372

AP600 LOW FLOW

CRITICAL HEAT FLUX (CHF)

TEST DATA ANALYSIS

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May 1995

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1.0 INTRODUCTION

One of the design bases for pressurized water reactors (PWR), including future AP600 reactors, is to prevent the limiting fuel rod in the reactor core from reaching departure from nucleate boiling (DNB) for condition I and II events. The heat flux at DNB is often referred to as critical heat flux (CHF). DNB correlations are developed from experimental data that simulate the reactor fuel design and core conditions. CHF is a function of local fluid conditions and can also be dependent upon fuel design. The primary DNB correlation used for the analysis of the AP600 fuel is the WRB-2 correlation (Reference 1).

The applicable range of parameters for the WRB-2 correlation is:

Pressure	$1440 \leq P \leq 2490$ psia
Local Mass Flow	$0.9 \leq G_{loc} \leq 3.7$ lbm/hr-ft.^{2}
Local Quality	$-0.1 \leq X_{loc} \leq 0.3$
Heated Length, Inlet to DNB Location	$L_h \leq 14$ feet
Grid Spacing	$10 \leq gsp \leq 26$ inches
Equivalent Hydraulic Diameter	$0.37 \leq D_e \leq 0.51$ inch
Equivalent Heated Diameter	$0.46 \leq D_h \leq 0.59$ inch

A complete loss-of-flow accident with all reactor coolant pumps (RCPs) tripped is a condition III event, but it is analyzed as a condition II event. A locked RCP rotor accident is a condition IV event. In the locked rotor analysis, fuel rods having a DNB Ratio (DNBR) below a DNBR limit are assumed to fail for radiological assessment.

In the postulated AP600 loss-of-flow and locked rotor accidents, the local mass fluxes in the hot channels at the DNB-limiting time steps are about 0.6×10^6 lbm/hr-ft.^{2} to 0.7×10^6 lbm/hr-ft.^{2} which are outside the applicable range of the WRB-2 correlation. To assess CHF performance of the AP600 fuel design at low-flow conditions, DNB tests were conducted at the Columbia University Heat Transfer Research Facility in New York between July 1993 and February 1994.

This report provides a description of the DNB test facility, test sections, and testing procedure for data collection. The report also describes data analysis and adjustment to the WRB-2 correlation based on the test results. The report qualifies the adjusted WRB-2 correlation for acceptance for the AP600 loss-of-flow and locked rotor applications.

2.0 TEST FACILITY

Westinghouse has obtained all of its CHF data from the Columbia University Heat Transfer Research Facility (HTRF). The facility consists of an instrumented high pressure loop that can supply water at pressures up to 2500 psia, flow rates up to 650 gpm, and inlet temperatures up to 650°F. The power supply is capable of delivering up to 12.5 megawatts dc. A description of the Columbia University test facility can be found in Reference 2.

The major components of the heat transfer loop are:

- Circulating pumps
- Flow control and measuring spool piping section
- Test section housing
- Heat exchangers (HXs)
- Mixing tee
- Water purification system
- Feedwater supply
- Makeup system
- Bleed system

Figure 2-1 shows the test section housing. It has only five major components:

- Pressure housing
- Grid plate
- Top adapter
- Shroud box
- Bottom adapter

Water from the measuring spool pipe enters the top of the pressure housing, flows down between the annulus, formed by the shroud and the pressure housing inner wall, passes through the bottom adapter holes and turns upward into the flow channel containing the test section. The resulting steam water mixture flows through the top adapter and grid plate into the mixing tree.

The instrumentation measurements used for the CHF tests include mass flux at the test section inlet, water temperature and total pressure at the test section inlet and outlet, differential pressures between axial locations in the test section, temperature in different sections of the test loop, and total dc power to the test section, and heater rod wall temperature. A computer-controlled data acquisition system recorded data during testing.

3.0 TEST SECTIONS

CHF test sections were constructed to accurately reflect the AP600 fuel design. There are two test sections: a typical section with heated rods only and a thimble test section containing a guide thimble tube in the center. The electrically heated rods were arranged in a 5x5 array with a 0.496-in.[2] pitch and a heated length of 14 feet (which bounds the actual fuel heated length of 12 feet). The heated rod diameter is 0.374 inch, and the thimble tube diameter is 0.474 inch. Similar to previous CHF tests (Reference 1), the test sections have a non-uniform radial power distribution with the peripheral rods having lower power than the interior rods. Figures 3-1 and 3-2 show the test configurations and radial power distributions for the typical and thimble test sections, respectively.

The zircaloy mixing vane (MV) grids and the intermediate flow mixer (IFM) grids were placed alternatively in a 10 inch spacing along the rod bundles. Thermocouples were located in the rods at different axial locations for CHF detection. Figure 3-3 shows the locations of grids and thermocouples along the heated length. A nonuniform axial power profile, similar to the power profiles used for previous CHF tests, was used for the AP600 tests (Reference 1). Figure 3-4 shows the axial power profile.

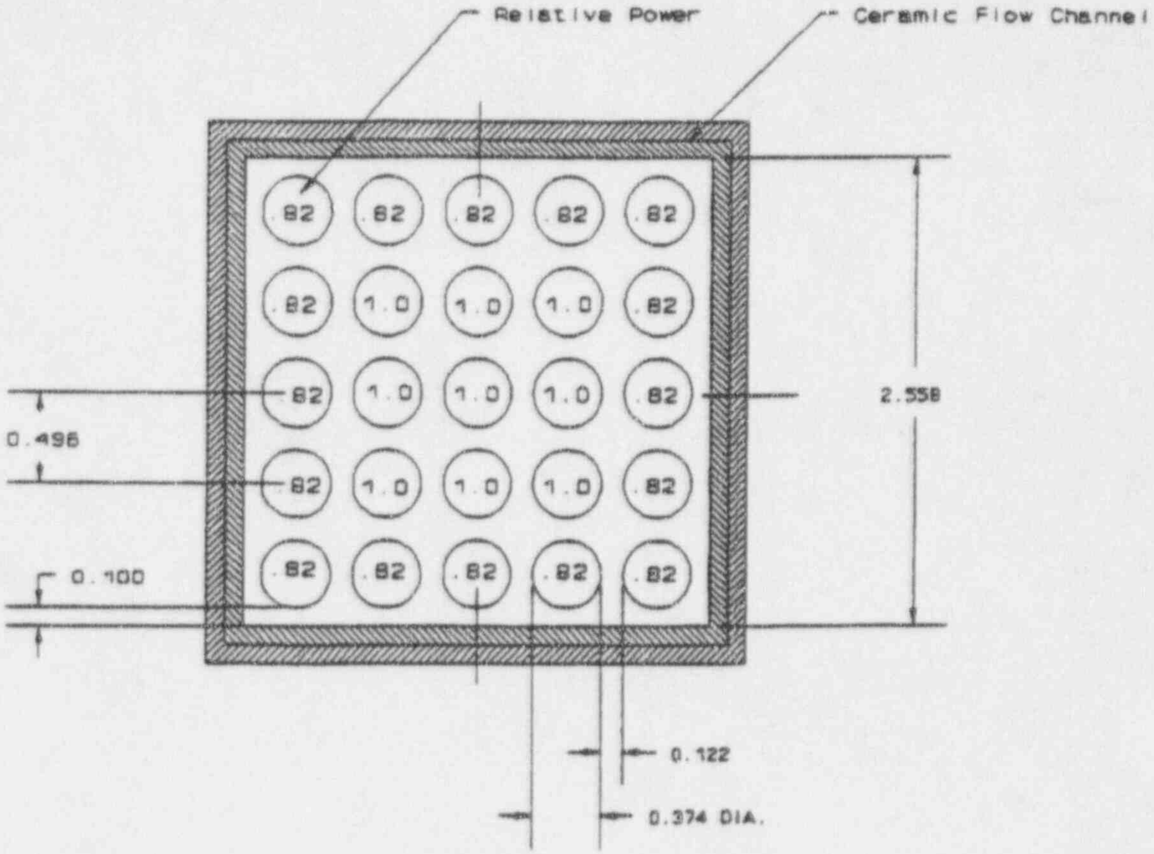

Figure 3-1 Typical Cell Cross Section

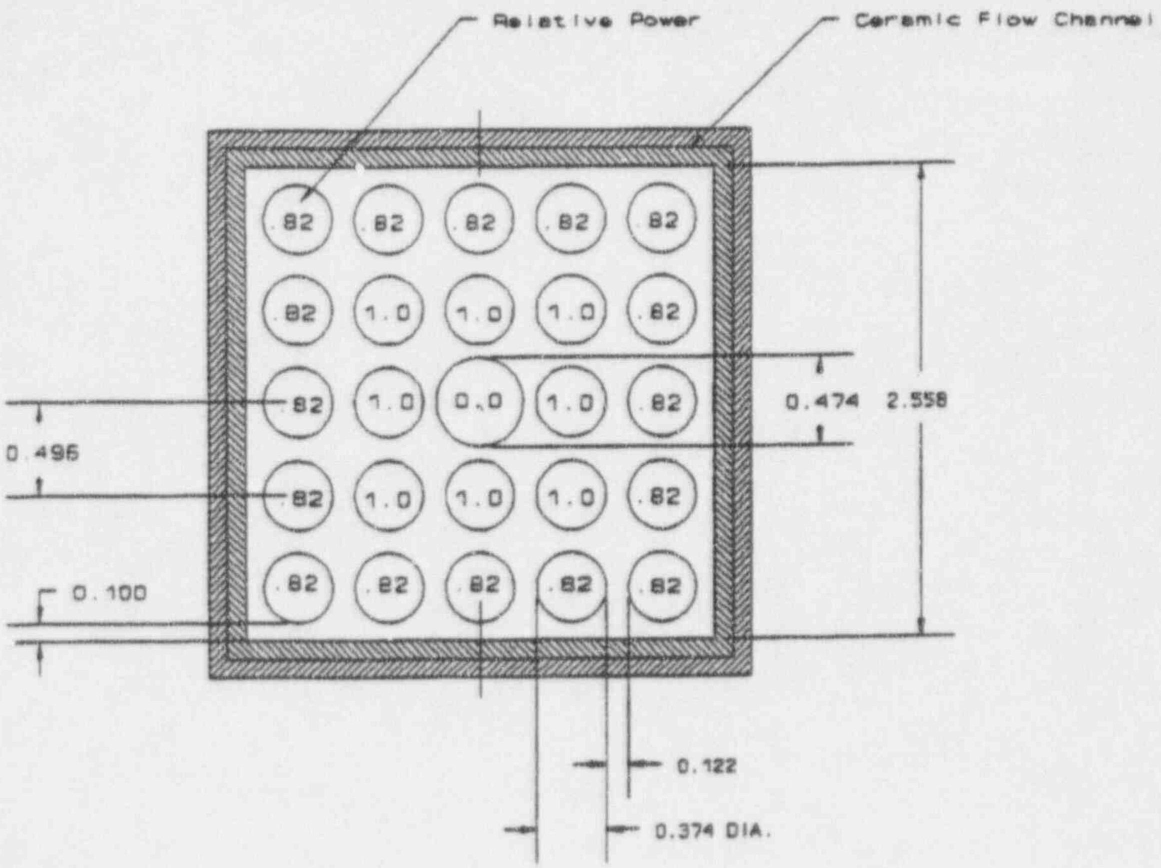

Figure 3-2 Thimble Cell Cross Section

(b,c)

Figure 3-3 Axial Geometry

(b,c)

Figure 3-4 Axial Power Profile for Westinghouse CHF Test

4.0 TEST PROCEDURE

The test procedure consisted of a cold-flow test, a heat balance test, and a CHF test.

The cold-flow test consisted of a series of pressure drop measurements on the rod bundle after the test section was installed in the test loop and before the power was connected. Differential pressure drops were taken at nominal conditions of 1000 psi., 80°F, and at several flow rates. Pressure drop data established a basis for comparison of hydraulic integrity of the test section.

The heat balance test included two heat balance checks, confirming that the test loop and test section instrumentation were in proper working order. The test was performed when the test loop reached equilibrium after initial heat up. Nominal conditions of 1500 psi, 400°F, $1.5x10^6$ lbm/hr-ft^2 mass flux and $1.2x10^6$ watt total power to the test section were set for heat loss calculation. Acceptance criterion for heat loss is less than 3 percent of the total heat input to the test section.

The CHF test was performed by maintaining constant test section outlet pressure, inlet temperature, and mass flux. Total power to the test section was then increased in small increments (less than 30 kW per step) until a temperature excursion occurred in one or more of the thermocouples positioned in the heater rods. The excursion was about 30°F, varying with system conditions. When the temperature excursion occurred, power to the test section was then reduced and preparation for the next test condition began.

5.0 TEST PARAMETERS

The range of system conditions for low-flow testing are:

Inlet Temperature (°F)	300 - 536
Inlet Mass Flux (10^6 lbm/hr-ft.^{2})	0.5 - 1.0
Exit Pressure (psia)	1500 - 2400

The system conditions bound the low-flow conditions encountered in the AP600 loss-of-flow and locked rotor accident analyses. The local mass fluxes in the hot channel at the DNB-limiting time increments are about 0.6×10^6 to 0.7×10^6 lbm/hr.-ft.^{2}. As a result, the range of inlet mass flow for the testing was 0.5×10^6 to 1.0×10^6 lbm/hr-ft.^{2}.

6.0 DATA SUMMARY

The low-flow CHF data are presented in Tables 6-1 and 6-2. These tables give inlet pressure, inlet mass flux, inlet temperature, and average bundle heat flux. They also identify the thermocouples that indicated a CHF event. Average heat flux includes a small adjustment to account for power losses in electrodes at the ends of each rod. The adjustment includes the changes in rod and electrode electrical resistivity as a function of temperature.

Rod numbering begins from one of the corner rods and continues around the 5 x 5 rectangular array in a concentric spiral, ending with the center rod. The numbering scheme used for the CHF rods is XX.Y, where XX is the rod number and Y is the thermocouple number. For example, CHF rod 24.2 indicates that CHF was observed in the second thermocouple of the 24^{th} rod.

TABLE 6-1
AP600 CHF TEST RESULTS
5x5 TYPICAL CELL

(b,c)

Run	Inlet Pressure (psia)	Inlet Mass Flux ($lbm/hr\text{-}ft.^2$) 10^6	Inlet Temperature (°F)	Average Heat Flux ($Btu/hr\text{-}ft.^2$) 10^6	Thermocouples Indicating CHF(1)			
6030								
6031								
6032								
6033								
6034								
6035								
6036								
6037								
6038								
6039								
6040								
6041								
6042								
6043								
6044								
6045								
6046								
6047								
6048								
6049								
6050								
6051								
6052								
6053								
6054								
6055								

Run	Inlet Pressure (psia)	Inlet Mass Flux (lbm/hr-ft.^{2}) 10^6	Inlet Temperature (°F)	Average Heat Flux (Btu/hr-ft.^{2}) 10^6	Thermocouples Indicating CHF[1]			
6056								
6057								
6058								
6059								
6060								
6061								
6062								
6063								
7021								
7022								
7023								
8016								
8017								
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8026								
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8036								
8037								
8038								
8039								
8040								
8041								
8042								

(b,c)

TABLE 6-1 (Cont.) AP600 CHF TEST RESULTS 5x5 TYPICAL CELL

Note:
(1) Thermocouple identification example: 24.2 = rod #24, axial position #2.

TABLE 6-2
AP600 CHF TEST RESULTS
5x5 THIMBLE CELL

Run	Inlet Pressure (psia)	Inlet Mass Flux (lbm/hr-ft.^{2}) 10^6	Inlet Temperature (F)	Average Heat Flux (Btu/hr-ft.^{2}) 10^6	Thermocouples Indicating CHF(1)			
2022								
2023								
2024								
2025								
2026								
2027								
2028								
2029								
2030								
2031								
2032								
2033								
2034								
2035								
2036								
2037								
2038								
2039								
2040								
2041								
2042								
2043								
2044								
2045								
2046								
2047								
2048								
2049								
2050								

(b,c)

TABLE 6.2 (Cont.)
AP600 CHF TEST RESULTS
5x5 THIMBLE CELL

Run	Inlet Pressure (psia)	Inlet Mass Flux (lbm/hr-ft.^{2}) 10^6	Inlet Temperature (F)	Average Heat Flux (Btu/hr-ft.^{2}) 10^6	Thermocouples Indicating CHF(1)			
2051								
2052								
2053								
2054								
2055								
2056								
2057								
2062								
2063								
2064								
2065								
2066								
2067								
2068								
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2072								
2073								
2074								
2075								
2076								
2077								
2078								
2079								
2080								
2081								
2082								
2083								

(b,c)

Note:
(1) Thermocouple identification example: 24.2 = rod # 24, axial position #2.

7.0 DATA ANALYSIS

The WRB-2 correlation is the primary DNB correlation used for the analysis of AP600 fuel. The original data range of the local mass flux for the WRB-2 correlation is between 0.9 and 3.7 x 10^6 lbm/hr-ft.^{2} (Reference 1). In the postulated loss-of-flow and locked rotor accidents, local mass fluxes in the hot channels at the DNB-limiting time steps are less than 0.9 x 10^6 lbm/hr-ft.^{2}. The CHF data described in Section 6.0 were used to evaluate the WRB-2 correlation for the loss-of-flow and locked rotor applications.

The WESTAR code (Reference 3) was used to calculate local fluid conditions in subchannels for each data point in Tables 6-1 and 6-2. WESTAR is a subchannel analysis code that calculates three-dimensional flow and enthalpy distributions in rod bundle geometries. The WRB-2 correlation predicts CHF based on local fluid conditions from WESTAR. WESTAR has been accepted by the U.S. Nuclear Regulatory Commission (NRC) for licensing reactor core thermal-hydraulic calculations, including the use of the currently licensed WRB-2 DNBR limit of 1.17 (Reference 4).

The WESTAR test section modeling is consistent with the WESTAR model for the AP600 reactor core. A higher turbulent mixing coefficient is used for data analysis but for AP600 safety analysis, the turbulent mixing coefficient is set at a lower value. Table 7.1 summarizes the WESTAR modeling of test sections.

Comparison of the predicted CHF with the measured CHF showed that the WRB-2 correlation tends to overpredict CHF at low-flow conditions. The magnitude of overprediction depends greatly on local mass flux and slightly on local pressure. Figures 7-1 and 7-2 show the ratio of measured to predicted CHF (M/P) plotted against local mass flux and local pressure, respectively. An adjustment to the WRB-2 correlation is necessary to correct the CHF overprediction.

TABLE 7.1 SUMMARY OF WESTAR MODELING	
Radial geometry	1/4th test section
Axial modal length, inch	4.2
Mixing coefficient	PA3 = 2.05*
Mixing vane grid K	
K-thimble	0.92
K-typical	0.84
K-side	0.82
K-corner	0.84
IFM grid K	
K-thimble	0.75
K-typical	0.60
K-side	0.56
K-corner	0.55

Note:

* The mixing coefficient used for safety analyses is PA3 = 1.32 (PA3 = 2.05 is equivalent to thermal diffusion coefficient (TDC) = 0.59 and PA3 = 1.32 is equivalent to TDC = .038 used in THINC code)

(a,c)

Figure 7-1 WRB-2 Measured-to-Predicted vs. Local Mass Flux

(a,c)

Figure 7-2 WRB-2 Measured-to-Predicted vs. Local Pressure

8.0 ADJUSTMENT TO WRB-2 CORRELATION

To correct the CHF over-prediction, a multiplier is applied to the WRB-2 predicted CHF as follows:

[ ]$^{(a,c)}$

where:

$q''_{DNB,\ adjusted}$ = adjusted WRB-2 predicted CHF

[ ]$^{(a,c)}$

gloc = local mass flux, 10^6 lbm/hr-ft.^{2}

[ ]$^{(a,c)}$

ploc = local pressure, psia*10^3

[ ]$^{(a,c)}$

$q''_{DNB,WRB-2}$ = original WRB-2 predicted CHF

The adjusted WRB-2 M/P's are plotted in Figures 8-1 and 8-2 against local mass flux and local pressure, respectively. The adjusted WRB-2 predictions are conservative compared to the low-flow data. The statistics of the adjusted M/P's for CHF data in Tables 6-1 and 6-2 are listed below:

Table #	# of Data	M/P Mean*	M/P Std Dev.*
6-1	58	[	]$^{(a,c)}$
6-2	58	[	]$^{(a,c)}$
6-1 & 6-2	116	[	]$^{(a,c)}$

* Adjusted WRB-2

The data range for the adjusted WRB-2 correlation is summarized below:

$$1503 \le \text{Pressure} \le 2430 \text{ psia}$$
$$0.48 \le \text{Local Mass Flow} \le 1.04\ 10^6 \text{ lbm/hr-ft.}^2$$
$$0.0 \le \text{Local Quality} \le 0.81$$

In AP600 safety analyses, if local mass flux in the hot channel is between 0.48 x 10^6 and 1.04 x 10^6 lbm/hr-ft.^{2}, the adjusted WRB-2 correlation is used for DNB Ratio (DNBR) calculations. The WRB-2 correlation is used when the local mass flux is between 1.0 x 10^6 and 3.7 x 10^6 lbm/hr-ft.^{2}.

Consistent with design acceptance criterion in the U.S. NRC Standard Review Plan NUREG-0800 (Reference 5), the DNB design criterion is that there is no DNB occurrence with a 95 percent probability at a 95 percent confidence level (95/95) on the most limiting fuel rod during normal operation, anticipated operational transients, and any transient conditions arising from faults of moderate frequency (condition I and II events). The loss-of-flow accident with all coolant pumps tripped is a condition III event, but it is analyzed as a condition II event. The locked rotor accident is a condition IV event. In the locked rotor analysis, fuel rods having DNBRs below a DNBR limit are assumed to fail for radiological assessment.

To meet the 95/95 design criterion, a limiting value of DNBR based on the correlation statistics can be determined by the Owen's method (Reference 6). Owen prepared tables which give values of k_p such that at least a proportion of p of the population is greater than $(M/P)_{AVG}$ - k_p*s with confidence υ, where $(M/P)_{AVG}$ is the sample mean and s is standard deviation. Owen's factor k_p accounts for uncertainties in the size of data sample.

The 95/95 DNBR limit for the adjusted WRB-2 correlation at the low-flow conditions is calculated based on the M/P statistics of DNB data in Table 6-2 only. As compared to the statistics based on Tables 6-1 and 6-2 or combined Tables 6-1 and 6-2, the M/P statistics based on Table 6-2 yields the highest DNBR limit. The DNBR limit to be applied to the AP600 loss-of-flow and locked rotor analyses is [ ]$^{(a,c)}$ with k_p = 2.03 for the 58 data points in Table 6-2:

95/95 DNBR Limit = [ ]$^{(a,c)}$

= [ ]$^{(a,c)}$

(a,c)

Figure 8-1 Adjusted WRB-2 Measured-to-Predicted vs. Local Mass Flux

(a,c)

Figure 8-2 Adjusted WRB-2 Measured-to-Predicted vs. Local Pressure

9.0 CONCLUSION

To assess the CHF performance of the AP600 fuel design at the low-flow conditions, DNB tests were conducted at the Columbia University Heat Transfer Research Facility using the test configurations reflecting the AP600 fuel design. The test conditions bounded the low-flow conditions encountered in the AP600 loss-of-flow and locked rotor accident analyses. The DNB test data were analyzed using the WESTAR code and the WRB-2 correlation. Based on the comparison with the test results, an adjustment was made to the WRB-2 correlation. The 95/95 DNBR limit with the adjusted WRB-2 correlation is [ ]$^{(a,c)}$ for the AP600 loss-of-flow and locked rotor applications.

10.0 REFERENCES

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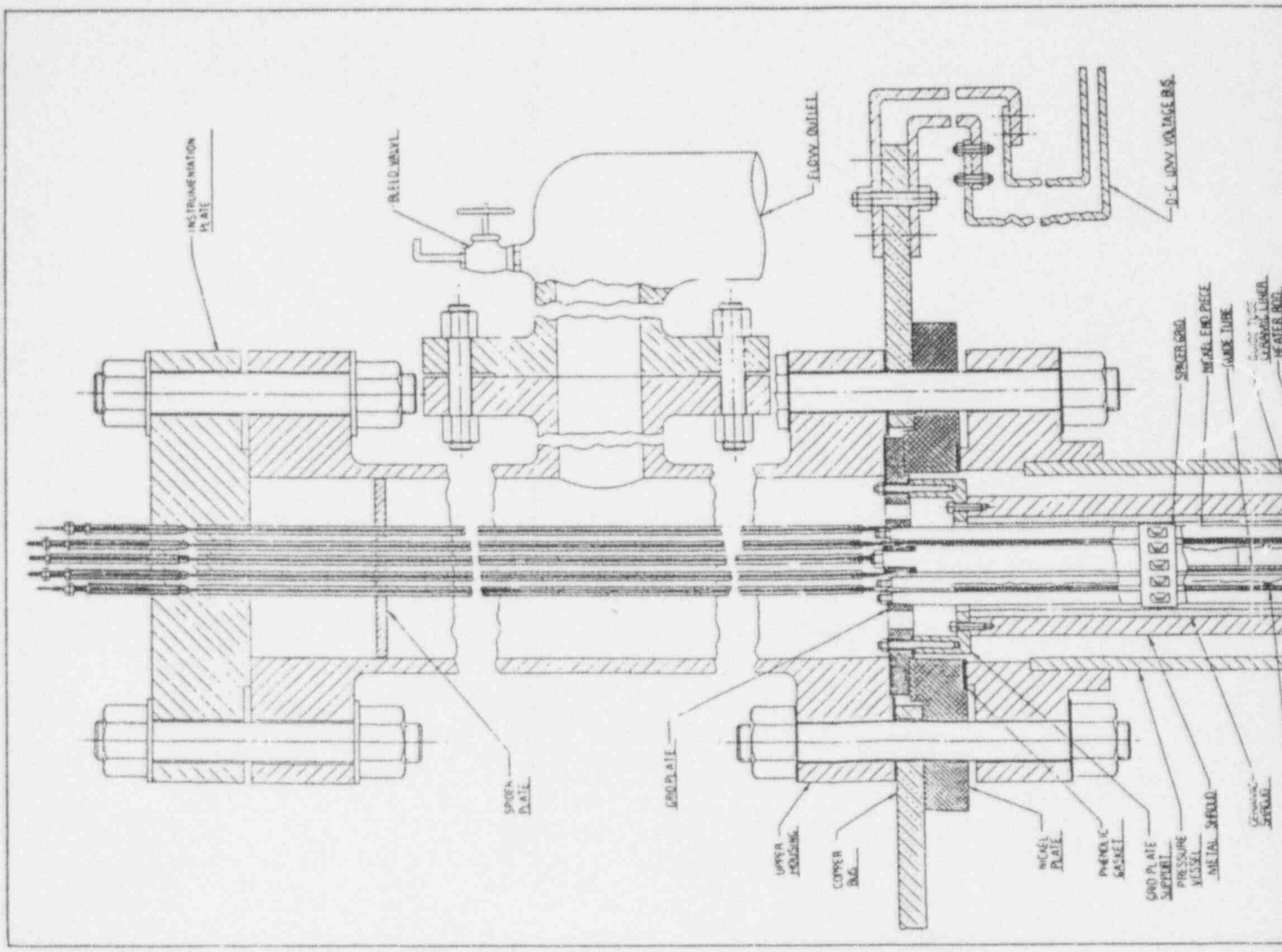
INSTRUMENTATION PLATE
BLEED VALVE
FLOW OUTLET
D-C LOW VOLTAGE BUS
SPACER GRID
NICKEL END PIECE
GUIDE TUBE
HEATER ROD
SPOOL PLATE
GRID PLATE
UPPER HOUSING
COPPER BUS
NICKEL PLATE
PHENOLIC GASKET
GRID PLATE SUPPORT
PRESSURE VESSEL
METAL SHROUD
CERAMIC SPACER

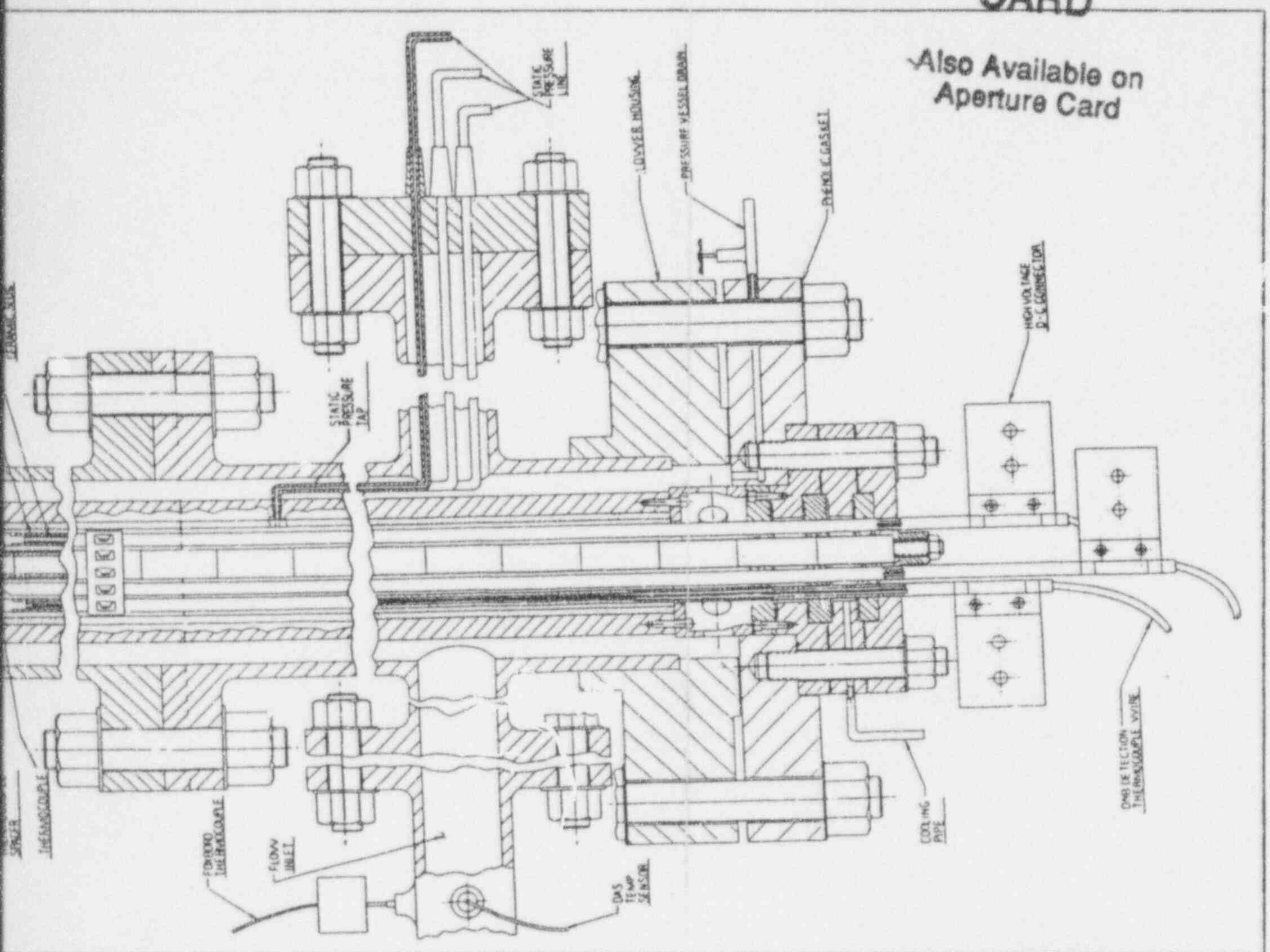

Figure 2-1
Elevation View of the Pressure Vessel and Test Section