NUS CORPORATION

NUS-TM-EC-9

SAFETY LIMIT ANALYSIS FOR THE MURR FACILITY

By

F. R. Vaughan

Prepared for

University of Missouri

May 1973

NUS CORPORATION
4 Research Place
Rockville, Maryland 20850

NUS-TM-EC-9

SAFETY LIMIT ANALYSIS FOR THE MURR FACILITY

By

F. R. Vaughan

Prepared for

University of Missouri

May 1973

NUS CORPORATION
4 Research Place
Rockville, Maryland 20850

Approved by:

D. G. Fitzgerald, Ph.D.
Project Manager

J. N. Sorensen
Manager, Reactor Engineering

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The University of Missouri authorized the NUS Corporation to develop safety limit curves for MURR operation. These curves establish the maximum allowable power limits for safe operation under different combinations of measurable reactor operating variables. The measurable operating variables or process variables used in this study include reactor power, pressurizer pressure, and coolant temperature and flow rate. The safety limits presented herein provide the basis for determining the limiting safety system set points and operating limits required in submission of a Safety Analysis Report pursuant to a license for proposed MURR operation at 10 MW.

For any combination of the process variables, safe reactor operation is achieved by limiting the reactor power to a level which avoids either (1) subcooled boiling burnout (or departure from nucleate boiling) or (2) flow instabilities which can lead to premature burnout. Operation above this power limit can cause unpredictably high fuel and clad temperatures and consequential permanent fuel damage and fission product release to reactor coolant. This condition must be avoided for every core region and for every reactor operating condition.

All data used in the determination of the MURR safety limits were obtained from the MURR Hazards Summary Reports (1, 2, 3)*, the MURR Design Data report (4), and the revised MURR hydraulic analysis (5).

---

* Numbers in parenthesis refer to References in Section 5.0.

2.0 CONCLUSIONS AND RESULTS

The results of the MURR safety limit analysis are summarized in Table 2.1 and are plotted on Figures 2.1 and 2.2. The data presented are reactor thermal power limits for a range of measurable coolant conditions at the core inlet and at two pressurizer operating pressures. The criterion used to establish the safety limit on reactor power depends on the combination of the independent process variables. This can be seen by referring to Table 2.1. The underscored table entries are the power limits as established by the criterion of avoiding any bulk boiling of the coolant, whereas the remaining entries reflect the thermal limits established by the subcooled burnout criterion. The safety limit criterion on incipient bulk boiling of the coolant is associated with experimentally observed premature burnout caused by hydraulic instabilities. In the present study, the power limits for coolant flow rates greater than 2800 pgm are always dictated by the burnout criterion, while for flow rates less than 800 gpm the incipient bulk boiling criterion dictates the safe power level.

Table 2.2 presents a summary of hot channel factors used in the analysis. The limiting channel (or hot channel) used as the basis for the safety limit analysis has a power level 2.72 times the average and a flow rate of 0.81 times the average. The safety limits given in Table 2.1 and Figures 2.1 and 2.2 implicitly depend on these power and flow-related factors. Any future changes in these factors will require a corresponding change to power limit results of this study. Changes to power-related factors can be treated in a straight forward manner; namely, by maintaining the product of the limiting power and the affected power factor equal for both the new and referenced condition. Corresponding changes to flow-related factors are more difficult to accommodate, because of the non-linear dependence of the limiting power

TABLE 2.1

SAFETY LIMITS FOR M U R R OPERATION

MAXIMUM ALLOWABLE CORE POWER LEVEL,MW WITH PRESSURIZER AT 60 PSIA

TEMPERATURE DEG F	INLET WATER CONDITIONS FLOW RATE,GPM 400.	800.	1200.	1600.	2000.	2400.	2800.	3200.	3600.	4000.
	200	450	700	950	1200	1450	1700	1950	2200	2450
120.	3.011	5.870	7.980	9.843	11.574	13.099	14.426	15.450	16.217	16.654
140.	2.650	5.262	7.299	9.035	10.582	11.960	13.155	14.071	14.729	15.075
160.	2.292	4.546	6.675	8.202	9.600	10.822	11.877	12.669	13.228	13.501
180.	1.935	3.834	5.667	7.409	8.612	9.685	10.603	11.267	11.715	11.906
200.	1.583	3.131	4.615	6.009	7.282	8.400	9.301	9.863	10.204	10.267

MAXIMUM ALLOWABLE CORE POWER LEVEL,MW WITH PRESSURIZER AT 75 PSIA

TEMPERATURE DEG F	INLET WATER CONDITIONS FLOW RATE,GPM 400.	800.	1200.	1600.	2000.	2400.	2800.	3200.	3600.	4000.
120.	3.278	6.334	8.647	10.742	12.668	14.435	16.050	17.394	18.532	19.438
140.	2.916	5.798	7.939	9.906	11.667	13.282	14.746	15.967	16.993	17.787
160.	2.556	5.080	7.317	9.067	10.676	12.138	13.458	14.534	15.437	16.139
180.	2.197	4.363	6.474	8.236	9.680	10.988	12.152	13.104	13.892	14.467
200.	1.843	3.656	5.415	7.099	8.686	9.845	10.868	11.689	12.339	12.810

NOTE...UNDERLINED POWER LEVELS ARE LIMITED BY BULK BOILING

FIGURE 2.1

MURR SAFETY LIMIT CURVES FOR PRESSURIZER AT 60 PSIA

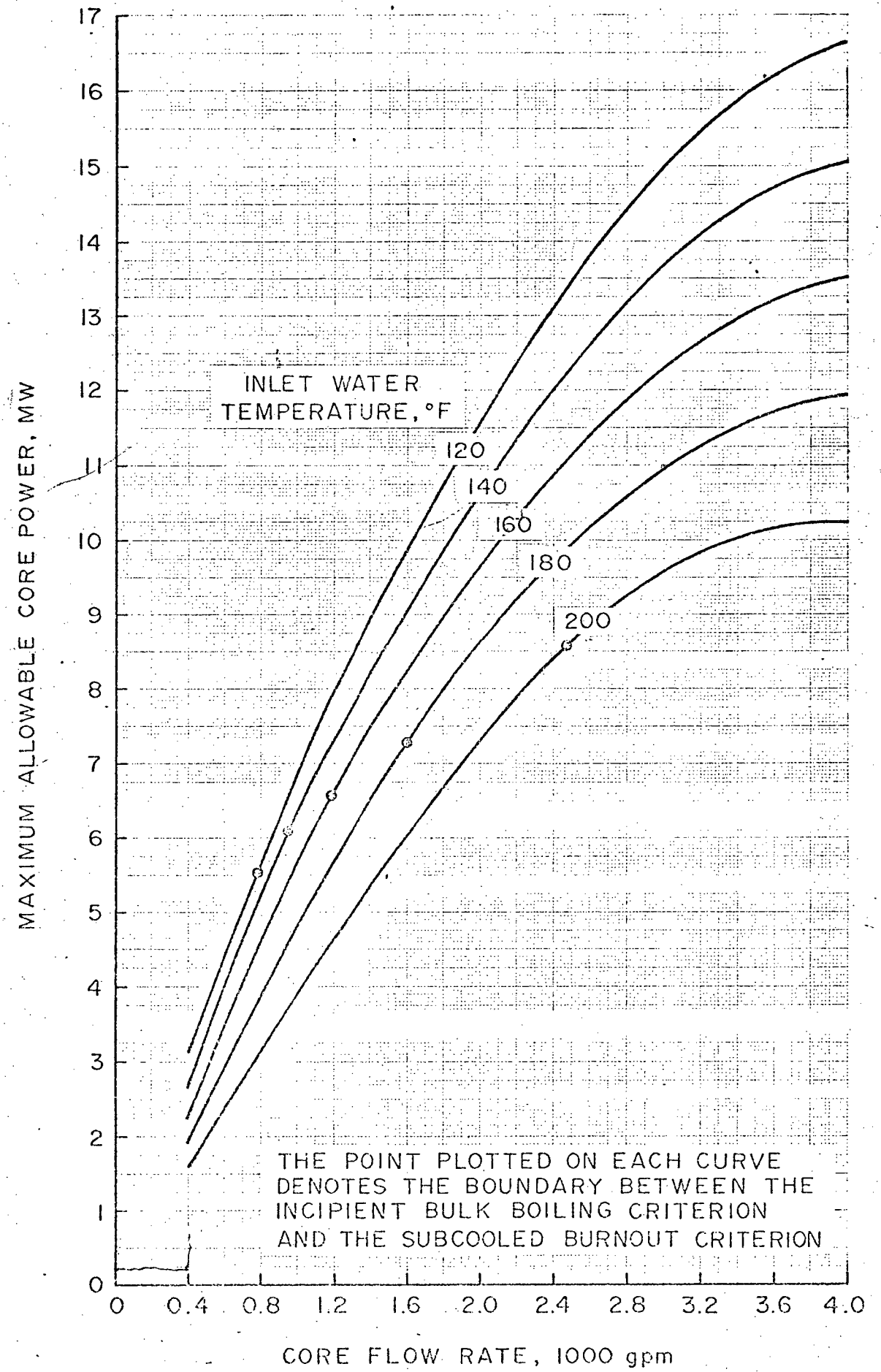

FIGURE 2.2
MURR SAFETY LIMIT CURVES
FOR PRESSURIZER AT 75 PSIA

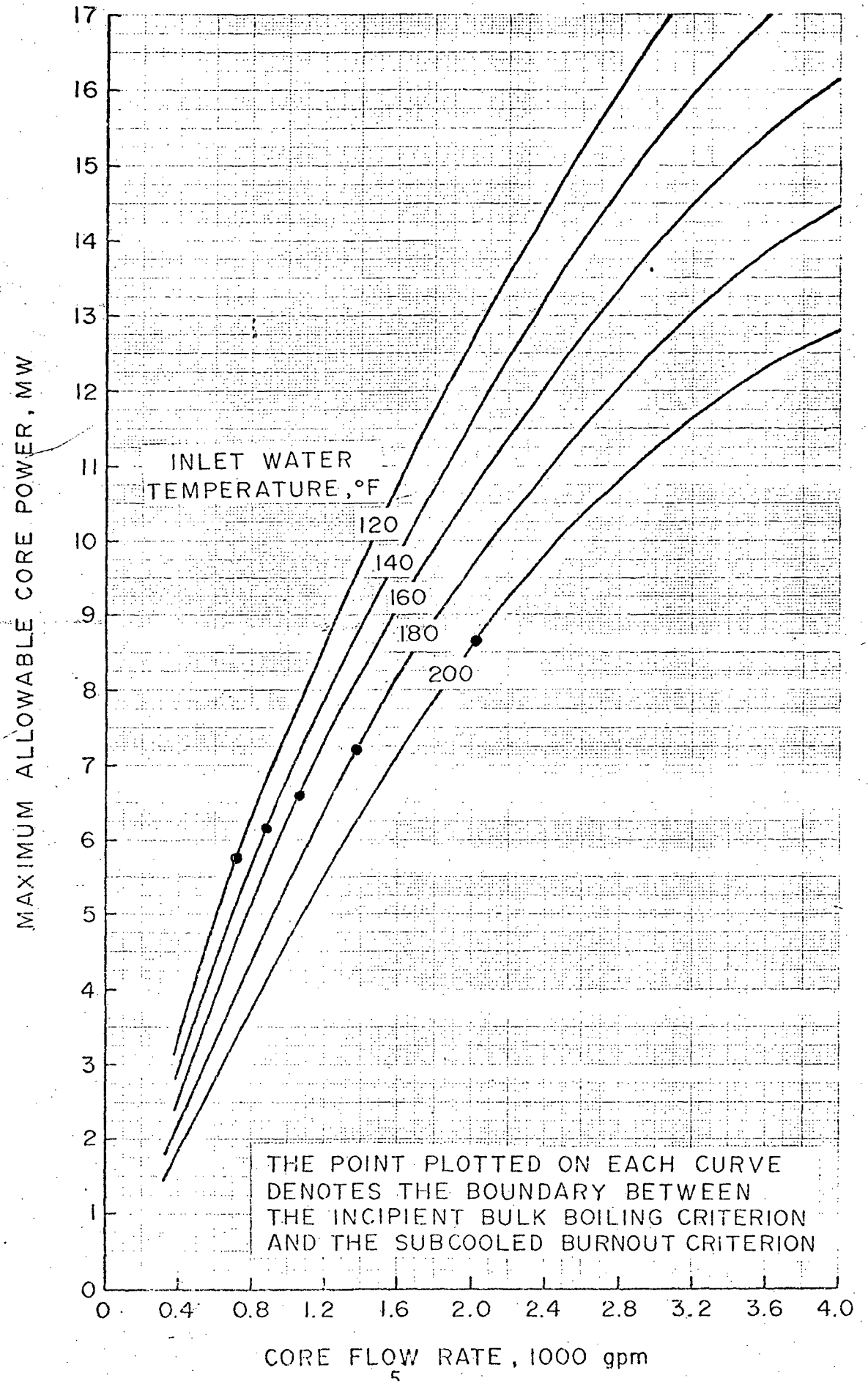

TABLE 2.2

SUMMARY OF M U R R HOT CHANNEL FACTORS

ON ENTHALPY RISE.....

POWER-RELATED FACTORS
NUCLEAR PEAKING FACTORS
RADIAL.....2.220
LOCAL(CIRCUMFERENTIAL).....1.040
NON-UNIFORM BURNUP.....1.112
AXIAL.....1.000
ENGINEERING HOT CHANNEL FACTORS ON ENTHALPY RISE
FUEL CONTENT VARIATION.....1.030
FUEL THICKNESS/WIDTH VARIATION.....1.030
OVERALL PRODUCT.....2.72

FLOW-RELATED FACTORS
CORE/LOOP FLOW FRACTION.....1.000
ASSEMBLY MINIMUM/AVERAGE FLOW FRACTION.....1.000
CHANNEL MINIMUM/AVERAGE FLOW FRACTION
INLET VARIATION.....1.000
WIDTH VARIATION.....1.000
THICKNESS VARIATION.....1./1.080 — 0.6
WITHIN CHANNEL MINIMUM/AVERAGE FLOW FRACTION
THICKNESS VARIATION.....1./1.050
EFFECTIVE FLOW AREA.....0.3231/0.3505
OVERALL PRODUCT.....0.81

ON HEAT FLUX.....

POWER-RELATED FACTORS
NUCLEAR PEAKING FACTORS
RADIAL.....2.220
LOCAL(CIRCUMFERENTIAL).....1.040
NON-UNIFORM BURNUP.....1.112
AXIAL.....1.432
ENGINEERING HOT CHANNEL FACTORS ON FLUX
FUEL CONTENT VARIATION.....1.030
FUEL THICKNESS/WIDTH VARIATION.....1.150
OVERALL PRODUCT.....4.35

ENERGY FRACTION GENERATED IN FUEL PLATE.....0.930

2.22 X 1.432 = 3.179

on the core flow rate. The effect of this non-linearity is to introduce a proportionately greater change in the limiting power level than the change in the flow-related factor. For small changes in flow (not to exceed 5%), it is possible to estimate the new limiting power from the slope of the power-flow curve (Figure 2.1 or 2.2) for the desired operating conditions. Larger changes in the flow-related factors will require a re-evaluation of the safety limits.

The safety limits presented in Table 2.1 or Figures 2.1 or 2.2 do not include any power adjustments which might account for

- power measurement errors
- flow measurement errors
- required overpower margins.

Such adjustments must be included before specifying actual core operating limits. As an example, take pressurizer pressure and core inlet temperature at the parametric values of 75 psia and 140°F, respectively. With an assumed flow measurement error of 5% and a nominal flow of 3600 gpm, actual flow is about 3400 gpm. At these conditions the maximum, i.e., safety limit power level, is (from Figure 2.2) 16.4 megawatts. The corresponding measured power level, assuming a 5% power measurement error, would be about 15.6 megawatts. With a limiting safety system setting (overpower scram) at 125% of nominal full power the resulting safety margin is 3.1 megawatts. The ratio of safety limit power level to scram setting power level is 15.6/12.5 = 1.25.

3.0 METHOD OF ANALYSIS

The method for evaluating the core power limits for Table 2.1 are discussed below. The details for selecting the safety limit criteria, and for using the BOLERO (6) computer program are included.

3.1 Safety Limit Criteria

The study objective was to determine core power limits for safe operation at specified combinations of possible core operating conditions. Safe operation here is defined to mean avoiding burnout (or DNB) where excessive fuel or clad temperatures could cause clad failure and thereby release fission products into the primary coolant. To avoid DNB, the heat flux at each local section in the core is maintained at a value less than the locally-evaluated DNB heat flux. It is also necessary to avoid any core operating conditions (such as hydraulic instability) that could prematurely reduce the DNB heat flux. The following discussion presents the basis for specifying criteria to include both possibilities.

The MURR fuel geometry (near rectangular channels in a closed matrix) and the MURR operating conditions (subcooled water near atmospheric pressure) are outside the normal range of interest for today's commercial reactors. Consequently, only a limited amount of experience is available for establishing safety limit criteria. Fortunately, however, the MURR fuel assembly geometry is similar to the Advanced Test Reactor (ATR) fuel element so that ATR experience (8,9) can be applied to MURR. Since the MURR fuel channel length (~24") is about one-half that of ATR, the use of ATR test results can, in fact, provide conservatism for MURR because investigators (10) have shown higher or equal burnout heat flux levels for shorter channel lengths. Similarly, the shorter channel lengths are less susceptible to the hydraulic instabilities related to incipient bulk boiling.

Other test reactors (HFIR, ETR) have design and operating conditions that depart further from the MURR conditions, and their test results were not directly useful in developing the MURR safety criteria.

Preliminary ATR testing (8) indicated that both subcooled boiling burnout and bulk boiling burnout can occur for the range of channel thicknesses then under design consideration. Tests were performed at Argonne in 1963 on three channel thicknesses (0.054", 0.072", 0.094"), and it was found that for the two thinnest channels (0.054", 0.072") the burnouts were due to hydraulic instability (or autocatalytic vapor binding) when the coolant reached saturation at the channel exit. Presumably, the hydraulic instabilities led to subnormal flow conditions and a lower burnout heat flux. Subcooled burnout occurred for the 0.094 inch channel before the coolant reached saturation conditions at channel exit. The subcooled burnout heat flux data obtained in these tests were 0.6 of the burnout heat flux predicted by the Bernath correlation (7):

$$\Phi_{DNB} = h_{bo} (T_{bo} - T_{sat} + \Delta T_{sub})$$

where:

$$h_{bo} = 10890. \left(\frac{D_e}{D_e + D_i}\right) + \frac{48}{D_e^{0.6}} \cdot V$$

$$T_{bo} = 1.8 \left[57 \ln P - 54 \left(\frac{P}{P+15}\right) - \frac{V}{4}\right] + 32.$$

T_{sat} = saturation temperature at P, ^{o}F

ΔT_{sub} = bulk water temperature, degrees subcooling, ^{o}F

D_e = wetted hydraulic diameter, ft

D_i = heated hydraulic diameter, ft

V = coolant velocity, fps

P = system pressure, psia

Subsequent full-scale ATR testing (9) at Battelle Northwest with a channel thickness of 0.070" confirmed the earlier test results; namely, that burnout induced by hydraulic instability was the limiting factor for ATR. In addition, it was established that the hydraulic instability condition did not correspond to initiation of local boiling, but to the beginning of bulk boiling at the channel exit in the region where the coolant enthalpy was highest. Test results also indicated that lateral mixing (in the channel) was quite small.

In view of the ATR experience, and in absence of burnout test results for MURR fuel and at MURR operating conditions, the following safety limit criteria were adopted for this study:

- The coolant exit temperature from the hot channel shall be less than the saturation temperature at the core exit pressure

- The local heat flux at any point in the core shall be less than 0.5 of the burnout heat flux as given by the Bernath correlation at that point.

The bulk boiling limitation is adopted to exclude occurrence of the in-core hydraulic instabilities related to incipient bulk boiling. The above burnout heat flux limitation is adopted to provide some additional design safety margin by a reduction of the correlated ATR test data by the factor 0.5/0.6 relative to the original Bernath correlation. The above criteria are sufficient to preclude the possibility of fuel failure and attendent fission product release due to excessive temperatures.

3.2 Calculational Method

The BOLERO program was used to perform the calculations which determine local conditions of enthalpy, heat flux, and DNB heat flux for the core hot channel. Since the Bernath burnout heat flux depends on absolute pressure, it was necessary to calculate the absolute pressure at the core exit for each set of inlet water conditions and core power. Since most BOLERO input is dependent on absolute pressure and on either flow rate or power, a special computer program MURRPGM, was written to generate consistent input for all the cases needed for the study. A description of the MURRPGM program, the basis for BOLERO input, and the treatment of BOLERO results are presented below.

3.2.1 MURRPGM Program

The MURRPGM program was developed to calculate the absolute pressure (psia) at the core outlet for every combination of operating conditions in this study. Since the core outlet pressure calculation required the same data as BOLERO, the program was expanded further to generate input cards for the BOLERO program. Appendix A contains a listing of MURRPGM.

The pressure drop from the pressurizer to the core outlet was calculated by correcting individual Δp components as given in reference (5) to new flow, temperature, and core power conditions (see Table 3.1). The new Δp components were then totaled and the result was subtracted from the desired pressurizer operating pressure (60 psia or 75 psia) to obtain the absolute pressure at the core outlet.

The method for correcting the reference Δp components depended on the type of pressure drop involved. For non-frictional components, pressure

TABLE 3.1

REFERENCE PRESSURE DROP DATA*

COMPONENT**	ΔP_o (PSI)	Q_o (GPM)	T_o (F)	FRICTIONAL	IN CORE
1,2,3	3.259	1800	155	YES	NO
4	0.2689	1800	155	NO	NO
5,6,...,10	4.08	3600	155	YES	NO
11	0.1977	3600	155	YES	NO
12	0.8980	3600	155	NO	NO
13	12.35	3600	165	YES	YES

* DATA FROM REFERENCE (5)

** COMPONENT DESCRIPTION USING NOTATION OF REFERENCE (5)

1. ACROSS PRESSURIZER SURGE LINE TO PRESSURIZER OUTLET
2. ACROSS 5 FEET OF 8 INCH PIPE
3. ACROSS 8 INCH Y STRAINER
4. ACROSS 8 INCH/12 INCH EXPANSION
5. ACROSS 80 FEET OF 12 INCH PIPE
6. ACROSS FOUR 12 INCH 90 DEGREE ELBOWS
7. ACROSS THREE 12 INCH 45 DEGREE ELBOWS
8. ACROSS ONE 12 INCH BUTTERFLY VALVE(507B)
9. ACROSS ONE 12 INCH SWING CHECK VALVE(502)
10. ACROSS ENTRANCE TO ANNULAR PRESSURE VESSEL
11. ACROSS 6 FEET OF ANNULAR PRESSURE VESSEL
12. ACROSS ENTRANCE TO FUEL ELEMENT PLATES
13. ACROSS CORE...25.5 INCHES OF FUEL ELEMENT PLATES..TO CORE EXIT

$K_{in} = 0.28$

$K_{exit} = 0.386$

drop is proportional to density and flow,

$$\Delta p = \Delta p_o \left[\frac{\rho\,(T)}{\rho\,(T_o)}\right]^{1.0} \left[\frac{Q}{Q_o}\right]^{2.0}$$

where the subscript o denotes the reference conditions as given in Table 3.1.

For the frictional loss components, the pressure drop was assumed to be given by the Blasius equation and,

$$\Delta p = \Delta p_o \cdot \left[\frac{\rho\,(T)}{\rho\,(T_o)}\right]^{0.8} \left[\frac{Q}{Q_o}\right]^{1.8} \left[\frac{\mu\,(T)}{\mu\,(T_o)}\right]^{0.2}$$

If the core pressure drop component was involved, then the temperature T in the above equation was taken as the average core temperature calculated from the core power and flow. Otherwise the value for T was the core inlet water temperature .

MURRPGM also includes:

- An iterative scheme to determine the core power level that would cause incipient bulk boiling at the hot channel exit.
- Interpolation routines to evaluate intermediate fluid property values from tabulated input values using absolute pressure as the independent variable.
- Simple transformations to generate BOLERO input from non-standard BOLERO flow and power units.

3.2.2 BOLERO Input

The BOLERO program performs all necessary thermal-hydraulic calculations required to establish the minimum ratio of the local burnout heat flux to

the local surface heat flux (DNBR) for a single coolant channel. BOLERO input specifies the single channel dimensions, operating conditions, and the Bernath DNB correlation and its parameters. A more detailed discussion is given in Appendix B.

The single channel analyzed in BOLERO is a representation of the thermally limiting channel (or hot channel). The channel power is 2.72 times average channel power, and the channel flow rate is 0.81 times average channel flow rate. The basis for these data and for the local heat flux multipliers are given in Table 2.2. The normalized axial power distribution used for the channel is given in Figure 1 of TM-WRP-62-10 contained in reference (4). This power distribution occurs at beginning core life when the control rods are partially inserted and represents the most limiting condition during core life due to the high flux level at the channel exit. Channel dimensions are developed from nominal core dimensions such as flow area (0.3505 ft^2), heat transfer surface area (184.28 ft^2) and core length 2.0 ft). The effects of worst-case dimensions are included in the corresponding hot channel factors.

BOLERO input data for the Bernath DNB correlation include a DNB heat flux multiplier (0.5), a heated-to-wetted perimeter ratio (0.924) and a saturation temperature corresponding to the absolute pressure at the core exit (available from the MURRPGM program results) for each core power, pressurizer pressure, and core inlet condition. This approach ensures the correct Bernath DNB heat flux when the minimum DNBR occurs at the channel exit, and produces a conservative result when the minimum DNBR occurs elsewhere in the channel.

3.2.3 BOLERO Output

The maximum core power levels summarized in Table 2.1 were limited by either the bulk boiling or DNB heat flux criterion. Those values limited by

bulk boiling (underscored values in Table 2.1) were immediately evident because BOLERO results indicated that

$$\text{DNBR} = \frac{\Phi\ \text{DNB}}{\Phi\ \text{LOCAL}} > 1.0$$

for the initial core power estimate evaluated by the MURRPGM program at the threshold of bulk boiling. No further iterative procedure was required because any core power increase to reach the DNB flux limit would also violate the bulk boiling criterion.

The core power levels limited by the DNB criterion were the result of an iterative procedure. The procedure included the sequential use of the MURRPGM program to calculate the absolute pressure at core exit and the BOLERO program to calculate the DNBR. The DNB-limited power levels in Table 2.1 were determined by terminating the iteration procedure when the 1.0000 ± 0.01.

$$\hat{\text{DNBR}} = 1.0000 \pm 0.01$$

4.0 DISCUSSION OF RESULTS

Figures 2.1 and 2.2 illustrate the effects of core operating conditions on the maximum allowable core power for safe MURR operation. The trends noted here generally represent the behavior of the two design criterion for various core operating conditions.

The variable most strongly affecting safe core operation is core flow rate. The higher the core flow rate, the higher the maximum allowable core power level. The effect is essentially linear at low core flow rates where the bulk boiling criterion is controlling and becomes non-linear as the flow rate is increased into the DNB controlled regions. The non-linearity in the safety limit is more pronounced for higher inlet water temperatures. Two competitive coolant flow related phenomena are responsible for this observed behavior. An increase in the coolant flow rate results in (1) lower absolute pressures at core exit which, in turn, decreases the water saturation temperature and thereby decreases the Bernath burnout heat flux limit; and (2) higher predictions of the Bernath burnout heat flux limit with increasing coolant velocity.

The allowable core power limit is inversely related to the core inlet water temperatures. This is readily understood in terms of a higher permissible core power level for an increased inlet subcooling; that is, the channel power to achieve incipient bulk boiling or local burnout increases as the inlet subcooling increases (coolant inlet temperature decreases) with all other variables held constant.

The effect of pressurizer pressure is available from a comparison of corresponding curves on Figures 2.1 and 2.2. Clearly, higher pressurizer pressure results

in an increase in the safety limits on core power due to the increase in the coolant saturation temperature and the pronounced absolute pressure dependence of Bernath correlation at low absolute pressure. As already noted, the influence of the coolant flow rate on the channel exit pressure and the dependence of the Bernath correlation on absolute pressure is responsible for the slope change observed in the safety limit curves of Figures 2.1 and 2.2.

5.0 REFERENCES

(1) "MURR Hazards Summary Report", University of Missouri Research Reactor Facility. (1965).

(2) "MURR Hazards Summary Report", Addendum 1, University of Missouri Research Facility, (1966).

(3) "MURR Hazards Summary Report", Addendum 3, University of Missouri Research Reactor Facility, (1972).

(4) "MURR Design Data, Volume I" (copy 86) by Internuclear Company (1962).

(5) "Revised Hydraulic Analysis of the MURR Primary Cooling System - 10 MW Operation", 1973.

(6) Schmidt, E.R., Couchman, M.L., and Edwards, D. R., BOLERO-II, Burnout Limit Evaluation Routine-II, NUS-TM-ENG-119 (Rev. 3, modified).

(7) Bernath, L. "A Theory of Local-Boiling Burnout and Its Application to Existing Data", Chem. Eng. Progm. Symp. Ser., 56, No. 30, 95-116 (1960).

(8) Croft, M.W., "Advanced Test Reactor Burnout Heat Transfer Tests", USAEC Report IDO-24475, Babcock & Wilcox Co., January 1964.

(9) Waters, E.D., "Heat Transfer Experiments for the Advanced Test Reactor," USAEC Report BNWL-216, Battelle-Northwest, May 1966.

(10) Tong, L.S., Boiling Crisis and Critical Heat Flux, USAEC Office of Information Services (1970) page 26.

APPENDIX A

THE MURRPGM PROGRAM LISTING

```
      PROGRAM MURRPGM(INPUT,OUTPUT,TAPE62)
C
C     M U R R SAFETY LIMIT ANALYSIS
C     PROGRAM TO CALCULATE CORE EXIT PRESSURE(PSIA) FOR GIVEN PRESSURE
C        DROP COMPONENTS SPECIFIED AT REFERENCE FLOW/TEMPERATURE VALUES
C        ...B O L E R O INPUT DATA CARDS ARE ALSO GENERATED BASED ON
C           THESE DATA
C        04/73 N U S CORP  F R VAUGHAN
C
      COMMON /PROPT/SPACE(301),HSAT,TSATT
      DIMENSION TITLE(8)
      DIMENSION DP0(50),Q0(50),RHO0(50),XMU0(50),FACTOR(50)
      DIMENSION TSAT(8),DENS(8),XMU(8),CP(8),H(8)
C                TSAT(I)...SATURATION TEMPERATURE,DEG F
      DATA TSAT
     * /  100.,  120.,  140.,  160.,  180.,  200.,  220.,  240./
C                DENS(I)...SATURATED WATER DENSITY,LB/CU FT
      DATA DENS
     * /61.996,61.728,61.387,61.013,60.569,60.132,59.630,59.102/
C                XMU(I)...VISCOSITY OF SATURATED WATER,LB/FT/HR
      DATA XMU
     * / 1.650, 1.353, 1.137, 0.970, 0.839, 0.738, 0.660, 0.595/
C                CP(I)...SPECIFIC HEAT OF SATURATED WATER,BTU/LB/DEG F
      DATA CP
     * /0.9976,0.9977,0.9988,1.0004,1.0022,1.0047,1.0079,1.0119/
C                H(I)...ENTHALPY OF SATURATED WATER,BTU/LB
      DATA H
     * / 67.97, 87.92,107.89,127.89,147.92,167.99,188.13,208.34/
C
      DATA IPUNCH/1/

C
C     ******************************************************************
C     HOT CHANNEL FACTORS AND OTHER DATA
      FDHE = 1.03*1.03
      FRAN = 2.220*1.040*1.112
C
      AR = 0.3231/0.3505
      FWE = 1./1.08/1.05
C
      FQE = 1.03*1.15
      FQR = 0.07
      DF = 0.5
      PR = 0.924
      FACTER = 1.-1.E-05
C     ******************************************************************
C
      HSFQ = (1.-FQR)*FQE/FDHE
C
  302 CONTINUE
C
C     INPUT...CARD 1...TITLE CARD      BLANK CC01-10 CAUSES PROGRAM STOP
      READ  100,TITLE
      IF(TITLE(1).EQ.10H           ) STOP
      PRINT 100,TITLE
```

```
      PRINT 100
C
C     INPUT...CARDS 2 TO J...FLUID PROPERTY LIBRARY DATA(SEE SUBR PROPCI)
      CALL PROPCDI(X,X,X,X,IPUNCH)
C
C     INPUT...CARD J+1...P0...PRESSURIZER PRESSURE,PSIA
      READ  102,P0
C
C
      N = 0
C
C     INPUT...CARDS J+2 TO K...REFERENCE PRESSURE DROP DATA FROM PRESSURIZER
C             DP00...REFERENCE PRESSURE DROP,PSID
C             Q000...REFERENCE FLOW FOR DP00,GPM
C             T...REFERENCE TEMPERATURE FOR Q00,DP00 VALUES,DEG F
C             FR...FRACTION OF CORE FLOW FOR WHICH Q00 APPLIES,FRACTIONAL
C             FACTOR0...TYPE OF DP00 CORRECTION REQUIRED
C                       0.0 FLOW AND DENSITY CORRECTION
C                       1.0 FRICTION FACTOR AND 0.0 CORRECTION
C                       2.0 FRICTION FACTOR AND 0.0 CORRECTION AT AVG CORE TEMPE
  200 READ 102,DP00,Q00,T,FR,FACTOR0
      IF(DP00.EQ.0.0) GO TO 201
C
      N = N+1
      DP0(N) = DP00
      Q0(N) = Q00
      FACTOR(N) = FACTOR0
      RHO0(N) = YVALUE(T,8,TSAT,DENS)
      XMU0(N) = YVALUE(T,8,TSAT,XMU)
      PRINT 102,DP0(N),Q0(N),T,FR,FACTOR(N),RHO0(N),XMU0(N)
      Q0(N) = Q0(N)/FR
      IF(N.LT.50) GO TO 200
C
C
  201 CALL STARTR(X,X,X,X,IPUNCH)
C     INPUT...CARD K+1...CORE OPERATING CONDITIONS
C             X...DUMMY
C             Q1...CORE INLET FLOW RATE,GPM    0.0 VALUE CAUSES EXIT FROM LOOP
C             T1...CORE INLET WATER TEMPERATURE,DEG F
C             P0...CORE POWER,MW
  300 READ 102,X,Q1,T1,P0
      IF(Q1.EQ.0.0) GO TO 301
      PRINT 121,P0,Q1,T1
      RHO1 = YVALUE(T1,8,TSAT,DENS)
      XMU1 = YVALUE(T1,8,TSAT,XMU)
      HIN = YVALUE(T1,8,TSAT,H)
      CHFL = 60.*0.13368*RHO1*Q1
  401 CONTINUE
      CHPO = P0
      DHAC = 3.4127E06*CHPO/CHFL
      T2 = T1 + DHAC/2.
      RHO2 = YVALUE(T2,8,TSAT,DENS)
      XMU2 = YVALUE(T2,8,TSAT,XMU )
      PRINT 102,X,Q1,T1,RHO1,XMU1,T2,RHO2,XMU2
C
```

```
C
      P = P0
      PRINT 102,P
      DO 202 J=1,N
      QR = Q1/Q0(J)
      RHOR = RHO1/RHO0(J)
      IF(FACTOR(J).EQ.2) RHOR = RHO2/RHO0(J)
      XMUR = XMU1/XMU0(J)
      IF(FACTOR(J).EQ.2) XMUR = XMU2/XMU0(J)
      F1 = QR*QR*RHOR
      F2 = (XMUR/RHOR/QR)**0.2
      DP = DP0(J)*F1
      IF(FACTOR(J).GT.0.0) DP = DP*F2
      P = P - DP
      PRINT 102,P,DP
  202 CONTINUE
      PRINT 102,P
C
C
      CALL PROPCD(P,X,X,X,2)
C
      DHMAX = HSAT-HIN
C
      DHHC = DHAC*FDHE*FRAN/AR/FWE
      IF(DHHC.LE.DHMAX) GO TO 400
C
      PRINT 120
      P0 = P0*DHMAX/DHHC
      P0 = P0*FACTER
      GO TO 401
C
  400 CONTINUE
      CALL TITLECD(P0,Q1,T1,P0,IPUNCH)
C
      CHPO = CHPO*FDHE*FRAN
      CHFL = CHFL*AR*FWE
      CALL RCONDCD(CHPO,CHFL,HIN,HSFQ,IPUNCH)
C
      CALL PROPCD(P,X,X,X,IPUNCH)
C
      CALL BNTHCD(DF,PR,TSATT,X,IPUNCH)
C
      CALL ENDCD(X,X,X,X,IPUNCH)
      GO TO 300
C
  301 CALL ENDR(X,X,X,X,IPUNCH)
      GO TO 302
C
  100 FORMAT(8A10)
  102 FORMAT(8F10.4)
  120 FORMAT(1X,90X,20H***WAS BOILING******)
  121 FORMAT(40H1 PRESSURIZER PRESSURE,PSIA.............F6.1/
     *       40H  FLOW RATE,GPM.........................F6.1/
     *       40H  INLET TEMPERATURE,DEG F...............F6.1/
     *      )
      END
```

```
      FUNCTION YVALUE(X,N,XA,YA)
C
C     ROUTINE TO LINEARLY INTERPOLATE BETWEEN N PAIRS OF (XA(I),YA(I))
C        DATA IN A DATA TABLE
C     NOTE......IF X.LT.XA(1),THEN YVALUE = YA(1)
C         ......IF X.GT.XA(N),THEN YVALUE = YA(N)
C     CHECKED OUT 07/11/72  F R VAUGHAN
C
C
C     INPUT   X...ABSCISSA VALUE FOR WHICH YVALUE IS DESIRED
C             N...NUMBER OF PAIRS OF (XA(I),YA(I) DATA IN DATA TABLE
C             XA...ARRAY OF ABSCISSA VALUES IN DATA TABLE
C             YA...ARRAY OF ORDINATE VALUES IN DATA TABLE
C
      DIMENSION XA(N),YA(N)
C
C
      IF(X.GT.XA(1)) GO TO 100
      J = 1
      GO TO 102
C
  100 IF(X.LT.XA(N)) GO TO 101
      J = N
  102 YVALUE = YA(J)
      RETURN
C
  101 DO 200 J=2,N
      IF(X.LT.XA(J)) GO TO 201
  200 CONTINUE
C
C
      ENTRY YYVALUE
  201 JJ = J-1
      YVALUE = YA(JJ) + (YA(J)-YA(JJ))*(X-XA(JJ))/(XA(J)-XA(JJ))
      RETURN
      END
```

```
      SUBROUTINE BOLEROI(X1,X2,X3,X4,IPUNCH)
C     ROUTINE TO GENERATE AND PUNCH INPUT CARDS FOR B O L E R O PROGRAM
C               IPUNCH...CARD PUNCH OPTION,0... TO SKIP,1... TO PUNCH
C
      COMMON /PROPT/ NTAB,TSAT(50),PSAT(50),VF(50),VG(50),HF(50),HFG(50)
     *               ,HSAT,TSATT
C
C
C
      ENTRY TITLECD
C     ROUTINE TO PUNCH .TITLE. CARD FOR BOLERO
C               PO...CORE POWER LEVEL,MW
C               QI...CORE FLOW RATE,GPM
C               TI...CORE INLET WATER TEMPERATURE,DEG F
C               PO...PRESSURIZER PRESSURE,PSIA
C
      PO = X1
      QI = X2
      TI = X3
      PO = X4
      PRINT 201,PO,QI,TI,PO
      IF(IPUNCH.EQ.1) WRITE(62,201) PO,QI,TI,PO
      RETURN
C
      ENTRY RCONDCD
C     ROUTINE TO PUNCH .RCOND. CARD FOR BOLERO
C               CHPO...CORE POWER,MW
C               CHFL...CORE FLOW,LB/HR
C               HIN...CORE INLET ENTHALPY,BTU/LB
C               HSFQ...LOCAL HOT-SPOT FACTOR,DIMENSIONLESS
C
      CHPO = X1
      CHFL = X2
      HIN = X3
      HSFQ = X4
      PRINT 202,CHPO,CHFL,HIN,HSFQ
      IF(IPUNCH.EQ.1) WRITE(62,202) CHPO,CHFL,HIN,HSFQ
      RETURN
C
      ENTRY PROPCDI
C     ROUTINE TO READ IN PROPERTY TABLES FOR .ENTRY. PROPCD
C
      NTAB = 0
C
C     INPUT...CARDS 2 TO J...FLUID PROPERTY LIBRARY DATA
C               TSATO...SATURATION TEMPERATURE AT PSATO,DEG F
C               PSATO...SATURATION PRESSURE AT TSATO,PSIA
C               VFO...SPECIFIC VOLUME OF LIQUID AT PSATO,CU FT/LB
C               VGO...SPECIFIC VOLUME OF VAPOR AT PSATO,CU FT/LB
C               HFO...ENTHALPY OF LIQUID AT PSATO,BTU/LB
C               HFGO...ENTHALPY OF VAPOR AT PSATO,BTU/LB
  100 READ 101,TSATO,PSATO,VFO,VGO,HFO,HFGO
      IF(TSATO.EQ.0.0) RETURN
C
      NTAB = NTAB+1
```

```
      TSAT(NTAB) = TSAT0
      PSAT(NTAB) = PSAT0
      VF(NTAB) = VF0
      VG(NTAB) = VG0
      HF(NTAB) = HF0
      HFG(NTAB) = HFG0
      GO TO 100
C
      ENTRY PROPCD
C     ROUTINE TO GENERATE .PROP. CARD FOR BOLERO PROGRAM
C             PSIA...SYSTEM PRESSURE.PSIA
C             X2...
C             X3...
C             X4...
C
      PSIA = X1
      HSAT = YVALUE(PSIA,NTAB,PSAT,HF)
      HFGG = YVALUE(PSIA,NTAB,PSAT,HFG)
      DENW = 1./YVALUE(PSIA,NTAB,PSAT,VF)
      DENR = DENW*YVALUE(PSIA,NTAB,PSAT,VG)
      TSATT = YVALUE(PSIA,NTAB,PSAT,TSAT)
      IF(IPUNCH.EQ.2) RETURN
C
      PRINT 203,PSIA,HSAT,HFGG,DENR,DENW
      IF(IPUNCH.EQ.1) WRITE(62,203) PSIA,HSAT,HFGG,DENR,DENW
      RETURN
C
      ENTRY BNTHCD
C     ROUTINE TO GENERATE .BNTH. CARD FOR BOLERO
C             DF...DESIGN FACTOR FOR BERNATH CORRELATION
C             PR...HEATED/WETTED PERIMETER RATIO
C             TSATT...SATURATION TEMPERATURE FOR SYSTEM PRESSURE,DEG F
C             X4...
C
      DF = X1
      PR = X2
      TSATT = X3
      PRINT 204,DF,PR,TSATT
      IF(IPUNCH.EQ.1) WRITE(62,204) DF,PR,TSATT
      RETURN
C
      ENTRY ENDCD
C     ROUTINE TO GENERATE .END. CARD FOR BOLERO
C             X1...
C             X2...
C             X3...
C             X4...
C
      PRINT 205
      IF(IPUNCH.EQ.1) WRITE(62,205)
      RETURN
C
      ENTRY STARTR
      IF(IPUNCH.EQ.1) WRITE(62,110)
      RETURN
```

```
C
      ENTRY ENDR
      IF(IPUNCH.EQ.1) WRITE(62,111)
      RETURN
C
  101 FORMAT(6E10.4)
  110 FORMAT(1X,3H[[C)
  111 FORMAT(1X,3H[[L)
  201 FORMAT(1X,32HTITLE       M U R R SAFETY STUDY ,F6.3, 3HMW ,F5.0, 4H
     *GPM ,F4.0, 6HDEG F ,F3.0, 5HPSIA ,2X,
     *    10H  T,Q,    P)
  202 FORMAT(1X,10HRCOND      ,F10.4,F10.1,F10.2,F10.4,20X,
     *    10H  T,Q,    P)
  203 FORMAT(1X,10HPROP       ,F10.1,F10.2,F10.2,F10.2,F10.3,10X,
     *    10H  T,Q,PR  )
  204 FORMAT(1X,10HBNTH       ,F10.4,F10.4,F10.2,30X,
     *    10H  T,Q,PR  )
  205 FORMAT(1X,04HEND )
      END
```

APPENDIX B

BOLERO Program Input Development

The sample BOLERO input data set given in Table B.1 was used in the MURR Safety Analysis. It is typical of all other cases and is the basis for discussing each BOLERO data card and its included data. The data on the DIMEN card and the AXIAL cards were fixed throughout the Safety Analysis, whereas all remaining cards had variable data and were for convenience, generated by the MURRPGM program. Each BOLERO input card and its data are discussed below:

The TITLE card specifies the heading of all BOLERO output for each data set.

The DIMEN card specifies hot channel (or core in this study) dimensions such as flow area (0.3505 ft^2), hydraulic diameter (0.15573 in.), heat transfer surface area (184.28 ft^2) and core length (2.0 ft). Nominal core dimensions are used since the hot channel factors account for extreme dimensions.

The AXIAL cards specify the normalized axial power distribution from core flow inlet to exit. This power shape corresponds to that occuring at beginning of core life when control rods are half-in, and is most limiting during core life because of the high flux level at core exit.

The RCOND card specifies the core operating conditions in terms of hot channel parameters. The related power and flow factors are given in Table 2.2. The hot channel power is 8.9278 MW (3.278 MW x 2.220 x 1.040 x 1.112 x 1.03 x 1.03)*.

---

* Rounding of computer output prevents an exact check of these numbers.

The hot channel flow is 160988.8 lb/hr (400. gpm x 60. x 0.13368 x 61.728/1.08/1.05 x 0.3231/0.3505) where the water density at 120°F is 61.728 lb/cu. ft. The inlet water enthalpy (at 120°F) is 87.92 BTU/lb. The local hot spot factor is required to reduce the hot channel power used in enthalpy calculations to the power required by heat flux values. Its 1.0383 value is calculated from 0.93 x 1.03 x 1.15/1.03/1.03.

The PROP card specifies the water properties for a given system pressure, which is the value calculated at the core (or channel) exit. This approach ensures the correct Bernath DNB heat flux when the DNB limit occurs at the channel exit, and produces a conservatism result when the DNB limit occurs elsewhere. For the example in Table B.1, where core conditions are 3.278 MW, core flow is 400 gpm, core inlet temperature is 120°F, and pressurizer is 75 psia, the calculated core exit pressure is 74.6 psia. The water properties corresponding to this absolute pressure are:

- saturated enthalpy of 277.18 BTU/lb
- latent heat of vaporization of 904.59 BTU/lb
- steam/water density ratio of 333.73
- water density of 57.071 lb/cu ft.

The BNTN card specifies data for the Bernath DNB heat flux correlation. It contains the Bernath DNB heat flux multiplier (0.5), the heated-to-wetted perimeter ratio (0.924), and the saturation temperature corresponding to an absolute pressure of 74.6 psia (307.22°F).

The END card specifies end of input for a data set, and initiates the BOLERO calculations.

TABLE B.1

SAMPLE B O L E R O INPUT DATA SET

```
TITLE       M U R R SAFETY STUDY  3.2784W   400GPM  120DEG F 75 PSIA      T,Q,    P
DIMEN       0.3505     0.15573    184.28     2.0
AXIAL 1 48  0.360      0.340      0.350      0.375      0.400      0.435      0.470
AXIAL 2     0.505      0.540      0.580      0.620      0.660      0.700      0.745
AXIAL 3     0.785      0.830      0.875      0.920      0.965      1.015      1.065
AXIAL 4     1.110      1.155      1.200      1.245      1.285      1.325      1.355
AXIAL 5     1.385      1.405      1.425      1.440      1.450      1.450      1.440
AXIAL 6     1.425      1.405      1.375      1.345      1.305      1.260      1.210
AXIAL 7     1.160      1.105      1.055      1.015      1.010      1.070
RCOND          8.9278  160988.8     87.92     1.0383                          T,Q,    P
PROP             74.6    277.18    904.59     333.73     57.071               T,Q,PR
BNTH            .5000     .9240    307.22                                      T,Q,PR
END
```