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LAPUR 6.0 User's Manual

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ABSTRACT

This report documents a series of programming upgrades to Version 6.0 of the LAPUR code. LAPUR, a computer program in FORTRAN, is a mathematical description of the core of a boiling water reactor. Its two linked modules, LAPURX and LAPURW, respectively solve the steady-state governing equations for the coolant and fuel and the dynamic equations for the coolant, fuel, and neutron field in the frequency domain. The main upgrade in LAPUR 6 is the ability to model part-length fuel rods and fuel spacers explicitly. General implementation descriptions are followed by a detailed description of input and output parameters of LAPURX and LAPURW. Sample inputs are included and stability benchmarks are noted.

CONTENT

1.0 INTRODUCTION

This report contains an updated User Manual for the new code version, LAPUR 6.0.

LAPUR, a computer program in FORTRAN, is a mathematical description of the core of a boiling water reactor (BWR). Its two linked modules, LAPURX and LAPURW, respectively solve the steady-state governing equations for the coolant and fuel and the dynamic equations for the coolant, fuel, and neutron field in the frequency domain. General implementation descriptions are followed by a detailed description of input and output parameters of LAPURX and LAPURW. Sample inputs and outputs are included and stability benchmarks are noted.

The LAPUR code has been validated in the past against a reasonable array of BWR test data. The validation of the LAPUR 6 version is the topic of a separate report. The old validation data include:

1. Peach Bottom tests (see Ref. 3).
2. Vermont Yankee stability tests (see Ref. 3).
3. Dresden local stability test (see Ref. 4).
4. Browns Ferry single-loop stability test (see Refs. 5and 6).
5. Susquehanna-2 stability tests (see Refs.7 and 8).
6. Grand Gulf-1 stability tests (see Refs 7 and 8).

2.0 LAPUR GENERAL DESCRIPTION

This section presents the computer program LAPUR, a version coded in the FORTRAN language of the mathematical description of a BWR. This program consists of two autonomous modules, LAPURX and LAPURW, which are linked by means of an intermediate storing device.

The first module, LAPURX, solves the coolant and the fuel steady-state governing equations as described in Sect. 3.2.1 of Ref. 1. Maps of core steady-state parameters are generated by LAPURX and stored into two data files for subsequent use by the dynamics module LAPURW.

The second module, LAPURW, solves the dynamic equations for the coolant, fuel, and neutron field in the frequency domain according to the formulations developed in Sect. 3 of Ref. 1.

2.1. GENERAL DESCRIPTION OF THE INPUT AND OUTPUT

General input requirements to run a problem are as outlined:

For steady-state calculation (LAPURX), system operating status:

1. State parameters: reactor pressure, thermal power generated, core flow rate, and coolant temperature at the inlet plenum.
2. Power map: Vertical power shape of representative channels and either steam exit quality or amount of power generated in each channel.
3. Fraction of power deposited into the coolant by neutron moderation and γ ray absorption.

For steady-state calculation (LAPURX), system design parameters:

1. Mechanical: channel box and fuel pin dimensions.
2. Physical: hydraulic diameters, friction multipliers, orifice flow coefficients, fuel and clad densities, and gap thermal conductance.

For steady-state calculation (LAPURX), user options:

1. Error criteria for the iterative calculations.
2. Adjustable parameters for two-phase correlations.
3. Number of nodes desired in the boiling part of a channel.
4. Output options.

For dynamic calculation (LAPURW), systems parameters:

1. Recirculation loop pressure to flow rate gain and time constant.

For dynamic calculation (LAPURW), neutronic parameters:

1. Effective neutron lifetime table.
2. Steady-state core reactivity table.
3. Delayed neutron fractions and their time constants.
4. Doppler reactivity coefficient.
5. Table of density reactivity coefficients.

For dynamic calculation (LAPURW), output options:

1. Frequencies of interest for the dynamic analysis.
2. Edit and plotting options.
3. Stability calculation options.

Note that each subcore must be assigned a set of neutronic parameters.

Steady-state calculation LAPURX generates a map of the thermohydraulic parameters in the core, that is, of the following:

1. Channel flow rate, pressure drops, and exit quality (or power) for each channel.
2. Nodal coolant density, void fraction, enthalpy, quality, velocities, and friction components at each node along each channel.
3. Set of coefficients for the dynamics calculation.

The dynamic calculation determines:

1. For the fuel, the response of the heat flux to the coolant and of the average temperature to driving perturbations of power generation, coolant temperature, and coolant flow rate at each node in every channel.
2. For the coolant flow in a channel box:

- The response of the coolant parameters at every node to driving perturbations of power generation at each subcore level, coolant flow rate, and coolant inlet temperature.
- The open-loop transfer function (TF) for the channel hydrodynamics, its natural frequency, and decay ratio.
- The reactivity feedback induced in each node by the driving perturbations. (This is accomplished by properly weighting the coolant density and fuel temperature perturbations with reactivity coefficients.)

3. For each nuclear subcore:

- Feedback reactivity TFs for driving perturbations in power at each subcore, inlet temperature, and core flow rate.
- Open-loop TF matrix; total core natural frequency and decay ratio.
- Closed-loop TF matrix of reactivity to power.

4. Nyquist and magnitude phase plots for all open-loop TFs; Bode plots for closed-loop TFs.

2.2. SUCCINCT DESCRIPTION OF THE PROGRAM

2.2.1. LAPURX, The Steady-State Module

This module follows the procedure described in Sect 3.2.1 of Ref. 1. Table 1 shows a structural description of the LAPURX subroutine calling sequence. Descriptions of the subroutines, input, and output of this program module are presented in Sects. 4.1, 4.2, and 4.3 of this report.

2.2.2. LAPURW, The Dynamics Module

This program is the coded version of the dynamic equations in the frequency domain of Sect. 3 of Ref. 1 and its corresponding appendices.

A structural listing of the subroutine calling sequence is shown in Table 2. Descriptions of the subroutine, input, and output are presented in Sects. 4.4, 4.5, and 4.6 of this report.

Table 1. LAPURX structural listing

```
MAIN:   INPUT:  INP1
                INP2
                INP3
        OUTIN
        READY:  THCL:           HCL:            CHECK
                        TSATP:          LINEAR
                        HFGP:           LINEAR
                        VOLUME
                        VGP:            LINEAR
                        FN
                        FPMU
                        FPK
                        FPRAN
        FLOW:           Do X = 1, N channels
                                SETUP
                                STEADY:         PREPAR
                                BOUNDY:         POWNW
                                                DCUMP
                                                TD:             FN
                                                HNBP:           FPK
                                                                FPRAN
                                                                FPMU
                                                TJLP
                                                VOLUME
                                                FN
                                NODE:           DCUMP
                                SUBOIL:         FN
                                                VOID
                                                TD:             FN
                                                HNBP:           ~
                                                FPK
                                BULK:           VOID
                                FRICT:          FPMU
                                                AF
                                                FF
                                DELTP:  PREPHI:         OMEGAP
                        End of IX[a]
                        DRUMW2
                        DO IX = 1, N channels
                                SETUP
                                STEADY:         ~
                                COEFR:  VOLUME
                                                HNBP:           ~
                                                TD:             FN
                                                HBBP
                                                FFF1
                                                FFF2
                                                DEFNRR
                                                OMEGAP
                                FUEL:           BESSI
                                                FTK:            LINEAR
                                                FTRC:           LINEAR
                                                FTDKDT:         FTK:            LINEAR
                                OUTST
                                OUTFUX
                                OUTCOR
                                DRUMW1
                                DRUMW3
                        End of IX
END
```

[a] A convergence test is made at this point to ensure the pressure boundary condition is satisfied.
To avoid repetition, the symbol ~ substitutes a subroutine structure already described in the table.

Table 2. LAPURW structural listing

```
MAIN:   INPUTW:
                        INPW1, INPW2, INPW3, INPW4, INPW5, INPW6
                        INXS2G
                        INCROD
        OUTINW
        DRUMR2
        TRANS:          WEIGHT:         Do IX = 1, N channels
                                                DRUMR1
                                                NODOS
                                                COUPXS:         COND
                                        End of IX
                        Do IW=1, N frequencies
                                Do IX = 1, N channels
                                        DRUMR1
                                        NODOS
                                        NODREA
                                        REACFA:         COEF
                                        JOSELE:         COND
                                                        DIF:            COND
                                        FUEL:           BESSI
                                                        FTK:            LINEAR
                                                        FTRC:           LINEAR
                                                        FTDKDT:         FTK:            LINEAR
                                        OUTFUX
                                        DRUMW3
                                        DRUMR3
                                        FUELW
                                        COEFIW
                                        FREQ
                                End of IX
                                RECIRC
                                ONECOR
                        End of IW
        RESPON:         OUTFUW:         PRINTA:         ANGLE
                        ANGLE
                        WDSKPR:         PRINTA
                        WDSKGH
                        STABGH:         DBDEG
                                        SPLIN
                                        SEVAL
                                        BREAL: EXP10
                                        BIMAG:          EXP10
                        MARGIN
                        PRINTB:         ANGLE
                        WDSKPR:         ~
                        WDSKPR:         ~
                        WDSKGH
                        STABGH:         ~
                        MARGIN
                        CONSIS
                        LIMIT
                        SENS:           STABGH:         ~
                                        MARGIN
                        MODE2:STABGH:           ~
                                        MARGIN
                                        LIMIT
        SEARCH:         STABGH:         ~
                        MARGIN
                        TRANS: ~
                        STABGH:         ~
                        CONSIS
        STOP
        END
```

Note: To avoid repetition, the symbol ~ substitutes a subroutine structure already described in the table.

2.2.3. Intermediate Storage Devices

Intermediate storage of data is used for two different purposes: (1) to provide a link between the steady state and the dynamics calculation and (2) to allow the orderly printing of the output TFs as a function of frequency while avoiding the need for excessive computer core memory space.

For the first purpose, the storage device can be tape, disk, or drum. The files are addressed as logical units 1 and 2. Their input/output operations are unformatted and sequential.

For the second purpose, a direct access on line disk or drum is required. Three files are created and assigned to logical units 10, 11, and 12. Data are transferred to and from the on-line device unformatted in 8 byte segments per direct access operation.

3.0 LAPUR 6 IMPLEMENTATION

3.1. DIFFERENCES BETWEEN LAPUR 5.2 AND LAPUR 5.1

The major improvements of LAPUR 5.2 with respect to LAPUR 5.1 are:

1. The maximum number of thermal-hydraulic regions was parameterized. The default value has a maximum number of 200 channels. Note: LAPUR calculations with up to 200 channels were verified against results from the old LAPUR 5.1 with no significant loss of precision. Calculations with more than 200 channels are typically not necessary due to symmetry considerations, but are possible; however, those calculations have not been verified here.
2. The maximum number of axial power shapes was parameterized so that each thermal-hydraulic region has its own axial and radial power shape. In the default compilation, the maximum number of axial power shape regions is 200.
3. The maximum number of bundle and fuel rod types was parameterized. In the default compilation, the maximum number of bundle types is 10. This allows modelling of mixed cores with up to 10 different fuel types.
4. The maximum number of frequencies was parameterized. The default value is 100. This allowed for better definition of the TFs and a more robust evaluation of the decay ratio. In the old version, it was often required to perform two LAPURW calculations, one to identify the frequency of oscillation using a coarse frequency mesh, and a second calculation with a fine mesh around the oscillation frequency. With 100 frequencies, a single calculation works for most cases.
5. All relevant dimensions of internal LAPUR variables were parameterized, so they can be modified in the future. File PARAM.FI contains the definitions for all these parameters. Note: these parameters have been left at their original values, and value changes have not been tested thoroughly; it is the responsibility of the user to verify that any future changes to these parameters does not result in significant loss of precision.
6. A well known behavior of LAPUR was that it would report very-high channel decay ratios if the channel was very stable. This required the use to manually check the phase and gain margins. This behavior was corrected by improving the decay-ratio estimation algorithm. The problem was related to an internal "spline fit" that LAPUR performs on the calculated TFs. For a very stable channel, the phase may cross the zero-degree level; since LAPUR maintains the phases negative, the phase jumps from -5 deg to -355 deg. The spline fit under those conditions cannot reproduce the discontinuity accurately, and as a result a very-high decay ratio is reported. This behavior was corrected in LAPUR5.2, which should calculate and report accurately low-channel-decay-ratio conditions.
7. The calculation of the Average Saturated Boiling Boundary has been added at the end of the LAPURX execution. This calculation is performed for output purposes only and does not affect the LAPURW input files; thus it does not affect the calculated decay ratios.
8. Two new output files are generated by LAPUR. These files have an ASCII "Comma Separated Value" (CSV) format and contain a summary of the most relevant output information. The file names are LAPURX.CSV and LAPURW.CSV and can be opened with most spreadsheet programs for further manipulation of the LAPUR output data. LAPURX.CSV contains the relative power and flow, the pressure drop, exit quality, and

the saturated boiling boundary of each channel. LAPURW.CSV contains the decay ratio and frequency for each channel and for the core, as well as the open-loop and closed-loop TFs as function of frequency.

9. During the detailed code review, the authors found and corrected one miscellaneous programming error.
10. The screen-input routines were removed. Batch is the only available mode for LAPUR 5.2. The executable files have been renamed LAPURX.EXE and LAPURW.EXE.

3.2. DIFFERENCES BETWEEN LAPUR 6.0 R.0 AND LAPUR 5.2

Appendix C contains a detailed description of all the improvements incorporated in LAPUR 6.0. A short summary of these improvements follows:

1. The two-phase friction multipliers for frictional forces and for local losses, have been improved, using updated relationships that are more realistic for the newest fuel designs.
2. The capability to model channels with variable areas, in order to represent more adequately the partial -length rods of the new fuel designs.
3. Several cells in the single-phase region have been defined, and the cell variables (densities, liquid velocities, temperatures) of the nonboiling region are calculated.
4. Local pressure losses (spacers) have been included.
5. Irreversible pressure losses due to contractions and expansions have been included.
6. During the detailed code review, the authors found and corrected a miscellaneous programming error.

3.3. LAPUR 6 INPUT AND OUTPUT FILES

The current implementation of LAPUR 6 expects the input data described in Sect. 4 of this report in two files named LAPURX.DAT and LAPURW.DAT. It generates the main (verbose) output to two files named LAPURX.OUT and LAPURW.OUT. A summary of the most relevant information is generated in ASCII Comma Separated Values (CSV) format in files LAPURX.CSV and LAPURW.CSV. LAPUR 6 also generates intermediate storage files that can be deleted after successful completion of a run. These files are named LAPUR.D1, LAPUR.D2, LAPUR.D3, LAPURW.T1, and LAPURW.T2.

3.4. OPERATING SYSTEM REQUIREMENTS

LAPUR5 does not require any special operating system. The current version is compiled as a Windows Console Application using Microsoft FORTRAN PowerStation.

3.5. INSTALLING AND EXECUTING LAPUR 6

LAPUR 6 is composed of two executable files: LAPURX.EXE, and LAPURW.EXE. LAPURX performs steady-state and initialization calculations. LAPURW computes the frequency domain or dynamic part of the calculations.To install LAPUR 6, simply copy the executable files to any directory.To run LAPUR 6, follow these steps:

1. Generate input files for the steady state (LAPURX) and dynamic (LAPURW) modules.
2. Rename these input files to LAPURX.DAT and LAPURW.DAT.

3. Execute LAPURX.EXE
4. Execute LAPURW.EXE
5. Rename the output files LAPURX.OUT, LAPURX.CSV, LAPURW.OUT, and LAPURW.CSV so that future runs will not overwrite them.

4.0 LAPUR INPUT PARAMETERS

4.1. LAPUR DIMENSION LIMITS

All arrays in LAPUR 6 are dimensioned using parameters instead of hard constants. These parameters are defined in file PARAM.FI, which is included in both LAPURX and LAPURW during the compilation step. These parameters are summarized in Table 3, and they can be changed and the program recompiled to generate a version with larger dimension limits; however, any changes would have to be verified to guarantee that programming errors do not affect the results.

Table 3. Dimension Limits for LAPUR Arrays

```
PARAMETER (NPSMAX  =200) ! Max # of power shapes                              (>= 6)
PARAMETER (NPSNMAX = 50) ! Max # of nodes of power shapes                     ( = 50)
PARAMETER (NCHMAX  =200) ! Max # of TH channels                               (>= 7)
PARAMETER (NFBMAX  = 10) ! Max # of channel types                             (>= 5)
PARAMETER (NVAMAX  = 10) ! Max # of variable area channels                    (>=10)
PARAMETER (NOVAMAX = 90) ! Max # of axial intervals channel                   ( = 90)
PARAMETER (NLLMAX  = 10) ! Max # of local loss channel types                  (>=10)
PARAMETER (NOLLMAX = 90) ! Max # of axial intervals ll-channel                ( = 90)
PARAMETER (NFRMAX  = 10) ! Max # of fuel rod types                            (>= 5)
PARAMETER (NFMMAX  = 10) ! Max # of friction multipliers                      (>=10)
PARAMETER (NFMNMAX = 90) ! Max # of axial intervals fri-mul                   ( = 90)
PARAMETER (NCIMAX  = 10) ! Max # of channel inlet types                       (>=10)
PARAMETER (NCINMAX = 10) ! Max # of pipes in series chan-in                   ( = 10)
PARAMETER (NCEMAX  = 10) ! Max # of channel exit types                        (>=10)
PARAMETER (NCENMAX = 10) ! Max # of pipes in series chan-ex                   ( = 10)
PARAMETER (NAPMAX  = 10) ! Max # of axial points edit rod                     (>=10)
PARAMETER (NOBMAX  = 90) ! Max # of axial nodes boiling                       (>=90)
PARAMETER (NOTMAX  =140) ! Max # of axial nodes total                         (>=140)
PARAMETER (NNBMAX  = 50) ! Max # of axial nodes nonboiling                    (>=50)
PARAMETER (NNJMAX  =  1) ! Max # of horizontal subcores                       (>= 1)
PARAMETER (NNKMAX  =  1) ! Max # of vertical subcores                         (>= 1)
PARAMETER (NNDMAX  = 40) ! Max # of sets of delay-n characterist              ( = 1)
PARAMETER (NROMAX  = 40) ! Max # of initial reactivities                      ( = 1)
PARAMETER (NNLMAX  = 40) ! Max # of neutron lifetime in subcore               ( = 1)
PARAMETER (NNCMAX  =200) ! Max # of neutron coupling coefficien               ( = 1)
PARAMETER (NDGMAX  = 6)  ! Max # of delayed n energy groups                   (>= 6)
PARAMETER (NBTMAX  = 3)  ! Max # of fuel bundle types (4f-b&1r)               (>= 3)
PARAMETER (NFTMAX  = 8)  ! Max # of different fuel types                      (>= 8)
PARAMETER (NXSEC = 7)    ! # of Xsect D1,D2,Sa1(inc scatt),Sa2,Sf1,Sf2,S1-2   (= 7)
PARAMETER (NECMAX  = 3)  ! Max # of order power expansion coeff               (>= 3)
PARAMETER (NAFMAX  = 6)  ! Max # of axial fuel intervales                     (>= 6)
PARAMETER (NACMAX  = 11) ! Max # of axial control bundles inter.              (>=11)
PARAMETER (NDRMAX  = 7) ! Max # of tables of dens. react. coeffs (ID 18)      (>= 7)
PARAMETER (NDRNMAX = 10) ! Max # of values table react. coeffs                (>=10)
PARAMETER (NFPMAX  = 100) ! Max # of frequency points                         (>=25)
PARAMETER (NSRMAX  = 20) ! Max # of subcritical reactivity o-pha              (>=20)
PARAMETER (NFUMAX  = 10) ! Max # of fuel radial nodes                         (>10)
```

4.2. ALPHABETICAL DESCRIPTION OF THE LAPURX SUBROUTINES

Notes on the format used in these descriptions:

1. "Input" indicates the means by which the subroutine receives the parameters on which it operates. The parameters may come from an outside source defined by a logical unit, from the calling program through shared COMMON areas, or as arguments.
2. "Output" indicates the means by which the parameters calculated or modified by the subroutine are disposed of. These can be transferred to the calling subroutine, a COMMON area, or an outside device.

Main

Subroutine BOUNDY

Called from: STEADY.

Input: (i) Argument: IX ≡ channel type.
(ii) COMMONS: DATA, INPT, REDY, REDY2, SETP, SETP2, PRPR, PRPR2.

Performs: (i) If $\mathrm{IOP}(3) \neq \dot{2}$, where the dot indicates "multiple," the position of the boiling boundary Z_{nb} is read as input; hence, the enthalpy and temperature at the boiling boundary are calculated accordingly.

(ii) If $\mathrm{IOP}(3) = \dot{2}$, the Jens Lottes correlation [Eq. (3.2.4)]* is used to determine the temperature of inception of subcooled boiling. Subsequently, the boiling boundary position and physical parameters for the nonboiling part of the flow in the channel are calculated.

Output: COMMONS: TBOUND, BNDY.

Subroutine BULK

Called from: STEADY.

Input: (i) Argument: IX.
(ii) COMMONS: TVOID, INPT, REDY, BNDY, NOHD, BOIL, BOIL2, BALK.

Performs: Calculation of the distributions of liquid and steam mass flow rates, void fraction, steam quality, and other parameters of interest at each node along the bulk boiling region. It also determines the position at which boiling would begin if subcooled boiling did not occur and the fraction of channel power deposited in its nonboiling length.

Output: COMMONS: BOIL, BOIL2, BALK.

Subroutine COEFR

Called from: FLOW.

Input: (i) Argument: IX.
(ii) COMMONS: DATA, INPT, REDY2, REDY, SETP2, SETP, PRPR2, BNDY, NOHD, NOHD2, BOIL, BOIL2, FRCT2, FRCT, PRP12, OMGP2, OMGP.
(iii) Output of the *subroutine*: OMEGAP.

Performs: Calculation of those coefficients in the set of dynamic equations in App. B10 and B11, which are frequency independent. Since some of the D coefficients of the

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* Citations of equations, appendices, and paragraphs throughout Sect. 3 refer to Reference 1 unless otherwise specified.

subcooled boiling region in App. B10 are frequency dependent, a set of coefficients B, which contain their frequency independent part, is generated here.
Output: COMMONS: TCOEFR, CEFR, CEFR2, CEFR3.

Subroutine DCUMP
Called from: BOUNDY, NODE
Input: Arguments I, ZM
Performs:
Output: DELPC

Subroutine DEFNRR
Called from: COEFR.
Input: Arguments: NR, DZ, DZR.
Performs: It defines the integration mesh for the coolant equations in the non-heated boiling sections of the channel. This is a provision to account for the possibility of having a series of different pipes connected at the exit of the heated channel. The length of the mesh is taken as DZ, the mesh length in the heated boiling section. The length of a non-heated section is stored in DZR(I), and the maximum number of nodes allowed in any of these sections is NR ≤ 10, that is, the value NRR(I) ≤ 10 where I is the non-heated section index.
Output: Argument: NRR ≡ number of nodes in the non-heated boiling section under consideration.

Subroutine DELTP
Called from: STEADY.
Input: COMMONS: DATA, INPT, REDY, SETP, SETP2, PRPR2, BNDY, NOHD, NOHD2, BOIL, BOIL2, FRCT, PRP12, OMGP, OMEGP2.
Performs: Calculation of the flow pressure losses at the inlet and outlet orifices and at every node along the length of the channel. It uses the subroutine PREPHI for those nodes in boiling sections of the channel.
Output: COMMON: DELTP.

Subroutine DRUMW1
Called from: FLOW.
Activated by: IOP(1) < 2.
Input: (i) Argument: IX.
(ii) COMMONS: SETP2, SETP, PRPR2, PRPR, BNDY, NOHD, NOHD2, BOIL, BOIL2, BALK, FRCT2, FRCT, DLTP, PRPI2, PRPI, OMGP2, OMGP, CEFR, CEFR3, CEFR2, REACOE.
Performs: Saving out of core the steady state thermohydraulic parameters of the coolant for each node along the length of channel IX. The map thus created will be used to define the initial conditions for subsequent dynamics calculations.
Output: Logical unit 1: Sequential unformatted writing of the content of the COMMON statements listed above.

Subroutine DRUMW2
Called from: FLOW.
Activated by: IOP(1) < 2.
Input: COMMONS: IIOP1, DATA, INPT, INPT2, REDY2, REDY, ADD1.
Performs: Saving out of core of the input data and the system parameters determined by the subroutine READY.
Output: Logical unit 2: Sequential writing of the content of the COMMON statements

listed above.

Subroutine DRUMW3

Called from: FLOW.
Activated by: IOP(1) < 2.
Input: (i) Argument: IX.
(ii) COMMONS: ADIN, FUL, FULIX.
Performs: Saving out of core of the thermal parameters of the fuel rods within a channel for subsequent use in the dynamics calculations.
Output: Logical unit 1: Sequential unformatted writing of the COMMON statements listed above.

Subroutine FLOW

Called from: MAIN.
Input: (i) Argument: NPAGE.
(ii) COMMONS: DATA, INPT, REDY, REDY2, IIOP1, PREBC, ADD1.
Performs: (i) Determination of the flow rate distribution among the fuel channels subject to uniform inlet and outlet pressure boundary conditions. To this effect an iterative procedure is followed. First, the thermohydraulic conservation equations are solved along the length of a channel by means of the subroutines SETUP(IX) and STEADY(IX). The mass flow rate, exit steam quality, and total pressure drop along the channel are retained prior to repeating the process with another channel. Once the pressure drops for all channels are known, they are compared to see if they are equal. If they are not equal, a new flow rate is estimated for each channel and a new iteration is started.
The results of the first iteration are used to determine the partial derivative of the total pressure drop with respect to the mass flow rate for each of the channels. These partial derivatives are used to determine the tentative pressure drop to which all the channels will converge and the corresponding flow rates. After the second iteration, a parabolic interpolation scheme is used to estimate the new flow rates, using the results of the two previous iterations. The maximum number of iterations provided for is 20.
(ii) Generation of the parameters needed as initial conditions for the subsequent dynamic calculations. To this effect, once that pressure drop convergence has been achieved, the subroutines SETUP(IX) and STEADY(IX) are called again to repeat the calculations of the last iteration. The subroutines COEFR(IX) and FUEL(IX) are called this time. Prior to starting with another channel, all parameters generated for the channel are transferred to a disk by means of the subroutines DRUMW1(IX) and DRUMW3(IX) and printed, if desired, by calling the subroutines OUTST(IX), OUTCOR (IX) and OUTFUX(IX).
Output: (i) COMMON: TFLOW.
(ii) Logical unit 1: The output of the subroutines DRUMW1(IX), DRUMW3(IX).
(iii) Logical unit 2: The output of the subroutine DRUMW2.
(iv) Logical unit 6: Under the heading: ***FLOW***, the flow characteristics of each channel type and the tentative pressure drop for the next iteration at every iteration step.

Subroutine FRICT

Called from: STEADY.
Input: COMMONS: INPT, REDY, SETP, SETP2, PRPR, BNDY.
Performs: Calculation of the Reynolds number for each of the flow regions and the corresponding Moody friction factor f and coefficient a2. It uses the function subroutines FF, AF, and FPMU.

Output: COMMONS: FRCT, FRCT2.

Subroutine FUEL

Called from: FLOW.

Input: (i) Argument: IX.

(ii) COMMONS: DATA, INPT, SETP, SETP2, PRPR, BNDY, NOHD, CEFR, CEFR3, ADIN, ADD1, IIOP1.

Performs: (i) Calculation of the temperature distribution across the fuel element at every node as described in the fuel steady state calculation (paragraph 3.2.2.1).

(ii) Calculation of the parameters α, β, and γ for the dynamics analysis as described in Eq. (3.2.42).

(iii) Saving into common FEL1 the characteristics of up to 10 vertical nodes as specified by NFPRT at input time.

Output: (i) COMMONS: TFUEL1, FUL, FEL1, FULIX.

(ii) Logical unit 6: Error message 3.

Subroutine INPUT

Called from: MAIN.

Input: Logical unit 5.

Performs: (i) Reading of the data which specify the steady state thermohydraulic calculations to be performed. The subroutines INP1, INP2, and INP3 are used to input some of the arrays.

(ii) Consistency check of some of the input data.

Output: (i) COMMONS: INPT, INPT2, DATA, REDY, REDY2, ADD1, ADIN, JJJ, PREBC, TINPUT, ICH, COFC.

(ii) Logical unit 6: Error message 1.

Subroutine INP1

Called from: INPUT

Input: NO, NNN

Performs: Reads an array of integers of length NO in the standard format 8I10 for the first line and 10X,7I10 for the continuation lines

Output: NNN

Subroutine INP2

Called from: INPUT

Input: NO, NNN, AAA, ID

Performs: Reads a two-dimensional array of floating point variables in the standard format 10X,7E10.5. The row index is input in ID.

Output: AAA(ID, *)

Subroutine INP3

Called from: INPUT

Input: NO, AAA

Performs: Reads an array of floating point variables in the standard format I10,7E10.5 for the first line and 10X,7E10.5 for the continuation lines

Output: AAA(*)

Subroutine LINEAR

Called from: FTK, FTRC, TSATP, VGP, HFGP.

Input: Arguments: X, XF, YF.

Performs: Linear interpolation within the table XF, YF to determine the value of Y that corresponds to that of X.
Output: Argument: Y.

Subroutine NODE
Called from: STEADY.
Activated by: BOUNGO ≠ 0.
Input: (i) Argument: IX.
(ii) COMMONS: DATA, INPT, REDY, SETP, PLRPR, PRPR2, BNDY,
Performs: (i) Definition of a new mesh along the channel so that there are N nodes in the boiling length of the channel.
(ii) Transformation of the nodal parameters to the new coordinate system. The parameters affected by the transformation are: nodal boundary ordinates ZCOM(J), normalized cumulative power generation CCOM(J), homogenized enthalpy HAV(J), mixed steam quality XMIX(J), and friction multipliers EKFL(J).
Output: (i) COMMONS: NOHD, NOHD2.
(ii) Logical unit 6: Error message 4.

Subroutine OMEGAP
Called from: COEFR and PREPHI.
Input: Arguments: J, GP, H, INO.
COMMONS: DATA, INPT, REDY, SETP, PRPR2, BOIL2.
Performs: Calculation of the Jones flow correction factor Ω for the Martinelli-Nelson two-phase friction multiplier and its derivatives. J is the node index number, GP is the mass flow rate in g/ cm^2 s, H is the relative subcooling of the liquid phase, and INO is a flag to indicate whether node J is in a heated section or not.
Output: COMMONS: OMGP, OMGP2.

Subroutine OUTCOR
Called from: FLOW
Input: IX, NPAGE
Performs: Outputs the steady state core conditions to the OUT file.
Output:

Subroutine OUTFUX
Called from: FLOW.
Input: (i) Arguments: IX, NPAGE, NFU.
(ii) COMMONS: DATA, ADDIN, FEL1.
Performs: Listing of the steady state thermal parameters of the fuel in each channel at selected vertical nodes for all the radial nodes in the fuel.
Output: (i) Argument: NPAGE.
(ii) Logical unit 6: Under the heading ***FUEL(IX =)*** the calculated fuel parameters are printed for each of the selected NFN0 vertical nodes and the 10 radial nodes.

Subroutine OUTIN
Called from: MAIN.
Activated by: INPUGO > 1.
Input: COMMONS; DATA, INPT, INPT2, REDY, ADD1, ADIN, PREBC, COFC, JJJ.
Performs: Printout of the input data.
Output: Logical unit 6: Check print of the data read by the subroutine INPUT.

Subroutine OUTST

Called from: FLOW.

Activated by: IOP(4) ≠ 0.

Input: (i) Arguments: IX, MMMM, NPAGE.

(ii) COMMONS: DATA, INPT, REDY, SETP, SETP2, PRPR, PRPR2, BNDY, NOHD, NOHD2, BOIL, BOIL2, BALK, FRCT, FRCT2, DELTP, OMGP, OMEGP2.

Performs: (i) The calculation of the partial derivatives: $\partial\beta/\partial Z$ and $\partial\beta/\partial X$ for each node for printing purposes only.

(ii) Printing of the thermohydraulic nodal parameters as determined by the subroutines READY and STEADY for each of the channels.

Output: (i) Arguments: NPAGE.

(ii) Logical unit 6: Under the heading: **STEADY***ITERATION MMMM: tables of the thermohydraulic parameters for each node and channel.

Subroutine POWNW

Called from: BOUNDY

Input: none

Performs:

Output ZF, F (in common /POWNW1/)

Subroutine PREPAR

Called from: STEADY.

Input: (i) Argument: IX.

(ii) COMMONS: DATA, REDY, STEP, SETP2.

Performs: (i) For a total of NP + 1 nodes, the calculation of the normalized cumulative power distribution CIN(I) at the nodal boundaries along the channel IX. The nodal mesh Z(I) is the one defined when reading in the power distribution in subroutine INPUT. The entrance to the first node is represented by the index I = 1.

(ii) Calculation of the inlet mass velocity w_0 in g/s, the base reference inlet linear velocity u_0 in cm/s, and the average heat flux through the heating surfaces in the channel q_{ave} cal/cm^2 s.

Output: COMMONS: PRPR, PRPR2.

Subroutine PREPHI

Called from: DELTP

Input: COMMONS: INPT, REDY, SETP, SETP2, BOIL, BOIL2.

Performs: Calculation of the Martinelli-Nelson two-phase friction multiplier ϕ^2 and its derivative by means of the set of coefficients COEFF in BLOCK DATA as described in App. B5.

Output: COMMONS: PRPI, PRPI2.

Subroutine READY

Called from: MAIN.

Input: (i) Argument: NPAGE.

(ii) COMMONS: DATA, INPT.

Performs: (i) Determination of the physical characteristics of the coolant water at the operating conditions in metric engineering units. This is accomplished by means of the function subroutines: THCL, TSATP, HFGP, VOLUME, VGP, FN, FPMU, FPK, and FPRAN.

(ii) Calculation of the factors k_s and r for the slip correlation, according to Eq. (B2.2) in App. B2.

(iii) Calculation of the coefficients a_i for the Martinelli-Nelson two-phase friction multiplier ϕ^2 according to Eq. (B5.2) in App. B5.

(iv) Estimation of the initial distributions of coolant flow rates and power generation or exit quality among the channels in the core for the iterative procedure described in Sect. 3.2 of Reference 1.

Output: (i) Argument: PAGE.

(ii) COMMONS: TREADY, REDY, REDY2.

(iii) Logical unit 6: (a) error message 2; (b) under the heading ***READY***, the fundamental thermohydraulic characteristics of the reactor core.

Subroutine SETUP

Called from: FLOW.

Input: (i) Argument: IX.

(ii) COMMONS: INPT, INPT2, JJJ, REDY.

Performs: (i) The selection of the parameters specific to channel type IX from the arrays in the subroutines INPUT and READY.

(ii) Calculation of the power fraction or exit quality corresponding to the new estimate of the channel flow rate during the iterative procedure.

Output: COMMONS: SETP, SETP2.

Subroutine STEADY

Called from: FLOW.

Input: (i) Argument: IX.

(ii) COMMONS: INPT, BNDY, BOIL, BOIL2, BALK, TBOUND, TNODE, TSUBOI, TBULK.

Performs: (i) Initialization to zero of the content of the COMMONS BOIL, BOIL2 and BALK.

(ii) Manages the solution of the thermohydraulic equations of the coolant flow by calling the subroutines PREPAR, BOUNDY, NODE, SUBOIL, BULK, FRICT, and DELTP in succession.

Output: COMMONS: BNDY, BOIL, BOIL2, BALK, TSTEAD.

Subroutine SUBOIL

Called from: STEADY

Input: (i) Argument: IX.

(ii) COMMONS: DATA, INPT, REDY, REDY2, SETP, SETP2, PRPR, PRPR2, BNDY, NOHD, NOHD2, ADD1.

Performs: Calculation of the liquid and steam mass flow rates, liquid enthalpy, void fraction, and other parameters of interest at each node along the subcooled boiling region of the channel. To this effect the continuity and energy equations are solved as described in Sect. 3.2 of Reference 1. The basis for the iterative procedure followed is that of Reference 4, p. 31. The function subroutines FN, FPK, TD, and HNBP and the subroutine VOID are used.

Output: (i) COMMONS: BOIL, BOIL2.

(ii) Logical unit 6: Error message 5.

Subroutine VOID

Called from: SUBOIL and BULK.

Input: (i) Arguments: IX, M, X02, H02.

(ii) COMMONS: DATA, INPT, REDY, SETP, BOIL2, ADD1.

Performs: Calculation of the void fraction as a function of steam quality and relative subcooling of the liquid phase as described in Sect. 3.2 of Reference 1.

Output: (i) Argument: B02.
(ii) COMMON: TVOID.
(iii) Logical unit 6: Error message 6.

BLOCK DATA

Performs: Initialization of the variables in the COMMON statements DATA and FNCT prior to execution of the first statement in the MAIN program.

The content of this data block is:

SG = g ≡ the gravitational acceleration in cm/s,

SBP0, SBP1 = c_i and d_i respectively ≡ table of coefficients for the Jones two-phase flow friction multiplier,

BBB = b_{ij} ≡ table of fitting coefficients of the Martinelli-Nelson friction factor ϕ^2, as described in App. B5.

A tabulation, based on the ASME steam tables, of the saturation temperature, the specific volume of saturated steam, and the enthalpy of evaporation of water vs pressure (from 0.2 to 3206.2 psia) is implemented by means of: ARG-ARG2 as pressure in psia, FCTI FCTII as T_{sat} in °F, FCT2 FCT22 as v_s in ft^3/lb, and FCT3 FCT33 as h_{f0} in Btu/lb.

Function Subroutine AF

Argument: f ≡ the smooth Moody friction factor.

Output: a_2 ≡ the exponent of the Reynolds number in the general expression for the Moody friction factor as described in Eq. (B7.4a).

Function Subroutine AF2

Argument: f_{II} ≡ the friction factor model II.

Output: $a_{2,II}$ ≡ the exponent of the Reynolds number in the general expression for the generic single-phase friction factor model II (Reference 13).

Function Subroutine BESSI

Arguments: N ≡ order of the modified Bessel function,
X ≡ argument.

Output: The value of IN(X), the modified Bessel function of order N, for the argument X. The algorithm used is valid for N < 3000 and X < 87. In the program, the subroutine FUEL uses the N = 0, that is, $I_0(X)$, function to represent the radial distribution of the power generation within the fuel pellets.

Function Subroutine CHECK

Arguments: P ≡ pressure in kg/cm^2,
T ≡ temperature in °C,
N and M ≡ indices.

Output: It fixes the lower and upper bounds for P and T so that if the input value is out of bounds, the boundary value is returned to the calling program. The index N determines which of the two variables is being checked; that is, N = 1 specifies pressure, while N = 2 specifies temperature. The bounds are

M = 1: $0.006 \leq P \leq 600.0$; $-1 \leq T \leq 505.7$;
M = 2: $0.006 \leq P \leq 250.0$; $-1 \leq T \leq 505.7$;
M = 3: $0.006 \leq P \leq 600.0$; $-1 \leq T \leq 800.0$.

Function Subroutine FF

Argument: Re ≡ the Reynolds number.

Output: The smooth Moody friction factor f corresponding to the value of the argument. It follows the description in App. B7. A maximum of 50 iterations is programmed for the solution of the transcendental Eq. (B7.3); if convergence is not achieved, that is, $f_{50} - f_{49} > 10^{-5}$ then the relation,

$$f = 0{,}213\ \mathrm{Re}^{-0.214}$$

is used.

Function Subroutine FF2(RE0)

Argument: RE0 ≡ the Reynolds number.

Output: The friction factor f_2 model II corresponding to the value of the argument. The equations of this model are:

$$f_2 = \mathrm{MAX}(\mathrm{FF}, \mathrm{FF}_{\mathrm{LAM}})$$

$$\mathrm{FF}_{\mathrm{LAM}} = \frac{64.0}{\mathrm{Re}_l}$$

$$\mathrm{FF} = \mathrm{AN} \cdot \left[1 + (\mathrm{BN} \cdot R_r) + \frac{\mathrm{CN}}{\mathrm{Re}_l}\right]^{\mathrm{DN}}$$

where AN, BN, CN, DN are input-user data, R_r is the relative roughness, and Re_l is the liquid Reynolds number

Function Subroutine FFF1(A_,B_)

Internal function called from: COEFR

Function Subroutine FFF2(A_,B_)

Internal function called from: COEFR

Function Subroutine FN(P,T)

Arguments: P ≡ pressure in kg/cm^2,
T ≡ temperature in °C.

Output: Liquid saturation enthalpy in cal/g.

Function Subroutine FPK(P,T)

Internal function called from: HNBP, READY, SUBOIL

Function Subroutine FPMU(P,T)

Arguments: P ≡ pressure in kg/cm^2,
T ≡ temperature in °C.

Output: Liquid dynamic viscosity in g/cm^2 s.

Function Subroutine FPRAN(P,T)

Arguments: P ≡ pressure in kg/cm^2,
T ≡ temperature in °C.

Output: Prandtl number for water, as a function of pressure and temperature. The correlations used are those of the code STABLE (Reference 10, pp. 73 74).

Function Subroutine FTDKDT

Argument: T ≡ temperature in °C.

Output: The temperature derivative of the heat conductivity of the UO_2 fuel pellet. It is based on the correlation used in the subroutine FTK.

Function Subroutine FTK(T)
Internal function called from: FTDKDT, FUEL

Function Subroutine FTRC(RHOF_,T)
Internal function called from: FUEL

Function Subroutine HBBP(P,Q)
Internal function called from: COEFR

Function Subroutine HCL(PD, TD)
Internal function called from: THCL

Function Subroutine HFGP(P)
Argument: P ≡ pressure in atm.
Output: Evaporation enthalpy in cal/g of water, as a function of system pressure P. The subroutine LINEAR is used to interpolate from the tables defined in BLOCK DATA prior to the application of the system of units transformation factors.

Function Subroutine HNBP(P,T,G,D)
Arguments: P ≡ pressure kg/cm^2
T ≡ temperature °C,
G ≡ flow rate g/s,
D ≡ hydraulic diameter cm.
Output: The convective heat transfer coefficient between the coolant and the fuel clad, in cal/(cm^2 °C s).

Function Subroutine POLY(N,A,X)
Internal function called from: VSCV.
Performs: Evaluates a polynomial trough succesive multiplications.

Function Subroutine TD(P,H)
Arguments: P ≡ pressure in atm,
H ≡ enthalpy in cal/g.
Output: The liquid temperature in °C as a function of pressure and liquid enthalpy. An iterative procedure is used based on the function subroutine FN (P,T).

Function Subroutine THCL(H,P)
Internal function called from: READY

Function Subroutine TJLP(P,QZ,H,TSAT)
Arguments: P ≡ pressure in kg/cm^2,
QZ ≡ surface heat flux cal/cm^2 s,
H ≡ convective heat transfer coefficient cal/cm^2 °C,
TSAT ≡ saturation temperature °C.
Output: The temperature of inception of subcooled boiling in °C. The Jens Lottes correlation in Eq. (3.2.4) is used.

Function Subroutine TSATP(P)
Argument: P ≡ pressure in atm.

Output: Saturation temperature in °C.

Function Subroutine VGP(P)

Argument: P ≡ pressure in atm.

Output: Specific volume of saturated steam in g/cm^3.

Function Subroutine VOLUME(P,T)

Arguments: P ≡ pressure in kg/cm^2,
T ≡ temperature in °C.

Output: Specific volume of liquid water in cm^3 /g.

Function Subroutine VSCV(T,ROV)

Argument: T ≡ temperature in °C.
ROV ≡ vapor density in g/cm^3.

Output: Dynamic viscosity of steam in N-s/m^2.

4.3. PREPARATION OF INPUT FOR LAPURX

4.3.1. Introduction

Data are read in by the subroutine INPUT. The input deck consists of a title card, data set cards, and a last card. The title card can contain up to 72 characters. These characters will be printed on each page of output to allow for easy identification of the case.

Each data set is preceded by an ID card that identifies the set. Thus, the sets need not be read in a specific sequence, although sets 1 and 2 have to be read before sets 7 or larger; set 3 before sets 4 and 5; and sets 35, 36, and 37 as well as the groups (38, 39, 40, 41, 42, 43, 44), (45, 46, 47, 48, 49, 50, 51, 52), (58, 59, 60, 61, 62), (63, 64, 65, 66), (67, 68, 69, 70, 71, 72) and (73, 74, 75, 76) must be read in sequence. All ID cards carry their number in format (I4). Most of the time the data cards use an (I10) format for integers and an (E10.3) format for the real values. All numbers are right justified. The input routine will accept commas to separate fields as long as each filed is less than 10 characters long. Note, however, that most continuation cards start with a "10X" format, so continuation card data must start in column 11 even if commas are used to separate the fields.

The last card is equivalent to an ID number equal to zero; thus a 0 in column 4 will terminate the input.

Once the input process is finished, the program will be executed.

When the calculations are finished, a new title card is sought by the subroutine INPUT. If a new title is found, a new case will be run.

For consecutive runs, only those data sets that change from one run to the next need be reentered.

Execution stops when the end of data card is found.

4.3.2. Input Description

4.3.2.1. First Card

Title ... columns 1 through 72.

4.3.2.2. Data Cards

Each data set is preceded by a card containing only the ID number of the corresponding data set in format (I4).

Description of the data sets:

Data set ID No.	FORTRAN symbols	Format	Comment
1	P,T0,POWT,WT,CWBYP,CPROMP,CPRBYP,UNITS	8E10.3	if UNITS=0
	PPSI,ENTBTU,POWT,WLBSHR,CWBYP,CPROMP,CPRBYP,UNITS	8E10.3	if UNITS=1
2	NXE,N,ICOFC(IOP(J),J=1,7)	10I5	NXE ≤ **NCHMAX** N ≤ **NOBMAX**

P,PPSI	P	System pressure P (kg/cm^2), PPSI (psia).
T0	T_0	Core inlet water temperature (°C).
ENTBTU	H	Core inlet water enthalpy (Btu/lb).
POWT	Pth	Total thermal power (MWth).
WT,WLBSHR	W	Total flow rate (active core + bypass) WT (kg/s); WLBSHR (lb/h).
CWBYP		Fraction of total flow through bypass.
CPROMP	γ_{pr}	Fraction of thermal energy given to water through moderation of neutron and γ-ray attenuation.
CPRBYP		Same as CPROMP but in bypass region.
UNITS		Option for units to be used with the following input variables:

Units	0	1
System pressure	kg/cm^2	psia
Inlet water condition	°C	Btu/lb
Core total flow	kg/s	lb/h
Channel mass velocity	g/cm^2 s	10^6 lb/ft^2 h

NXE	Number of regions within which the thermohydraulic behavior of the channels is uniform (≡ thermal region: same exit quality, same hydraulic diameter, same flow rate, and same power shape).
N	Number of axial nodes desired in the boiling region of the channels.
IOP(1)	Option for the calculation of the flow distribution among channels in the steady state and for the calculation of TFs.

IOP(1)	0	1	2	3
flow distribution	0	X	0	X
transfer function	0	0	X	X

0 calculated
X not calculated

IOP(2) Input option for GPOW(IX) and FPOW(IX) (see IDs 8 and 9, respectively).

IOP(2)	0	1	2	3
GPOW(IX)	X	X	0	0
FPOW(IX)	Xe	Pf	Xe	Pf

0 necessary
X unnecessary
Xe read as exit quality
Pf read as relative power

IOP(3) Option to specify ZNBM, EKS, and R by input (see IDs 12 and 6, respectively).

IOP(3)	0	1	2	3
ZNBM	X	0	X	0
EKS and R	X	X	0	0

0 specified by input
X calculated by the program

IOP(4)	If = 0, it will print the steady state results. If ≠ 0, it will not do it.
IOP(5)	Edit option for the results of the subroutine FUEL1. If = 0, yes. If = 1, no.
IOP(6)	Input option for NFNO and NFPRT(I) (see ID 54). If = 0, edit FUEL1 at default node numbers. If ≠ 0, data set 54 is required.
IOP(7)	Output option for the results of COEFR. If = 0, yes. If ≠ 0, no.

3	NPD,(NPPP(I),I=1,NPD)	8I10	NPD ≤ **NPSMAX**
4	((DELZM(IP,I),I=1,NPPP(IP)),IP=1,NPD)	10X,7E10.3, (10X,7E10.3)	
5	((POWM(IP,I),I=1,NPPP(IP)),IP=1,NPD)	10X,7E10.3, (10X,7E10.3)	

NPD		Number of regions within which the axial power distributions are uniform (power shape regions).
NPPP(IP)		Number of axial nodes for the specification of the relative nodal power in the IP-th power shape region.
DELZM(IP,I)	Δz_i	Length of the I-th node in region IP (cm) I = 1:bottom of the core.
POWM(IP,I)	$f(z)$	Relative nodal power of the I-th node in region IP.

6	EKS,R,SA0,SA1,SA2,SA3,SA4	7E10.3	See IOP(3) @ ID 1

EKS	k_s	Constant for Bankoff's slip correlation.
R	r	Constant to modify Bankoff's slip correlation; App. B2.
SA0, SA1, SA2, SA3, SA4	S_{a0} ~ S_{a4}	Coefficients for the calculation of the power distribution within a fuel rod.

7	NXE,(NPOW(IX),IX=1,NXE)	8I10, (10X,7I10)	NXE ≤ **NCHMAX**

NPOW(IX) Nuclear region number to which the IX-th thermal region belongs.

8	NXE,(GPOW(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	See IOP(2), ID 1

GPOW(IX) G_p Channel mass velocity.

$(g/cm^2)/s$ if UNITS = 0.

$(Mlb/ft^2\ h)$ if UNITS = 1.

Unnecessary when IOP(2) = 0 or 1.

9	NXE,(FPOW(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	See IOP(2), ID 1

FPOW(IX) If IOP(2) = 1 or 3:

= f_{ix}, relative power generated in region IX.

If IOP(2) = 0 or 2:

= Xe_{ix}, exit quality for region IX.

10	NXE,(EKCPM(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	

EKCPM(IX) $k_{c'}$ Contraction coefficient at the inlet of the channels.

11	NXE,(EKEPM(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	

EKEPM(IX) $k_{e'}$ Contraction coefficient at the exit of the channels. If the flow is expanded, it has a negative value.

12	NXE,(ZNBM(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	See IOP(3)

ZNBM(IX) Z_{nb} Position of the boiling boundary from the bottom of the channel (cm).

13	NXE,(ZELP(IX),IX=1,NXE)	I10,7E10.3, (10X,7E10.3)	

ZELP(IX) Z_{LP} Height of the channel inlet measured from the point at which pressure is uniform (cm). Used to calculate the ΔP_{inlet} due to gravity.

14	NXE,(NCH(IX),IX=1,NXE)	8I10, (10X,7I10)	

NCH(IX) Number of channels in thermal region IX.

15	NXE,(NROD(IX),IX=1,NXE)	8I10, (10X,7I10)	

NROD(IX) Number of fuel rods in a channel from region IX.

16	NXE,(NDIM(IX),IX=1,NXE)	8I10, (10X,7I10)	
17	NTD,(ELM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	NTD ≤ **NFBMAX**
18	NTD,(WHTM(ITD),ITD=1,NTD)	I10,7EI0.3, (10X,7E10.3)	
19	NTD,(A0M(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
20	NTD,(ACELM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
21	NTD,(DEM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
22	NTD,(BETOMM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
23	NTD,(BETGMM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
24	NTD,(FPM(ITD),ITD=1,NTD)	I10,7E10.3, (10X,7E10.3)	
25	NTD,(CLAMPM(ITD),ITD=I,NTD)	I10,7E10.3, (10X,7E10.3)	

NDIM(IX)		Channel type of the IX-th thermal region.
NTD		Number of channel types.
ELM(ITD)	L	Height of the ITD-th type channel (cm).
WHTM(ITD)	W_{ht}	Heat transfer area per unit axial length of the channel (cm).
A0M(ITD)	A_0	Channel flow area (cm^2).
ACELM(ITD)	A_{cell}	The same as A0M(ITD) (cm^2). This value is used for the calculation of the relative water density in the reactivity feedback model. If the density reactivity coefficient is defined for the density of active coolant. $A_0 = A_{cell}$.
DEM(ITD)	D_e	Hydraulic diameter (cm).
BETOMM(ITD)	β_Ω	Parameter for the calculation of Ω in the subcooled boiling region, App. B6.
BETGMM(ITD)	β_γ	Parameter for the calculation of γ in the subcooled boiling region, App. B2.
FPM(ITD)	f_p	Adjustable parameter to correlate the calculated and measured void fraction distribution in the subcooled boiling region. It is inversely related to the fraction of energy invested in voids in the S.B. region, App. B3.
CLAMPM	c'	Adjustable parameter for the same purpose as f_p. This one is directly related to the mean lifetime of the voids in the S.B. region, App. B4.

26	NXE,(NFUEL(IX),IX=1,NXE)	8I10, (10X,7I10)	
27	NTFU,(RHOFM(IFU),IFU=I,NTFU)	I10,7E10.3, (10X,7E10.3)	NTFU ≤ **NFRMAX**
28	NTFU,(TFM(IFU),IFU=1,NTFU)	I10,7EI0.3, (10X,7E10.3)	
29	NTFU,(RHOCCM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
30	NTFU,(EKCLM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
31	NTFU,(TCM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
32	NTFU,(HGAPM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
33	NTFU,(TGAPM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	

NFUEL(IX)		Fuel rod type of the IX-th thermal region.
NTFU		Number of fuel rod types.
RHOFM(IFU)	ρ_{fu}	Density of the fuel in the IFU-th type of fuel rod (g/cm^3).
TFM(IFU)	T_f	Fuel pellet diameter (cm).
RHOCCM(IFU)	c_c	Cladding heat capacity (cal/cm^3 °C).
EKCLM(IFU)	k_c	Cladding thermal conductivity (cal/cm s °C).
TCM(IFU)	t_c	Cladding thickness (cm).
HGAPM(IFU)	h_{gap}	Gap heat transfer coefficient (cal/cm^2 s °C).
TGAPM(IFU)	t_{gap}	Gap width (cm).

34	NXE,(NFRC(IX),IX=1,NXE)	8I10, (10X,7I10)	
35	NTFR,(NFM(IFR),IFR=1,NTFR)	8I10, (10X,7I10))	NTFR ≤ **NFMMAX**
36	((DZFM(IFR,I),I=1,NFM(IFR)),IFR=1,NTFR)	10X,7E10.3, (10X,7E10.3)	
37	((EKFM(IFR,I),I=1,NFM(IFR)),IFR=1,NTFR)	10X,7E10.3, (10X,7E10.3)	

NFRC(IX)		Friction multiplier type of the IX-th thermal region.
NTFR		Number of friction multiplier types.
NFM(IFR)		Number of axial intervals for the IFR-th type friction multiplier.
DZFM(IFR,I)	Δz_{fr}	Length of the I-th axial interval within which the friction multiplier is uniform (cm). (I = 1 bottom of the core).
EKFM(IFR,I)	k_f	Friction multiplier for the I-th axial interval.

38	NXE,(NIN(IX),IX=1,NXE)	8I10, (10X,7I10)	
39	NTIN,(NCM(IIN),IIN=1,NTIN)	8I10, (10X,7I10)	NTIN ≤ **NCIMAX**
40	((DZINM(IIN,I),I=1,NCM(IIN)),IIN=1,NTIN)	10X,7E10.3, (10X,7E10.3)	
41	((AINM(IIN,I),I=1,NCM(IIN)),IIN=1,NTIN)	10X,7E10.3, (10X,7E10.3)	
42	((DEINM(IIN,I),I=1,NCM(IIN),IIN=1,NTIN)	10X,7E10.3, (10X,7E10.3)	
43	((EKCINM(IIN,I),I=1,NCM(IIN)),IIN=1,NTIN)	10X,7E10.3, (10X,7E10.3)	
44	((EKFINM(IIN,I),I=1,NCM(IIN)),IIN=1,NTIN)	10X,7E10.3, (10X,7E10.3)	

NIN(IX)		Channel inlet piping type of the IX-th thermal region.
NTIN		Number of channel inlet piping types.
NCM(IIN)		Number of pipes in series in the IIN-th type of piping.
DZINM(IIN,I)	Δz_{in}	Length of the I-th inlet pipe (cm) I = 1 ≡ the nearest pipe to the channel inlet.
AINM(IIN,I)	A_{in}	Flow area of the I-th inlet pipe (cm^2).
DEINM(IIN,I)	D_{ein}	Hydraulic diameter of the I-th inlet pipe (cm).
EKCINM(IIN,I)	K'_{cin}	Contraction coefficient at the boundary between the (I+1)-th and the I-th pipes.
EKFINM(IIN,I)	k_{fin}	Friction multiplier for the I-th pipe.

45	NXE,(NEX(IX),IX=1,NXE)	8I10, (10X,7I10)	
46	NTEX,(NEXM(IEX),IEX=1,NTEX)	8I10, (10X,7I10)	NTEX ≤ **NCEMAX**
47	((DZEXM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	
48	((AEXM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	
49	((DEEXM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	
50	((EKEXM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	
51	((EKFEXM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	
52	((THETEM(IEX,I),I=1,NEXM(IEX)),IEX=1,NTEX)	10X,7E10.3, (10X,7E10.3)	

NEX(IX)		Exit piping type of the IX-th thermal region.
NTEX		Number of exit piping types.
NEXM(IEX)		Number of pipes in series in the IEX-th type of piping.
DZEXM(IEX,I)	z_{ex}	Length of the I-th exit pipe (cm) I = 1: the nearest pipe to the exit of the channel.
AEXM(IEX,I)	A_{ex}	Flow area of the I-th exit pipe (cm^2).
DEEXM(IEX,I)	D_{ex}	Hydraulic diameter of the I-th exit pipe (cm).
EKEXM(IEX,I)	k_{ex}	Contraction coefficient at the boundary between the (I-1)-th and the I-th pipes.
EKFEXM(IEX,I)	k_{fex}	Friction multiplier for the I-th pipe.
THETEM(IEX,I)	θ_{ex}	Angle of the I-th pipe tilt from vertical.

53	(EPSINP(I),I=1,8)	8E10.3	

EPSINP(I) ε_i Convergence criteria for the iterative calculations.

*Calculation of the flow distribution among the channels:

EPSINP(1)	(0.02)	pressure drop relative error $\leq \varepsilon_1$.
EPSINP(2)	(0.01)	total flow relative error $\leq \varepsilon_2$.
EPSINP(3)	(0.01)	mass velocity relative error $\leq \varepsilon_3$.

*Calculation of the flow quality in the subcooled boiling region:

EPSINP(4)	(0.00002)	flow quality error $\leq \varepsilon_4$.

*Calculation of void fraction:

EPSINP(5)	(0.001)	void fraction relative error $\leq \varepsilon_5$.

*Calculation of boundary between the subcooled and the bulk boiling regions:

EPSINP(6)	(10^{-9})	normalized degree of subcooling error $\leq \varepsilon_6$.

*Calculation of the steady state temperature distribution within a fuel rod:

EPSINP(7)	(0.01)	fuel temperature relative error $\leq \varepsilon_7$.
EPSINP(8)	(0.05)	fuel heat transfer energy balance relative error $\leq \varepsilon_8$.

54	NFNO,(NFPRT(I),I=1,NFNO)	8I10, (10X,7I10)	See IOP(6) NFNO ≤ **NAPMAX**

NFNO	Number of axial points to edit the transient response of the fuel rods.
NFPRT(I)	Axial node number to edit the transient response of the fuel rods.

57	ZN, SN	10X,2E10.3	

ZN	Parameter to vary the axial power shape peak location.
SN	Parameter to vary the axial power shape peaking factor.

If ID 57 is input, the axial power shape is calculated as

$$P(Z) = \left[\sin \pi \left(\frac{Z}{H} \right)^{1/ZN} \right]^{SN}$$

58	NXE,(NDIMV(IX),IX=1,NXE)	8I10, (10X,7I10)	
59	NTDV,(NODV(NV),NV=1,NTDV)	8I10, (10X,7I10)	NTDV ≤ **NVAMAX**
60	((DZVM(NV,I),I=1,NODV(NV)),NV=1,NTDV)	10X,7E10.3, (10X,7E10.3)	
61	((AVM(NV,I),I=1,NODV(NV)),NV=1,NTDV)	10X,7E10.3, (10X,7E10.3)	
62	((DEVM(NV,I),I=1,NODV(NV)),NV=1,NTDV)	10X,7E10.3, (10X,7E10.3)	

NDIMV(IX)	Variable-area channel type of the IX-th thermal region.
NTDV	Number of variable-area channel types.
NODV(NV)	Number of axial intervals for the NV-th type, variable-area channel.
DZVM(NV,I)	Top height from bottom of the I-th variable-area axial interval of channel variable-area NV-type (cm).
AVM(NV,I)	Boiling cell flow area of the I-th variable-area axial interval of channel variable-area NV-type (cm^2).

DEVM(NV,I)	Hydraulic diameter of the I-th variable-area axial interval of channel variable-area NV-type (cm).

63	NXE,(NDIMLL(IX),IX=1,NXE)	8I10, (10X,7I10)	
64	NTDLL,(NODLL(NLL),NLL=1,NTDLL)	8I10, (10X,7I10)	NTDLL ≤ **NLLMAX**
65	((DZLLM(NLL,I),I=1,NODLL(NLL)),NLL=1,NTDLL)	10X,7E10.3, (10X,7E10.3)	
66	((EKLLM(NLL,I),I=1,NODLL(NLL)),NLL=1,NTDLL)	10X,7E10.3, (10X,7E10.3)	

NDIMLL(IX)	Local pressure loss type of the IX-th thermal region.
NTDLL	Number of local-loss channel types.
NODLL(NLL)	Number of axial intervals for the NLL-th type, local loss channel.
DZLLM(NLL,I)	Top height from bottom of the I-th local loss axial interval for channel local loss type NLL-th (cm).
EKLLM(NLL,I)	Local loss constant for the I-th axial interval of channel local loss type NLL-th.

67	NTFU,(IFFM(IFU),IFU=1,NTFU)	8I10, (10X,7I10)	NTFU ≤ **NFRMAX**
68	NTFU,(ANM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
69	NTFU,(BNM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
70	NTFU,(CNM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
71	NTFU,(DNM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
72	NTFU,(RRM(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	

These cards (67-72) are necessary only if the Friction Factor Model II is used. The equations of this model are:

$$FF = MAX(FF, FF_{LAM})$$

$$FF_{LAM} = \frac{64.0}{Re_l}$$

$$FF = AN \cdot \left[1 + (BN \cdot R_r) + \frac{CN}{Re_l}\right]^{DN}$$

where AN, BN, CN, DN are input-user data, R_r is the relative roughness, and Re_l is the liquid Reynolds number

IFFM(IFU)		Friction factor model II option, for the IFU-th fuel rod type. If IFFM = 2, the friction factor model II is used.
ANM(IFU)	AN	Coeficient AN for the friction factor model II option, for the IFU-th fuel rod type.
BNM(IFU)	BN	Coeficient BN for the friction factor model II option, for the IFU-th fuel rod type.
CNM(IFU)	CN	Coeficient CN for the friction factor model II option, for the IFU-th fuel rod type.

DNM(IFU)	DN	Coeficient DN for the friction factor model II option, for the IFU-th fuel rod type.
RRM(IFU)	R_r	Relative roughness for the friction factor model II option, for the IFU-th fuel rod type.

73	NTFU,(IFMM(IFU),IFU=1,NTFU)	8I10, (10X,7I10)	NTFU ≤ **NFRMAX**
74	NTFU,(AJUSTAA1M(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
75	NTFU,(AJUSTAB1M(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	
76	NTFU,(AJUSTAC1M(IFU),IFU=1,NTFU)	I10,7E10.3, (10X,7E10.3)	

These cards (73-76) are necessary only if the Friction Multiplier Model II (Chisholm-Baroczy) is used. The equations of this model are:

$$\mathrm{GMSQ} = \left[\left(\frac{\mu_g}{\mu_F}\right)^{0.2}\left(\frac{\rho_l}{\rho_g}\right)\right]$$

$$\mathrm{BGM} = \sqrt{\mathrm{GMSQ}}$$

$$B = \frac{55.0}{[\mathrm{AJUSTAB}_1 \cdot G]^{0.5}} \quad \mathrm{BGM} \le 9.5$$

$$B = \frac{520.0}{\mathrm{BGM} \cdot [\mathrm{AJUSTAB}_1 \cdot G]^{0.5}} \quad 9.5 < \mathrm{BGM} < 28$$

$$B = \frac{15000.0}{\mathrm{GMSQ} \cdot [\mathrm{AJUSTAB}_1 \cdot G]^{0.5}} \quad 28 \le \mathrm{BGM}$$

$$\phi_{l0}^2 = \mathrm{AJUSTAC}_1 \cdot$$
$$\left\{1.+(\mathrm{GMSQ}-1.)\cdot\left[B\cdot \mathrm{AJUSTAA}_1 \cdot XF^{0.9}\cdot(1.-\mathrm{AJUSTAA}_1\cdot XF)^{0.9} + \mathrm{AJUSTAA}_1\cdot XF^{1.8}\right]\right\}$$

where μ_g is the steam viscosity; μ_F is the saturated liquid viscosity; ρ_l is the saturated liquid density; ρ_g is the steam density; $\mathrm{AJUSTAA}_1$, $\mathrm{AJUSTAB}_1$, $\mathrm{AJUSTAC}_1$ are fit factors for G, XF and Global (default=1.0, 1.0, 1.0); G is the mass flux (kg/m^2 s); and XF is the flow quality.

IFMM(IFU)	Friction multiplier model II option, for the IFU-th fuel rod type. If IFMM= 2, the friction multiplier model II is used.
AJUSTAA1M(IFU)	Coeficient $\mathrm{AJUSTAA}_1$ for the friction multiplier model II option, for the IFU-th fuel rod type.
AJUSTAB1M(IFU)	Coeficient $\mathrm{AJUSTAB}_1$ for the friction multiplier model II option, for the IFU-th fuel rod type.
AJUSTAC1M(IFU)	Coeficient $\mathrm{AJUSTAC}_1$ for the friction multiplier model II option, for the IFU-th fuel rod type.

4.4. OUTPUT DESCRIPTION OF LAPURX

First, the date of the day is printed, followed by a listing generated by OUTIN of the input parameters using the input mnemonics are described in App. C2 of Reference 1.

Next, a list of those system parameters directly calculated from the input parameters is printed by READY.

What follows next depends on the selected options in card 2. Provided that they have not been bypassed by the options, the subroutines produce output in the following sequence:

a. During the Iterations*

*Calculation controlled by IOP(1).

Let M be the number of iterations required to find the steady state flow distribution. Then,

FLOW_m

prints its output M - 1 times, once for each iteration (i.e., for all m = 1 to M - 1).

b. When the Steady State Is Found

$\text{STEADY}_M(\text{IX})^{\dagger}$ $\text{FUELX(IX)}^{\ddagger}$ COEFR(IX)^{**}

Print their output NXE times, once for each channel, that is, for all IX = 1 to NXE, followed by the output of FLOW_M. The subindex M indicates the values corresponding to the converged last flow iteration.

†Output controlled by IOP(4).

‡Output controlled by IOP(5).

**Output controlled by IOP(7).

Description of the Output Generated by These Subroutines

- OUTIN

Prints the INPUT parameters using the same mnemonics found in the input instructions.

- READY

The parameters printed are:

Mnemonics	Math & Units	Description
IX-INITIAL POWER RATIO	$\dfrac{\Phi_{ix}}{\sum_{ix} \text{NCH}_{ix}\,\Phi_{ix}}$	Fraction of total power that is produced per fuel bundle pertaining to region IX, it will remain constant unless the exit quality is the variable fixed by NOPT(5).
T0=TIN	(°C)	Water inlet temperature.
TSAT	(°C)	Water saturation temperature.
H0	(cal/g)	Enthalpy of inlet water.
HF	(cal/g)	Enthalpy of water at TSAT.
HFG	(cal/g)	Enthalpy of evaporation of water.
RHOLIN	(g/cm^3)	Density of inlet water.
RHOL	(g/cm^3)	Density of water at TSAT.
RHOS	(g/cm^3)	Density of steam at TSAT.
MU(T0)	$\mu_{T0}\ (\text{kg s/cm}^2)$	Dynamic viscosity of water at T0.
MU(TSAT)	$\mu_{Tsat}\ (\text{kg s/cm}^2)$	Dynamic viscosity of water at TSAT.
K(T0)	$k_{T0}\left(\dfrac{\text{cal}}{\text{s cm}\,^\circ\text{C}}\right)$	Heat conductivity of water at T0.
K(TSAT)	$k_{Tsat}\left(\dfrac{\text{cal}}{\text{s cm}\,^\circ\text{C}}\right)$	Heat conductivity of water at TSAT.

PRAN(T0)	Pr_{T0}	Prandtl number for water at T0.
PRAN(TSAT)	Pr_{Tsat}	Prandtl number for water at TSAT.
ETA	η	= 1 - RHOS/RHOL.
XI	$\frac{p v_s}{J h_{fg}}$	Mechanical to thermal power ratio of the evaporation process.
KS,R	$k_{s,r}$	Correction coefficient for the Bankoff steam water slip correlation

- STEADY(IX)

The output of this subroutine is performed by OUTST. Note: those variables whose headings in the printout are self explanatory are not included in this description.

Under the heading "Subcooled and Bulk Boiling Regions":

I	i	Node number
Z	z (cm)	Vertical position of the lower node boundary.
Dβ/DZ	$\frac{\partial \beta}{\partial z}$ (cm^{-1})	Void fraction gradient.
Dβ/DX	$\frac{\partial \beta}{\partial z}$	Slope of void fraction vs quality.
DPAC	(kg/cm^2)	Pressure drop from inlet due to acceleration.
DPDH	(kg/cm^2)	Pressure drop from inlet due to gravitation.
DPFR	(kg/cm^2)	Pressure drop from inlet due to friction.

Under the heading "Subcooled Boiling Region":

Subcool enthalpy	$\frac{h_f - h_i}{h_{fg}}$	Enthalpy difference to saturation, relative to h_{fg}.
FS01	$F_{s_{01}}$	Fraction of energy invested in voids at the entrance of the node. See App. B3.
FS02	$F_{s_{02}}$	Fraction of energy invested in voids at the exit of the node.
FPH1	$F(\phi)$	Heat flux dependent factor for the calculation of the bubble lifetime in the SBR. See App. B4.

In the next page:

NNB		Number of nodes in the nonboiling region (NBR).
NSB		Number of nodes in the subcooled boiling region (SBR).
NBB		Number of nodes in the bulk boiling region (BBR).
QAV	q_{av} (cal/cm^2 s)	Average heat flux rate in the channel.
W0	ω_0 (g/s)	Total mass flow rate through the channel.
U0	u_0 (cm/s)	Volumetric flow rate per unit area (fluid velocity) in the channel at saturated liquid density equivalent mass.
KFNB	kf_{nb}	Crude friction factor multiplier for the NBR.
LAM0	λ_0 (s^{-1})	Parameter for the calculation of the mean lifetime of the bubbles in the subcooled boiling region.
TAUK	τ_k (s)	Node transient time corresponding to the stream density equivalent mass fluid velocity.

C17		Bulk boiling boundary subcooling to void transformation factor.
TZNB	T_{z1} (°C)	Temperature of the water at the subcooled boiling boundary (SBB).
ZNB	$z_{nb}=z_1$ (cm)	Position of the SBB.
ZB	$z_b=z_2$ (cm)	Position of the boiling boundary if subcooled boiling did not occur.
ZBB	z_{bb} (cm)	Position of the bulk boiling boundary (BBB).
IZNB	$E_{i_{z_{nb}}}$	Fraction of power deposited in the coolant in the NBR.
IZB	$E_{i_{z_b}}$	Fraction of bundle power invested in heating the water to saturation temperature.
IZBB	$E_{i_{z_{bb}}}$	Fraction of power deposited in the coolant below the BBB.
HZNB	$h_{z_{nb}}$ (cal/g)	Enthalpy of the water at the SBB.
DELTAH	Δh (cal/g)	Enthalpy increment in the NBR.
RHOZNB	$\rho_{z_{nb}}$ (g/cm^3)	Density of water at the SBB.
RHOLB	ρ (g/cm^3)	Average density of water below the BBB.
CPSB	$c_{p_{sb}}$ (cal/g °C)	Specific heat of water at the average temperature of the NBR.
CPSAT	$c_{p_{sat}}$ (cal/g °C)	Specific heat of water at saturation temperature.
CPAVG	$c_{p_{avg}}$ (cal/g °C)	Average specific heat of water in the NBR.
OMEGA	Ω	Jones correction factor to the Martinelli-Nelson two - phase friction multiplier. See App. B6.
DOMDY0	$\left(\dfrac{\partial\Omega}{\partial y}\right)_0$	Slope of the Jones factor vs flow rate relation.
H02LAST	H_{02}	Degree of subcooling, relative to h_{fg}, at the exit of the last subcooled boiling node.
FNB	f_{nb}	Moody single phase friction coefficient in the NBR.
FSB	f_{sb}	Moody single phase friction coefficient in the SBR.
FBB	f_{bb}	Moody single phase friction coefficient in the BBR.
A2NB	$a_{2_{nb}}$	Reynolds number exponent for the nonboiling region.
A2SB	$a_{2_{sb}}$	Reynolds number exponent for the SBR.
A2BB	$a_{2_{bb}}$	Reynolds number exponent for the BBR.
RE(T0)	Re_{T_0}	Reynolds number for the fluid at temperature T0.
RE(TSAT)	$Re_{T_{sat}}$	Reynolds number for the fluid at temperature TSAT.
EKFL	k_f	Surface friction factor multiplier for those nodes in the boiling region.

In the next output page, the results of the solution of the momentum equation are printed in self explanatory fashion.

- FLOW

M	Flow redistribution iteration number.

QPL		Average pressure drop in the channels (slope weighted).
WTP		Total core flow rate.
IX		Channel type number.
NCH		Number of channels of a type in the core.
POWFR		Power fraction of the core total that is generated in one channel.
QG	(g/cm^2 s)	Channel mass velocity.
QX		Channel exit steam quality.
QP	(kg/cm^2)	Channel pressure drop.
WN0	(g/s)	Mass flow rate in a channel region.
POWT		Nominal power generated in the core.

- FUEL

I	i	Vertical node number.
NFU		Cross sectional fuel ring zone number.
P	(cal/s cm)	Power generated in a ring per unit length.
T	(°C)	Fuel temperature at the center of the ring.
K	(cal/s cm °C)	Fuel thermal conductivity.
RHOCF	(cal/cm3 °C)	Specific heat of the fuel.
CAP	(cal/cm °C)	Heat capacity per unit length of fuel.
RES	(s cm °C/cal)	Thermal resistance. The last ring includes the gap and the inner half of the clad. See Eq. (3.2.17).
ALP	α	Parameters for the transient analysis. See Eq. (3.2.42).
BET	β	
GAM	γ	
PTP	(cal/s cm)	Total power generated in the node that is transmitted to the coolant by convection.
TC	(°C)	Temperature at the center of the clad.
TG	(°C)	Temperature of the gap.
TAV	(°C)	Fuel average temperature.
RFUEL		Average thermal resistance of the fuel.
RGAP		Thermal resistance of the gap.
RCLD1		Thermal resistance of the inner half of the clad.
RCLD2		Thermal resistance of the outer half of the clad.
EPSW		Effect of the film coefficient on the thermal conductance of the outer half of the clad and water film. See Eq. (3.2.34).
EPSY		Effect of the flow rate on the convective heat transfer coefficient. See Eq. (3.2.36).

- COEFR

The output of this subroutine if performed by OUTCOR:

HL0	(cal/g)	Liquid phase enthalpy.
TL0	(°C)	Liquid phase temperature.
RHO	(g/cm^3)	Liquid phase density.
RHOA	(g/cm^3)	Average nodal density. See Eq. (3.2.8).
HTC	(cal/cm2 °C)	Convective heat transfer coefficient. See App. B1.

DRS	$\frac{\partial \rho_a}{\partial s}$ (g/cm^3)	Partial derivative of nodal density with respect to liquid temperature factor s in the NBR. See Eq. (B9.8).
DRH	$\frac{\partial \rho_a}{\partial H}$ (g/cm^3)	Partial derivative of nodal density respect to the degree of subcooling with H in the SBR. See Eq. (B9.14).
DRB	$\frac{\partial \rho_a}{\partial \beta}$ (g/cm^3)	Partial derivative of nodal density with respect to the void fraction β in the boiling region. See Eq. (B9.14).
C1 C4		Coefficients of Eq. (B9.17).
C4 C12		Coefficients of Eq. (B9.4).
C13 C16,C21,C22		Coefficients of Eq. (B10.3).
TAU =	$\frac{\rho_1 z_1}{\rho_2 u_0}$	Nonboiling region transit time constant.
TAUA =	$\frac{\Delta z_i}{2u_0}$	Nodal transit time constant. See Eq. (B9.17).
TAUL =	C18 τ_{NBR}	Pressure differential between inlet plenum and boiling boundary time constant. See Eq. (B10.2b). Note that τ_{NBR} = TAUIP (DZ = z).
TAUIP	$\frac{u_0 \Delta z_i}{gL}$	Nodal momentum transfer time constant. See Eq. (B10.2a).
C17		Enthalpy to void TF at the boiling boundary. See Eq. (B9.22b).
C18		Flow to pressure drop from plenum to the boiling boundary gain coefficient. See Eq. (B10.2b).

4.5. ALPHABETICAL DESCRIPTION OF THE LAPURW SUBROUTINES

MAIN

Subroutine ANGLE

Called from: PRINTA, PRINTB and RESPON.
Input: Arguments: A ≡ imaginary number,
B ≡ real number,
C ≡ angle in the range 90,
IFLG ≡ quadrant flag,
ICOUNT ≡ counter,
I ≡ number of vectors to be printed in a row.
Performs: Calculation of the true angle in degrees defined by A and B. The vectors IFLG, ICOUNT, and I are used to track the displacement of the vector pointer defined by A and B in the plane (R, Im) as the subroutine is called repeatedly. The purpose is to account for crossings of the imaginary axis by the pointer. It adjusts C by adding 180° when the pointer moves clockwise, and by subtracting 180° when it moves counterclockwise.
Output: Argument: C ≡ corrected angle.

Subroutine COEFIW

Called from: TRANS.
Input: (i) Arguments: IX ≡ channel index number,
CSS ≡ complex driving perturbation.
(ii) COMMONS: INPT, REDY, SETP, PRPR, BNDY, NOHD, NOHD2, BOIL, BOIL2, CEFR, CEFR2, FEEL.
Performs: Calculation of the frequency dependent coefficients needed to solve the thermohydrodynamic equations.
Output: COMMON: CEFI.

Subroutine COND

Internal routine called from: COUPXS, DIF, JOSELE, PEPE.

Subroutine CONSIS

Internal routine called from: RESPON, SEARCH

Subroutine COUPXS

Internal routine called from: WEIGHT

Subroutine DBDEG

Called from: STABGH.
Input: Arguments: X ≡ real part vector,
Y ≡ imaginary part vector,
N ≡ length of the vectors X, and Y.
Performs: Determination of the magnitude in decibels and phase in degrees of the complex number X + jY.
Output: Arguments: AMAG ≡ magnitude in decibels,
PH ≡ phase in degrees.

Subroutine DIF

Internal routine called from: JOSELE

Subroutine DRUMR1

Called from: WEIGHT and TRANS.

Input: IX ≡ channel number index.

Performs: Sequential reading of the coolant steady state parameter map of a channel into the COMMON statements listed below. This subroutine is the read equivalent to DRUMW1 in LAPURX.

Output: COMMONS: SETP2, SETP, PRPR2, PRPR, BNDY, NOHD, NOHD2, BOIL, BOIL2, BALK, FRCT2, FRCT, DLTP, PRPI2, PRPI, OMGP2, OMGP, CEFR, CEFR3, CEFR2, REACOE.

Subroutine DRUMR2

Called from: MAIN.

Input:

Performs: Sequential reading of steady state data into the COMMON areas listed below. This subroutine is the read equivalent to the write subroutine DRUMW2 in LAPURX.

Output: COMMONS: IIOP1, DATA, INPT, INPT2, REDY2, REDY, ADD.

Subroutine DRUMR3

Called from: TRANS.

Input: IX ≡ channel number index.

Performs: Sequential reading of the fuel steady state parameter map into the COMMON areas listed below. This subroutine is the read equivalent to DRUMW3 in LAPURX.

Output: COMMONS: ADIN, FUL, FULIX.

Subroutine DRUMW3

Called from: TRANS

Input: (i) Argument: IX.
(ii) COMMONS: ADIN, FUL, FULIX.

Performs: Saving out of core of the thermal parameters of the fuel rods within a channel for subsequent use in the dynamics calculations.

Output: Logical unit 1: Sequential unformatted writing of the COMMON statements listed above.

Subroutine FREQ

Called from: TRANS.

Input: IX ≡ channel type index,
CSS ≡ complex driving perturbation,
PSIA ≡ reactivity weighting factors array,
DKDRHO ≡ density reactivity coefficients array,
CDYPB ≡ complex driving flow rate perturbation,
CDRAMB ≡ complex driving power generation perturbation,
CDTIN ≡ complex driving coolant temperature perturbation,
IW ≡ frequency index number,
JJJ ≡ flag,
MX ≡ maximum number of channel types,

MP ≡ maximum number of thermohydraulic nodes,
MJ ≡ maximum number of subcores in a horizontal plane.
COMMONS: DOPP, REACOE, NODS, INPT, REDY, SETP2, SETP, BNDY, BOIL, BOIL2, CEFR, CEFR2, FEEL, CEFI, ADD1.

Performs:
(i) Solves the continuity and energy equations for the coolant at each node along the channel. As indicated in the response of the nodal mass flow rate, liquid temperature and void fraction (hence, density) to the driving perturbations are calculated.
(ii) The nodal density perturbations are multiplied by the reactivity coefficients and weighting factors to yield reactivity contribution of each subcore.
(iii) The momentum equations are subsequently solved to generate the channel pressure TFs.
(iv) The response of the average temperature of the fuel is determined by means of Eq. (3.2.43). Subsequently, multiplication by the Doppler reactivity coefficient and weighting factors produces the Doppler reactivity TFTFs.

Output:
(i) Argument: CDROA ≡ coolant density response map.
(ii) COMMONS: FRIQ, FEL2.

Subroutine FUEL

Called from: TRANS

Input:
(i) Argument: IX.
(ii) COMMONS: DATA, INPT, SETP, SETP2, PRPR, BNDY, NOHD, CEFR, CEFR3, ADIN, ADD1, IIOP1.

Performs:
(i) Calculation of the temperature distribution across the fuel element at every node as described in the fuel steady state calculation (paragraph 3.2.2.1).
(ii) Calculation of the parameters α, β, and γ for the dynamics analysis as described in Eq. (3.2.42).
(iii) Saving into common FEL1 the characteristics of up to 10 vertical nodes as specified by NFPRT at input time.

Output:
(i) COMMONS: TFUEL1, FUL, FEL1, FULIX.
(ii) Logical unit 6: Error message 3.

Subroutine FUELW

Called from: TRANS.

Input:
(i) Arguments: IX ≡ channel type index number,
CSS ≡ complex driving perturbation's frequency.
(ii) COMMONS: INPT, BNDY, NOHD, CEFR3, ADIN, ADD1, FUL, FULIX.

Performs: Solution of fuel dynamics equations, as described in paragraph (3.2.23), for three unity driving perturbations of power generation, coolant flow rate, and coolant temperature, one at a time. This subroutine yields the set of fuel TFs a_q, b_q, c_q and a_T, b_T, c_T for each node along the channel, as described in paragraph (3.2.3).

Output: COMMONS: FEEL, FEL2.

Subroutine INCROD

Called from: INPUTW

Input:

Performs: Reading of control-rod data when cross sections are specified

Output:

Subroutine INPUTW

Called from: MAIN.

Input: Logical unit 5.
Performs: Reading of the data that specify the dynamic calculation to be performed. The subroutines INPW1, INPW2, INPW3, INPW4, INPW5, and INPW6 are called to input some of the data arrays. Three kinds of information are input: (i) reactor constitution in terms of thermohydraulic channel types, composition of the nuclear subcores; (ii) neutronic parameters; and (iii) output options.
Output:
(i) COMMONS: TITLEW, INOUT, NNNNN, TESTSU, DOPP, RELOOP, NNEUTR, XNEUTR, NDENRE, DENRE, WINK, NODS, MPLO.
(ii) Logical unit 6: Error message (self explanatory).

Subroutine INPW1

Called from: INPUTW
Input: NO, NNN
Performs: Reads an array of integers of length NO in the standard format 8I10 for the first line and 10X,7I10 for the continuation lines
Output: NNN

Subroutine INPW2

Called from: INPUTW
Input: NO, NNN, AAA, ID
Performs: Reads a two-dimensional array of floating point variables in the standard format 10X,7E10.5. The row index is input in ID.
Output: AAA(ID, *)

Subroutine INPW3

Called from: INPUTW
Input: NO, AAA
Performs: Reads an array of floating point variables in the standard format I10,7E10.5 for the first line and 10X,7E10.5 for the continuation lines.
Output: AAA(*)

Subroutine INPW4

Called from: INPUTW
Input: MA, I1, I2, N1
Performs: Reads a two dimensional integer array in the standard format 10X,7I10.
Output: MA

Subroutine INPW5

Called from: INPUTW
Input: MA, I1, I2, I3, N1, N2
Performs: Reads a three dimensional integer array in the standard format 10X,7I10.
Output: MA

Subroutine INPW6

Called from: INPUTW
Input: A, I1, I2
Performs: Reads a two dimensional real array in the standard format 10X,7E10.5.
Output:

Subroutine INXS2G

Called from: INPUTW

Input: none
Performs: Reads the cross section data
Output: A(), the cross section coefficients

Subroutine JOSELE

Called from: REACFA
Input: BETAXS_ IFT, ICT, D
Performs: Computes the void reactivity coefficient
Output: D

Subroutine LIMIT

Called from: MODE2, RESPON
Input: GM, H0
Performs: Estimates the limit cycle amplitude and average power increase given an unstable reactor configuration
Output: PMAX, P0, R0, IER

Subroutine LINEAR

Called from: FTK, FTRC
Input: X,Y,XF,YF
Performs: Perform linear interpolation
Output: Y

Subroutine MARGIN

Called from: MODE2, RESPON, SEARCH, SENS
Input: GH, W, NW
Performs: This subroutine estimates the phase and gain margins of an open-loop TF
Output: PM, WPM, GM, WGM

Subroutine MODE2

Called from: RESPON
Input: NPAGE
Performs: This subroutine estimates and prints the stability of the first subcritical mode as a function of subcritical reactivity
Output: none

Subroutine NODOS

Called from: WEIGHT and TRANS.
Input: (i) Arguments: IX ≡ channel index number,
X ≡ vector containing the quantity to be integrated over the core volumes,
MX ≡ maximum length of the vector X,
WE ≡ vector with the integrand weighting factors,
MW ≡ maximum length of the vector WE,
XAVKJ ≡ zeroed 4 by 10 array,
L, LL, and LLL ≡ flags.
(ii) COMMONS: REDY, BNDY, NOHD, NODS, INPT.
Performs: (i) Calculation of the cores boundaries in terms of the thermohydrodynamic node index numbers along a channel.
(ii) Calculation of the power generated in each nuclear core.
(iii) Calculation of the integrals

$$\int_{V_{ix,k}} X W\, dV\,;\quad \int_{V_{ix,k}} W\, dV\,;\quad \int_{V_{k,j}} X W\, dV\,;\quad \int_{V_{k,j}} W\, dV\,;$$

and the averaging ratio

$$\frac{\int_{V_{k,j}} X W\, dV}{\int_{V_{k,j}} W\, dV}\,;$$

where

$V_{ix,k} \equiv$ volume of channel ix within the nuclear core level k,

$V_{k,j} \equiv$ volume of the nuclear core of coordinates k,j.

The effect of the flags is the following:

If $L \le 0$	W(I) = WE for all I = 1 to MX;
$L > 0$	W(I) = WE(I) for all I = 1 to MX;
If $LL \le 0$	calculate the core's boundaries and power [steps (i) and (ii)];
$LL \ge 0$	perform averaging ratio;
$LL = N$	≡ number of nodes in the boiling region of channel, then the X array needs to be padded with zeroes and shifted;
If $LLL < 0$	the vectors X and WE contain center of node values;
$LLL > 0$	the vectors X and WE contain node boundary values;

Output: (i) Argument:
(ii) COMMONS: NODS.

Subroutine NODREA

Called from: TRANS
Input: NBN, IX
Performs: Gets the node numbers where there is a boundary of cross section types
Output:

Subroutine ONECOR

Called from: TRANS.
Input: (i) Arguments: IW ≡ frequency index,
I011 ≡ pointer index for direct access file 11,
CSS ≡ complex driving perturbation,
NDG ≡ number of delayed neutron groups,
ELSTR ≡ effective neutron lifetime,
BTF ≡ vector of delayed neutron fractions,
RAMDA ≡ vector of delayed neutron lifetimes.
(ii) COMMONS: RCLOOP, INPT, TCHAN.
Performs: (i) Calculation of the forward neutronic reactivity to power TFTFs according to the point kinetics model.
(ii) Calculation of the Doppler and density reactivity TFTFs.
Output: (i) Logical unit 11: Content of the COMMONS: TFCHAN and TFREAC.
(ii) COMMONS: NKINET, TFREAC.

Subroutine OUTFUW

Called from: RESPON.
Input: (i) Arguments: IX ≡ channel index number,
NPAGE ≡ printed page number,
NFU ≡number of radial nodes in the fuel pin.
(ii) COMMONS: TITLEW, WINP, OUTF.

Performs: Printing of the fuel TFs a_q, b_q, c_q and a_T, b_T, c_T at selected elevations, with the help of the subroutine PRINTA.
Output: Logical unit 6: Fuel TFTFs under the headings CAQ, CAT, CBQ, CBT, CCQ, and CCT as a function of frequency.

Subroutine OUTFUX

Called from: TRANS
Input: IX, NPAGE, NFU_
Performs: Prints fuel information
Output:

Subroutine OUTINW

Called from: MAIN.
Activated by: INPWGO > 1.
Input: COMMON: DATA, TITLEW, INOUT, NNNNN, DOPP, RELOOP, NNEUTR, XNEUTR, NDENRE, DENRE, NODS, WINP, MPLO.
Performs: Print out the input data and transformation of the frequency units from those read (Hz) to the working units (rad/s).
Output: Logical unit 6: Check print of the data read by the subroutine INPUT.

Subroutine PRINTA

Called from: OUTFUW, WDSKPR.
Input: Arguments: IW ≡ frequency index number,
W ≡ frequency vector in rad/s,
CA ≡ complex vector,
CB ≡ complex vector,
IFLG ≡ quadrant flag,
COUNT ≡ counter.
Performs: Calculation of the magnitude and phase in decibels and degrees, respectively, of the elements of the two vectors CA and CB prior to printing them as a function of frequency in hertz. Flags IFLG and ICOUNT track the quadrant to which an element of the vector belongs so that the subroutine ANGLE can decide the angle that corresponds to the next element of the vector.
Output: Logical unit 6: Frequency, real part, imaginary part, magnitude (in dB), and phase (in deg) of the three vectors W, CA, and CB.

Subroutine PRINTB

Called from: RESPON
Input: Arguments: IW ≡ frequency index number,
W ≡ frequency vector in rad/s,
CA ≡ complex vector,
CB ≡ complex vector,
CC ≡ complex vector.
Produces: Printing of the four vectors W, CA, CB, and CB similarly to PRINTA.
Output: Logical unit 6: Magnitude (in dB) and phase (in deg) of vectors CA, CB, and CC as a function of frequency W in hertz.

Subroutine REACFA

Called from: TRANS.
Input: (i) Arguments: IX ≡ channel type index,

NBN ≡ total number of thermohydraulic nodes in the channel,
RHOA = ρ_a ≡ map of average nodal coolant density in the channel,
RHOL = ρ_2 ≡ coolant density at saturation temperature.

(ii) COMMONS: NNNNN, NDENRE, DENRE, NODS.

Performs: Determination of the core map of density reactivity coefficients by means of the function COEF and subroutine JOSELE operating on the input data tables.

Output: Argument: DKDRHO (IX, I, IJ) ≡ map of density reactivity coefficients for channel type IX in horizontal nuclear core region IJ.

Subroutine RECIRC

Called from: TRANS.

Input: (i) Argument: CSS ≡ complex driving perturbation.
(ii) COMMONS: RCLOOP, TFCHAN.

Performs: Calculation of the recirculation loop TFs as indicated in Eq. (3.3.22).

Output: COMMONS: RCLOOP

Subroutine RESPON

Called from: MAIN.

Input: (i) Arguments: NPACE ≡ output printed page number,
NK ≡ number of cores in the vertical direction,
NJ ≡ number of cores in the horizontal plane,
NFU ≡ number of radial nodes within the fuel pin,
NXE ≡ number of channel types.
(ii) COMMONS: WINP, ADIN, OUTF, TITLEW, NKINET, MPLO.
(iii) Direct access logical units 10, 11, and 12.

Performs: Management of the output of the program.
(i) It takes the information stored on the on line direct access disk and prints it in an orderly manner.
(ii) Calls the stability analysis routine STABGH to calculate the natural frequency and decay ratio of the flow channels and the core.

Subroutine SEARCH

Called from: MAIN

Input: NPAGE

Performs: Searches for the position of the complex pole in the full complex plane by iteration and prints the results.

Output: none

Subroutine SENS

Called from: RESPON

Input: NPAGE

Performs: This subroutine recomputes the reactivity to power TF and estimates and prints the decay ratio for various values of density reactivity coefficient, and recirculation loop parameters

Output: none

Subroutine SPLIN

Called from: STABGH

Input:

Performs: Spline interpolation
Output:

Subroutine STABGH
Called from: MODE2, RESPON, SEARCH, SENS.
Input: (i) Arguments: IOPT ≡ flag,
IXGHF ≡ channel type number,
NPAGE ≡ print out page number,
XGH ≡ open-loop TFTF
(ii) COMMONS: WINP, MPLO.
Performs: The stability analysis of the system represented by the open-loop TF XGH. Smith's method is used to infer the decay ratio and natural frequency as described in Reference 11, pp. 120 128. A third order Lagrange interpolation scheme is used to calculate the distance to the (-1, 0) point and subsequently to generate smooth plots. IOPT = 1 indicates that the stability analysis corresponds to that of a channel. IOPT = 0 corresponds to the whole core power stability.
Output: (i) Logical unit 6: Under the heading ***STABGH*** the results of the stability assessment are printed.
(ii) COMMONS: MAGPH, ZXYW, GHDBDG.

Subroutine TRANS
Called from: MAIN, SEARCH.
Input: (i) Argument: NPAGE ≡ printed output page number.
(ii) COMMONS: NNNNN, DOPP, NNEUTR, NDENRE, DENRE, WINP, RCLOOP, NKINET, NODS, INPT, INPT2, REDY2, REDY, SETP.
(iii) Subroutines: DRUMR1, DRUMR3.
Performs: (i) Definition of direct access files 10, 11, and 12, and zeroing of some arrays.
(ii) Management of the frequency domain dynamic calculations.
First, the reactivity weighting factors for each of the cores are calculated by the auxiliary subroutine WEIGHT. Second, a big loop is opened to sequentially solve all the dynamic equations for one particular frequency at a time. After storing the calculated TFTF in the three direct access files, the loop is repeated for a new frequency.
The solution of the dynamic equations for a particular frequency proceeds as follows:
(i) The steady state coolant and fuel parameters corresponding to a particular channel are read from the intermediate storage device by means of the subroutines DRUMR1 and DRUMR3.
(ii) Based on the steady state coolant density map and the input reactivity coefficients, the weighted reactivity factor map is generated by subroutine REACFA.
(iii) Based on the steady state fuel parameters, the fuel dynamic equations are solved by means of FUELW for the current channel type and frequency. This yields the fuel TFs $a_{q,T}$ $b_{q,T}$, and $c_{q,T}$ described in paragraph (3.2.2).
(iv) Prior to the solution of the coolant dynamic equations, a set of frequency dependent coefficients based on the steady state calculation is generated by means of the subroutine COEFIW.
(v) The thermohydrodynamic equations of the coolant are solved sequentially at each of the nodes along the channel by means of the subroutine FREQ. This subroutine determines a map of the response of

coolant density, density reactivity, Doppler reactivity, and pressure drop to driving perturbations of (1) channel inlet flow rate, (2) inlet coolant temperature, and (3) power generation at any specific point along the channel. To this effect, the solution of the thermohydraulic equation is repeated several times. Unity driving perturbations of inlet flow rate, power generation in the segment of channel length within the boundaries of each nuclear core, and coolant inlet temperature are considered one at a time while the rest of the independent parameters are kept equal to zero. This process yields the set of channel TFTFs in paragraph 3.2.5. Note that steps (i) through (vi) are repeated for each one of the channel types.

(vi) Taking into consideration the lower plenum flow boundary condition, the flow redistribution impedances in paragraph 3.3.4 are calculated, that is, the particular driving perturbation to particular channel flow rate TFTF, for each of the following perturbations: total core flow rate, inlet plenum temperature, and power perturbation in any of the nuclear cores.

(vii) The reactivity feedback TFTFs [Eqs. (3.3.11) and (3.3.12)] are next determined for each of the nuclear cores.

(viii) By means of the subroutine RECIRC and based on the input dynamic characteristics, the recirculation loop TFTFs are determined. They provide the link between the three driving perturbations mentioned.

(ix) By means of the subroutine ONECOR the forward neutronic TFTF is determined.

(x) By combining the neutronic and feedback TFTFs the openand closed-loop TFTFs are obtained.

<u>Output</u>: Logical unit 10 direct access: Channels fuel and coolant TFTFs.
Logical unit 11 direct access: Point kinetics TFTF
Logical unit 12 direct access: Multicore TFTF

Subroutine WDSKGH

Called from: RESPON.
Input: Arguments: NW ≡ number of frequencies,
NF ≡ direct access file number,
NOR ≡ position of the pointer,
NRECL ≡ number of records separating the values of a TFTF for two consecutive frequencies.
Performs: Picks from the specified file all of the values pertaining to the TFTF of interest.
Output: Argument: X ≡ vector with the TFTF of interest.

Subroutine WDSKPR

Called from: RESPON.
Input: Arguments: W ≡ vector of frequencies in rad/s,
NW ≡ number of frequencies,
KMOD2 ≡ flag,
NF ≡ file number,
NR ≡ pointer position,
NRECF ≡ number of records separating two consecutive frequencies of the same TFTF in the disk file,
NDEL ≡ number of records separating the two TFTFs to be printed on the same line.

Performs: Selectively picks the data stored in the direct access file and prints two TFTFs as a function of frequency by means of PRINTA. Since PRINTA requires two TFTFs when only one TFTF needs to be printed out, KMOD2 ≡ 0, and thus the second TFTF is printed as zero.

Output: Through PRINTA the content of the direct access file address by the pointer.

Subroutine WEIGHT

Called from: TRANS.

Input: (i) Argument: ALPKJ ≡ ratio of total core to individual nuclear core.

Performs:
- (i) Prior normalization of the input power shapes; the map of power squared nodal weighting factors is determined.
- (ii) By means of the subroutine NODOS, the power and power squared quantities corresponding to each nuclear core are calculated.
- (iii) The ratio,

$$\text{ALPKJ} = \alpha_{k,j} = \frac{\int_{V_T} \Phi^2 dV}{\int_{V_{k,j}} \Phi^2 dV}$$

where V_T and $V_{k,j}$ are the total and core "k,j" volumes, respectively, is determined. Note, k and j are the vertical and horizontal subcore position indices.

Output:
- (i) Argument: ALPKJ.
- (ii) COMMONS: NODS, REACWT.

Function Subroutine BESSI(N,X)

Arguments: N ≡ order of the modified Bessel function,
X ≡ argument.

Output: The value of $I_N(X)$, the modified Bessel function of order N, for the argument X. The algorithm used is valid for N < 3000 and X < 87. In the program, the subroutine FUEL uses the N = 0, that is, $I_0(X)$, function to represent the radial distribution of the power generation within the fuel pellets.

Function Subroutine BIMAG

Arguments: X ≡ magnitude in decibels,
Y ≡ phase in degrees.

Output: Imaginary component of the vector defined by X and Y.

Function Subroutines BREAL

Arguments: X ≡ magnitude in decibels,
Y ≡ phase in degrees.

Output: Real component of the vector defined by X and Y.

Function Subroutine COEF

Called from: REACFA.

Input: Arguments: RA ≡ ordinate;
NR ≡ number of points in the table, i.e., length of DR and RT;
DR ≡ vector with the ordinates of the data points;
RT ≡ vector with the abscissas of the data points.

Performs: Lagrange interpolation of the table defined by the vectors (DR, RT) to generate the value that corresponds to the ordinate RA.

Output: COEF ≡ ordinate corresponding to RA in the table (DR, RT).

Function Subroutine EXP10

Argument: X ≡ a real number.

Output: The value EXP10 = 10^X.

Function Subroutine FTDKDT(T)

Argument: T ≡ temperature in °C.

Output: The temperature derivative of the heat conductivity of the UO_2 fuel pellet. It is based on the correlation used in the subroutine FTK.

Function Subroutine FTK(T)

Internal routine called from: FTDKDT, FUEL

Function FTRC(RHOF_,T)

Internal routine called from: FUEL

Double Precision Function SEVAL(N, U, X, Y, B, C, D)

Internal routine called from: STABGH

4.6. PREPARATION OF INPUT FOR LAPURW

4.6.1. Introduction

Data are read in from logical unit 5 by the subroutine INPUTW. The input deck consists of a title card, data set cards, and a last card. The title card can contain up to 72 characters. These characters will be printed on each page of output for identification convenience.

Each data set is preceded by an ID card that identifies the set. The data sets need not be read in sequence, but the following should be considered: set 1 must be read before any other set except for sets 4, 17, 21, and 26; the sets within the groups (5, 6, 7, 8), (9, 10), (11, 12), (15, 16), and (18, 19, 20, 21) must be read in order.

A 11 ID cards carry their number in format I4. All of the numbers are right justified.

The last card is equivalent to an ID number equal to zero, thus a 0 in column 4 will terminate the input and initialize the execution of the program.

When the run is finished, a new title card is sought by the subroutine INPUTW. If the end of data is found in logical unit 5, then the execution stops; otherwise, a new case will be input and run. Note that for consecutive runs, only those data sets that change need to be entered.

Because the dynamic equations solved by LAPURW are based on linearization about the steady state conditions calculated by LAPURX, the compatibility with the input of LAPURX must be kept in mind when preparing input for LAPURW.

The link to LAPURX consists of sequential unformatted reading from the intermediate storage device into the appropriate COMMON areas. Provisions for the correct files to be accessible through logical units 1 and 2 must be made.

4.6.2. Input Description

4.6.2.1. First Card

Title ... columns 1 through 72.

4.6.2.2. Data Cards

Each data set is preceded by a card containing only the ID in format (I4).
Description of the data sets:

Data set ID No.	FORTRAN symbols	Format	Comment
1	NX, NJ, NK	3I5	NX ≤ **NCHMAX** NJ = 1 NK = 1

NX		Number of regions within which the fuel channels can be assumed thermohydraulically equal. Hence, only NX representative channel types need to be analyzed in detail. Note that NX has the same value as NXE in the LAPURX steady state run.
NJ		Number of nuclear subcores in a horizontal plane.
NK		Number of nuclear subcores in the vertical direction. Note that NJ x NK̃ total number of nuclear subcores in which the reactor core assembly is mathematically partitioned for analysis purposes.

2	((NCHXJ (IX,IJ),IX=1,NX),IJ=1,NJ)	10X,7I10	

NCHXJ(IX,IF)		Number of channels of type IX present in the horizontal nuclear mesh of index IJ. Note that SUM(NCHXJ(IX,IJ) for IJ = 1, NJ) = NCH(IX) in LAPURX.

3	(ZK(IK),IK=1,NK)	10X,4E10.5	

ZK(IK)	(cm)	Elevation, from the bottom of the core, of the upper boundary plane of the vertical nuclear mesh of index IK.

4	TAUPY, GAINPY	10X,2E10.5	

TAUPY	(s^{-1})	Time constant of the pressure to flow recirculation loop TFTF
GAINPY		Gain of the TFTF mentioned above.

5	NNEUT, NDG	2I5	NNEUT ≤ **NNDMAX** NDG ≤ **NDGMAX**
6	((IDGKJ(IK,IJ),IK=1,NK),IJ=1,NJ)	10X,7I10	
7	((BTFR(IG,IN),IG=1,NDG),IN=1,NNEUT)	10X,7E10.5, (10X,7E10.5)	
8	((XLAMD(IG,IN),IG=1,NDG),IN=1,NNEUT)	10X,7E10.5, (10X,7E10.5)	

NNEUT	Number of different sets of delayed neutron characteristics to be input.
NDG	Number of delayed neutron energy groups to be read.
IDGKJ(IK,IJ)	Identification index number to locate in the tables the delayed neutron characteristics of a subcore (IK,IJ) (i.e., IN below).
BTFR(IG,IN)	Table of delayed neutron fractions as a function of energy group IG and subcore index IN.
XLAND(IG,IN)	Table of delayed neutron decay constants as a function of energy group IG and subcore index IN.

9	((IRHOKJ(IK,IJ),IK=1,NK),IJ=1,NJ)	10X,7I10	
10	NNERO,(RHOO(IR),IR=1,NNERO)	I10,7E10.5, (10X,7E10.5)	NNERO ≤ **NROMAX**

IRHOKJ(IK,IJ)	Table of index numbers identifying a value of the table RHOO with the initial reactivity of the subcore of indices (IK,IJ).
NNERO	Length of the table RHOO.
RHOO	Table of initial reactivity values.

11	((IELSKJ(IK,IJ),IK=1,NK),IJ=1,NJ)	10X,7I10	
12	NNELS,(ELST(IE),IE=I,NNELS)	I10,7E10.5, (10X,7E10.5)	NNELS ≤ **NNLMAX**

IELSKJ(IK,IJ)	Table of index numbers identifying a value of the table ELST with the neutron lifetime in the subcore of indices (IK,IJ).
NNELS	Length of the table ELST.
ELST	Table of neutron lifetime.

13	NFT, NCOPOL	14I5	
	((((A(IXST,IABC,ICT,IFT),IXST=1,7),IABC=1,NCOPOL),ICT=1,2),IFT=1,NFT)	10X,7E10.4, (10X,7E10.4)	
	RHOLXS, RHOSXS	10X,2E10.4	
	NBT	10X, I5	

	Input for I = 1, NBT {
	IBT, NZXS(IBT)
	(ZXS(IZXS, IBT), IZXS = 1, NZXS(IBT))
	(JFT(IZXS, IBT), IZXS = 1, NZXS(IBT))
	}
		
		10X,14I5
		10X, 7E10.4
		10X, 7E10.4	

	Input for I = 1, NXE {
	IX,(NCHXBXJ(IBT, IX), IBT = 1, NBT)
	}
		10X, 7E10.4	

A	Two group cross section expansion coefficients. IXST refers to the cross section type (1 - fast diffusion coefficient, 2 - thermal diffusion coefficient, 3 - fast absorption cross section, 4 - thermal absorption cross section, 5 -

	fast fission cross section, 6 - thermal fission cross section, 7 remonition from fast group = absorption + scattering). IABC refers to the power expansion coefficients. ICT = 1 is an uncontrolled bundle and ICT = 2 is a controlled bundle. IFT refers to the fuel type.
JFT	Fuel type of axial interval IZXS for bundle type IBT.
NBT	Number of bundle types.
NCHXBJ	Number of channels of type IX that correspond to bundle type IBT.
NCOPOL	Order of the cross section expansion in power series of the density.
NFT	Number of different fuel types.
NZXS	Number of different axial intervals with constant fuel.
RHOLXS	Liquid density at pressure used in calculation of A.
RHOSXS	Steam density at pressure used in calculation of A.
ZXS	Upper height of axial fuel interval IZXS for bundle type IBT.

14	Input for I = 1, NBT {
	IBT, NZCR(IBT)
	(ZCR(IZCR, IBT), IZCR =1, NZC)
	}
		10X, 14I5
		10X,7E10.4	

	NNBC	10X, I5	

	Input for I = 1, NNBC {
	IBT, IX
	(XNBC(IZCR, IBT, IX), IZCR = 1, NZCR(IBT))
	}
		10X, 14I5
		10X, 7E10.4	

NNBC	Number of bundle types with nonzero number of controlled bundles. Bundles not input are taken as uncontrolled.
NZCR	Number of regions in which the number of bundles controlled can be considered constant.
XNBC	Number of bundles controlled in axial region IZCR of bundles type IBT and thermohydraulic region (channel) IX.
ZCR	Upper boundary of region IZCR.

Note: ID 14 must be read after ID 13. If IDs 13 and 14 are read, and IDs number 11, 12, LAPUR will compute neutron lifetime. If IDS 18 through 21 are omitted, LAPUR will compute density reactivity coefficients.

15	((ICOUPL(KJ1,KJ2),KJ1=1,NKJ), KJ2=1,NKJ)	10X,7I10	NKJ = NK*NJ
16	NNCOU,(COUPL(IC),IC=1,NNCOU)	I10,7E10.5, (10X,7E10.5)	NNCOU ≤ **NNCMAX**

ICOUPL(KJ1,KJ2)	Table of index numbers identifying a value of the table COUPL with the coupling coefficients between the subcores defined by KJ1 and KJ2, where KJ1 = K1 + (J1 - 1) × NK for subcore (K1,J1).
NNCOU	Length of the table COUPL.
COUPL	Table of neutron coupling coefficients.

17	CDOPP	10X,E10.5	

CDOPP $\frac{\partial k}{\partial T}$ [% °C] Doppler reactivity coefficient of the fuel.

18	N0COE,(LENG(IN0),IN0=1,N0COE)	8I10, (10X,7I10)	N0COE ≤ **NDRMAX**
19	(((IDNCOE(IX,IK,IJ),IX=1,NX),IK=1,NK),IJ=1,NJ)	10X,7I10, (10X,7I10)	
20	((DENSR1(I,J),J=1,LENG(I)),I=1,N0COE)	10X,7E10.5, (10X,7E10.5)	LENG(I) ≤ **NDRNMAX**
21	((REACT1(I,J),J=1,LENG(I),I=1,N0COE)	10X,7E10.5, (10X,7E10.5)	LENG(I) ≤ **NDRNMAX**

N0COE		Length of the table LENG.
LENG(IN0)		Index table containing the lengths of each of the sets of reactivity tables to be read into DENSR1 REACT1.
IDNCOE		Identification index numbers to locate in the sets of tables the correspondent to the channel IX and the subcore of indices (IK,IJ).
DENSR1	$\frac{\rho}{\rho_f}$	Set of tabulated values of relative water density.
REACT1	$\frac{\partial k}{\partial \rho}$	[% g^{-1} cm^3] Set of tabulated density reactivity coefficients.

These two matrices define a set of tables of reactivity coefficients in units of (%ΔK)/K per g/cm$_3$ as function of the relative water density. The set that applies for a particular channel and subcore is specified by IDNCOE.

22	NW,(W(IW),IW=1,NW)	I10,7E10.5, (10X,7E10.5)	NW ≤ **NFPMAX**

NW		Number of frequency points at which the dynamic response is to be calculated.
W	ω (Hz)	Frequency.

23	(IOPTW(I),I=1,22)	14I5, (14I5)	

IOPTW(M) Output options.
If IOPTW(M) = 0, no output of type M is produced by the subroutine RESPON.
If IOPTW(M) = 1 yes, output is produced.

The following outputs can be controlled:

IOPTW(1)	Fuel TFs a_q, a_T, b_q, b_T, c_q, c_T. See paragraph 3.2.2.
IOPTW(2)	Channel nodal TFs ≡ unity power perturbation response along a channel.
IOPTW(3)	Channel TFs.
IOPTW(4)	Core flow impedances z_Y, z_q, z_T.
IOPTW(5)	Recirculation loop TFs.
IOPTW(6)	Core feedback, point kinetics open-loop, and closed-loop TFTFs.
IOPTW(7)	Multicore power perturbation to pressure at the boiling boundary TFTFs of a channel, CCXK ≡ $C_{x,k}$. See Eq. (3.2.88c) and matrix C at App. B11.
IOPTW(8)	Multicore inlet flow rate to moderator density reactivity contribution to a core TFTFs CEKJ ≡ E_k. See Eqs. (3.3.1a) and matrix E at App. B11.
IOPTW(9)	Multicore inlet temperature to moderator density reactivity TFTFs CHKJ ≡ h_k. See Eq. (3.3.1c) and vector $\overline{h}$ at App. B11.

IOPTW(10)	Multicore power to core flow TFTFs CZQKJ $\equiv \bar{z}_q$ at Eq. (B12.2).
IOPTW(11)	Multicore power to moderator density reactivity TFTFs, CFKPJK $\equiv f_{k,k'}$. See Eq. (3.3.1b) and matrix F at App. B11.
IOPTW(12)	Multicore power to channel flow rate TFTFs CMXJK $\equiv$ matrix M, in Eqs. (3.3.10) and (B12.9).
IOPTW(13)	Multicore power to total moderator reactivity feedback TF matrix CQ $\equiv$ Q in Eqs. (3.3.23a) and (B12.14).
IOPTW(14)	Multicore total flow rate to total moderator reactivity feedback TF matrix CR $\equiv$ R in Eqs. (3.3.23b) and (B12.16).
IOPTW(15)	Multicore inlet temperature to total moderator reactivity feedback TF matrix CS $\equiv$ S in Eqs. (3.3.23c) and (B12.18).
IOPTW(16)	Multicore core to core power TF matrix CHQ $\equiv$ matrix H in Eq. (3.3.17) with Q as in Eq. (B12.14).
IOPTW(17)	Multicore reactor core flow rate to individual core power TF $\overline{Z}_R$ in Eq. (3.3.20).
IOPTW(18)	Multicore inlet temperature to individual core power TF vector $\overline{Z}_S$ in Eq. (3.3.20).
IOPTW(19)	Multicore closed-loop reactivity to power TF matrix Z in Eq. (3.3.16).
IOPTW(20)	Sum of the column elements of the feedback TF matrix H, that is, CDENFB$_{ROW}$ = SUM [$H_{row,col}$] for all columns.
IOPTW(21)	Sum of the column elements of the closed-loop TF matrix Z, that is, CLOSEK$_{ROW}$ = SUM [$Z_{row,col}$] for all columns.
IOPTW(22)	CRFBAC and CLTFPK, the total core reactivity feedback and power response to a unity reactivity vector perturbation. CRFBAC = SUM[CDEFB$_{ROW}$] for all rows. CLTFPK = SUM[CLOSEK$_{ROW}$] for all rows.

24	(ISTAB(IX),IX=1,NX+1)	14I5, (14I5)	

ISTAB(IX)	Stability calculation options: = 0 $\equiv$ no; 1 $\equiv$ yes. IX indicates channel type for which the hydrodynamic stability is to be calculated. When IX = NX + 1 the total core open-loop TF is analyzed if ISTAB(NX + 1) = 1.

25	(IPLOT(IX),IX=1,NX+2)	14I5, (14I5)	

IPLOT(IX)	Plotting options: = 0 $\equiv$ no; = 1 $\equiv$ yes. IX refers to the open-loop TF of channel type IX. IX = NX + 1 indicates total core open-loop TF Magnitude phase and Nyquist plots are produced for the open-loops.

26	REAMUL	7E10.5	

REAMUL	Density reactivity coefficient multiplier. If REAMUL is negative, its absolute value is taken, but a sensitivity calculation is performed on density reactivity coefficient and recirculation loop parameters.

29	NRHOSC,(RHOSC(I),I=1, NRHOSC)	I10,7E10.5	

NRHOSC	Number of subcritical reactivities at which out of phase mode stability is to be determined.
RHOSC	Array of values of the reactivity of the first subcritical neutronic mode. Note: If ID 29 is read, LAPUR5 will estimate the stability of the first subcritical neutronic mode with a parallel channel thermohydraulic feedback. If the subcritical reactivity is known, use that value and NRHOSC=1. NRHOSC>1 allows for a sensitivity calculation with little cost.

30	NSRCH	I10	

NSRCH	Number of iterations in the full Laplace domain (with real part of s not equal to 0., i.e., $s = r + jw, r \neq 0$). This is done to improve the estimate of the decay ratio. It essentially multiplies the computation time by NSRCH + 1.

31	WPCNT	E10.4	

WPCNT	Flow rate (percent of nominal). Note: If ID 31 is read after ID 4 (ID 4 may not be present), LAPUR5 computes a crude estimate of the gain and time constant of the recirculation loop based on the flow rate. This is useful for scoping calculations, but the correct value is recommended for important calculations.

32	GAINPY, TAUPY, RL_P2, RL_P3, RL_Z1, RL_Z2	8F10.0	

Extended Recirculation Loop Transfer Function. If this card is present, the pressure-to-core flow T.F used is:

$$RLPY = \frac{\delta Y}{\delta n} = \frac{GAINPY\left[1 + RL\_Z1 \times s + RL\_Z2 \times s^2\right]}{\left[1 + TAUPY \times s + RL\_P2 \times s^2 + RL\_P3 \times s^3\right]}$$

GAINPY		Gain of the pressure to flow recirculation loop TF
TAUPY	(s^{-1})	Time constant of the pressure to flow recirculation loop TF
RL_P2		Pole constant for the pressure to flow recirculation loop TF
RL_P3		Pole constant for the pressure to flow recirculation loop TF
RL_Z1		Zero constant for the pressure to flow recirculation loop TF
RL_Z2		Zero constant for the pressure to flow recirculation loop TF

4.7. OUTPUT DESCRIPTION OF LAPURW

First, the date is printed, followed by a listing produced by OUTINW of the input parameters with the same mnemonics and self explanatory headings. What follows next is the output generated by the subroutine NODOS. This subroutine produces the power in MW, average coolant density, and void fraction in each of the nuclear subcores in which the reactor is divided.

Next, the output of the TFs generated by the different subroutines is produced in the order described below. The normalization factors for the TFs are the following:

For pressure:	RHOL × L × 10^{-3} (kg/cm^2), with RHOL in (g/cm^3) and L in cm. RHOL is the density of water at saturation temperature. L is the height of the channel.
For flow:	W0 is the channel mass flow rate at steady state conditions. WT is the total core flow rate.
For power:	POW is the total power of the channel in cal/s. POWKJ is the total subcore power.
For temperature:	1 °C.

Description of the Output Generated by the Subroutines

***FUELW

The output of this subroutine is performed by OUTFUW, when invoked by RESPON, if IOPTW(1) = 1. For each channel IX and selected vertical nodes I, the following nodal TFs are printed as a function of frequency ω:

Mnemonics	Math & Units	Description
CAQ	a_q	Coolant flow rate at the node level-to-heat flux from fuel to coolant TF
CAT	a_T	Coolant flow rate at the node level-to-average fuel pellet temperature TF (of interest for Doppler reactivity).
CBQ	b_q	Power generation rate in the fuel-to-heat flux to coolant TF
CBT	b_T	Power generation rate in the fuel-to-average fuel pellet temperature TF
CCQ	c_q	Liquid phase coolant temperature at the node level-to-heat flux to coolant TF
CCT	c_T	Liquid phase coolant temperature-to-average fuel temperature TF

Note that CAQ $\equiv a_q$ and CAT $\equiv a_T$ are equal to (0. , 0.) at those nodes within the boiling length of the channel because of the assumption of independence of the convective heat transfer coefficient.

*****FREQ - TRANS**

The output of this subroutine is performed from RESPON as follows:

Unity Power Perturbations (when IOPTW(2) = 1)

Under this heading the frequency response along the length of a channel to pressure, power, and inlet temperature unit perturbation is printed.

The following prefixes are used with the variables printed:

M meaning magnitude in absolute units.
TH meaning phase in degrees.

R meaning real part.
I meaning imaginary part.

The variables whose responses are printed for all of the frequencies ω(Hz) are:

DKNB	(%ΔK)	Density reactivity response in the NBR.
DKSB	(%ΔK)	Density reactivity response in the SBR.
DKBB	(%ΔK)	Density reactivity response in the BBR.
DKN	(%ΔK)	Density reactivity response in the channel.
Y(NSB+1)		Flow rate response at the entrance of the BBR.
Y(NBB+1)		Flow rate response at the exit of the BBR.
Y(NR+1)		Flow rate response at the exit of the exit.
H(NSB+1)		Degree of subcooling response at the entrance of the BBR.
Y(1)		Flow rate response at the entrance of the SBR.
B(NSB+1)		Void fraction response at the exit of the SBR.
B(NBB+1)		Void fraction response at the exit of the BBR.
B(NR+1)		Void fraction response at the exit of the exit pipe.
CDR		Doppler reactivity response of the channel.
P(NR+1)		Pressure response at the exit of the exit pipe.
P(NBB+1)		Pressure response at the exit of the BBR.
P(NSB+1)		Pressure response at the exit of the SBR.
P(1)		Pressure response at the exit of the NBR.

The various TFS OF A CHANNEL are printed (if IOPW(3) = 1) for all the channels under the underlined heading. Note that the units of reactivity used in this section are the percent of absolute units Δk.

CAX	a_{ix}	Flow/pressure TF for channel.
CABX	$a_{ix} \times b_{ix}$	Open-loop TF of channel.
CBX	b_{ix}	Channel flow rate to pressure at the boiling boundary TF
CCX	c_{ix}	Channel power to pressure at the boiling boundary TF
CDX	d_{ix}	Channel inlet temperature to pressure at the boiling boundary TF
CDYX	$d_{y_{ix}}$	Channel flow rate to Doppler reactivity TF
CDQX	$d_{q_{ix}}$	Channel power to Doppler reactivity TF
CDTX	$d_{t_{ix}}$	Channel inlet temperature to Doppler reactivity TF
CEX	e_{ix}	Channel flow rate to density reactivity TF
CFX	f_{ix}	Channel power to density reactivity TF
CHX	h_{ix}	Channel inlet temperature to density reactivity TF
CLX	L_{ix}	Total flow rate to individual channel flow rate TF
CMX	M_{ix}	Total core power to individual channel flow rate TF
CNX	N_{ix}	Core inlet temperature to individual channel flow rate TF

*****STABGH**

This subroutine when invoked by ISTAB(IX) = 1 will produce the output of the stability analysis of channel IX in a self explanatory format in accordance with the theory in Reference 12, pp. 29 37. The TF object of the stability analysis is $CABX_{ix}$.

*****Core Flow Impedances**

Output is done by RESPON provided IOPTW(4) = 1.

CZY	z_Y	Total flow rate to channel inlet pressure TF

$$z_y = \frac{1.}{\sum_{ix} \frac{a_{ix} \times g_{ix}}{1. + a_{ix} \times b_{ix}}}$$

CZQ z_q Total core power to channel inlet pressure TF

$$z_q = z_y \times \sum_{ix} \frac{a_{ix} \times g_{ix} \times c_{ix}}{1. + a_{ix} \times b_{ix}}$$

CZT z_T Inlet temperature to channel inlet pressure TF

$$z_T = z_y \times \sum_{ix} \frac{a_{ix} \times g_{ix} \times d_{ix}}{1. + a_{ix} \times b_{ix}}$$

*****RECIRC**

Output produced by RESPON provided IOPTW(5) = 1. Under the heading, RECIRCULATION LOOP TFs:

RLPY Pressure to core flow TF:

$$RLPY = \frac{\delta Y}{\delta n} = \frac{GAINPY}{1 + TAUPY \times s}$$

CQY Total core power to core flow TF:

$$CQY = \frac{\delta Y}{\delta q} = \frac{z_q \times RLPY}{1 - RLPY \times z_y}$$

Note that CLYT = $\frac{\delta T}{\delta Y}$ and CQT = $\frac{\delta T}{\delta q}$ = CLYT × CQY are not printed since $\frac{\delta T}{\delta Y}$ is taken as (0., 0.) in this program.

*****ONECOR**

Output produced by RESPON provided IOPTW(6) = 1. Under the heading CORE REACTIVITY FEEDBACK TFs:

CAR A_r Total flow rate to density reactivity TF

$$A_r = \sum_{ix} e_{ix} \times L_{ix}$$

CAD A_d Total flow rate to Doppler reactivity TF

$$A_d = \sum_{ix} d_{y_{ix}} \times L_{ix}$$

CBR B_r Total core power to density reactivity TF

$$B_r = \sum_{ix} f_{ix} + e_{ix} \times M_{ix}$$

CBD B_d Total core power to Doppler reactivity TF

$$B_d = \sum_{ix} d_{t_{ix}} + d_{y_{ix}} \times M_{ix}$$

CCR C_r Inlet temperature to density reactivity TF

$$C_r = \sum_{ix} h_{ix} + e_{ix} \times N_{ix}$$

CCD C_d Inlet temperature to Doppler reactivity TF

$$C_d = \sum_{ix} d_{t_{ix}} + d_{y_{ix}} \times N_{ix}$$

CHAR H_{ar} Total core power to density reactivity through flow.

		$H_{ar} = A_r \times CQY$
CHAD	H_{ad}	Total core power to Doppler reactivity TF through the perturbation of flow rate. $H_{ad} = A_d \times CQY$
CHCR	H_{cr}	Total core power to density reactivity TF through the perturbation of inlet temperature. $H_{cr} = C_r \times CQT$
CHCD	H_{cd}	Total core power to Doppler reactivity TF through the perturbation of inlet temperature. $H_{cd} = C_d \times CQT$
CHR	H_r	Total core power to total density reactivity TF This is the hydrodynamic feedback loop. $H_r = H_{ar} + H_{cr} + B_r$
CHD	H_d	Total core power to total Doppler reactivity TF This is the fuel temperature feedback loop. $H_d = H_{ad} + H_{cd} + B_d$

Under the heading NEUTRON KINETICS LOOP:

CG	G	Total reactivity to total core power TF This is the neutron kinetics or forward loop. $G = \frac{\delta q}{\delta k_\varepsilon}$ (point kinetics)

Under the heading FEEDBACK LOOP:

CH	H	Total core power to total reactivity TF This is the overall feedback loop. $H = H_r + H_d$

Under the heading OPEN-LOOP RESPONSE:

CGH	$G \times H$	Open-loop reactivity TF of reactivity.

Under the heading CLOSED-LOOP RESPONSE:

G1GH	$\frac{G}{1 + G \times H}$	Closed-loop reactivity to power TF

*****STABGH**

Provided that ISTAB(NXE + 1), the results of the stability analysis of the core open-loop TF GH are printed by means of RESPON.

*****FREQ TRANS**

Provided that IOPTW(7 to 22) = 1, the following multicore TFs are printed from RESPON:

CCXK	$c_{x,k}$	Subcore k power to pressure at the boiling boundary of channel X TF Refer to Eq. (3.2.88c) and matrix C at App. B11.
CEKJ	$e_{k,j}$	Inlet flow rate into horizontal zone j to moderator density reactivity feedback of the subcore at level k [i.e., subcore (k,j)]. According to Eq. (3.3.1a) and App. B11, $e_{k,j} = \sum_x e_{x,k,j} \times Nch_{x,j}$

CHKJ	$h_{k,j}$	Inlet coolant temperature into horizontal zone j to moderator density reactivity of the subcore at level k [i.e., subcore (k,j)]. According to Eq. (3.3.1c) and App. B11, $h_{k,j} = \sum_{x} h_{x,k,j} \times Nch_{x,j}$
CZQKJ	$z_{q_{k,j}}$	Subcore (k,j) power to total reactor core flow TF vector z_q at Eq. (B12.2).
CFKJK	$f_{k^1,j,k}$	Subcore (k^1,j) power to moderator density reactivity of subcore (k,j) TF See Eq. (3.3.1b) and matrix F of App. B.
CMXJK	M_{x,j_1,k,j_2}	Subcore (k,j_2) power to inlet flow rate to the channel X placed in zone j_1, TF See Eq. (3.3.10) and matrix M in App. B12.
CQ	Q	Matrix of subcore (k_1,j_1) power to moderator density reactivity of subcore (k_2,j_2) TFs. See Eqs. (3.3.11) and (B15.14).
CR	R	Vector of total core flow rate to moderator density reactivity of subcore (k,j) TFs. See Eqs. (3.3.11) and (B12.16).
CS	S	Vector of inlet coolant temperature to moderator density reactivity of subcore (k,j) TFs. See Eqs. (3.3.11) and (B12.18).
CHQ		Feedback matrix of power at subcore (k_1,j_1) to reactivity at subcore (k_2,j_2), including flow redistribution effects. It corresponds to Eq. (3.3.23a).
CHRY	R*	Feedback vector containing the TFs of total core inlet flow rate to reactivity at subcore (k,j). It corresponds to Eq. (3.3.23b).
CHST	S*	Feedback vector containing the TFs of inlet coolant temperature to reactivity at subcore (k,j). It corresponds to Eq. (3.3.23c).
CG1MGH	z_{k_2,j_2,k_1,j_1}	Closed-loop [external reactivity at subcore (k_1,j_1) to power at subcore (k_2,j_2)] TF matrix. It corresponds to Eq. (3.3.16) using Q* as indicated by Eq. (3.3.23a).
CDENFB		Vector containing the total reactivity effect on each subcore due to a simultaneous unity perturbation of reactivity error in every subcore; that is, $CDENFB_{j,k} = \sum_{j'} \sum_{k'} Q^*_{j,k,j',k'}$
CLOSEK		Vector containing the closed-loop power response of each subcore (k,j) due to a simultaneous unity perturbation of external reactivity in every subcore; that is, $CLOSEK_{j,k} = \sum_{j'} \sum_{k'} z_{j,k,j',k'}\, ALPKJ_{j',k'}$
CRFBAC		Sum of the point kinetics reactivity feedback TFs of each nuclear subcore.

CLTFPK	Sum of the closed-loop TFs of each subcore to yield the total reactor core power response to a simultaneous unity perturbation of reactivity in each subcore; that is, $\mathrm{CLTFPK} = \sum_{j'} \sum_{k'} \mathrm{CLOSEK}_{j,k}\, \mathrm{POWKJ}_{j,k} / \mathrm{POWT}$

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APPENDIX A
SAMPLE LAPURX AND LAPURW INPUTS FOR A TYPICAL BWR

The following input decks represent a quarter-core configuration for a typical BWR

LAPURX V6.0 SAMPLE INPUT DECK:

```
LAPURX 6 SAMPLE INPUT DECK
   1
  982.55, 507.77,1609.40,.2958E+08, 0.0879, 0.031, 0.487, 1.0
   2
156, 45, 0, 1, 0, 0, 0, 0, 0
   3
156, 27,27,27,27,27,27,27,
          27,27,27,27,27,27,27,
          27,27,27,27,27,27,27,
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  .1E-2     .5E-3     .5E-3     .2E-4     .5E-3     .1E-8     .5E-3     .5E-7
   58
 156,     1,      1,      1,      1,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           3,      4,
   59
      4,        3,         4,         4,         1
   60
           74.010    414.290   450.260
           72.840    293.360   397.040   450.260
           72.840    293.360   414.290   450.260
         450.260
   61
         105.91,    98.58,  105.91
         102.42,    96.28,  104.08,  110.27
          98.98,    92.78,  104.36,  110.56
          95.08
   62
         1.473,   1.343,   1.473
         1.276,   1.176,   1.392,   1.506
         1.107,   1.020,   1.310,   1.415
         0.969
   63
 156,     1,      1,      1,      1,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
           2,      2,      2,      2,      2,      2,      2,
```

```
              2,      2,      2,      2,      2,      2,      2,
              3,      4,
   64
           4,        8,         8,         9,         7
   65
               81.300,  132.730,  183.780,  234.840,  286.270,  337.300,  388.380,
              444.340
               81.300,  132.730,  183.780,  234.840,  286.270,  337.300,  388.380,
              445.790
               72.770,  113.410,  154.050,  194.690,  240.410,  286.130,  337.310,
              388.490,  444.810
               89.730,  148.630,  207.530,  266.430,  325.330,  384.230,  444.640,
   66
               1.205,    1.205,    1.205,    1.205,    1.205,    1.205,    1.205,
               0.670,
               1.290,    1.290,    1.290,    1.290,    1.290,    0.830,    0.830,
               0.579,
               1.007,    0.930,    0.930,    0.930,    0.930,    0.930,    0.576,
               0.576,    0.676,
               0.567,    0.567,    0.567,    0.567,    0.567,    0.567,    0.537,
   67
           4,        2,         2,         2,         2
   68
           4,   0.1002,    0.1002,    0.1002,    0.2380
   69
           4,    1.000,     1.000,     1.000,     1.000
   70
           4,    1.000,     1.000,     1.000,     1.000
   71
           4,   0.1246,    0.1246,    0.1246,    0.2000
   72
           4,   -1.000,    -1.000,    -1.000,    -1.000
   73
           4,        2,         2,         2,         2
   74
           4,    1.000,     1.000,     1.000,     1.000
   75
           4,    1.000,     1.000,     1.000,     1.000
   76
           4,    1.000,     1.000,     1.000,     1.000
    0
```

LAPURW V6.0 SAMPLE INPUT DECK:

```
LAPURW 6 SAMPLE INPUT DECK
   1
  156    1    1
   2
                  11        14        15         8         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         3         3
                   3         3         3         3         3         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         4         4         4         4         4
                   4         4         5         5         5         5         5
                   6         6         6         6         6         6         7
                   8         8         9         1        11        11         6
                   4         4
   3
              450.2600
   4
                0.55    -0.80
   5
    1    6
   6
                   1
   7
        6  0.161E-03 0.111E-02 0.994E-03 0.209E-02 0.810E-03 0.203E-03
   8
        6   0.012813  0.031492  0.124571  0.328380  1.408783  3.830869
   9
                   1
  10
         1       0.0
  11
                   1
  12
        1 0.3632E-04
  17
          -0.271E-02
  18
         1         7
  19
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
            1         1         1         1         1         1         1
```

```
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1         1         1         1         1         1
          1         1
20
         0.0       0.2       0.4       0.6       0.8       1.0       1.2
21
         25.2069   20.0838   15.6386   11.8715    8.7823    6.3711    4.6379
22
     100     0.010     0.100     0.120     0.140     0.160     0.180     0.200
             0.210     0.220     0.230     0.240     0.250     0.260     0.270
             0.280     0.290     0.300     0.310     0.320     0.330     0.340
             0.350     0.360     0.370     0.380     0.390     0.400     0.410
             0.420     0.430     0.440     0.450     0.460     0.470     0.480
             0.490     0.500     0.510     0.520     0.530     0.540     0.550
             0.560     0.570     0.580     0.590     0.600     0.610     0.620
             0.630     0.640     0.650     0.660     0.670     0.680     0.690
             0.700     0.710     0.720     0.730     0.740     0.750     0.760
             0.770     0.780     0.790     0.800     0.810     0.820     0.830
             0.840     0.850     0.860     0.870     0.880     0.890     0.900
             1.000     1.100     1.200     1.300     1.400     1.500     1.600
             1.700     1.800     1.900     2.000     3.000     4.000     5.000
             6.000     7.000     8.000     9.000    10.000    20.000    50.000
           100.000   200.000
23
  0    1    1    1    1    1    0    0    0    0    0    0    0    0
  0    0    0    0    0    0    0    0
24
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1    1    1    1    1    1    1    1    1    1    1    1
  1    1    1
28
   1.19
29
       6     0.000    -0.500    -1.060    -1.089    -1.500    -2.000
30
       4
 0
```

APPENDIX B
SAMPLE LAPURX AND LAPURW OUTPUT FOR A TYPICAL BWR

OUTPUT FILE LAPURX.CSV:

```
LAPURX 6 SAMPLE INPUT DECK

 Ch,NCH,Fuel,Power,Flow,delta-P,Exit,Zb
 , ,Type,(%),(%),(bar),Quality,(m)
  1, 11,  1,     39.0827,     71.7374,      0.4583,      0.1212,      1.5539,
  2, 14,  1,     32.0004,     69.6844,      0.4583,      0.0945,      1.8266,

(... channels 3 to 154 deleted here)

155,  4,  3,     78.6193,    110.0030,      0.4583,      0.1741,      1.1959,
156,  4,  4,     83.2990,     99.9911,      0.4583,      0.2110,      1.0750,
```

OUTPUT FILE LAPURW.CSV:

```
LAPURW RUN: LAPURW 6 SAMPLE INPUT DECK
 LAPURX RUN: LAPURX 6 SAMPLE INPUT DECK

CHANNEL STABILITY:
CH,DR,FREQ,PHASE-MARGIN,,GAIN-MARGIN
, ,(Hz),(DEG),(Hz),,(Hz)
  1,    0.00,    6.68, ******, ******,  10.41,    0.32
  2,    0.00,    5.79, ******, ******,  10.49,    0.34

(... channels 3 to 154 deleted here)

155,    0.00,    4.00, ******, ******,   5.14,    0.41
156,    0.00,    0.26, ******, ******,  18.04,    0.39

CORE OUT-PHASE STABILITY:
REACT,DR,FREQ,PHASE-MARGIN,,GAIN-MARGIN,,AMPL,AVG
($),,(Hz),(DEG),(Hz),,(Hz),(%),(%)
  0.00,   1.02,   0.53, -0.87,  0.53,   0.98,   0.53,152.84,   1.47,
 -0.50,   0.63,   0.50, 30.20,  0.45,   1.59,   0.54,100.00,   0.00,
 -1.06,   0.39,   0.48, 81.02,  0.28,   2.28,   0.54,100.00,   0.00,
 -1.09,   0.39,   0.48, 82.72,  0.27,   2.32,   0.54,100.00,   0.00,
 -1.50,   0.29,   0.47, 96.97,  0.19,   2.83,   0.55,100.00,   0.00,
 -2.00,   0.21,   0.47,105.34,  0.14,   3.45,   0.55,100.00,   0.00,

OPEN AND CLOSED-LOOP TRANSFER FUNCTIONS:
FREQ,OPEN-LOOP,,CLOSED-LOOP,
(Hz),(AMP),(PHASE-DEG),(AMP),(PHASE-DEG)
   0.100,    0.385E+01,    89.40,    0.591E+00,    55.94,
   0.120,    0.331E+01,    86.12,    0.670E+00,    58.54,

(... frequencies 0.140 Hz to 50 Hz deleted here)

 100.000,    0.788E-04,    13.15,    0.427E+00,   -76.77,
 200.000,    0.201E-04,     6.67,    0.218E+00,   -83.29,

CORE IN-PHASE STABILITY:
DR, FREQ, PHASE-MARGIN,, GAIN-MARGIN,
,(Hz),(DEG),(Hz),,(Hz)
  0.55,    0.44,  22.51,    0.40,    1.59,    0.49,
```

APPENDIX C
DETAILED DESCRIPTION OF LAPUR 6 MODIFICATIONS

CONTENTS

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

Thermal hydraulic stability of boiling water reactors (BWRs) has been a primary concern since the beginning of BWR technological development. The phenomena started being studied empirically and theoretically. For many years, no BWR experienced a power oscillation event.

The evolution of the technology saw design changes and increases in power density. These developments gave rise to stability problems. The very first power oscillation incidents occurred in the 1980s and continued through the early 1990s. Although many reactors suffered such instabilities, the La Salle incident in 1988 brought the issue of BWR stability as a worldwide safety concern to the forefront. The regulatory agency of every country required a stability revision on their BWR plants.

General Electric, together with the BWR Owners Group (BWROG), solved the problem temporarily by limiting the process in those regions sensitive to instabilities, creating a criterion about how to avoid instability issues and providing the operators with better training regarding instability.

In 1992, the incident in Washington Nuclear Plant Unit-2 (WNP-2) led the U.S. Nuclear Regulatory Commission (NRC) to request a definitive solution to the instability problem. GE and BWROG gave different solutions depending on the reactor; the solutions were based on the following detection and suppression and on prevention.

In Spain, the Consejo de Seguridad Nuclear (CSN) required the implementation of these solutions to the affected Spanish reactors. Thus, the most suitable methodology was chosen and introduced at each plant.

From 1995 to 1998, Iberdrola in cooperation with Iberdrola Ingeniería Consultoría and the Universidad Politécnica de Valencia (UPV) developed a method to apply the E1A methodology using LAPUR 5, which was created by the United States' Oak Ridge National Laboratory (ORNL) (Ref. 7), as well as a program called PAPU, created by the UPV, for generating kinetic parameters.

The application methodology and the programs used were licensed by the CSN; Iberdrola used them to perform the stability analysis of the last three reloads at the Cofrentes Nuclear Plant.

In 2000, ORNL and UPV collaborated on a new version, LAPUR 5.2 (Ref. 2); it was modeled at a higher level of detail, which provided better estimations of the stability margins.

LAPUR is a code for computing the parameters that define operational stability in BWRs. This program consists of two autonomous modules, LAPURX, which solves the steady-state thermal hydraulic governing equations (assuming a constant channel flow area), and LAPURW, which computes the decay ratio in the frequency domain.

Because of the widespread safety concerns over BWR instability issues, the European nuclear community approved the NACUSP project (2001–2004), for which Iberdrola and UPV collaborated.

The UPV and Iberdrola deemed it necessary to improve LAPUR for two main reasons:

1. The new fuel designs have incorporated higher power densities and power profiles geared to the lower part of reactor's core, as well as partial-length rods, gadolinium rods, etc., that, although they are more efficient from a neutronic viewpoint, from a stability viewpoint, cause the fuel to behave differently.
2. The different types of instabilities, especially the so-called out-of-phase, which has been observed recently during the BWR operation and start-up, allow the use of tools and applied methodologies that can more precisely estimate the stability margins, ensuring that no instability events occur that would require a forced outage or risk facility availability.

In pursuit of the improvements to LAPUR, it was necessary to perform certain modifications. The thermal-hydraulic methodology will be based on LAPUR 5.2 code (Ref. 2). Its prediction capability will be improved performing the following modifications.

1.1.1. Improvements made in LAPUR 5.1 to obtain LAPUR 5.2

The major improvements of LAPUR 5.2 with respect to LAPUR 5.1 are:

1. The maximum number of thermal-hydraulic regions was parameterized. The default value is 200 channels. Note: LAPUR calculations with up to 200 channels were verified against results from LAPUR 5.1 with no significant loss of precision. Calculations with more than 200 channels are typically unnecessary due to symmetry considerations, but are possible; however, those calculations were not verified here.
2. The maximum number of axial power shapes was parameterized so that each thermal-hydraulic region could have its own axial and radial power shape. The default value of axial power shape regions is 200.
3. The maximum number of bundle and fuel rod types was parameterized. The default value is 10. This allows modeling of mixed cores with up to 10 different fuel types.
4. The maximum number of frequencies was parameterized. The default value is 100 frequencies. This upgrade allowed for better definition of the transfer functions and a more robust evaluation of the decay ratio. The old version often required two LAPURW calculations, one to identify the frequency of oscillation using a coarse frequency mesh, and a second calculation with a fine mesh around the oscillation frequency. With 100 frequencies, a single calculation works for most cases.
5. All relevant dimensions of internal LAPUR variables were parameterized so they could be modified in the future. File PARAM.FI contains the definitions for all these parameters. Note: These parameters were left at their original values, and value changes have not been tested thoroughly; it is the user's responsibility to verify that any future changes to these parameters do not result in significant loss of precision.
6. A well known behavior of LAPUR 5.1 was that it would report very high channel decay ratio if the channel was very stable. The user would have to compensate for this by manually checking the phase and gain margins. In LAPUR 5.2, this behavior was corrected by improving the decay-ratio estimation algorithm. The problem was related to an internal "spline fit" that LAPUR performed on the calculated transfer functions. For a very stable channel, the phase might cross the zero-degree level; since LAPUR maintains the phases negative, the phase jumps from -5 deg to -355 deg. The spline fit under those conditions cannot reproduce the discontinuity accurately and as a result,

would report a very high decay ratio. This behavior was corrected in LAPUR 5.2 to allow the accurate calculation and reporting of low-channel-decay-ratio conditions.

7. The calculation of the average saturated boiling boundary was added at the end of the LAPURX execution. This calculation is performed for output purposes only and does not affect the LAPURW input files; thus, it does not affect the calculated decay ratios.
8. Two new output files are generated by LAPUR 5.2. These files have an ASCII comma separated value (CSV) format and summarize the most relevant output information. The file names are LAPURX.CSV and LAPURW.CSV and can be opened with most spreadsheet programs for further manipulation of the LAPUR output data. LAPURX.CSV contains the relative power and flow, the pressure drop, exit quality, and the saturated boiling boundary of each channel. LAPURW.CSV contains the decay ratio and frequency for each channel and for the core, as well as the open-loop and closed-loop transfer functions as function of frequency.
9. The screen-input routines were removed. "Batch" is the only available mode for LAPUR 5.2. The executable files have been renamed LAPURX.EXE and LAPURW.EXE.
10. During the detailed code review, the authors found and corrected one miscellaneous programming error.

1.1.2. Thermal-Hydraulic Improvements from LAPUR 5.2 to LAPUR 6.0

The major improvements of LAPUR 6.0 with respect to LAPUR 5.2 are:

1. The two-phase friction multipliers, even for frictional forces as for local losses, have been improved, using updated relationships that are more realistic for the newest fuel designs.
2. The capability to model channels with variable area, in order to represent more adequately the partial length rods of the new fuel designs.
3. Several cells in the single-phase region have been defined, and the cell variables (densities, liquid velocities, temperatures) of the nonboiling region are calculated.
4. The local pressure losses (spacers) have been included.
5. The irreversible pressure losses due to contractions and expansions have been included.
6. During the detailed code review, the authors found and corrected three miscellaneous programming errors.
7. Finally, the stability prediction capability of the new code was validated through data collected from Cofrentes Nuclear Power Plant, as well as data from other plants, for example, Ringhals and Forsmark.

CHAPTER 2. THERMAL HYDRAULIC IMPROVEMENTS

2.1. IMPLEMENTATION OF THE VARIABLE AREA AND THE NEW FRICTION MODELS INTO THE CODE LAPUR

The current version LAPUR 5 has various model deficiencies (Ref. 5, Ref. 6); these are listed below:

1. There is no model to evaluate local or secondary losses in the cells of the fuel elements. Only friction losses are modeled. Therefore, it is necessary to include the local losses through a multiplier to account for frictional losses, obtaining the equivalent pressure drop.
2. It does not allow for the existence of a variable area in the fuel elements. Hence, reversible losses or gaining pressures and irreversible losses have to be modeled by means of a frictional multiplier.
3. Two-phase friction multipliers are estimated by using the Martinelli-Nelson multiplier, which uses the Jones correction factor. This multiplier overestimates friction pressure drop for steam qualities greater than 0.6, so it must be modified to reproduce the available experimental data.

This section documents the implementation of new correlations for computing friction and local losses, as well as capabilities for modeling bundles with variable cross-area in LAPUR. The selection of basic models to implement in LAPUR is compiled in Reference 1. The friction and local models selected are generic and do not include the proprietary information of fuel vendors. Fuel vendors obtain from experimental data accurate friction models (single-phase friction factors and two-phase multipliers) to use in their codes. This is a good way to obtain accurate friction models, since they are strongly dependent on geometry and surface roughness. However, it is more feasible for the utility to perform updates of generic models to obtain a good agreement with data supplied by fuel vendors. With these objectives, generic friction models are combined with free parameters to reproduce with a good degree of approximation the results reported by vendors.

Section 2.2 presents the modifications made in LAPURX related to the variable flow area. Section 2.3 presents the modifications made in LAPURX related to the friction model II. Section 2.4 presents the modifications made in LAPURX related to the losses. Section 2.5 presents the modifications made in LAPURX related to the new coefficients obtained in the momentum equation with variable flow area. Section 2.6 presents other minor modifications made in LAPURX related to the thermal hydraulics. Section 2.7 presents the modifications made in LAPURW.

2.2. MODIFICATIONS IN LAPURX RELATED TO THE VARIABLE FLOW AREA

In this section, we present the following improvements:

- Theory of the application.
- Reading, storing, and preparing the new variables. These new variables are the axial flow area and the axial hydraulic diameter of each type of channel.
- Printing new variables.
- Calculating cell variables, including the flow area and hydraulic diameter for each cell of the nonboiling and boiling regions.

2.2.1. Theory of the Application

The current version LAPUR 5 considers, for the momentum conservation (pressure drops), the nonboiling region as one "collapsed-cell." The new version LAPUR 6.0 computes all the nonboiling cells variables of the momentum conservation equations.

The old LAPUR 5 does not allow for the existence of a variable cross-area in the fuel elements. The channel has a constant axial flow area A_0 (input user LAPURX data card 19). The new version LAPUR 6.0 has the capability for modelling bundles with variable cross-area.

2.2.2. Variable Cross Flow Area and Hydraulic Diameter—LAPUR Modifications

Four subroutines have been modified:

- The subroutine INPUT: read the new variables.
- The subroutine OUTIN: print the new variables.
- The subroutine SETUP: select from the arrays the specific parameters of the channel type IX.
- The subroutine NODE: transform the nodal parameters to the new coordinate system.

Subroutine INPUT—Read the new variables.

```
580     CALL INP1(NXE,NDIMV)
        GO TO 6000
590     CALL INP1(NTDV,NODV)
        GO TO 6000
600     CALL INP2(NTDV,NODV,DZVM,NVAMAX)
        GO TO 6000
610     CALL INP2(NTDV,NODV,AVM,NVAMAX)
        GO TO 6000
620     CALL INP2(NTDV,NODV,DEVM,NVAMAX)
        GO TO 6000
```

Variable	Dimension	Subroutine	Description	Units
AVM(IBM,I)	NVAMAX,NV	INPUT-user	Boiling cell flow area	cm2
DEVM(IBM,I)	NVAMAX,NV	INPUT-user	Hydraulic diameter	cm
DZVM(JJ,JJJ)	NVAMAX,NV	INPUT-user	Top height from bottom of the JJJ-th variable-area axial interval of channel variable-area JJ-type	cm
NDIMV(J)	NXE	INPUT-user	Variable-area channel type of the J-th thermal region	
NODV(J)	NTDV	INPUT-user	Number of axial intervals for the J-th type, variable-area channel	
NTDV	----	INPUT-user	Number of variable-area channel types	
NVAMAX	----	param.fi	PARAMETER (NVAMAX = 10) ! Max # of variable area channels	

Subroutine OUTIN—Print the new variables.

```
   58 WRITE(6, 444)
      WRITE(6, 158)II, NXE , (NDIMV(J), J=1,NXE)
      GO TO 200
   59 WRITE(6, 159)II, NTDV , (NODV(J),J=1,NTDV)
      GO TO 200
   60 DO 322 JJ=1,NTDV
      JI=NODV(JJ)
      IF(JJ.EQ.1) WRITE (6, 160)II, (DZVM(JJ,JJJ),JJJ=1,JI)
      IF(JJ.NE.1) WRITE (6, 301) (DZVM(JJ,JJJ),JJJ=1,JI)
  322 CONTINUE
      GO TO 200
   61 DO 323 JJ=1,NTDV
      JI=NODV(JJ)
      IF(JJ.EQ.1) WRITE (6, 161)II, (AVM(JJ,JJJ),JJJ=1,JI)
      IF(JJ.NE.1) WRITE (6, 301) (AVM(JJ,JJJ),JJJ=1,JI)
  323 CONTINUE
      GO TO 200
   62 DO 324 JJ=1,NTDV
      JI=NODV(JJ)
      IF(JJ.EQ.1) WRITE (6, 162)II, (DEVM(JJ,JJJ),JJJ=1,JI)
      IF(JJ.NE.1) WRITE (6, 301) (DEVM(JJ,JJJ),JJJ=1,JI)
  324 CONTINUE
      GO TO 200
```

…….

```
  158 FORMAT(1H0,4X,'(',I2,') ',8HNXE      = I5   /10X,8HNDIMV   =
7I12  ,
     1                    / (18X, 7I12)   )
  159 FORMAT(1H0,4X,'(',I2,') ', 8HNTDV    = I5 / 10X,8HNODV    =
7I12
     1                    ,/ (18X, 7I12)  )
  160  FORMAT(1H0,4X,'(',I2,')  ',8HDZVM       =     7F12.4     /
(18X,7F12.4) )
  161  FORMAT(1H0,4X,'(',I2,')  ',8HAVM        =     7F12.4     /
(18X,7F12.4) )
  162  FORMAT(1H0,4X,'(',I2,')  ',8HDEVM       =     7F12.4     /
(18X,7F12.4) )
```

Subroutine SETUP—Select the parameters specific to channel type IX from the arrays.

```
      IBM=NDIMV(IX)
      NV=NODV(IBM)
      DO I=1,NV
          DZV(I)  = DZVM(IBM,I)
          AV(I)   = AVM(IBM,I)
          DEV(I)  = DEVM(IBM,I)
      ENDDO
C
      IF (NV.EQ.0)THEN
          DZV(1)  = EL
          AV(1)   = A0
          DEV(1)  = DE
      ENDIF
```

Subroutine NODE—Transform the nodal parameters to the new coordinate system.

Cell parameters (length averaged)

```
C LAPUR6 I:1
C NEW LINE
      DIMENSION DDV(NOVAMAX)
C LAPUR6 END
```

…….

```
C Calculation of cell flow area and cell hydraulic diameter
C DZV(I) Height to the top of the I-th axial interval
C        within the flow area is uniform.
C        Input data card 60.
C DDV(I) Length of the I-th axial interval within the flow area is
uniform.
C
        IF(NV.LE.1)  GO TO 2510
          DDV(1) = DZV(1)
      DO 1260 I=2,NV
          DDV(I) = DZV(I) - DZV(I-1)
 1260 CONTINUE
C
          L2 =  1
      DO 1500 J=1,NNB
      DO 1380 I=1,NV
          L = I
        IF(ZCOM(J+1).LE.DZV(L))  GO TO 1400
 1380 CONTINUE
          L  = NV
 1400 CONTINUE
          L1 = L2
          L2 = L
```

```
          LL = L2 - (L1+1)
        IF(LL)  1420,1440,1460
 1420     DEVNBL(J) = DEV(L1)
          AVNBL(J)  = AV(L1)
          GO TO 1500
 1440     DEVNBL(J) = (DEV(L1)*(DZV(L1)-ZCOM(J))
     1                +DEV(L2)*(ZCOM(J+1)-DZV(L1)))
     2                /(ZCOM(J+1)-ZCOM(J))
          AVNBL(J)  = (AV(L1)*(DZV(L1)-ZCOM(J))
     1              +AV(L2)*(ZCOM(J+1)-DZV(L1)))
     2                /(ZCOM(J+1)-ZCOM(J))
          GO TO 1500
 1460     TEMP0= 0.0
          TEMP1= 0.0
          LL1   = L1 + 1
          LL2   = L2 - 1
      DO 1480 I=LL1,LL2
          TEMP0 = TEMP0 + DEV(I)*DDV(I)
 1480     TEMP1 = TEMP1 + AV(I)*DDV(I)
          DEVNBL(J) = (DEV(L1)*(DZV(L1)-ZCOM(J))+TEMP0
     1              +DEV(L2)*(ZCOM(J+1)-DZV(L2-1)))
     2                /(ZCOM(J+1)-ZCOM(J))
          AVNBL(J)  = (AV(L1)*(DZV(L1)-ZCOM(J))+TEMP1
     1              +AV(L2)*(ZCOM(J+1)-DZV(L2-1)))
     2                /(ZCOM(J+1)-ZCOM(J))
 1500 CONTINUE
C
      DO 2500 J=1,N
      DO 2380 I=L2,NV
          L = I
        IF(ZPP(J+1).LE.DZV(L))  GO TO 2400
 2380 CONTINUE
          L  = NV
 2400 CONTINUE
          L1 = L2
          L2 = L
          LL = L2 - (L1+1)
        IF(LL)  2420,2440,2460
 2420     DEVL(J) = DEV(L1)
          AVL(J)  = AV(L1)
          GO TO 2500
 2440     DEVL(J) = (DEV(L1)*(DZV(L1)-ZPP(J))
     1              +DEV(L2)*(ZPP(J+1)-DZV(L1)))/DZ
          AVL(J)  = (AV(L1)*(DZV(L1)-ZPP(J))
     1              +AV(L2)*(ZPP(J+1)-DZV(L1)))/DZ
          GO TO 2500
 2460     TEMP0= 0.0
          TEMP1= 0.0
          LL1   = L1 + 1
          LL2   = L2 - 1
      DO 2480 I=LL1,LL2
 2480     TEMP0 = TEMP0 + DEV(I)*DDV(I)
```

```
          TEMP1 = TEMP1 + AV(I)*DDV(I)
          DEVL(J)  =  (DEV(L1)*(DZV(L1)-ZPP(J))+TEMP0
     1                +DEV(L2)*(ZPP(J+1)-DZV(L2-1)))/DZ
          AVL(J)   =  (AV(L1)*(DZV(L1)-ZPP(J))+TEMP1
     1                +AV(L2)*(ZPP(J+1)-DZV(L2-1)))/DZ
 2500 CONTINUE
          GO TO 2600
 2510 CONTINUE
        IF(ZNB.GT.DZV(1))   GO TO 2540
      DO 2511 J=1,NNB
          DEVNBL(J)  = DEV(1)
          AVNBL(J)   = AV(1)
 2511 CONTINUE
      DO 2512 J=1,N
          DEVL(J)  = DEV(1)
          AVL(J)   = AV(1)
 2512 CONTINUE
          GO TO 2600
C
 2520 CONTINUE
          WRITE (6,9000)   (TITLE(I),I=1,18)
          WRITE (6,9100)   IX
      NODEGO=1.0
      RETURN
 2540 CONTINUE
          WRITE (6,9000)   (TITLE(I),I=1,18)
          WRITE (6,9300)   IX,ZNB
      NODEGO=1.0
      RETURN
C
 2600 CONTINUE
C
```

Cell edge flow area

```
C Calculation of cell edge flow area and hydraulic diameter
         IF(NV.LE.1)   GO TO 5510
C
          AVNBCL(1)  = AV(1)
          DEVNBCL(1)= DEV(1)
      DO 4500 J=1,NNB
      DO 4380 I=1,NV
          L = I
        IF(ZCOM(J+1).LE.DZV(L))   GO TO 4400
 4380 CONTINUE
          L   = NV
 4400 CONTINUE
          AVNBCL(J+1)  = AV(L)
          DEVNBCL(J+1)= DEV(L)
 4500 CONTINUE
C
```

```
          AVCL(1) = AVNBCL(NNB+1)
          DEVCL(1)= DEVNBCL(NNB+1)
      DO 5500 J=1,N
      DO 5380 I=1,NV
          L = I
        IF(ZPP(J+1).LE.DZV(L))  GO TO 5400
 5380 CONTINUE
          L  = NV
 5400 CONTINUE
          AVCL(J+1) = AV(L)
          DEVCL(J+1)= DEV(L)
 5500 CONTINUE
          GO TO 5600
C
 5510 CONTINUE
        IF(ZNB.GT.DZV(1))  GO TO 5540
      DO 5511 J=1,NNB+1
           AVNBCL(J)  = AV(1)
           DEVNBCL(J) = DEV(1)
 5511 CONTINUE
      DO 5512 J=1,N+1
          AVCL(J)  = AV(1)
          DEVCL(J) = DEV(1)
 5512 CONTINUE
          GO TO 5600
C
 5520 CONTINUE
          WRITE (6,9000)  (TITLE(I),I=1,18)
          WRITE (6,9100)  IX
      NODEGO=1.0
      RETURN
 5540 CONTINUE
          WRITE (6,9000)  (TITLE(I),I=1,18)
          WRITE (6,9300)  IX,ZNB
      NODEGO=1.0
      RETURN
C
 5600 CONTINUE
.......
9300 FORMAT(1H0,10X, 42HZNB IS GREATER THAN SIGMA(DZV(I),I=1,NV).
     1       /// 10X, I10, 1PE15.5 )
```

Variable	Dimension	Subroutine	Description	Units
AVCL(M)	N+1	NODE	Boling cell edge flow area	cm2
AVL(I)	N	NODE	Boiling cell flow area - length averaged	cm2
AVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge flow area	cm2
AVNBL(I)	NNB	NODE	Nonboiling cell flow area - length averaged	cm2
DDV(I)	NV	NODE	Length of the I-th variable-area axial interval	cm
DEVCL(J+1)	N+1	NODE	Hydraulic diameter boiling cell edge	cm
DEVL(I)	N	NODE	Hydraulic diameter boiling cell - length averaged	cm
DEVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge hydraulic diameter	cm
DEVNBL(I)	NNB	NODE	Nonboiling cell hydraulic diameter - length averaged	cm
DZV(I)	NV	SETUP	Top height from bottom of the I-th variable-area axial (DZVM)	cm
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm
ZNB	----	BOUNDY & SETUP	Position of the boiling boundary	cm
ZPP(J+1)	N+1	NODE	Boiling cell edge height ZPP(1)=ZNB	cm

2.2.3. Calculation of Cell Variables—LAPUR Modifications

The following cell variables are calculated in subroutine FRICT:

- Normalized enthalpies [cal/g] (HVNBL, HVL).
- Temperatures [°C] (TVNBL, TVL).
- Liquid dynamic viscosities [g/cm^2 s] (EMUVNBL, EMUVL).
- Densities [g/cm^3] (RHOVNBL, RHOVL).
- Liquid velocities [cm/s] (UVNBL, UVL).
- Reynolds numbers (REVNBL, REVL).
- Friction factors (FNBL, FFL).
- Coefficient a_2 used by the Moody friction factor (A2NBL, A2L)

Subroutine FRICT—Calculate cell variables.

```
C LAPUR6 I:73
C NEW LINES
C Center cell variables
C
      DO 400 I=1,NNB
       HVNBL(I)=H0+(HFG*XE(IX)+HF-H0)*(CCOM(I+1)+CCOM(I))/2.
       TVNBL(I)=TD(P,HVNBL(I))
       EMUVNBL(I)=FPMU(P,TVNBL(I))
       RHOVNBL(I)=1/VOLUME(P,TVNBL(I))
       UVNBL(I)=W0/(RHOVNBL(I)*AVNBL(I))
       REVNBL(I)=(RHOVNBL(I)*UVNBL(I)*DEVNBL(I))/(EMUVNBL(I))
```

```
       FNBL1(I)=FF(REVNBL(I))
       A2NBL1(I)=AF(FNBL1(I))
C
       IF (IFF .EQ. 2) THEN
        FNBL2(I)   = FF2(REVNBL(I))
        A2NBL2(I)  = AF2(FNBL2(I),REVNBL(I))
         FNBL(I)   = FNBL2(I)
         A2NBL(I)  = A2NBL2(I)
       ELSE
        FNBL(I)   = FNBL1(I)
        A2NBL(I)  = A2NBL1(I)
       ENDIF
 400  ENDDO
C
      DO 410 I=1,NSB
       HVL(I)=HF-(H(I)+H(I+1))*HFG/2.
       TVL(I)=TD(P,HVL(I))
       EMUVL(I)=FPMU(P,TVL(I))
       RHOVL(I)=1/VOLUME(P,TVL(I))
       UVL(I)=W0/(RHOVL(I)*AVL(I))
       REVL(I)=(RHOVL(I)*UVL(I)*DEVL(I))/(EMUVL(I))
       FL1(I)=FF(REVL(I))
       A2L1(I)=AF(FL1(I))
C
       IF (IFF .EQ. 2) THEN
        FL2(I)   = FF2(REVL(I))
        A2L2(I)  = AF2(FL2(I),REVL(I))
         FFL(I)  = FL2(I)
         A2L(I)  = A2L2(I)
       ELSE
        FFL(I)  = FL1(I)
        A2L(I)  = A2L1(I)
       ENDIF
  410 ENDDO
C
      DO 420 I=NSB+1,N
       HVL(I)=HF
       TVL(I)=TSAT
       EMUVL(I)=FPMU(P,TSAT)
       RHOVL(I)=1/VOLUME(P,TSAT)
       UVL(I)=W0/(RHOVL(I)*AVL(I))
       REVL(I)=(RHOVL(I)*UVL(I)*DEVL(I))/(EMUVL(I))
       FL1(I)=FF(REVL(I))
       A2L1(I)=AF(FL1(I))
C
       IF (IFF .EQ. 2) THEN
        FL2(I)   = FF2(REVL(I))
        A2L2(I)  = AF2(FL2(I),REVL(I))
         FFL(I)  = FL2(I)
         A2L(I)  = A2L2(I)
       ELSE
        FFL(I)  = FL1(I)
```

```
        A2L(I) = A2L1(I)
       ENDIF
  420 ENDDO
C
C Cell edges variables
C
      RHOVNBCL(1)=RHOLI
      DO 430 I=2,NNB
        RHOVNBCL(I)=(RHOVNBL(I-1)*(ZCOM(I)-ZCOM(I-1))+
     1                 RHOVNBL(I)*(ZCOM(I+1)-ZCOM(I)))/(ZCOM(I+1)-
ZCOM(I-1))
  430 ENDDO
      RHOVNBCL(NNB+1)=RHOZNB
C LAPUR6 END
```

Variable	Dimension	Subroutine	Description	Units
A2L(I)	N	FRICT	Coefficient a2 for boiling region, used by the Moody friction factor	
A2NBL(I)	NNB	FRICT	Coefficient a2 for nonboiling region, used by the Moody friction factor	
AVL(I)	N	NODE	Boiling cell flow area - length averaged	cm2
AVNBL(I)	NNB	NODE	Nonboiling cell flow area - length averaged	cm2
CCOM(I+1)	NNB+N+1	NODE	Normalized cumulative power generation cell edge (From 0.0 to 1.0)	
DEVL(I)	N	NODE	Hydraulic diameter boiling cell - length averaged	cm
DEVNBL(I)	NNB	NODE	Nonboiling cell hydraulic diameter - length averaged	cm
DZ	----	NODE	Boiling cell length	cm
EMUVL(I)	N	FRICT	Boiling cell liquid dynamic viscosity	g/cm2 s
EMUVNBL(I)	NNB	FRICT	Nonboiling liquid dynamic viscosity	g/cm2 s
FFL(I)	N	FRICT	*Friction factor for boiling region*	
FNBL(I)	NNB	FRICT	Friction factor for nonboiling region	
H(I+1)	NSB+1	SUBOIL & BULK	Normalized subcooled cell edge enthalpy H(1)=HZNB	cal/g
H0	-----	READY	Inlet enthalpy	cal/g
HF	-----	READY	Saturated liquid enthalpy	cal/g
HFG	-----	READY	Evaporation enthalpy	cal/g
HVL(I)	N	FRICT	Normalized boiling cell enthalpy	cal/g
HVNBL(I)	NNB	FRICT	Normalized nonboiling cell enthalpy	cal/g
N	-----	INPUT-user	Number of axial nodes desired in the boiling region of the channels	
NNB	-----	BOUNDY	Number of Nonboiling cells	
NSB	-----	BOUNDY	Number of Subcooled boiling cells	
P	-----	INPUT-user	System pressure	kg/cm2
REVL(I)	N	FRICT	Boiling cell Reynolds	
REVNBL(I)	NNB	FRICT	Nonboiling cell Reynolds	
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBCL(I+1)	NNB+1	FRICT	Nonboiling cell edge density	g/cm3

Variable	Dimension	Subroutine	Description	Units
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
TSAT	----	READY	Saturated temperature	°C
TVL(I)	N	FRICT	Boiling cell temperature	°C
TVNBL(I)	NNB	FRICT	Nonboiling cell temperature	°C
UVL(I)	N	FRICT	Boiling cell liquid velocity -no steam- (w0/rhol*a_cell)	cm/s
UVNBL(I)	NNB	FRICT	Nonboiling cell liquid velocity	cm/s
W0	-----	PREPAR	Reference channel mass flow rate	g/s
XE(IX)	NXE	READY & SETUP	Channel exit quality	
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm

2.3. MODIFICATIONS IN LAPURX RELATED TO FRICTION MODEL II

In this section, we present the following modifications:

- Reading, storing, and preparing the new variables.
- Calculating cell variables.

2.3.1. Theory

Friction model I is the old LAPUR 5 model, and comprises the Moody Single-Phase Friction Factor and the Martinelli-Nelson Two-Phase Friction Multiplier.

Friction model II comprises the Generic Single-Phase Friction Factor and the Chisholm-Baroczy Friction Multiplier. This friction model II will be used only if variable IFFM=2 (input-user data on card 67) and variable IFMM=2 (input-user data on card 73).

2.3.1.1. Friction model I

The friction model I comprises the Moody Single-Phase Friction Factor and the Martinelli-Nelson Two-Phase Friction Multiplier. The Moody friction factor f_M for one-phase flow along smooth surfaces can be expressed by

$$f_M = a_1 Re^{-a_2} \tag{1}$$

where a_1 and a_2 are coefficients that depend on the Reynolds number, and Re is the Reynolds number of the flow

$$Re = \frac{w D_H}{\mu A} = G\frac{D_H}{\mu} = G\frac{4A}{\mu P_w}. \tag{2}$$

For laminar flow conditions, i.e., Re < 2300:

$$f_M = \frac{64}{Re} \tag{3}$$

hence, $a_1 = 64$, $a_2 = 1$.

For turbulent flow conditions, i.e., Re > 2300, the following transcendental equation applies:

$$f_M^{-1/2} = 2\log\left(\mathrm{Re}\, f_M^{1/2}\right) - 0.8 \tag{4}$$

The determination of the factor f_M for a given Re requires an iterative procedure.

Once f_M has been determined, the coefficients of the general expression $f_M = a_1 \mathrm{Re}^{-a_2}$ can be calculated using following expression obtained by Jones

$$a_2 = \frac{4(\log\ e) f_M^{1/2}}{1 + 2(\log\ e) f_M^{1/2}}$$

$$a_1 = \frac{f_M}{\mathrm{Re}^{-a_2}} \tag{5}$$

where e = 2.71 the base of the natural logarithms, and log x = $\log_{10}$ x.

A commonly used relation for turbulent flow of water in BWRs uses $a_1 = 0.213$ and a_2 =0.214.

The Martinelli-Nelson Two-Phase Friction Multiplier has been widely used in two-phase flow pressure-drop analyses. It was originally developed for horizontal turbulent flow but has been found reasonably accurate for vertical flows. Several modifications have been suggested to account for flow pattern characteristics and flow rates.

A polynomial fit valid for x < 0.7 was synthesized by Jones (Ref. 7) as

$$\phi_{MN}^2 = e^{\sum_{i=1}^{4} a_i [\ln(100x+1)]^i} \tag{6}$$

where

$x \equiv$ steam quality, and

$a_i \equiv$ pressure-dependent fitted parameters given by

$$a_i = \sum_{j=1}^{8} b_{ij} P_j \tag{7}$$

where

$b_{ij} \equiv$ fitting coefficients, giving by Jones

$P_1 = 1$

$P_2 = 1.42234 \times 10^{-2}$ P

$P_j = P_2 P_{j-1}$; j= 3, 6; and

$P \equiv$ system pressure in [Kg/cm^2]

2.3.1.2. Friction model II

Friction model II comprises the Generic Single-Phase Friction Factor and the Chisholm-Baroczy Friction Multiplier; it also allows the use of different friction models selecting specific coefficients (Ref. 10). The equations of this model are:

$$FF_{LAM} = \frac{64.0}{Re_l} \tag{8}$$

$$FF = AN \cdot \left[1 + \left(BN \cdot R_r\right) + \frac{CN}{Re_l}\right]^{DN} \tag{9}$$

$$FF = MAX\left(FF, FF_{LAM}\right) \tag{10}$$

where the coefficients AN, BN, CN, DN are fuel-specific and are validated by each vendor; R_r is the relative roughness; and Re_l is the liquid Reynolds number.

The two-phase friction multiplier model II uses the fit of Chisholm to the model of Baroczy (Ref. 8). This model uses the following equations:

$$GMSQ = \left[\left(\frac{\mu_g}{\mu_F}\right)^{0.2}\left(\frac{\rho_F}{\rho_g}\right)\right] \tag{11}$$

$$BGM = \sqrt{GMSQ} \tag{12}$$

$$B = \frac{55.0}{\left[AJUSTAB1 \cdot G\right]^{0.5}} \quad BGM \le 9.5 \tag{13}$$

$$B = \frac{520.0}{BGM \cdot \left[AJUSTAB1 \cdot G\right]^{0.5}} \quad 9.5 < BGM < 28 \tag{14}$$

$$B = \frac{15000.0}{GMSQ \cdot \left[AJUSTAB1 \cdot G\right]^{0.5}} \quad 28 \le BGM \tag{15}$$

$$\phi_{CB}^2 = AJUSTAC_1 \cdot \left\{1.0 + \left(GMSQ - 1.0\right) \cdot \left[B \cdot AJUSTAA_1 \cdot XF^{0.9} \cdot \left(1.0 - AJUSTAA_1 \cdot XF\right)^{0.9} + AJUSTAA_1 \cdot XF^{1.8}\right]\right\} \tag{16}$$

where μ_g is the steam viscosity

μ_F is the saturated liquid viscosity

ρ_F is the saturated liquid density

ρ_g is the steam density

AJUSTAA1, AJUSTAB1, AJUSTAC1 are fit factors for G, XF and Global (default=1.0, 1.0, 1.0)

G is the mass flux [kg/m^2 s]

XF is the flow quality

We note that the Chisholm-Baroczy model is used only to improve the pressure drop at steady state but not to compute the perturbations around the steady-state point.

To obtain the Chisholm-Baroczy coefficients used in the momentum equations, we obtain the relation between the Chisholm-Baroczy two-phase friction multiplier, ϕ_{CB}^2, and the Martinelli-Nelson two-phase friction multiplier, ϕ_{MN}^2, times the Jones two-phase friction multiplier correction factor, Ω, at steady-state conditions denoted by the subindex 0:

$$f_{CB-MN,0} = \left(\frac{\phi_{CB}^2}{\phi_{MN}^2 \cdot \Omega} \right)_0 \tag{17}$$

then

$$f_M \left(\frac{\phi_{CB}^2}{\phi_{MN}^2 \cdot \Omega} \right)_0 \phi_{MN}^2 \, \Omega \frac{G^2}{2\rho} = f_M f_{CB-MN,0} \, \phi_{MN}^2 \, \Omega \frac{G^2}{2\rho} \tag{18}$$

equivalent to the LAPUR 5 model, but $f_{CB-MN,0}$ is calculated by LAPUR 6.0 automatically for steady-state conditions. When computing the partial derivatives for LAPURW, the partial derivative of this correction factor, $f_{CB-MN,0}$, is zero.

2.3.2. Friction Model II—LAPUR modifications

2.3.2.1. Friction factor model

Friction factor model II will be used only if IFFM=2 (input-user data on card 67). This model needs the coefficients:

- AN, BN, CN, DN (input-user data cards 68-71)
- R_r is the relative roughness (input-user data card 72)

The new function FF2 (x_frict.for) calculates this friction factor. The partial derivate of this friction factor is used by LAPURW 6.0:

$$\frac{\partial FF}{\partial y} = FF_0 \left[2 - \frac{CN \cdot DN}{Re_{l0}} \cdot \frac{1}{\left[1 + (BN \cdot R_r) + \dfrac{CN}{Re_{l0}} \right]} \right] = FF_0 (2 - A2V) \tag{19}$$

The new function AF2 (x_frict.for) computes the coefficient A2V for friction factor model II.

Three subroutines are modified:

- The subroutine INPUT: read the new variables.
- The subroutine OUTIN: print the new variables.
- The subroutine SETUP: select the parameters specific to channel type IX from the arrays.

Two new functions are added:

- The function FF2: Calculate the new friction factor for model II.
- The function AF2: Calculate the new coefficient A2V for model II.

2.3.2.2. Friction factor model II—LAPUR modifications

Subroutine INPUT—Read the new variables.

```
670     CALL INP1(NTFU,IFFM)
        GO TO 6000
680     CALL INP3(NTFU,ANM)
        GO TO 6000
690     CALL INP3(NTFU,BNM)
        GO TO 6000
700     CALL INP3(NTFU,CNM)
        GO TO 6000
710     CALL INP3(NTFU,DNM)
        GO TO 6000
720     CALL INP3(NTFU,RRM)
        GO TO 6000
```

Subroutine OUTIN—Print the new variables.

```
67 WRITE (6, 444)
   WRITE (6, 167)II, NTFU , (IFFM(J),J=1,NTFU)
   GO TO 200
68 WRITE (6, 168)II, NTFU , (ANM(J),J=1,NTFU)
   GO TO 200
69 WRITE (6, 169)II, NTFU , (BNM(J),J=1,NTFU)
   GO TO 200
70 WRITE (6, 170)II, NTFU , (CNM(J),J=1,NTFU)
   GO TO 200
71 WRITE (6, 171)II, NTFU , (DNM(J),J=1,NTFU)
   GO TO 200
72 WRITE (6, 172)II, NTFU , (RRM(J),J=1,NTFU)
   GO TO 200
```

…….

```
    167 FORMAT(1H0,4X,'(',I2,') ',8HNTFU    = I5 /10X,8HIFFM   = 7I12
       1                          ,/  (18X, 7I12)   )
    168  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,8HANM      =
  7F12.4
       1                          ,/   (18X, 7F12.4)  )
    169  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,8HBNM      =
  7F12.4
       1                          ,/   (18X, 7F12.4)  )
    170  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,8HCNM      =
  7F12.4
       1                          ,/   (18X, 7F12.4)  )
    171  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,8HDNM      =
  7F12.4
       1                          ,/   (18X, 7F12.4)  )
    172  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,8HRRM      =
  7F12.4
       1                          ,/   (18X, 7F12.4)  )
```

Subroutine SETUP—Select the parameters specific to channel type IX from the arrays.

```
      IFF    = IFFM  (IBM)
      AN     = ANM   (IBM)
      BN     = BNM   (IBM)
      CN     = CNM   (IBM)
      DN     = DNM   (IBM)
      RR     = RRM   (IBM)
```

Function FF2 (new function)—Calculate the new friction factor for model II.

```
  C LAPUR6 I:16
  C NEW LINES
  C Friction factor model II
  C
  C
        FUNCTION FF2(RE0)
  C
        INCLUDE 'X_common.fi'
          IF(RE0-2300.0)  100,100,200
    100     FF2 = 64./RE0
            GO TO 500
    200     FF2 = AN*(1+(BN*RR)+CN/RE0)**DN
            CON1 =64./RE0
            FF2 = AMAX1(FF2,CON1)
    500 CONTINUE
        RETURN
        END
  C
  C LAPUR6 END
```

Function AF2 (new function)—Calculate the new coefficient A2V (=AF2) for model II.

```
C LAPUR6 I:12
C NEW LINES
C Coefficient A2V for friction factor model II
      FUNCTION AF2(F0P,REBL)
C
      INCLUDE 'X_common.fi'
          CON=64.0/REBL
          IF(CON-F0P) 100,200,200
  100     AF2 = (CN*DN)/((1+BN*RR)*REBL+CN)
          GO TO 300
  200     AF2 = 1.0
  300 CONTINUE
      RETURN
      END
C LAPUR6 END
```

2.3.2.3. Friction multiplier model

Friction multiplier model II will be used only if IFMM=2 (input-user data on card 73). This model needs the coefficients:

- AJUSTAA1, AJUSTAB1, AJUSTAC1 (input-user data cards 74-76) (default=1.0, 1.0, 1.0)

We create a two new functions, VISC and POLY (x_subs.for), calculate the dynamic viscosity of steam (Ref 12). In the subroutine PREPHI (x_subs.for) we calculate this friction multiplier and its partial derivates.

Four subroutines are modified:

- The subroutine INPUT: read the new variables.
- The subroutine OUTIN: print the new variables.
- The subroutine SETUP: select the parameters specific to channel type IX from the arrays.
- The subroutine PREPHI: calculate the new friction multiplier

Two new functions are added:

- The function VSCV: calculate dynamic viscosity of steam
- The function POLY: used by function VSCV.

2.3.2.4. Friction multiplier model II—LAPUR modifications

Subroutine INPUT—Read the new variables.

```
730     CALL INP1(NTFU,IFMM)
        GO TO 6000
740     CALL INP3(NTFU,AJUSTAA1M)
        GO TO 6000
750     CALL INP3(NTFU,AJUSTAB1M)
        GO TO 6000
760     CALL INP3(NTFU,AJUSTAC1M)
        GO TO 6000
```

Subroutine OUTIN—Print the new variables.

```
73 WRITE (6, 444)
   WRITE (6, 173)II, NTFU , (IFMM(J),J=1,NTFU)
   GO TO 200
74 WRITE (6, 174)II, NTFU , (AJUSTAA1M(J),J=1,NTFU)
   GO TO 200
75 WRITE (6, 175)II, NTFU , (AJUSTAB1M(J),J=1,NTFU)
   GO TO 200
76 WRITE (6, 176)II, NTFU , (AJUSTAC1M(J),J=1,NTFU)
   GO TO 200
```

……

```
  173 FORMAT(1H0,4X,'(',I2,') ',8HNTFU   = I5 /10X,8HIFMM    = 7I12
     1                      ,/  (18X, 7I12)    )
  174  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,11HAJUSTAA1M=
7F12.4
     1                      ,/   (18X, 7F12.4)   )
  175  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,11HAJUSTAB1M=
7F12.4
     1                      ,/   (18X, 7F12.4)   )
  176  FORMAT(1H0,4X,'(',I2,')  ',8HNTFU     =  I5   /10X,11HAJUSTAC1M=
7F12.4
     1                      ,/   (18X, 7F12.4)   )
```

Subroutine SETUP—Select the parameters specific to channel type IX from the arrays.

```
IFM      = IFMM  (IBM)
AJUSTAA1= AJUSTAA1M(IBM)
AJUSTAB1= AJUSTAB1M(IBM)
AJUSTAC1= AJUSTAC1M(IBM)
```

Subroutine PREPHI—Calculate the new friction multiplier.

```
C Baroczy's two phase friction multiplier
C    G      - MASS FLUX (KG/M**2-SEC)
C    GP    - MASS FLUX (G/CM**2-SEC)
C    XF    - FLOW QUALITY
C    VISCG - VAPOUR VISCOSITY
C    VISCF - SATURATED LIQUID VISCOSITY (G/CM-SEC)
C    RHOL  - SATURATED LIQUID DENSITY (G /CM**3)
C    RHOG  - VAPOUR DENSITY (G/CM**3)
C
   IF (IFM .NE. 2) GO TO 100
   G = GP*10.0
   RHOL   = 1.0/VOLUME(P,TSAT)
   RHOG   = 1.0/VGP(P)
   VISCG  = VSCV(TSAT,RHOG)
   VISCF  = FPMU(P,TSAT)
C
    GMSQ=(VISCG/VISCF)**0.2*(RHOL/RHOG)
    BGM=SQRT(GMSQ)
C
   TPFM(1)    = 1.0
   DTPFMDB0(1) = 0.0
   DTPFMDH0(1) = 0.0
   DTPFMDY0(1) = 0.0
   DO J= 2, NP1
C
    IF (BGM .LE. 9.5) THEN
     BB=55.0/(( AJUSTAB1*G)**0.5)
    ELSEIF (BGM .GE. 28.0) THEN
      BB=15000.0/(GMSQ*( AJUSTAB1*G)**0.5)
     ELSE
      BB=520.0/(BGM*(AJUSTAB1*G)**0.5)
    ENDIF
C
    XF=X(J)
C
   IF(X(J).LT.0.0) XF=0.0
C
    TPFM(J) =  AJUSTAC1*(1.0+(GMSQ-1.0)*
  >             (BB*AJUSTAA1*XF**0.9*(1-AJUSTAA1*XF)**0.9
  >              +AJUSTAA1*XF**1.8))
C Partial derivative
    BB1         =(0.9*BB*
```

```
     >             (1.0-2.0*AJUSTAA1*XF)/
     >             (XF**0.1*(1.0-AJUSTAA1*XF)**0.1))
       DTPFMDB0(J)=AJUSTAC1*AJUSTAA1*(GMSQ-1.0)*
     >             (BB1+1.8*XF**0.8)*DXDB0(J)
C
       IF(H(J).EQ. 0.0) THEN
        DTPFMDH0(J)=0.0
       ELSE
        DTPFMDH0(J)=AJUSTAC1*AJUSTAA1*(GMSQ-1.0)*
     >             (BB1+1.8*XF**0.8)*DXDH0(J)
       ENDIF
C
       BB2 = -0.5*(BB*G**0.5)*(W0/A0)**(-0.5)
       DTPFMDY0(J)=AJUSTAC1*(GMSQ-1.0)*
     >             (AJUSTAA1*XF**0.9*(1.0-AJUSTAA1*XF)**0.9)
     >             *BB2
      ENDDO
C
```

Function VSCV (new function)—Calculate dynamic viscosity of steam.

```
C LAPUR6 I:53
C NEW LINES
      FUNCTION VSCV (T,ROV)
C
C
C   DYNAMIC VISCOSITY OF STEAM AS FUNCTION OF TEMPERATURE AND DENSITY
C        DENSITY   RO             IN (KG/CU.M)
C        TEMPERATURE T            IN (C)
C        DYNAMIC VISCOSITY VSCV0  IN (N S/SQ.M.)
C        DYNAMIC VISCOSITY VSCV   IN (G/SQ.CM. S)
C
      DIMENSION A(3), F(4), G(4)
      DATA A/3.53D-8, 6.765D-11, 1.021D-14/, B/.407D-7/, C/8.04D-6/,
     &     D/1.858D-7/, E/5.9D-10/,
     &       F/-.2885D-5, .2427D-7, -.67893333333D-10, .6317037037D-
13/,
     &     G/.176D3, -.16D1, .48D-2, -.47407407407D-5/
C
      RO=ROV*1.0E+3
      V1      = B*T + C
      IF(T .LE. 300.) GO TO 100
      IF(T .GE. 375.) GO TO 110
      VSCV0          =       V1      +      POLY(4,F(1),T)*RO      +
POLY(4,G(1),T)*POLY(3,A(1),RO)*
     &RO
C
      GO TO 140
  100 CONTINUE
      VSCV0    = V1 - RO*(D - E*T)
      IF(VSCV0.LT.1.D-7) VISV =1.D-7
```

```
C
      GO TO 140
  110 CONTINUE
      VSCV0    = V1 + POLY(3,A(1),RO)*RO
C
  140 CONTINUE
      VSCV     = VSCV0*10.
      RETURN
      END
C
```

Function POLY (new function)—Used by function VSVC.

```
C
C
      FUNCTION POLY(N,A,X)
C
      DIMENSION A(N)
C
      POLY     = 0.
      L        = N
  100 CONTINUE
      POLY=POLY*X+A(L)
      L=L-1
      IF(L.GT.0) GO TO 100
      RETURN
      END
C
C
C
C LAPUR6 END
```

2.4. MODIFICATIONS IN LAPURX RELATED TO PRESSURE LOSSES CAUSED BY AREA CHANGES

In this section, we present modifications related to the following losses:

- Gravity
- Acceleration
- Friction
- Irreversible expansion losses
- Irreversible contraction losses
- Local

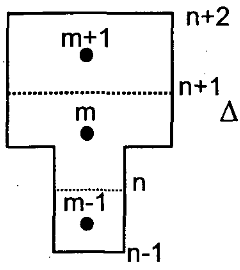
2.4.1. *Gravity Losses*

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In LAPUR 6.0, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, the LAPUR 6.0 computes the gravity-pressure losses due to an area change as follows:

$$\left(\frac{\partial P}{\partial z}\right)_G = \rho_l(z)\cdot g\cdot\cos\theta \qquad (20)$$



$$\Delta P]_n^{n+1} = \rho_l(m)\cdot g\cdot\cos\theta\cdot[z(n+1)-z(n)] \qquad (21)$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPDHNB1(J);J=1,NNB].

Boiling region

For this region

$$\left(\frac{\partial P}{\partial z}\right)_G = [\alpha(z)\cdot(1-\eta)\cdot\rho_F + (1-\alpha(z))\cdot\rho_l(z)]\cdot g\cdot\cos\theta \tag{22}$$

$$\Delta P]_n^{n+1} = \left[\left(\frac{\alpha(n)+\alpha(n+1)}{2}\right)\cdot(1-\eta)\cdot\rho_F + \left(1-\frac{\alpha(n)+\alpha(n+1)}{2}\right)\cdot\rho_l(m)\right]\cdot g\cdot\cos\theta\cdot dz \tag{23}$$

Subroutine DELP (x_frict.for), which has been modified, computes gravity pressure losses at every node along the length of the channel [DPDHP1(J);J=1,N+1] [DPDHP1(1)=0.0].

2.4.1.1. Gravity losses—LAPUR modifications

Subroutine DELP—Calculates gravity pressure losses at every node along the length of the channel.

Nonboiling region

```
          DPDHNB1(1)  =  (ZCOM(2)-ZCOM(1))*COS(TETA)*RHOVNBL(1)*0.001
.......
         DO 210 J=2,NNB
          DPDHNB1(J)  =  DPDHNB1(J-1)  +
     1                   (ZCOM(J+1)-ZCOM(J))*COS(TETA)*RHOVNBL(J)*0.001
.......
  210    CONTINUE
.......
          DPDHNB2  =  DPDHNB1(NNB)
.......
          DPDHNB2  =  0.0
```

Boiling region

```
          DPDHP1(1)   =  0.
 .......
        DO 260 M=2,NP1
 C LAPUR6 I:
 C NEW LINES
          BETM  =  (BETA(M)+BETA(M-1))/2.
          DPDHP1(M)  =  DPDHP1(M-1)  +  COS(TETA)*DZ*0.001
     1                  *  (BETM*(1.-ENU)*RHOL+(1-BETM)*RHOVL(M-1))
.......
  260 CONTINUE
.......
          DPDHSB1  =  DPDHP1(NSBP1)
.......
          DPDHBB1  =  DPDHP1(NP1)  -  DPDHP1(NSBP1)
```

Variable	Dimension	Subroutine	Description	Units
BETA(M)	N+1	SUBOIL & BULK	Boiling cell edge void fraction (BETA(1)=0.0)	
DPDHNB1(J)	NNB	DELP	Nonboiling cell accumulative gravity pressure drop	Kg/cm2
DPDHP1(M)	N+1	DELP	Boiling accumulative cell edges gravity pressure drop DPDHP1(1)=0.0	Kg/cm2
DZ	----	NODE	Boiling cell length	cm
ENU	----	READY	1-(RHOS/RHOL)	
NNB	-----	BOUNDY	Number of Nonboiling cells	
RHOL	----	READY	Saturated liquid density	g/cm3
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
TETA	----	BLOCK DATA	Angle	
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm

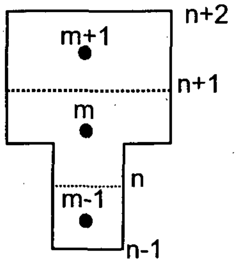
2.4.2. Acceleration Losses

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In the LAPUR 6.0 code, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, the LAPUR 6.0 computes the acceleration pressure losses due to an area change as follows:

$$\left(\frac{\partial P}{\partial z}\right)_{ac} = \frac{w_l^2}{A(z)}\frac{\partial}{\partial z}\left(\frac{1}{\rho_l(z)\cdot A(z)}\right) \tag{24}$$



$$\Delta P\Big]_n^{n+1} = \frac{w_l^2}{A(m)}\left(\frac{1}{\rho_l(n+1)\cdot A(n+1)} - \frac{1}{\rho_l(n)\cdot A(n)}\right) \tag{25}$$

LAPUR 6.0 computes the cell flow areas [AVNBL(m); m=1,NNB] and cell edge flow areas [AVNBCL(m); m=1,NNB+1] in subroutine NODE. The values AVNBL are length-averaged.

Subroutine DELP (x_frict.for) computes these pressure losses [DPACNB1(J);J=1,NNB].

The liquid cell edge densities $\rho_l(n)$ are calculated in subroutine DELP, using the cell values $\rho_l(m)$:

First cell edge:

$$\rho_l(1) = \rho_{lINLET} \tag{26}$$

Intermediate cell edges:

$$\rho_l(n) = \frac{\rho_l(m-1)\cdot\left(\frac{z(n)-z(n-1)}{2}\right) + \rho_l(m)\cdot\left(\frac{z(n+1)-z(n)}{2}\right)}{\left(\frac{z(n)-z(n-1)}{2}\right) + \left(\frac{z(n+1)-z(n)}{2}\right)} = \tag{27}$$

$$= \frac{\rho_l(m-1)\cdot(z(n)-z(n-1)) + \rho_l(m)\cdot(z(n+1)-z(n))}{z(n-1)+z(n+1)}$$

Last cell edge:

$$\rho_l(NNB+1) = \frac{\rho_l(m=NNB)\cdot(z(NNB+1)-z(NNB)) + \rho_l(1\_BR)\cdot DZ}{[z(NNB+1)-z(NNB)]+DZ} \tag{28}$$

Boiling region

For this region

$$\left(\frac{\partial P}{\partial z}\right)_{ac} = \frac{1}{A(z)}\cdot u_0^2 \cdot \rho_F \cdot A_0^2 \ \frac{\partial}{\partial z}\left(B(Z)\frac{1}{A(z)}\right) \tag{29}$$

$$\Delta P\Big]_n^{n+1} = \frac{1}{A(m)}\cdot u_0^2 \cdot \rho_F \cdot A_0^2 \left(\frac{B(n+1)}{A(n+1)} - \frac{B(n)}{A(n)}\right) \tag{30}$$

where B is:

$$B = \frac{[1-\alpha(1-\gamma^2(1-\eta))]}{[1-\alpha(1-\gamma(1-\eta))]^2} \tag{31}$$

and γ is the slip ratio

$$\gamma = \frac{u_g}{u_l} \tag{32}$$

LAPUR 6.0 computes the cell flow areas [AVL(m); m=1,N] and cell edge flow areas [AVCL(m); m=1,N+1] in subroutine NODE. The values AVL are length-averaged.

Subroutine DELP (x_frict.for) computes these pressure losses [DPACP1(J);J=1,N+1] [DPACP1(1)=0.0], which are multiplied by (0.001/g).

One subroutine, DELP, has been modified. DELP performs the calculation of acceleration pressure losses at every node along the length of the channel.

2.4.2.1. Acceleration losses—LAPUR modifications

Subroutine DELP—Calculate acceleration pressure losses at every node along the length of the channel.

Nonboiling region

```
            RHOC1= RHOLI
            RHOC2=(RHOVNBL(1)*(ZCOM(2)-ZCOM(1))+
     1               RHOVNBL(2)*(ZCOM(3)-ZCOM(2)))/(ZCOM(3)-ZCOM(1))
            DPACNB1(1) = (0.001*W0**2/SG)/AVNBL(1)*
     1                   (1/(RHOC2*AVNBCL(2))-1/(RHOC1*AVNBCL(1)))
C
         DO 215 J=2,NNB-1
            RHOC1=(RHOVNBL(J-1)*(ZCOM(J)-ZCOM(J-1))+
     1                 RHOVNBL(J)*(ZCOM(J+1)-ZCOM(J)))/(ZCOM(J+1)-ZCOM(J-
1))
            RHOC2=(RHOVNBL(J)*(ZCOM(J+1)-ZCOM(J))+
     1                   RHOVNBL(J+1)*(ZCOM(J+2)-ZCOM(J+1)))/(ZCOM(J+2)-
ZCOM(J))
            DPACNB1(J) = DPACNB1(J-1)+(0.001*W0**2/SG)/AVNBL(J)*
     1                   (1/(RHOC2*AVNBCL(J+1))-1/(RHOC1*AVNBCL(J)))
 215     CONTINUE
C
            J=NNB
            IF (NNB==1) THEN
               RHOC1=RHOLI
            ELSE
               RHOC1=RHOC2
            END IF
            RHOC2=(RHOVNBL(J)*(ZCOM(J+1)-ZCOM(J))+
     1               RHOVL(1)*DZ)/(ZCOM(J+1)-ZCOM(J)+DZ)
            DPACNB1(J) = DPACNB1(J-1)+(0.001*W0**2/SG)/AVNBL(J)*
     1                   (1/(RHOC2*AVNBCL(J+1))-1/(RHOC1*AVNBCL(J)))
C
......
            DPACNB2 = DPACNB1(NNB)
......
            DPACNB2 = 0.0
```

Boiling region

```
            DPACP1(1) = 0.
.......
         DO 260 M=2,NP1
```

```
......
              CON2= 0.001*RHOL*U0**2*A0**2/SG
              DPACP1(M)  = DPACP1(M-1)+CON2/AVL(M-1)
         1                   *(B0(M)/AVCL(M)-B0(M-1)/AVCL(M-1))
......
    260 CONTINUE
......
              DPACSB1  =  DPACP1(NSBP1)
......
              DPACBB1  =  DPACP1(NP1)  -  DPACP1(NSBP1)
```

Variable	Dimension	Subroutine	Description	Units
A0	----	SETUP	Channel flow area (Input data A0M(NTD))	cm2
AVCL(M)	N+1	NODE	Boling cell edge flow area	cm2
AVL(I)	N	NODE	Boiling cell flow area - length averaged	cm2
AVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge flow area	cm2
AVNBL(I)	NNB	NODE	Nonboiling cell flow area - length averaged	cm2
B0(M)	N+1	SUBOIL & BULK	B in momentum equation	
DPACNB1(J)	NNB	DELP	Nonboiling cell accumulative acceleration pressure drop	kg/cm2
DPACP1(M)	N+1	DELP	Boiling accumulative cell edges acceleration pressure drop DPACP1(1)=0.0	kg/cm2
DZ	----	NODE	Boiling cell length	cm
NNB	-----	BOUNDY	Number of Nonboiling cells	
RHOL	----	READY	Saturated liquid density	g/cm3
RHOLI	----	READY	Inlet liquid density	g/cm3
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
SG	----	BLOCK DATA	Gravitational acceleration	cm/s2
U0	----	PREPAR	Reference channel velocity	cm/s
W0	-----	PREPAR	Reference channel mass flow rate	g/s
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm

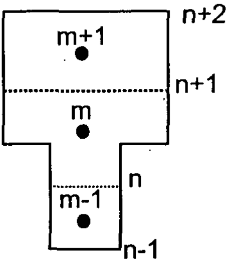
2.4.3. *Friction Losses*

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In the LAPUR 6.0 code, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, LAPUR 6.0 computes the friction pressure losses due to an area change as follows:

$$\Delta P(z)=\frac{\rho_l(z)\cdot u^2(z)}{2}\cdot f(z)\cdot\frac{\Delta z}{D_H(z)}\cdot K_F(z) \qquad (33)$$



$$\Delta P\Big]_n^{n+1}=\frac{\rho_l(m)\cdot u^2(m)}{2}\cdot f(m)\cdot\frac{K_F(m)}{D_H(m)}\cdot\left[z(n+1)-z(n)\right] \qquad (34)$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPFRNB1(J);J=1,NNB].

Boiling region

For this region we can use either friction model I (using the Martinelli-Nelson correlation):

$$\Delta P(z)=\frac{\rho_l(z)\cdot u_{l0}^2(z)}{2}\cdot f(z)\cdot\frac{\Delta z}{D_H(z)}\cdot\left\{\phi_{MN}^2(z)\cdot\Omega(z)\right\}\cdot K_F(z) \qquad (35)$$

$$\Delta P\Big]_n^{n+1}=\frac{\rho_l(m)\cdot u_{l0}^2(m)}{2}\cdot f(m)\cdot\frac{K_F(m)}{D_H(m)}\cdot DZ\cdot\left[\frac{\left\{\phi_{MN}^2(n)\cdot\Omega(n)\right\}+\left\{\phi_{MN}^2(n+1)\cdot\Omega(n+1)\right\}}{2}\right] \qquad (36)$$

Or friction model II (using Chisholm-Baroczy correlation):

$$\Delta P(z)=\frac{\rho_l(z)\cdot u_{l0}^2(z)}{2}\cdot f(z)\cdot\frac{\Delta z}{D_H(z)}\cdot\left\{\phi_{CB}^2(z)\right\}\cdot K_F(z) \qquad (37)$$

$$\Delta P\Big]_N^{N+1}=\frac{\rho_l(m)\cdot u_{l0}^2(m)}{2}\cdot f(M)\cdot\frac{K_F(m)}{D_H(m)}\cdot DZ\cdot\left[\frac{\left\{\phi_{CB}^2(n)\right\}+\left\{\phi_{CB}^2(n+1)\right\}}{2}\right] \qquad (38)$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPFRP1(J);J=1,N+1] [DPFRP1(1)=0.0].

Note that $K_F(z)$ is the LAPUR 5 friction multiplier that was used to meet the LAPUR pressure loss to other more-accurate codes. For LAPUR 6.0 calculations, the term $\left\{\phi_{CB}^2(z)\right\}$ replaces the old $K_F(z)$, which must be set to 1.0.

Note that this is the formulation for steady-state LAPURX calculation. The formulation for LAPURW is described in Sect. 2.7 and used a combination of models I and II for the derivative terms.

Two subroutines are modified:

- The subroutine NODE, which calculates the cell friction multiplier for the nonboiling region
- The subroutine DELP, which calculates friction pressure losses at every node along the length of the channel.

2.4.3.1. Friction losses—LAPUR modifications

Subroutine NODE—Calculates the cell friction multiplier for the nonboiling region.

```
C Calculation of cell friction multiplier
       IF(NF.LE.1)  GO TO 3510
C
C DDD(I) Height to the top of the I-th axial interval within
C        the friction is uniform.
C DZF(I) Length of the I-th axial interval within the friction is
uniform.
C        Input data card 36
C
         L2 =  1
      DO 3500 J=1,NNB
      DO 3380 I=1,NF
         L = I
        IF(ZCOM(J+1).LE.DDD(L))  GO TO 3400
 3380 CONTINUE
         L  = NF
 3400 CONTINUE
         L1 = L2
         L2 = L
         LL = L2 - (L1+1)
        IF(LL)  3420,3440,3460
 3420    EKFNBL(J) = EKFF(L1)
         GO TO 3500
 3440    EKFNBL(J) = (EKFF(L1)*(DDD(L1)-ZCOM(J))
    1                +EKFF(L2)*(ZCOM(J+1)-DDD(L1)))
    2                /(ZCOM(J+1)-ZCOM(J))
         GO TO 3500
 3460    TEMP0= 0.0
         LL1  = L1 + 1
         LL2  = L2 - 1
      DO 3480 I=LL1,LL2
 3480    TEMP0 = TEMP0 + EKFF(I)*DZF(I)
         EKFNBL(J) = (EKFF(L1)*(DDD(L1)-ZCOM(J))+TEMP0
    1                +EKFF(L2)*(ZCOM(J+1)-DDD(L2-1)))
    2                /(ZCOM(J+1)-ZCOM(J))
 3500 CONTINUE
```

```
          GO TO 3600
  3510 CONTINUE
       EPS=0.000001
       IF((ZNB-DZF(1)).GT.EPS)GO TO 540
       DO 3511 J=1,NNB
          EKFNBL(J) = EKFF(1)
  3511 CONTINUE
          GO TO 3600
 C
  3520 CONTINUE
          WRITE (6,9000)  (TITLE(I),I=1,18)
          WRITE (6,9100)  IX
       NODEGO=1.0
       RETURN
  3540 CONTINUE
          WRITE (6,9000)  (TITLE(I),I=1,18)
          WRITE (6,9200)  IX,ZNB
       NODEGO=1.0
       RETURN
 C
  3600 CONTINUE
 C
```

Subroutine DELP—Calculates friction pressure losses at every node along the length of the channel.

Nonboiling region

```
            REB=REVNBL(1)
            CON1= 0.001*RHOVNBL(1)*UVNBL(1)**2/(2.*SG*DEVNBL(1))
            TEMP1=FF(REB)
            IF(IFF .EQ. 2) TEMP1=FF2(REB)
            FR1=TEMP1*CON1*EKFNBL(1)
            DPFRNB1(1) = FR1*(ZCOM(2)-ZCOM(1))
  C
          DO 210 J=2,NNB
```

……

```
            REB=REVNBL(J)
            CON1= 0.001*RHOVNBL(J)*UVNBL(J)**2/(2.*SG*DEVNBL(J))
            TEMP1=FF(REB)
            IF(IFF .EQ. 2) TEMP1=FF2(REB)
            FR1=TEMP1*CON1*EKFNBL(J)
            DPFRNB1(J) = DPFRNB1(J-1) + FR1*(ZCOM(J+1)-ZCOM(J))
     210  CONTINUE
```

…….

```
            DPFRNB2 = DPFRNB1(NNB)
```

…….

```
            DPFRNB2 = 0.0
```

Boiling region

```
               DPFRP1(1) = 0.
......
          DO 260 M=2,NP1
......
               REB=REVL(M-1)
               CON1= 0.001*RHOVL(M-1)*UVL(M-1)**2/(2.*SG*DEVL(M-1))
               TEMP1=FF(REB)
               IF(IFF .EQ. 2) TEMP1=FF2(REB)
               FR1=TEMP1*CON1*EKFL(M-1)
               TEMP2=T20(M-1)
               TEMP3=T20(M)
               IF(IFM .EQ. 2) THEN
                TEMP2=TPFM(M-1)
                TEMP3=TPFM(M)
                DPFRP1(M) = DPFRP1(M-1) + FR1*DZ
     1                     *(TEMP3+TEMP2)/2.
              ELSE
                DPFRP1(M) = DPFRP1(M-1) + FR1*DZ
     1                     *(OMEGA(M)*TEMP3+OMEGA(M-1)*TEMP2)/2.
               ENDIF
......
        260 CONTINUE
.......
               DPFRSB1 = DPFRP1(NSBP1)
.......
               DPFRBB1 = DPFRP1(NP1) - DPFRP1(NSBP1)
```

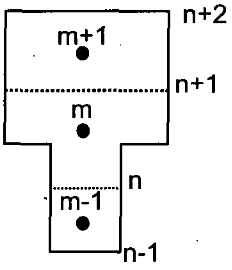
Variable	Dimension	Subroutine	Description	Units
DEVL(I)	N	NODE	Hydraulic diameter boiling cell - length averaged	cm
DEVNBL(I)	NNB	NODE	Nonboiling cell hydraulic diameter - length averaged	cm
DPFRNB1(J)	NNB	DELP	Nonboiling cell accumulative friction pressure drop	Kg/cm2
DPFRP1(M)	N+1	DELP	Boiling accumulative cell edges friction pressure drop DPFRP1(1)=0.0	Kg/cm2
DZ	----	NODE	Boiling cell length	cm
EKFL(I)	N	NODE	Boiling cell friction multiplier	
EKFNBL(J)	NNB	NODE	Nonboiling cell friction multiplier	
IFF	----	SETUP	Flag for friction factor model to use	
IFM	----	SETUP	Flag for friction multiplier model to use	
NNB	-----	BOUNDY	Number of Nonboiling cells	
OMEGA(M)	N+1	OMEGAP	Boiling cell edge Jones flow correction factor for Martinelli-Nelson. OMEGA(1)=1.0	
REVL(I)	N	FRICT	Boiling cell Reynolds	
REVNBL(I)	NNB	FRICT	Nonboiling cell Reynolds	
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
SG	----	BLOCK DATA	Gravitational acceleration	cm/s2
T20(M)	N+1	PREPHI	Boiling cell edge Martinelli-Nelson two-phase friction multiplier T20(1)=1.0	
TPFM(J)	N+1	PREPHI	Boiling cell edge Baroczy-Chisholm two-phase friction multiplier TPFM(1)=1.0	
UVL(I)	N	FRICT	Boiling cell liquid velocity -no steam- (w0/rhol*a_cell)	cm/s
UVNBL(I)	NNB	FRICT	Nonboiling cell liquid velocity	cm/s
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm

2.4.4. Irreversible Expansion Losses

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In the LAPUR 6.0 code, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, the LAPUR 6.0 uses the Vennard formulation (Ref. 9) to compute the irreversible expansion losses due to an area change:



$$\Delta P(m) = (1-\sigma(m))^2 \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)} \tag{39}$$

$$\sigma(m) = \frac{A(n)}{A(n+1)} \tag{40}$$

$$G(n) = \rho_l(n) \cdot u_l(n) = \frac{w_0}{A(n)} \tag{41}$$

To consider that a sudden enlargement produces a pressure loss, we compute the cross-sectional area variation σ. The irreversible pressure loss is calculated as:

$$\Delta P(m) = (1-\sigma(m))^2 \cdot \frac{(w_0/A(n))^2}{2 \cdot \rho_l(m)} \tag{42}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPEXNB(J);J=1,NNB].

Note. To prevent computational noise, irreversible expansion losses are set to 0 if $(\sigma-1)<0.001$.

Boiling region

For this region, LAPUR 6.0 uses the homogeneous two-phase multiplier formulation (Ref. 11):

$$\Delta P(m) = (1-\sigma(m))^2 \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)}\left[1+\left(\frac{\rho_l(m)}{\rho_g(m)}-1\right)\cdot x(m)\right] \tag{43}$$

$$\sigma(m) = \frac{A(n)}{A(n+1)} \tag{44}$$

$$G(n) = \rho_l(n)\cdot u_l(n) = \frac{w_0}{A(n)} \tag{45}$$

where x(m) is the cell edge quality.

To consider that a sudden enlargement produces an irreversible pressure loss, we compute the cross-sectional area variation σ. The irreversible pressure loss is calculated as:

$$\Delta P(m) = (1-\sigma(m))^2 \cdot \frac{(w_0/A(n))^2}{2 \cdot \rho_l(m)}\left[1+\left(\frac{\rho_l(m)}{\rho_g(m)}-1\right)\cdot x(m)\right] \tag{46}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPEXP(J);J=1,N].

Note: To prevent computational noise, irreversible expansion losses are set to 0 if $(\sigma-1)<0.001$.

One subroutine, DELP, has been modified. DELP performs the calculation of expansion pressure losses at every node along the length of the channel.

2.4.4.1. Irreversible expansion losses—LAPUR modifications

Subroutine DELP—Calculates expansion pressure losses at every node along the length of the channel

Nonboiling region

```
          SIGMA=AVNBCL(1)/AVNBCL(2)
```

```
               IF((1.0-SIGMA).LE.0.001) THEN
                DPEXNB(1)=0.0
               ELSE
                TEMP0=1.0
                TEMP1=(1.0-SIGMA)**2
                CON1=W0/AVNBCL(1)
                TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVNBL(1))
                DPEXNB(1)=TEMP0*TEMP1*TEMP2
               ENDIF
     C
            DO 216 J=2,NNB
               SIGMA=AVNBCL(J)/AVNBCL(J+1)
               IF((1.0-SIGMA).LE.0.001) THEN
                DPEXNB(J)=DPEXNB(J-1)+0.0
               ELSE
                TEMP0=1.0
                TEMP1=(1.0-SIGMA)**2
                CON1=W0/AVNBCL(J)
                TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVNBL(J))
                DPEXNB(J)=DPEXNB(J-1)+TEMP0*TEMP1*TEMP2
               ENDIF
      216   CONTINUE
...... .
               DPEXNB2 = DPEXNB (NNB)
...... .
               DPEXNB2 = 0.0
```

Boiling region

```
               DPEXP(1)  = 0.
......
               SIGMA=AVCL(1)/AVCL(2)
               IF((1.0-SIGMA).LE.0.001) THEN
                DPEXP(2)=0.0
               ELSE
                TEMP0=(1.0+(RHOVL(1)/RHOS-1)*X(1))
                TEMP1=(1.0-SIGMA)**2
                CON1=W0/AVCL(1)
                TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVL(1))
                DPEXP(2)=TEMP0*TEMP1*TEMP2
               ENDIF
     C
            DO 266 J=2,N
               SIGMA=AVCL(J)/AVCL(J+1)
               IF((1.0-SIGMA).LE.0.001) THEN
                DPEXP(J)=DPEXP(J-1)+0.0
               ELSE
                TEMP0=(1.0+(RHOVL(J)/RHOS-1)*X(J))
                TEMP1=(1.0-SIGMA)**2
                CON1=W0/AVCL(J)
                TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVL(J))
```

```
                DPEXP(J)=DPEXP(J-1)+TEMP0*TEMP1*TEMP2
               ENDIF
      266   CONTINUE
......
               DPEXSB   = DPEXP (NSB)
......
               DPEXBB   = DPEXP (N)    - DPEXP (NSB)
```

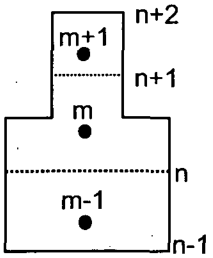
Variable	Dimension	Subroutine	Description	Units
AVCL(M)	N+1	NODE	Boling cell edge flow area	cm2
AVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge flow area	cm2
DPEXNB(J)	NNB	DELP	Nonboiling cell accumulative expansion pressure drop	kg/cm2
DPEXP(J)	N	DELP	Boiling cell accumulative expansion pressure drop	kg/cm2
N	-----	INPUT-user	Number of axial nodes desired in the boiling region of the channels	
NNB	-----	BOUNDY	Number of Nonboiling cells	
RHOS	----	READY	Steam density	g/cm3
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
SG	----	BLOCK DATA	Gravitational acceleration	cm/s2
W0	-----	PREPAR	Reference channel mass flow rate	g/s
X(M)	N+1	SUBOIL & BULK	Channel boiling cell edge quality. X(1)=0.0	

2.4.5. Irreversible Contraction Losses

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In the LAPUR 6.0 code, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, the LAPUR 6.0 uses the Vennard formalism (Ref. 9) to compute the irreversible contraction losses due to an area change:



$$\Delta P(m) = \sigma(m)^2 \cdot 0.385 \cdot \left(1 - \frac{1}{\sigma(m)}\right) \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)} \tag{47}$$

$$\sigma(m) = \frac{A(n)}{A(n+1)} \tag{48}$$

$$G(n) = \rho_l(n) \cdot u_l(n) = \frac{w_0}{A(n)} \tag{49}$$

To consider that a sudden contraction produces a pressure loss, we compute the cross-sectional area variation σ. The irreversible pressure loss is calculated as:

$$\Delta P(m) = \sigma(m)^2 \cdot 0.385 \cdot \left(1 - \frac{1}{\sigma(m)}\right) \cdot \frac{(w_0/A(n))^2}{2 \cdot \rho_l(m)} \tag{50}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPCONB(J);J=1,NNB].

Note. To prevent computational noise, irreversible contraction losses are set to 0 if $(\sigma - 1) < 0.001$.

Boiling region

For this region, LAPUR 6.0 uses the homogeneous two-phase multiplier formulation (Ref. 11):

$$\Delta P(m) = \sigma(m)^2 \cdot 0.385 \cdot \left(1 - \frac{1}{\sigma(m)}\right) \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)} \left[1 + \left(\frac{\rho_l(m)}{\rho_g(m)} - 1\right) \cdot x(m)\right] \tag{51}$$

$$\sigma(m) = \frac{A(n)}{A(n+1)} \tag{52}$$

$$G(n) = \rho_l(n) \cdot u_l(n) = \frac{w_0}{A(n)} \tag{53}$$

where x(M) is the cell edge quality.

To consider that a sudden contraction produces a pressure loss, we compute the cross-sectional area variation σ. The irreversible pressure loss is calculated as:

$$\Delta P(m) = \sigma(m)^2 \cdot 0.385 \cdot \left(1 - \frac{1}{\sigma(m)}\right) \cdot \frac{(w_0/A(n))^2}{2 \cdot \rho_l(m)} \left[1 + \left(\frac{\rho_l(m)}{\rho_g(m)} - 1\right) \cdot x(m)\right] \tag{54}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPCOP(J);J=1,N].

Note: To prevent computational noise, irreversible contraction losses are set to 0 if $(\sigma - 1) < 0.001$.

One subroutine, DELP, is modified. DELP calculates contraction pressure losses at every node along the length of the channel.

2.4.5.1. Irreversible contraction losses—LAPUR modifications

Subroutine DELP—Calculation of contraction pressure losses at every node along the length of the channel

Nonboiling region

```
              SIGMA=AVNBCL(1)/AVNBCL(2)
              IF((SIGMA-1.0).LE.0.001) THEN
               DPCONB(1)=0.0
              ELSE
               TEMP0=1.0
               TEMP1=SIGMA**2*0.385*(1-1/SIGMA)
               CON1=W0/AVNBCL(1)
               TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVNBL(1))
               DPCONB(1)=TEMP0*TEMP1*TEMP2
              ENDIF
      C
            DO 218 J=2,NNB
              SIGMA=AVNBCL(J)/AVNBCL(J+1)
              IF((SIGMA-1.0).LE.0.001) THEN
               DPCONB(J)=DPCONB(J-1)+0.0
              ELSE
               TEMP0=1.0
               TEMP1=SIGMA**2*0.385*(1-1/SIGMA)
               CON1=W0/AVNBCL(J)
               TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVNBL(J))
               DPCONB(J)=DPCONB(J-1)+TEMP0*TEMP1*TEMP2
              ENDIF
       218  CONTINUE
.......
              DPCONB2 = DPCONB (NNB)
.......
              DPCONB2 = 0.0
```

Boiling region

```
              DPCOP(1)   = 0.
......
              SIGMA=AVCL(1)/AVCL(2)
              IF((SIGMA-1.0).LE.0.001) THEN
               DPCOP(1)=0.0
              ELSE
               TEMP0=(1.0+(RHOVL(1)/RHOS-1)*X(1))
               TEMP1=SIGMA**2*0.385*(1-1/SIGMA)
               CON1=W0/AVCL(1)
               TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVL(1))
               DPCOP(1)=TEMP0*TEMP1*TEMP2
              ENDIF
```

```
C
      DO 268 J=2,N
         SIGMA=AVCL(J)/AVCL(J+1)
         IF((SIGMA-1.0).LE.0.001) THEN
          DPCOP(J)=DPCOP(J-1)+0.0
         ELSE
          TEMP0=(1.0+(RHOVL(J)/RHOS-1)*X(J))
          TEMP1=SIGMA**2*0.385*(1-1/SIGMA)
          CON1=W0/AVCL(J)
          TEMP2=(0.001/SG)*CON1**2/(2.0*RHOVL(J))
          DPCOP(J)=DPCOP(J-1)+TEMP0*TEMP1*TEMP2
         ENDIF
 268  CONTINUE
......
         DPCOSB  = DPCOP (NSB)
......
         DPCOBB  = DPCOP (N)   - DPCOP (NSB)
```

Variable	Dimension	Subroutine	Description	Units
AVCL(M)	N+1	NODE	Boling cell edge flow area	cm2
AVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge flow area	cm2
DPCONB(J)	NNB	DELP	Nonboiling cell accumulative contraction pressure drop	kg/cm2
DPCOP(J)	N	DELP	Boiling cell accumulative contraction pressure drop	kg/cm2
N	-----	INPUT-user	Number of axial nodes desired in the boiling region of the channels	
NNB	-----	BOUNDY	Number of Nonboiling cells	
RHOS	----	READY	Steam density	g/cm3
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
SG	----	BLOCK DATA	Gravitational acceleration	cm/s2
W0	-----	PREPAR	Reference channel mass flow rate	g/s
X(M)	N+1	SUBOIL & BULK	Channel boiling cell edge quality. X(1)=0.0	

2.4.6. Local Losses

Nonboiling region

In LAPUR 5, the nonboiling region comprises only one node. In the LAPUR 6.0 code, the nonboiling region has been partitioned into several cells, according to the LAPURX input data file.

For this region, the LAPUR 6.0 computes the local losses (spacers) as:

$$\Delta P(m) = K_L(m) \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)} \tag{55}$$

$$G(n) = \rho_l(n) \cdot u_l(n) = \frac{w_0}{A(n)} \tag{56}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPLLNB(J);J=1,NNB]. In addition, we obtain a nodal “equivalent Martinelli-Nelson” local loss coefficient, which is used in the calculation of the momentum frequency-dependent coefficients, in subroutine COEFR, which are needed to solve the thermo-hydro-dynamic equations:

$$K_{L-MN}(m) = \frac{\Delta P_{local}(m)}{\Delta P_{friction}(m)} \tag{57}$$

Boiling region

For this region, the LAPUR 6.0 computes the local losses (spacers) at steady state as:

$$\Delta P(m) = K_L(m) \cdot \left[1 + \left(\frac{\rho_l(m)}{\rho_g(m)} - 1\right) \cdot x(m)\right] \cdot \frac{G^2(n)}{2 \cdot \rho_l(m)} \tag{58}$$

$$G(n) = \rho_l(n) \cdot u_l(n) = \frac{w_0}{A(n)} \tag{59}$$

Subroutine DELP (x_frict.for) computes these pressure losses [DPLLP(J);J=1,N]. In addition, we obtain a nodal “equivalent Martinelli-Nelson” local loss coefficient, which is used in the calculation of the momentum frequency-dependent coefficients, in subroutine COEFR, needed to solve the thermo-hydro-dynamic equations:

$$K_{L-MN}(m) = \frac{\Delta P_{local}(m)}{\Delta P_{friction}(m)} \tag{60}$$

Five subroutines are modified:

- Subroutine INPUT: Read the new variables.
- Subroutine OUTIN: Print the new variables.
- Subroutine SETUP: Selection of the parameters specific to channel type IX from the arrays.
- Subroutine NODE: Transformation of the nodal parameters to the new coordinate system.
- Subroutine DELP: Calculation of local pressure losses at every node along the length of the channel.

2.4.6.1. Local losses—LAPUR modifications

Subroutine INPUT—Read the new variables.

```
630      CALL INP1(NXE,NDIMLL)
         GO TO 6000
640      CALL INP1(NTDLL,NODLL)
         GO TO 6000
650      CALL INP2(NTDLL,NODLL,DZLLM,NLLMAX)
         GO TO 6000
660      CALL INP2(NTDLL,NODLL,EKLLM,NLLMAX)
         GO TO 6000
```

Variable	Dimension	Subroutine	Description	Units
DZLLM(JJ,JJJ)	NLLMAX,NLL	INPUT-user	Elevation measured from the channel entrance of local loss JJJ. Index JJ represents the type of local-loss channel	cm
EKLLM(JJ,JJJ)	NLLMAX,NLL	INPUT-user	Local-loss constant of local loss JJJ. Index JJ represents the type of local-loss channel	
NDIMLL(J)	NXE	INPUT-user	Local pressure-loss type of the J-th thermal region	
NLLMAX	----	param.fi	PARAMETER (NLLMAX = 10) ! Max # of local-loss channel	
NODLL(J)	NTDLL	INPUT-user	Number of axial intervals for the J-th type, local-loss channel	
NTDLL	----	INPUT-user	Number of local-loss channel types	

Subroutine OUTIN—Print the new variables.

```
63 WRITE(6, 444)
   WRITE(6, 163)II, NXE , (NDIMLL(J), J=1,NXE)
   GO TO 200
64 WRITE(6, 164)II, NTDLL , (NODLL(J),J=1,NTDLL)
   GO TO 200
65 DO 325 JJ=1,NTDLL
```

```
      JI=NODLL(JJ)
      IF(JJ.EQ.1) WRITE (6, 165)II, (DZLLM(JJ,JJJ),JJJ=1,JI)
      IF(JJ.NE.1) WRITE (6, 301) (DZLLM(JJ,JJJ),JJJ=1,JI)
  325 CONTINUE
      GO TO 200
   66 DO 326 JJ=1,NTDLL
      JI=NODLL(JJ)
      IF(JJ.EQ.1) WRITE (6, 166)II, (EKLLM(JJ,JJJ),JJJ=1,JI)
      IF(JJ.NE.1) WRITE (6, 301) (EKLLM(JJ,JJJ),JJJ=1,JI)
  326 CONTINUE
      GO TO 200
```

....

```
  163 FORMAT(1H0,4X,'(',I2,') ',8HNXE      = I5   /10X,8HNDIMLL  =
7I12  ,
     1                          / (18X, 7I12)    )
  164 FORMAT(1H0,4X,'(',I2,') ', 8HNTDV     = I5 / 10X,8HNODLL   =
7I12
     1                          ,/ (18X, 7I12)  )
  165  FORMAT(1H0,4X,'(',I2,')   ',8HDZLLM      =      7F12.4     /
(18X,7F12.4) )
  166  FORMAT(1H0,4X,'(',I2,')   ',8HEKLLM      =      7F12.4     /
(18X,7F12.4) )
```

Subroutine SETUP—Select the parameters specific to channel type IX from the arrays.

```
      IBM=NDIMLL(IX)
      NLL=NODLL(IBM)
      DO I=1,NLL
          DZLL(I)  = DZLLM(IBM,I)
          EKLL(I)  = EKLLM(IBM,I)
      ENDDO
```

Subroutine NODE—Transform the nodal parameters to the new coordinate system

```
C Calculation of nodal local loss
         IF(NLL.LE.0)  GO TO 7510
C
         I1=1
C
      DO 6000 I=1,NNB
         EKLLNBL(I)=0.0
 6000 ENDDO
C
      DO 6500 J=1,NNB
      DO 6380 I=I1,NLL
        IF(ZCOM(J+1).LT.DZLL(I))  GO TO 6400
          EKLLNBL(J)=EKLLNBL(J)+EKLL(I)
          I1=I1+1
```

```
 6380 CONTINUE
 6400 CONTINUE
 6500 CONTINUE
C
      DO 7000 I=1,N
         EKLLL(I)=0.0
 7000 ENDDO
C
      DO 7500 J=1,N
      DO 7380 I=I1,NLL
       IF(ZPP(J+1).LT.DZLL(I))  GO TO 7400
          EKLLL(J)=EKLLL(J)+EKLL(I)
          I1=I1+1
 7380 CONTINUE
 7400 CONTINUE
 7500 CONTINUE
C
 7510 CONTINUE
```

Variable	Dimension	Subroutine	Description	Units
DZLL(I)	NLL	SETUP	Top height from bottom of the I-th local loss axial interval (DZLLM)	cm
EKLLL(J)	N	NODE	Local-loss constant for the J-th boiling axial cell	
EKLLNBL(J)	NNB	NODE	Local-loss constant for the J-th non-boiling axial cell	
ZCOM(J+1)	NNB+N+1	COEFR & NODE	Accumulative cell edges height. ZCOM(1)=0.0	cm

Subroutine DELP—Calculates local pressure losses at every node along the length of the channel

Nonboiling region

```
          TEMP0=1.0
          CON1=W0/AVNBCL(1)
          TEMP1=(0.001/SG)*CON1**2/(2.0*RHOVNBL(1))
          DPLLNB(1)=TEMP0*TEMP1*EKLLNBL(1)
C
          EKLFNB(1)=DPLLNB(1)/DPFRNB1(1)
C
       DO 217 J=2,NNB
          TEMP0=1.0
          CON1=W0/AVNBCL(J)
          TEMP1=(0.001/SG)*CON1**2/(2.0*RHOVNBL(J))
          DPLLNB(J)=DPLLNB(J-1)+TEMP0*TEMP1*EKLLNBL(J)
C
          EKLFNB(J)=(DPLLNB(J)-DPLLNB(J-1))/
     1                   (DPFRNB1(J)-DPFRNB1(J-1))
 217   CONTINUE
```

……

```
               DPLLNB2 = DPLLNB (NNB)
......
               DPLLNB2 = 0.0
```

Boiling region

```
               TEMP0=(1.0+(RHOVL(1)/RHOS-1)*X(1))
               CON1=W0/AVCL(1)
               TEMP1=(0.001/SG)*CON1**2/(2.0*RHOVL(1))
               DPLLP(1)=TEMP0*TEMP1*EKLLL(1)
      C
               EKLF(1)=DPLLP(1)/DPFRP1(2)
      C
            DO 267 J=2,N
               TEMP0=(1.0+(RHOVL(J)/RHOS-1)*X(J))
               CON1=W0/AVCL(J)
               TEMP1=(0.001/SG)*CON1**2/(2.0*RHOVL(J))
               DPLLP(J)=DPLLP(J-1)+TEMP0*TEMP1*EKLLL(J)
      C
               EKLF(J)=(DPLLP(J)-DPLLP(J-1))/
           1           (DPFRP1(J+1)-DPFRP1(J))
       267  CONTINUE
......
               DPLLSB  = DPLLP (NSB)
......
               DPLLBB  = DPLLP (N)   - DPLLP (NSB)
```

Variable	Dimension	Subroutine	Description	Unit
AVCL(M)	N+1	NODE	Boling cell edge flow area	cm2
AVNBCL(J+1)	NNB+1	NODE	Nonboiling cell edge flow area	Cm2
DPLLNB(J)	NNB	DELP	Nonboiling cell accumulative local pressure drop	kg/cm2
DPLLP(J)	N	DELP	Boiling cell accumulative local pressure drop	kg/cm2
RHOS	----	READY	Steam density	g/cm3
RHOVL(I)	N	FRICT	Boiling cell density	g/cm3
RHOVNBL(I)	NNB	FRICT	Nonboiling cell density	g/cm3
SG	----	BLOCK DATA	Gravitational acceleration	Cm/s2
W0	-----	PREPAR	Reference channel mass flow rate	g/s
X(M)	N+1	SUBOIL & BULK	Channel boiling cell edge quality. X(1)=0.0	

2.5. LAPURX 6 COEFFICIENTS OF THE MOMENTUM EQUATION

In this section, we present the modifications made in LAPURX and related to the new coefficients obtained for the momentum equation with variable area in the frequency domain that will be used for the solution of LAPURW.

2.5.1. LAPUR 6.0 Nonboiling Region Coefficients

The normalized conservation momentum equation in the nonboiling region is:

$$-L\frac{\partial\Pi}{\partial z}\frac{A(z)}{A_0}=\frac{u_0}{g}\frac{\partial y}{\partial t}+\frac{u_0}{g}\frac{\partial}{\partial z}\left(\frac{\rho_F}{\rho_l}y^2\frac{A_0}{A(z)}\right)+F(z)y^{(2-a_2)}\left(\frac{A_0}{A(z)}\right)+\frac{\rho_l}{\rho_F}\frac{A(z)}{A_0}\cos\theta \tag{61}$$

where Π is the normalized pressure

$$\Pi=\frac{P}{g\rho_F L} \tag{62}$$

y is the normalized mass flow rate

$$y=\frac{w}{w_0} \tag{63}$$

and F(z) is the single-phase friction corresponding to a fluid of density ρ_l moving at speed u_0, and for the nonboiling region is equal to:

$$F(z)=f_0(z)\frac{u_0^2}{2gD_H(z)}\frac{\rho_F}{\rho_l} \tag{64}$$

Linearizing the conservation equation (61) around the steady-state point, and Laplace transforming the resulting equation, and considering the crud-deposition friction multiplier K_F (Ref. 7), yields:

$$-L_0\frac{A(Z)}{A_0}\frac{\partial}{\partial z}\left(\delta\overline{\Pi}\right)=\frac{u_0}{g}s\,\delta\overline{y}+\frac{u_0^2}{g}2\frac{\partial}{\partial z}\left(\frac{\rho_F}{\rho_0}\frac{A_0}{A(z)}\delta\overline{y}\right)+\left[K_F(F(z))(2-a_2)\left(\frac{A_0}{A(z)}\right)\right]_0\delta\overline{y} \tag{65}$$

Integrating equation (65) over the length of the i-th node yields:

$$\begin{aligned}
&-\Delta\overline{\Pi}_{NB}=-\left(\delta\overline{\Pi}_{ZNB}-\delta\overline{\Pi}_{in}\right)=\\
&\left\{\frac{u_0}{L_0\,g}s\left[\sum_{i=1}^{N_{NB}}\left(\Delta z_i\frac{A_0}{A_{a,i}}\right)+\frac{A_0}{A_{in}}L_{in}\right]\right\}\delta\overline{y}_{in}\\
&+\left\{\frac{u_0^2}{L_0\,g}2\rho_F\left[\sum_{i=1}^{N_{NB}}\left(\left(\frac{1}{\rho_{l,i+1}}\frac{A_0}{A_{i+1}}-\frac{1}{\rho_{l,i}}\frac{A_0}{A_i}\right)\frac{A_0}{A_{a,i}}\right)+\left(\frac{1}{\rho_{l,1}}-\frac{1}{\rho_{in}}\right)\right]\right\}\delta\overline{y}_{in}\\
&+\left\{\frac{u_0^2}{L_0\,g}\left(\frac{A_0\,\rho_F}{A_{in}\,\rho_{in}}\right)^2K_{cc}\right\}\delta\overline{y}_{in}\\
&+\left\{\frac{u_0^2}{L_0\,g}\frac{\rho_F}{\rho_0}\left[\left(\frac{\rho_0}{2}\sum_{i=1}^{N_{NB}}f_{0,i}\,(2-a_2)_i\,\Delta z_i\frac{K_{F,i}}{2}\left(\left(\frac{1}{D_{H,i+1}}\frac{1}{\rho_{l,i+1}}\frac{A_0}{A_{i+1}}+\frac{1}{D_{H,i}}\frac{1}{\rho_{l,i}}\frac{A_0}{A_i}\right)\frac{A_0}{A_{a,i}}\right)\right)\right.\right.\\
&\left.\left.+\left(f_{0,in}\,K_{C,in}\left(\frac{A_0}{A_{in}}\right)^2\frac{(2-a_{2,in})}{2D_{H,in}}L_{in}\right)\right]\right\}\delta\overline{y}_{in}
\end{aligned} \tag{66}$$

where A_a is the length-averaged node flow area.

The irreversible pressure losses due to sudden expansions and contractions and local losses (spacer), are not included in equation (66). These are given by:

$$\frac{u_0^2}{L_0\, g}\rho_F \sum_{i=1}^{N_{NB}} \frac{1}{\rho_{l,a,i}} \times \left[\frac{A_{i+1}}{A_{a,i}} \left(\frac{A_0}{A_i} \right)^2 \left(\sum_{k=1}^{N_{exp}} \left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k} \right] + \sum_{k'=1}^{N_{con}} \left[\sigma_{k'}^2\, K_{con,irr,k'}\, \delta^{Kr}_{z,z_{k'}} \right] \right) \right] \delta \bar{y}_{in} \tag{67}$$

where

$$K_{exp,irr,k} = \left[1 - \sigma(z_k) \right]^2 \tag{68}$$

$$\sigma(z_k) = \frac{A_i}{A_{i+1}} \tag{69}$$

and z_k indicates the expansion position

$$K_{con,irr,k'} = 0.385 \left(1 - \frac{1}{\sigma(z_{k'})} \right) \tag{70}$$

$$\sigma(z_{k'}) = \sigma_{k'} = \frac{A_{i'}}{A_{i'+1}} \tag{71}$$

and $z_{k'}$ indicates the contraction position.

We note that the irreversible local pressure losses for the nonboiling region obtained using equation (55) is only used at steady state, but is not used to compute the perturbations around the steady-state point.

The irreversible local pressure loss due to the spacer in the i-th node is converted in equivalent friction pressure losses:

$$\left(\Delta P_{Spacer,i} \right)_0 = K_{L-F,i} \left(\Delta P_{Friction,i} \right)_0 \tag{72}$$

where $K_{L-F,i}$ is the equivalent friction coefficient for local loss for the i-th node given by:

$$K_{L-F,i} = \frac{\left(\Delta P_{Spacer,i} \right)_0}{\left(\Delta P_{Friction,i} \right)_0} = \frac{\left(K_{L,i} \dfrac{G_i^2}{2\rho_{L,i}} \right)_0}{\left(K_{F,i}\, f_i \dfrac{G_i^2}{2\rho_{L,i}} \right)_0} = \frac{\left(K_{L,i} \right)_0}{\left(K_{F,i}\, f_i \right)_0} \tag{73}$$

Then, including this equivalent friction pressure loss by means of the coefficient $K_{L-F,i}$, we obtain that the total friction coefficient in the i-th node, $K_{F+L,i}$, is given by:

$$K_{F+L,i}\, f_i = K_{F,i} \left(1 + K_{L-F,i} \right) f_i \tag{74}$$

Adding the irreversible pressure losses in equation (66), we obtain

$$
\begin{aligned}
-\Delta\overline{\Pi}_{NB} = & \left\{\frac{u_0}{L_0\, g} s \left[\sum_{i=1}^{N_{NB}} \left(\Delta z_i \frac{A_0}{A_{a,i}}\right) + \frac{A_0}{A_{a,i}} L_{in}\right]\right\} \delta\overline{y}_{in} \\
& + \left\{\frac{u_0^2}{L_0\, g} \frac{\rho_F}{\rho_0} \left(EKACPV + EKNBPV + EKCCP + EKINP + EKLLV\right)\right\} \delta\overline{y}_{in}
\end{aligned}
\tag{75}
$$

where the coefficients are given by:

$$
EKACPV = \Bigg\{ 2\rho_0 \Bigg[\sum_{i=1}^{N_{NB}} \Bigg(\Bigg(\frac{1}{\rho_{l,i+1}} \frac{A_0}{A_{i+1}} - \frac{1}{\rho_{l,i}} \frac{A_0}{A_i} \Bigg) \frac{A_0}{A_{a,i}} \Bigg) + \Bigg(\frac{1}{\rho_{l,1}} - \frac{1}{\rho_{in}} \Bigg) \Bigg] \Bigg] \Bigg\}
\tag{76}
$$

$$
EKNBPV = \left(\frac{\rho_0}{2} \sum_{i=1}^{N_{NB}} f_{0,i} \left(2 - a_2\right)_i \Delta z_i \frac{K_{F+L,i}}{2} \left(\left(\frac{1}{D_{H,i+1}} \frac{1}{\rho_{l,i+1}} \frac{A_0}{A_{i+1}} + \frac{1}{D_{H,i}} \frac{1}{\rho_{l,i}} \frac{A_0}{A_i} \right) \frac{A_0}{A_{a,i}} \right) \right)
\tag{77}
$$

$$
EKCCP = \left(\frac{A_0\, \rho_F}{A_{in}\, \rho_{in}} \right)^2 K_{cc}
\tag{78}
$$

$$
EKINP = \left(f_{0,in} K_{C,in} \left(\frac{A_0}{A_{in}} \right)^2 \frac{\left(2 - a_{2,in}\right)}{2 D_{H,in}} L_{in} \right)
\tag{79}
$$

$$
EKLLV = \rho_0 \sum_{i=1}^{N_{NB}} \frac{1}{\rho_{l,a,i}} \times \left[\frac{A_{i+1}}{A_{a,i}} \left(\frac{A_0}{A_i} \right)^2 \left(\sum_{k=1}^{N_{exp}} \left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k} \right] + \sum_{k'=1}^{N_{con}} \left[\sigma^2_{k'} K_{con,irr,k'}\ \delta^{Kr}_{z,z_{k'}} \right] \right) \right] \delta\overline{y}_{in}
\tag{80}
$$

In a more compact form we can write:

$$
-\Delta\overline{\Pi}_{NB} = \left\{\frac{u_0}{L_0\, g} s \left[\sum_{i=1}^{N_{NB}} \left(\Delta z_i \frac{A_0}{A_{a,i}}\right) + \frac{A_0}{A_{a,i}} L_{in}\right]\right\} \delta\overline{y}_{in} + \left\{\frac{1}{CV_{18}}\right\} \delta\overline{y}_{in}
\tag{81}
$$

where

$$
\frac{1}{CV_{18}} = \frac{u_0^2}{L_0\, g} \frac{\rho_F}{\rho_0} \left(EKACPV + EKNBPV + EKCCP + EKINP + EKLLV\right)
\tag{82}
$$

Thus, from equation (81) we can write

$$
\begin{aligned}
\delta\bar{y}_{in} &= \frac{1}{\left\{\frac{u_0}{g}\left[\frac{1}{L_0}\sum_{i=1}^{N_{NB}}\left(\Delta z_i\,\frac{A_0}{A_{a,i}}\right)+\mathrm{EKIP}\right]s+\frac{1}{CV_{18}}\right\}}\left(-\Delta\bar{\Pi}_{NB}\right) \\
&= \frac{CV_{18}}{\left\{CV_{18}\,\frac{u_0}{g}\left[\frac{1}{L_0}\sum_{i=1}^{N_{NB}}\left(\Delta z_i\,\frac{A_0}{A_{a,i}}\right)+\mathrm{EKIP}\right]s+1\right\}}\left(-\Delta\bar{\Pi}_{NB}\right) \qquad (83) \\
&= \frac{CV_{18}}{\left\{\tau V_L\ s+1\right\}}\left(-\Delta\bar{\Pi}_{NB}\right)
\end{aligned}
$$

where:

$$
\mathrm{EKIP} = \left(\frac{A_0}{A_{in}}\,\frac{L_{in}}{L_0}\right) \qquad (84)
$$

and

$$
\tau V_L = CV_{18}\,\frac{u_0}{g}\left[\frac{1}{L_0}\sum_{i=1}^{N_{NB}}\left(\Delta z_i\,\frac{A_0}{A_{a,i}}\right)+\mathrm{EKIP}\right] \qquad (85)
$$

The LAPUR 6.0 new coefficients, used in subroutine COEFR, are

$$
\mathrm{EKACPV} = \left\{2\,\rho_0\left[\sum_{i=1}^{N_{NB}}\left(\left(\frac{1}{\rho_{l,i+1}}\,\frac{A_0}{A_{i+1}}-\frac{1}{\rho_{l,i}}\,\frac{A_0}{A_i}\right)\frac{A_0}{A_{a,i}}\right)+\left(\frac{1}{\rho_{l,1}}-\frac{1}{\rho_{in}}\right)\right]\right\} \qquad (86)
$$

$$
\mathrm{EKNBPV} = \left(\frac{\rho_0}{2}\sum_{i=1}^{N_{NB}} f_{0,i}\left(2-a_2\right)_i\,\Delta z_i\,\frac{K_{F+L,i}}{2}\left(\left(\frac{1}{D_{H,i+1}}\,\frac{1}{\rho_{l,i+1}}\,\frac{A_0}{A_{i+1}}+\frac{1}{D_{H,i}}\,\frac{1}{\rho_{l,i}}\,\frac{A_0}{A_i}\right)\frac{A_0}{A_{a,i}}\right)\right) \qquad (87)
$$

$$
\tau V_L = CV_{18}\,\frac{u_0}{g}\left[\frac{1}{L_0}\sum_{i=1}^{N_{NB}}\left(\Delta z_i\,\frac{A_0}{A_{a,i}}\right)+\mathrm{EKIP}\right] \qquad (88)
$$

$$
\mathrm{EKLLV} = \rho_0\sum_{i=1}^{N_{NB}}\frac{1}{\rho_{l,a,i}}\times\left[\frac{A_{i+1}}{A_{a,i}}\left(\frac{A_0}{A_i}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\,\delta^{Kr}_{z,z_{k'}}\right]\right)\right]\delta\bar{y}_{in} \qquad (89)
$$

One subroutine, COEFR, is modified.

2.5.1.1. New nonboiling region coefficients—LAPUR modifications

Subroutine COEFR

```
TEMP1=0.0
TEMP2=0.0
TEMP3=0.0
```

```
      DO 570 I=1,NNB
       TEMP1=TEMP1+
     1       FNBL(I)*EKFNBL(I)*(EKLFNB(I)+1)*(2.0-A2NBL(I))*
     2       (ZCOM(I+1)-ZCOM(I))
     3      *(A0/(DEVNBCL(I+1)*RHOVNBCL(I+1)*AVNBCL(I+1))+
     4       A0/(DEVNBCL(I)*RHOVNBCL(I)*AVNBCL(I)))*(A0/AVNBL(I))
       TEMP2=TEMP2+
     1      (A0/(RHOVNBCL(I+1)*AVNBCL(I+1))-
     2       A0/(RHOVNBCL(I)*AVNBCL(I)))*(A0/AVNBL(I))
       TEMP3=TEMP3+
     1       (ZCOM(I+1)-ZCOM(I))*(A0/AVNBL(I))
  570 ENDDO
          EKNBPV = (RHOLI/2.0)*TEMP1
          EKACPV = (2.0*RHOLI)*TEMP2
C
          TEXP = 0.0
          TCON = 0.0
C
      DO I=1,NNB
          SIGMA=AVNBCL(I)/AVNBCL(I+1)
          IF((1.0-SIGMA).LE.0.001) THEN
            TEXP = 0.0 + TEXP
          ELSE

TEXP=(1.0/RHOVNBL(I))*AVNBCL(I+1)/AVNBL(I)*(A0/AVNBCL(I))**2
     1           *(1.0-SIGMA)**2 + TEXP
          ENDIF
C
          SIGMA=AVNBCL(I)/AVNBCL(I+1)
          IF((SIGMA-1.0).LE.0.001) THEN
            TCON = 0.0 + TCON
          ELSE

TCON=(1.0/RHOVNBL(I))*AVNBCL(I+1)/AVNBL(I)*(A0/AVNBCL(I))**2
     1           *SIGMA**2*0.385*(1.-1./SIGMA) + TCON
          ENDIF
C
      ENDDO
C
          EKLLV = RHOLI*(TEXP+TCON)
C
          C18V                                                       =
1./(Q4*RHOL/RHOLI*(EKACPV+EKNBPV+EKINP+EKCPP+EKLLV))
          TAULV  = C18V*(TEMP3/EL+EKIP)*U0/SG
C
          IF(FLOW_AREA_VAR.EQ.1)THEN
          C18  = C18V
          TAUL = TAULV
          ENDIF
```

2.5.2. LAPUR 6.0 Boiling Region Coefficients

The LAPUR 6.0 has two friction models. Model I comprises the Martinelli-Nelson two-phase friction multiplier. Model II comprises the Chisholm-Baroczy friction multiplier.

2.5.2.1. Friction model I

The normalized conservation momentum equation in the boiling region, using the Martinelli-Nelson friction model ϕ_{MN}^2 and the Jones flow rate corrector Ω, is:

$$\begin{aligned} -L\frac{\partial \Pi}{\partial z}\frac{A(z)}{A_0} &= \frac{u_0}{g}\frac{\partial y}{\partial t}+\frac{u_0^2}{g}\frac{\partial}{\partial z}\left(B\,y^2\,\frac{A_0}{A(z)}\right) \\ &+F(z)\,y^{(2-a_2)}\,\phi_{MN}^2\,\Omega\left(\frac{A_0}{A(z)}\right)+(1-\alpha\,\eta)\cos\theta\,\frac{A(z)}{A_0} \end{aligned} \qquad (90)$$

where Π is the normalized pressure

$$\Pi=\frac{P}{g\rho_F\,L} \qquad (91)$$

y is the normalized mass flow rate

$$y=\frac{w}{w_0} \qquad (92)$$

B is:

$$B=\frac{\left[1-\alpha\left(1-\gamma^2(1-\eta)\right)\right]}{\left[1-\alpha\left(1-\gamma(1-\eta)\right)\right]^2} \qquad (93)$$

γ is the slip ratio

$$\gamma=\frac{u_g}{u_l} \qquad (94)$$

and F(z) is the single-phase friction corresponding to a fluid of density ρ_l moving at speed u_0, is equal to:

$$F(z)=f_0(z)\frac{u_0^2}{2gD_H(z)}\,\frac{\rho_F}{\rho_l} \qquad (95)$$

Linearizing the conservation equation (90) around the steady-state point, and Laplace transforming the resulting equation, and considering the crud-deposition friction multiplier K_F (Ref. 7), yields, for the Martinelli-Nelson friction model:

$$
\begin{aligned}
-L_0 \frac{A(Z)}{A_0}\frac{\partial}{\partial z}\delta\bar{\Pi} &= \frac{u_0}{g}\, s\, \delta\bar{y} + \frac{\partial}{\partial z}\left\{\left[\frac{u_0^2}{g}\frac{A_0}{A(z)}2B\right]_0 \delta\bar{y}\right\} \\
&+ \left[(K_F\, F(z))(2-a_2)\phi_{MN}^2\, \Omega\left(\frac{A_0}{A(z)}\right)\right]_0 \delta\bar{y} + \left[(K_F\, F(z))\phi_{MN}^2\left(\frac{A_0}{A(z)}\right)\frac{\partial \Omega}{\partial y}\right]_0 \delta\bar{y} \\
&+ \left[-\eta\cos\theta\left(\frac{A(z)}{A_0}\right)\right]_0 \delta\bar{\alpha} + \left[(K_F\, F(z))\Omega\left(\frac{A_0}{A(z)}\right)\frac{\partial \phi_{MN}^2}{\partial \alpha}\right]_0 \delta\bar{\alpha} \\
&+ \frac{\partial}{\partial z}\left\{\left[\frac{u_0^2}{g}\left(\frac{A_0}{A(z)}\right)\frac{\partial B}{\partial \alpha}\right]_0 \delta\bar{\alpha}\right\} + \left[(K_F\, F(z))\phi_{MN}^2\left(\frac{A_0}{A(z)}\right)\frac{\partial \Omega}{\partial H}\right]_0 \delta\bar{H} \\
&+ \frac{\partial}{\partial z}\left\{\left[\frac{u_0^2}{g}\left(\frac{A_0}{A(z)}\right)\frac{\partial B}{\partial H}\right]_0 \delta\bar{H}\right\}
\end{aligned}
\qquad (96)
$$

where H is the normalized degree of sub-cooling

$$
H = \frac{h_F - h_l}{h_{fg}} \qquad (97)
$$

Integrating equation (96) over the length of the j-th node yields:

$$
\begin{aligned}
&-\left(\delta\overline{\Pi}_{j+1}-\delta\overline{\Pi}_{j}\right)= \\
&\Bigg\{\frac{u_0}{gL_0}\Delta z_j\frac{A_0}{A_{a,j}}s+4\frac{u_0^2}{gL_0}B_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}}+ \\
&\quad +K_F\,f_{0,j}\frac{u_0^2}{2gL_0}\left(\left(2-a_2\right)_j\Omega_j+\left(\frac{\partial\Omega}{\partial y}\right)_j\right)\phi_{MN,j+1}^2\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}}\Bigg\}\delta\overline{y}_{a,j} \\
&+\Bigg\{2\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial\alpha}\right)_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}}-\eta\frac{\Delta z_j}{L_0}\cos\theta \\
&\quad +K_Ff_{0,j}\frac{u_0^2}{2gL_0}\Omega_j\left(\frac{\partial\phi_{MN}^2}{\partial\alpha}\right)_{j+1}\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}}\Bigg\}\delta\overline{\alpha}_{a,j} \\
&+\Bigg\{K_F\,f_{0,j}\frac{u_0^2}{2gL_0}\left(\frac{\partial\Omega}{\partial H}\right)_{j+1}\phi_{MN,j+1}^2\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \\
&\quad +2\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial H}\right)_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}}\Bigg\}\delta\overline{H}_{a,j} \\
&-\Bigg\{2\frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}B_{j+1}+\frac{A_0}{A_j}B_j\right] \\
&\quad +K_Ff_{0,j}\frac{u_0^2}{2gL_0}\left(\left(2-a_2\right)_j\Omega_j+\left(\frac{\partial\Omega}{\partial y}\right)_j\right)\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}D_{H,j+1}}\phi_{MN,j+1}^2-\frac{A_0}{A_jD_{H,j}}\phi_{MN,j}^2\right]\Bigg\}\delta\overline{y}_j \\
&-\Bigg\{\frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{,j+1}}\left(\frac{\partial B}{\partial\alpha}\right)_{j+1}+\frac{A_0}{A_j}\left(\frac{\partial B}{\partial\alpha}\right)_j\right] \\
&\quad +K_Ff_{0,j}\frac{u_0^2}{2gL_0}\Omega_j\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[-\frac{A_0}{A_jD_{H,j}}\left(\frac{\partial\phi_{MN}^2}{\partial\alpha}\right)_j+\frac{A_0}{A_{j+1}D_{H,j+1}}\left(\frac{\partial\phi_{MN}^2}{\partial\alpha}\right)_{j+1}\right]\Bigg\}\delta\overline{\alpha}_j \\
&-\Bigg\{K_F\,f_{0,j}\frac{u_0^2}{2gL_0}\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[-\frac{A_0}{A_jD_{H,j}}\left(\frac{\partial\Omega}{\partial H}\right)_j\phi_{MN,j}^2+\frac{A_0}{A_{j+1}D_{H,j+1}}\left(\frac{\partial\Omega}{\partial H}\right)_{j+1}\phi_{MN,j+1}^2\right] \\
&\quad +\frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}\left(\frac{\partial B}{\partial H}\right)_{j+1}+\frac{A_0}{A_j}\left(\frac{\partial B}{\partial H}\right)_j\right]\Bigg\}\delta\overline{H}_j
\end{aligned}
\tag{98}
$$

where A_a is the length-averaged node flow area, and:

$$
\delta\overline{y}_{a,j}=\frac{\delta\overline{y}_j+\delta\overline{y}_{j+1}}{2}
\tag{99}
$$

$$\delta\bar{\alpha}_{a,j} = \frac{\delta\bar{\alpha}_j + \delta\bar{\alpha}_{j+1}}{2} \tag{100}$$

$$\delta\bar{H}_{a,j} = \frac{\delta\bar{H}_j + \delta\bar{H}_{j+1}}{2} \tag{101}$$

The irreversible pressure losses due to sudden expansions and contractions, and local losses (spacer), are not included in equation (98). These are given by:

$$\begin{aligned}
&\frac{u_0^2}{2gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0(1^{st})}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\,\delta^{Kr}_{z,z_{k'}}\right]\right)\right]\left(\frac{\partial\phi_H^2}{\partial\alpha}\right)_{0,a,j}\delta\bar{\alpha}_{a,j} \\
&+\frac{u_0^2}{2gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0(1^{st})}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\,\delta^{Kr}_{z,z_{k'}}\right]\right)\right]\left(\frac{\partial\phi_H^2}{\partial H}\right)_{0,a,j}\delta\bar{H}_{a,j} \\
&+\frac{u_0^2}{2gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0(1^{st})}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\,\delta^{Kr}_{z,z_{k'}}\right]\right)\right]\phi^2_{H,0,a,j}\,\delta\bar{y}_{a,j}
\end{aligned} \tag{102}$$

where

$$K_{exp,irr,k} = [1-\sigma(z_k)]^2 \tag{103}$$

$$\sigma(z_k) = \frac{A_i}{A_{i+1}} \tag{104}$$

and z_k indicates the expansion position

$$K_{con,irr,k'} = 0.385\left(1-\frac{1}{\sigma(z_{k'})}\right) \tag{105}$$

$$\sigma(z_{k'}) = \sigma_{k'} = \frac{A_{i'}}{A_{i'+1}} \tag{106}$$

and $z_{k'}$ indicates the contraction position.

We note that the irreversible local pressure losses for the boiling region obtained using equation (58) are only calculated at steady state; the equation is not used to compute the perturbations around the steady-state point.

The irreversible local pressure loss due to the spacer in the j-th node is converted in equivalent friction pressure losses:

$$(\Delta P_{Spacer,j})_0 = K_{L-F,j}(\Delta P_{Friction,j})_0 \tag{107}$$

where $K_{L\text{-}F,j}$ is the equivalent friction coefficient for local loss for the j-th node given by:

$$K_{L-F,j} = \frac{\left(\Delta P_{Spacer,j}\right)_0}{\left(\Delta P_{Friction,j}\right)_0} = \frac{\left(K_{L,j}\,\phi_{H,j}^2\,\dfrac{G_j^2}{2\rho_{l,j}}\right)_0}{\left(K_{F,j}\,f_j\,\phi_{MN,j}^2\,\Omega_j\,\dfrac{G_j^2}{2\rho_{l,j}}\right)_0} = \frac{\left(K_{L,j}\,\phi_{H,j}^2\right)_0}{\left(K_{F,j}\,f_j\,\phi_{MN,j}^2\,\Omega_j\right)_0} \tag{108}$$

Then, including this equivalent friction pressure loss by means of the coefficient $K_{L\text{-}F,j}$, we obtain that the total friction coefficient in the j-th node, $K_{F+L,j}$, is given by:

$$K_{F+L,j}\,f_j = K_{F,j}\left(1 + K_{L-F,j}\right)f_j \tag{109}$$

Adding the irreversible pressure losses in equation (98), for the Martinelli-Nelson friction model, we obtain:

$$\begin{aligned} -\left(\delta\overline{\Pi}_{j+1} - \delta\overline{\Pi}_j\right) = -\Delta\overline{\Pi}_j = \\ \left[\tau V_j\,s + CV5_j + CV9_j + CV13N_j\right]\delta\overline{y}_{a,j} \\ + \left[CV7_j - C4_j + CV11_j + CV14N_j\right]\delta\overline{\alpha}_{a,j} + \left[CV21_j + CVN21_j\right]\delta\overline{H}_{a,j} \\ - \left[CV6_j + CV10_j\right]\delta\overline{y}_j - \left[CV8_j + CV12_j\right]\delta\overline{\alpha}_j - \left[CV22_j\right]\delta\overline{H}_j \end{aligned} \tag{110}$$

or in a more compact form:

$$\begin{aligned} -\Delta\overline{\Pi}_j = {} & \left(\tau V_j\,s + CV13_j + CVN13_j\right)\delta\overline{y}_{a,j} \\ & + \left(CV14_j + CVN14_j\right)\delta\overline{\alpha}_{a,j} + \left(CV21_j + CVN21_j\right)\delta\overline{H}_{a,j} \\ & - CV15_j\,\delta\overline{y}_j - CV16_j\,\delta\overline{\alpha}_j - CV22_j\,\delta\overline{H}_j \end{aligned} \tag{111}$$

where

$$\tau V_j = \frac{u_0}{gL_0}\,\Delta z_j\,\frac{A_0}{A_{a,j}} \tag{112}$$

$$CV5_j = 4\,\frac{u_0^2}{gL_0}\,B_{j+1}\,\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \tag{113}$$

$$CV9_j = K_{F+L,j}\,f_{0,j}\,\frac{u_0^2}{2gL_0}\left(\left(2 - a_2\right)_j\Omega_j + \left(\frac{\partial\Omega}{\partial y}\right)_j\right)\phi_{MN,j+1}^2\,\Delta z_j\,\frac{1}{D_{H,j+1}}\,\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \tag{114}$$

$$CV7_j = 2\,\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial\alpha}\right)_{j+1}\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \tag{115}$$

$$C4_j = \eta\,\frac{\Delta z_j}{L_0}\cos\theta \tag{116}$$

$$CV11_j = K_{F+L,j} f_{0,j} \frac{u_0^2}{2gL_0} \Omega_j \left(\frac{\partial \phi_{MN}^2}{\partial \alpha} \right)_{j+1} \Delta z_j \frac{1}{D_{H,j+1}} \frac{A_0}{A_{j+1}} \frac{A_0}{A_{a,j}} \tag{117}$$

$$CV21_j = K_{F+L,j} f_{0,j} \frac{u_0^2}{2gL_0} \left(\frac{\partial \Omega}{\partial H} \right)_{j+1} \phi_{MN,j+1}^2 \Delta z_j \frac{1}{D_{H,j+1}} \frac{A_0}{A_{j+1}} \frac{A_0}{A_{a,j}} + 2 \frac{u_0^2}{gL_0} \left(\frac{\partial B}{\partial H} \right)_{j+1} \frac{A_0}{A_{j+1}} \frac{A_0}{A_{a,j}} \tag{118}$$

$$CV6_j = 2 \frac{u_0^2}{gL_0} \frac{A_0}{A_{a,j}} \left[\frac{A_0}{A_{j+1}} B_{j+1} + \frac{A_0}{A_j} B_j \right] \tag{119}$$

$$CV10_j = K_{F+L,j} f_{0,j} \frac{u_0^2}{2gL_0} \left((2-a_2)_j \Omega_j + \left(\frac{\partial \Omega}{\partial y} \right)_j \right) \frac{\Delta z_j}{2} \frac{A_0}{A_{a,j}} \left[\frac{A_0}{A_{j+1} D_{H,j+1}} \phi_{MN,j+1}^2 - \frac{A_0}{A_j D_{H,j}} \phi_{MN,j}^2 \right] \tag{120}$$

$$CV8_j = \frac{u_0^2}{gL_0} \frac{A_0}{A_{a,j}} \left[\frac{A_0}{A_{j+1}} \left(\frac{\partial B}{\partial \alpha} \right)_{j+1} + \frac{A_0}{A_j} \left(\frac{\partial B}{\partial \alpha} \right)_j \right] \tag{121}$$

$$CV12_j = K_{F+L,j} f_{0,j} \frac{u_0^2}{2gL_0} \Omega_j \frac{\Delta z_j}{2} \frac{A_0}{A_{a,j}} \left[- \frac{A_0}{A_j D_{H,j}} \left(\frac{\partial \phi_{MN}^2}{\partial \alpha} \right)_j + \frac{A_0}{A_{j+1} D_{H,j+1}} \left(\frac{\partial \phi_{MN}^2}{\partial \alpha} \right)_{j+1} \right] \tag{122}$$

$$\begin{aligned} CV22_j = {} & K_{F+L,j} f_{0,j} \frac{u_0^2}{2gL_0} \frac{\Delta z_j}{2} \frac{A_0}{A_{a,j}} \left[- \frac{A_0}{A_j D_{H,j}} \left(\frac{\partial \Omega}{\partial H} \right)_j \phi_{MN,j}^2 + \frac{A_0}{A_{j+1} D_{H,j+1}} \left(\frac{\partial \Omega}{\partial H} \right)_{j+1} \phi_{MN,j+1}^2 \right] \\ & + \frac{u_0^2}{gL_0} \frac{A_0}{A_{a,j}} \left[\frac{A_0}{A_{j+1}} \left(\frac{\partial B}{\partial H} \right)_{j+1} + \frac{A_0}{A_j} \left(\frac{\partial B}{\partial H} \right)_j \right] \end{aligned} \tag{123}$$

$$CVN14_j = \frac{u_0^2}{2gL_0} \left[\frac{A_{j+1}}{A_{a,i}} \left(\frac{A_0}{A_j} \right)^2 \left(\sum_{k=1}^{N_{exp}} \left[K_{exp,irr,k} \ \delta_{z,z_k}^{Kr} \right] + \sum_{k'=1}^{N_{con}} \left[\sigma_{k'}^2 K_{con,irr,k'} \delta_{z,z_{k'}}^{Kr} \right] \right) \right] \left(\frac{\partial \phi_H^2}{\partial \alpha} \right)_{0,a,j} \tag{124}$$

$$CVN21_j = \frac{u_0^2}{2gL_0} \left[\frac{A_{j+1}}{A_{a,i}} \left(\frac{A_0}{A_j} \right)^2 \left(\sum_{k=1}^{N_{exp}} \left[K_{exp,irr,k} \ \delta_{z,z_k}^{Kr} \right] + \sum_{k'=1}^{N_{con}} \left[\sigma_{k'}^2 K_{con,irr,k'} \delta_{z,z_{k'}}^{Kr} \right] \right) \right] \left(\frac{\partial \phi_H^2}{\partial H} \right)_{0,a,j} \tag{125}$$

$$CVN13_j = \frac{u_0^2}{gL_0} \left[\frac{A_{j+1}}{A_{a,i}} \left(\frac{A_0}{A_j} \right)^2 \left(\sum_{k=1}^{N_{exp}} \left[K_{exp,irr,k} \ \delta_{z,z_k}^{Kr} \right] + \sum_{k'=1}^{N_{con}} \left[\sigma_{k'}^2 K_{con,irr,k'} \delta_{z,z_{k'}}^{Kr} \right] \right) \right] \phi_{H,0,a,j}^2 \tag{126}$$

$$CV13_j = CV5_j + CV9_j \tag{127}$$

$$CV14_j = CV7_j - C4_j + CV11_j \tag{128}$$

$$CV15_j = CV6_j + CV10_j \tag{129}$$

$$CV16_j = CV8_j + CV12_j \tag{130}$$

The new coefficients, computed in subroutine COEFR that will be used in LAPURW, _(IFMM option equal 1, data card 73,_ are:

$$\tau V_j = \frac{u_0}{gL_0}\Delta z_j \frac{A_0}{A_{a,j}} \tag{131}$$

$$CV5_j = 4\frac{u_0^2}{gL_0}B_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \tag{132}$$

$$CV9_j = K_{F+L,j}\, f_{0,j}\frac{u_0^2}{2gL_0}\left((2-a_2)_j\Omega_j + \left(\frac{\partial\Omega}{\partial y}\right)_j\right)\phi^2_{MN,j+1}\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \tag{133}$$

$$CV7_j = 2\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial\alpha}\right)_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \tag{134}$$

$$CV11_j = K_{F+L,j}f_{0,j}\frac{u_0^2}{2gL_0}\Omega_j\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_{j+1}\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \tag{135}$$

$$CV21_j = K_{F+L,j}f_{0,j}\frac{u_0^2}{2gL_0}\left(\frac{\partial\Omega}{\partial H}\right)_{j+1}\phi^2_{MN,j+1}\Delta z_j\frac{1}{D_{H,j+1}}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} + 2\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial H}\right)_{j+1}\frac{A_0}{A_{j+1}}\frac{A_0}{A_{a,j}} \tag{136}$$

$$CV6_j = 2\frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}B_{j+1} + \frac{A_0}{A_j}B_j\right] \tag{137}$$

$$CV10_j = K_{F+L,j}f_{0,j}\frac{u_0^2}{2gL_0}\left((2-a_2)_j\Omega_j + \left(\frac{\partial\Omega}{\partial y}\right)_j\right)\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}D_{H,j+1}}\phi^2_{MN,j+1} - \frac{A_0}{A_jD_{H,j}}\phi^2_{MN,j}\right] \tag{138}$$

$$CV8_j = \frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}\left(\frac{\partial B}{\partial\alpha}\right)_{j+1} + \frac{A_0}{A_j}\left(\frac{\partial B}{\partial\alpha}\right)_j\right] \tag{139}$$

$$CV12_j = K_{F+L,j}f_{0,j}\frac{u_0^2}{2gL_0}\Omega_j\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[-\frac{A_0}{A_jD_{H,j}}\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_j + \frac{A_0}{A_{j+1}D_{H,j+1}}\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_{j+1}\right] \tag{140}$$

$$\begin{aligned} CV22_j = {} & K_{F+L,j}\, f_{0,j}\frac{u_0^2}{2gL_0}\frac{\Delta z_j}{2}\frac{A_0}{A_{a,j}}\left[-\frac{A_0}{A_j\,D_{H,j}}\left(\frac{\partial\Omega}{\partial H}\right)_j\phi^2_{MN,j} + \frac{A_0}{A_{j+1}\,D_{H,j+1}}\left(\frac{\partial\Omega}{\partial H}\right)_{j+1}\phi^2_{MN,j+1}\right] \\ & + \frac{u_0^2}{gL_0}\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}\left(\frac{\partial B}{\partial H}\right)_{j+1} + \frac{A_0}{A_j}\left(\frac{\partial B}{\partial H}\right)_j\right] \end{aligned} \tag{141}$$

$$CVN14_j = \frac{u_0^2}{2gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\ \delta^{Kr}_{z,z_{k'}}\right]\right)\right]\left(\frac{\partial\phi_H^2}{\partial\alpha}\right)_{0,a,j} \tag{142}$$

$$CVN21_j = \frac{u_0^2}{2gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\ \delta^{Kr}_{z,z_{k'}}\right]\right)\right]\left(\frac{\partial\phi_H^2}{\partial H}\right)_{0,a,j} \tag{143}$$

$$CVN13_j = \frac{u_0^2}{gL_0}\left[\frac{A_{j+1}}{A_{a,i}}\left(\frac{A_0}{A_j}\right)^2\left(\sum_{k=1}^{N_{exp}}\left[K_{exp,irr,k}\ \delta^{Kr}_{z,z_k}\right]+\sum_{k'=1}^{N_{con}}\left[\sigma^2_{k'}\,K_{con,irr,k'}\ \delta^{Kr}_{z,z_{k'}}\right]\right)\right]\phi^2_{H,0,a,j} \tag{144}$$

$$CV13_j = CV5_j + CV9_j \tag{145}$$

$$CV14_j = CV7_j - C4_j + CV11_j \tag{146}$$

$$CV15_j = CV6_j + CV10_j \tag{147}$$

$$CV16_j = CV8_j + CV12_j \tag{148}$$

2.5.2.2. Friction model II

Model II comprises the Chisholm-Baroczy Friction Multiplier. This model is used when the IFMM option is equal to 2 (input user data card 73).

We note that the Chisholm-Baroczy model is used only to improve the pressure drop at steady state, but not to compute the perturbations around the steady-state point.

To obtain the Chisholm-Baroczy coefficients, we obtain the relation between the Chisholm-Baroczy two-phase friction multiplier, ϕ^2_{CB} and the Martinelli-Nelson two-phase friction multiplier, ϕ^2_{MN} times the Jones two-phase friction multiplier correction factor, Ω:

$$F_{CB-MN,j} = \left(\frac{\phi^2_{CB,j}}{\phi^2_{MN,j}\cdot\Omega_j}\right)_0 \tag{149}$$

note that this factor is defined at steady state, so that the partial derivatives are zero.

Then, using this relation, the equation obtained is:

$$\begin{gathered}
-\left(\delta\overline{\Pi}_{j+1}-\delta\overline{\Pi}_j\right)=-\Delta\overline{\Pi}_j=\\
\left[\tau V_j\, s+CV5_j+CVB9_j+CV13N_j\right]\delta\overline{y}_{a,j}\\
+\left[CV7_j-C4_j+CVB11_j+CV14N_j\right]\delta\overline{\alpha}_{a,j}+\left[CVB21_j+CVN21_j\right]\delta\overline{H}_{a,j}\\
-\left[CV6_j+CVB10_j\right]\delta\overline{y}_j-\left[CV8_j+CVB12_j\right]\delta\overline{\alpha}_j-\left[CVB22_j\right]\delta\overline{H}_j
\end{gathered} \tag{150}$$

or in a more compact form:

$$\begin{aligned}-\Delta\overline{\Pi}_j = {} & \left(\tau V_j\, s + CVB13_j + CVN13_j\right)\delta\overline{y}_{a,j} \\ & + \left(CVB14_j + CVN14_j\right)\delta\overline{\alpha}_{a,j} + \left(CV21_j + CVN21_j\right)\delta\overline{H}_{a,j} \\ & - CVB15_j\,\delta\overline{y}_j - CVB16_j\,\delta\overline{\alpha}_j - CVB22_j\,\delta\overline{H}_j\end{aligned} \tag{151}$$

where the new Chisholm-Baroczy coefficients are:

$$CVB9_j = K_{F+L,j}\, f_{0,j}\,\frac{u_0^2}{2gL_0}\left(\left(2-a_2\right)_j\Omega_j + \left(\frac{\partial\,\Omega}{\partial\,y}\right)_j\right)F_{CB-MN,j+1}\,\phi^2_{MN,j+1}\Delta z_j\,\frac{1}{D_{H,j+1}}\,\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \tag{152}$$

$$CVB11_j = K_{F+L,j} f_{0,j}\,\frac{u_0^2}{2gL_0}\,\Omega_j\,F_{CB-MN,j+1}\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_{j+1}\Delta z_j\,\frac{1}{D_{H,j+1}}\,\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \tag{153}$$

$$\begin{aligned}CVB21_j = {} & K_{F+L,j} f_{0,j}\,\frac{u_0^2}{2gL_0}\left(\frac{\partial\Omega}{\partial H}\right)_{j+1} F_{CB-MN,j+1}\,\phi^2_{MN,j+1}\Delta z_j\,\frac{1}{D_{H,j+1}}\,\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}} \\ & + 2\,\frac{u_0^2}{gL_0}\left(\frac{\partial B}{\partial H}\right)_{j+1}\frac{A_0}{A_{j+1}}\,\frac{A_0}{A_{a,j}}\end{aligned} \tag{154}$$

$$\begin{aligned}CVB10_j = {} & K_{F+L,j} f_{0,j}\,\frac{u_0^2}{2gL_0}\left(\left(2-a_2\right)_j\Omega_j + \left(\frac{\partial\Omega}{\partial y}\right)_j\right) \\ & \frac{\Delta z_j}{2}\,\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}D_{H,j+1}}F_{CB-MN,j+1}\,\phi^2_{MN,j+1} - \frac{A_0}{A_j D_{H,j}}F_{CB-MN,j}\,\phi^2_{MN,j}\right]\end{aligned} \tag{155}$$

$$\begin{aligned}CVB12_j = {} & K_{F+L,j} f_{0,j}\,\frac{u_0^2}{2gL_0}\,\Omega_j\,\frac{\Delta z_j}{2}\,\frac{A_0}{A_{a,j}} \\ & \left[-\frac{A_0}{A_j D_{H,j}}F_{CB-MN,j}\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_j + \frac{A_0}{A_{j+1}D_{H,j+1}}F_{CB-MN,j+1}\left(\frac{\partial\phi^2_{MN}}{\partial\alpha}\right)_{j+1}\right]\end{aligned} \tag{156}$$

$$\begin{aligned}CVB22_j = {} & K_{F+L,j}\, f_{0,j}\,\frac{u_0^2}{2gL_0}\,\frac{\Delta z_j}{2}\,\frac{A_0}{A_{a,j}} \\ & \left[-\frac{A_0}{A_j\, D_{H,j}}\left(\frac{\partial\,\Omega}{\partial\,H}\right)_j F_{CB-MN,j}\phi^2_{MN,j} + \frac{A_0}{A_{j+1}\, D_{H,j+1}}\left(\frac{\partial\,\Omega}{\partial\,H}\right)_{j+1} F_{CB-MN,j+1}\phi^2_{MN,j+1}\right] \\ & + \frac{u_0^2}{gL_0}\,\frac{A_0}{A_{a,j}}\left[\frac{A_0}{A_{j+1}}\left(\frac{\partial B}{\partial H}\right)_{j+1} + \frac{A_0}{A_j}\left(\frac{\partial B}{\partial H}\right)_j\right]\end{aligned} \tag{157}$$

$$CVB13_j = CV5_j + CVB9_j \tag{158}$$

$$CVB14_j = CV7_j - C4_j + CVB11_j \tag{159}$$

$$CVB15_j = CV6_j + CVB10_j \tag{160}$$

$$CVB16_j = CV8_j + CVB12_j \tag{161}$$

These new coefficients are computed in subroutine COEFR, and it will be used in LAPURW if IFMM option is equal to 2 (input user data card 73).

2.5.2.3. New boiling region coefficients—LAPUR modifications

Three subroutines are modified:

- Subroutine COEFR.
- Subroutine PREPHI
- Subroutine OMEGAP

Subroutine COEFR

```
      INTEGER FLOW_AREA_VAR
      DATA FLOW_AREA_VAR/ 1 /
C
      DIMENSION     CV5(NOBMAX)      ,CV6(NOBMAX)      ,CV7(NOBMAX)
,CV8(NOBMAX)
     >                                                 ,CV9(NOBMAX)
,CV10(NOBMAX),CV11(NOBMAX),CV12(NOBMAX)
     >
,CV13(NOBMAX),CV14(NOBMAX),CV15(NOBMAX),CV16(NOBMAX)
     >         ,CV21(NOBMAX),CV22(NOBMAX)
      DIMENSION                                        CVB9(NOBMAX)
,CVB10(NOBMAX),CVB11(NOBMAX),CVB12(NOBMAX)
     >
,CVB13(NOBMAX),CVB14(NOBMAX),CVB15(NOBMAX),CVB16(NOBMAX)
     >         ,CVB21(NOBMAX),CVB22(NOBMAX)
      DIMENSION CVEX(NOBMAX),CVCO(NOBMAX)
     >         ,CVN13(NOBMAX),CVN14(NOBMAX),CVN21(NOBMAX)
```

....

```
          QA   = A0/AVL(J)
          QB   = A0/AVCL(J)
          QB1  = A0/AVCL(J+1)
          QV3  = FFL(J)*U0**2/(2.*SG*DEVCL(J)) * DZ/EL
          QV31= FFL(J)*U0**2/(2.*SG*DEVCL(J+1)) * DZ/EL
C
          CV21(J)=
QV31*T20(J+1)*DOMDH0(J+1)*EKFL(J)*(EKLF(J)+1)*QB1*QA
     1             + 2.*Q4*DBDH0(J+1)*QB1*QA
          CV22(J)=  (QV31*(T20(J+1)*DOMDH0(J+1)*QB1)
     1                                  -   QV3*(T20(J)*DOMDH0(J)*QB))*
EKFL(J)*(EKLF(J)+1)
```

```
     2            *QA/2.0 + Q4*(DBDH0(J+1)*QB1+DBDH0(J)*QB)*QA
C
      IF(IFM.EQ.2)THEN
      FCBMN=T20(J)*OMEGA(J)/TPFM(J)
      FCBMN1=T20(J+1)*OMEGA(J+1)/TPFM(J+1)
          CVB21(J)=
QV31*T20(J+1)*DOMDH0(J+1)*EKFL(J)*(EKLF(J)+1)*QB1*QA
     1            *FCBMN1+ 2.*Q4*DBDH0(J+1)*QB1*QA
          CVB22(J)= (QV31*(T20(J+1)*DOMDH0(J+1)*QB1*FCBMN1)
     1                          -QV3*(T20(J)*DOMDH0(J)*QB*FCBMN))*
EKFL(J)*(EKLF(J)+1)
     2            *QA/2.0 + Q4*(DBDH0(J+1)*QB1+DBDH0(J)*QB)*QA
      ENDIF
```

....

```
          QA = A0/AVL(J)
          QB = A0/AVCL(J)
          QB1= A0/AVCL(J1)
          QQFV = FFL(J)*U0**2/(2.*SG)
          QQAV = A2L(J)
          QQFV = QQFV*EKFL(J)*(EKLF(J)+1)
          QQFV0= QQFV/DEVCL(J)
          QQFV1= QQFV/DEVCL(J1)
C
          QV6   = QQFV  *((2.-QQAV)*OMEGA(J)+DOMDY0(J))*DZ/EL
          QV60  = QQFV0*((2.-QQAV)*OMEGA(J)+DOMDY0(J))*DZ/EL
          QV61  = QQFV1*((2.-QQAV)*OMEGA(J)+DOMDY0(J))*DZ/EL
C
          CV5(J)  = 4.*Q4*B0(J1)*QB1*QA
          CV6(J)  = 2.*Q4*(B0(J1)*QB1+B0(J)*QB)*QA
          CV7(J)  = 2.*Q4*DBDB0(J1)*QB1*QA
          CV8(J)  = Q4*(DBDB0(J1)*QB1+DBDB0(J)*QB)*QA
      CV9(J) =QV61*FFF1(T20(J1),T20(J))*QB1*QA

CV10(J)=QV6*FFF2(T20(J1)*QB1/DEVCL(J1),T20(J)*QB/DEVCL(J))*QA

CV11(J)=QQFV1*OMEGA(J)*DZ/EL*FFF1(DT2DB0(J1),DT2DB0(J))*QB1*QA
      CV12(J)=QQFV*OMEGA(J)*DZ/EL
     >
*FFF2(DT2DB0(J1)*QB1/DEVCL(J1),DT2DB0(J)*QB/DEVCL(J))*QA
          CV13(J)  =  CV5(J)  +  CV9(J)
          CV14(J)  =  CV7(J)  -  C4(J)  +  CV11(J)
          CV15(J)  =  CV6(J)  +  CV10(J)
          CV16(J)  =  CV8(J)  +  CV12(J)
C
      IF(IFM.EQ.2)THEN
      FCBMN=T20(J)*OMEGA(J)/TPFM(J)
      FCBMN1=T20(J+1)*OMEGA(J+1)/TPFM(J+1)
C
      CVB9(J) =QV61*FFF1(T20(J1)*FCBMN1,T20(J)*FCBMN)*QB1*QA
      CVB10(J)=QV6*FFF2(T20(J1)*FCBMN1*QB1/DEVCL(J1),
```

```
     1                       T20(J)*FCBMN*QB/DEVCL(J))*QA
      CVB11(J)=QQFV1*OMEGA(J)*DZ/EL*FFF1(DT2DB0(J1)*FCBMN1,
     1                                    DT2DB0(J)*FCBMN)*QB1*QA
      CVB12(J)=QQFV*OMEGA(J)*DZ/EL
     >        *FFF2(DT2DB0(J1)*FCBMN1*QB1/DEVCL(J1),
     >              DT2DB0(J)*FCBMN*QB/DEVCL(J))*QA
C
          CVB13(J)  =  CV5(J)  +  CVB9(J)
          CVB14(J)  =  CV7(J)  -  C4(J)  +  CVB11(J)
          CVB15(J)  =  CV6(J)  +  CVB10(J)
          CVB16(J)  =  CV8(J)  +  CVB12(J)
C
          SIGMA=AVCL(J)/AVCL(J+1)
          IF((1.0-SIGMA).LE.0.001)  THEN
            CVEX(J)  =  0.0
          ELSE
            TEMP0=(1.0-SIGMA)**2
            TEMP1=(1.0/SG)*U0**2/EL
            TEMP2=AVCL(J+1)/AVL(J)*(A0/AVCL(J))**2
            CVEX(J)  =  TEMP0*TEMP1*TEMP2
          ENDIF
C
          SIGMA=AVCL(J)/AVCL(J+1)
          IF((SIGMA-1.0).LE.0.001)  THEN
            CVCO(J)  =  0.0
          ELSE
            TEMP0=SIGMA**2*0.385*(1.-1./SIGMA)
            TEMP1=(1.0/SG)*U0**2/EL
            TEMP2=AVCL(J+1)/AVL(J)*(A0/AVCL(J))**2
            CVCO(J)  =  TEMP0*TEMP1*TEMP2
          ENDIF
C
            CVN14(J)=  (CVEX(J)+CVCO(J))
     >                *(DHMDB0(J)+DHMDB0(J+1))/2
            CVN21(J)=  (CVEX(J)+CVCO(J))
     >                *(DHMDH0(J)+DHMDH0(J+1))/2
            CVN13(J)=  (CVEX(J)+CVCO(J))*2.
     >                *(HM0(J)+HM0(J+1))/2
C
             IF(FLOW_AREA_VAR.EQ.1)THEN
            TAUIPV(J)  =  TAUIP*(A0/AVL(J))
            C5  (J)  =  CV5  (J)
            C6  (J)  =  CV6  (J)
            C7  (J)  =  CV7  (J)
            C8  (J)  =  CV8  (J)
            C9  (J)  =  CV9  (J)
            C10(J)  =  CV10(J)
            C11(J)  =  CV11(J)
            C12(J)  =  CV12(J)
            C13(J)  =  CV13(J)+CVN13(J)
            C14(J)  =  CV14(J)+CVN14(J)
            C15(J)  =  CV15(J)
```

```
        C16(J) = CV16(J)
        C21(J) = CV21(J)+CVN21(J)
        C22(J) = CV22(J)
            IF(IFM.EQ.2)THEN
        C9  (J) = CVB9 (J)
        C10(J) = CVB10(J)
        C11(J) = CVB11(J)
        C12(J) = CVB12(J)
        C13(J) = CVB13(J)+CVN13(J)
        C14(J) = CVB14(J)+CVN14(J)
        C15(J) = CVB15(J)
        C16(J) = CVB16(J)
        C21(J) = CVB21(J)+CVN21(J)
        C22(J) = CVB22(J)
           ENDIF
         ENDIF
```

Subroutine PREPHI—Homogeneous multiplier (ϕ_H) and partial derivatives $\left(\frac{\partial \phi_H}{\partial \alpha}\right)$.

```
C Homogeneous multiplier and partial derivatives
      DO J= 1, NP1
       HM0(J)=1+(RHOL/RHOG-1)*X(J)
      ENDDO
C
      DHMDB0(1) = 0.0
      DHMDH0(1) = 0.0
      DO J= 2, NP1
       DHMDB0(J) = (RHOL/RHOG-1)*DXDB0(J)
       DHMDH0(J) = (RHOL/RHOG-1)*DXDH0(J)
      ENDDO
```

2.6. OTHER MODIFICATIONS MADE IN LAPURX 6.0

In this section, we present other modifications made in LAPURX 6.0.

Subroutine MAIN —LAPUR 6.0 prints a new title.

```
C LAPUR6 M:1
C MODIFICATION
C     WRITE(*,'('' LAPUR5X RUN TITLE :''/'' ** '',18A4,'' **'')')
      WRITE(*,'('' LAPUR6X RUN TITLE :''/'' ** '',18A4,'' **'')')
C LAPUR6 END
```

Subroutine DRUMW1—New commons used for intermediate storage.

```
      EQUIVALENCE  (XDL1(1),DPIN1),(XFRI(1),IFFM(1))
     >            ,(XFR3(1),IFF),(XCTP(1),TPFM(1))
```

....

```
      DIMENSION    XDL1(N_DLTP1)
      DIMENSION    XFRI(N_FRICC)
      DIMENSION    XFR3(N_FRIC1)
      DIMENSION    XCTP(N_CTPFM)
```

....

```
      WRITE (NDISK1)  XDL1
      WRITE (NDISK1)  XFRI
      WRITE (NDISK1)  XFR3
      WRITE (NDISK1)  XCTP
```

Subroutine FRICT—This routine is a function of the individual channel type in LAPUR 6.

```
C       SUBROUTINE FRICT
      SUBROUTINE FRICT(IX)
```

Subroutine DELTP—This routine is a function of the individual channel type in LAPUR 6.

```
C       SUBROUTINE DELTP
      SUBROUTINE DELTP(IX)
```

LAPUR 6.0 has additional pressure terms, which require an additional calculation of the total pressure loss.

```
         DPNB2    =  DPDHNB2  +  DPFRNB2  +  DPACNB2  +  DPEXNB2  +
DPLLNB2 +
     1           DPCONB2
```

....

```
         DPSB1    = DPDHSB1 + DPFRSB1 + DPACSB1 + DPEXSB + DPLLSB
+
     1             DPCOSB
```

....

```
         DPBB1    = DPDHBB1 + DPFRBB1 + DPACBB1 + DPEXBB + DPLLBB
+
     1             DPCOBB
```

....

```
C LAPUR6 M:4
C MODIFICATION
C          DPTOT  = DPIN   + DPNB   + DPSB   + DPBB   + DPR
C          DPFR   = DPFRIN + DPFRNB + DPFRSB + DPFRBB + DPFRR
C          DPDH   = DPDHIN + DPDHNB + DPDHSB + DPDHBB + DPDHR
C          DPAC   =          DPACNB + DPACSB + DPACBB
          DPTOT1   = DPIN   + DPNB   + DPSB   + DPBB   + DPR
          DPFR1  = DPFRIN + DPFRNB + DPFRSB + DPFRBB + DPFRR
          DPDH1  = DPDHIN + DPDHNB + DPDHSB + DPDHBB + DPDHR
          DPAC1  =          DPACNB + DPACSB + DPACBB
C LAPUR6 END
C LAPUR6 I:7
C NEW LINES
          DPTOT  = DPIN   + DPNB2   + DPSB1   + DPBB1   + DPR
          DPFR   = DPFRIN + DPFRNB2 + DPFRSB1 + DPFRBB1 + DPFRR
          DPDH   = DPDHIN + DPDHNB2 + DPDHSB1 + DPDHBB1 + DPDHR
          DPAC   =          DPACNB2 + DPACSB1 + DPACBB1
          DPEX   =          DPEXNB2 + DPEXSB  + DPEXBB
          DPLL   =          DPLLNB2 + DPLLSB  + DPLLBB
          DPCO   =          DPCONB2 + DPCOSB  + DPCOBB
C LAPUR6 END
```

Subroutine INPUT—New input data reading

```
C      READ (4,9000,END=700)   (TITLE(I),I=1,18)
      READ (4,9000,END=7700)   (TITLE(I),I=1,18)
```

....

```
C      DO 6000 I=1,60
      DO 6000 I=1,80
```

....

```
C      IF(III.LT.0.OR.III.GE.70) GO TO 800
      IF(III.LT.0.OR.III.GE.80) GO TO 800
```

....

```
C     4          570), III
     4
570,580,590,600,610,620,630,640,650,660,670,680,690,700,
     5       710,720,730,740,750,760), III
```

....

```
C  700 CONTINUE
 7700 CONTINUE
```

....

```
C LAPUR6 M:1
C MODIFICATION
C    WRITE(*,'('' *** LAPUR5X ***''/
      WRITE(*,'('' *** LAPUR6X ***''/
C LAPUR6 END
```

Subroutine OUTIN—New input data printing

```
C     4         57),II
     4        57, 58 ,59 ,60 ,61 ,62 ,63 ,64 ,65 ,66 ,67 ,68 ,69
,70 ,
     5       71, 72 ,73 ,74 ,75 ,76),II
```

....

```
C   330  FORMAT(1H1,//19H  ***  INPUT  DATA  ***    ,60X,15H***  LAPURX
*** //
C     1   2X, 18A4 )
  330 FORMAT(1H1,//19H *** INPUT DATA ***  ,60X,
     1   22H*** LAPURX 6.0     *** // 2X, 18A4 )
```

Subroutine NODE—Prevent convergence problems during the LAPURX 6.0 initial flow iteration

```
C LAPUR6 M:1 I:1
C MODIFICATION AND NEW LINE
C        IF(ZNB.GT.EL)  GO TO 540
      EPS=0.000001
      IF((ZNB-EL).GT.EPS)GO TO 540
C LAPUR6 END
```

....

```
C LAPUR6 M:1 I:1
C MODIFICATION AND NEW LINE
C        IF(ZNB.GT.DZF(1))  GO TO 540
      EPS=0.000001
      IF((ZNB-DZF(1)).GT.EPS)GO TO 540
C LAPUR6 END
```

Subroutine OUTST—Print new pressure drops

```
C LAPUR6 M:5
C MODIFICATION
C                                                 WRITE       (6,9720)
(HEAD2(I),I=1,2),HEAD6,DPDHNB,DPFRNB,DPACNB,DPNB
C                                                 WRITE       (6,9720)
(HEAD3(I),I=1,2),HEAD7,DPDHSB,DPFRSB,DPACSB,DPSB
C                                                 WRITE       (6,9720)
(HEAD4(I),I=1,2),HEAD6,DPDHBB,DPFRBB,DPACBB,DPBB
```

```
C      WRITE (6,9710) (HEAD5(I),I=1,2),DPDHR,DPFRR,DPCONR,DPR
C             WRITE (6,9730)                  DPDH   ,DPFR   ,DPAC
,DPCONT,DPTOT
      WRITE (6,9720) (HEAD2(I),I=1,2),HEAD6
     1
,DPDHNB2,DPFRNB2,DPACNB2,DPEXNB2,DPCONB2,DPLLNB2
     2                ,DPNB2
      WRITE (6,9720) (HEAD3(I),I=1,2),HEAD7
     1
,DPDHSB1,DPFRSB1,DPACSB1,DPEXSB,DPCOSB,DPLLSB,DPSB1
      WRITE (6,9720) (HEAD4(I),I=1,2),HEAD6
     1
,DPDHBB1,DPFRBB1,DPACBB1,DPEXBB,DPCOBB,DPLLBB,DPBB1
      WRITE (6,9710) (HEAD5(I),I=1,2),DPDHR,DPFRR,DPCONR,DPR
      WRITE (6,9730)  DPDH,DPFR,DPAC,DPEX,DPCO,DPLL,DPCONT,DPTOT
C LAPUR6 END
```

....

```
C LAPUR6 M:7
C MODIFICATION
C 9700 FORMAT(1H0,///' STEADY STATE PRESSURE DROPS (KG/CM2)'
,10X,
C     1   'FLOW RATE=',1PE13.5,' G/S CM2',
C       1///30X, 'DENSITY HEAD',4X,8HFRICTION ,4X,12HACCELERATION
,2X,
C     2       11HCONTRACTION ,6X, 5HTOTAL   )
C            9710             FORMAT(//3X,2A4,2X,13HCONFIGURATION
,2P2E14.4,14X,1P2E14.4)
C        9720        FORMAT(//3X,2A4,A1,1X,14HBOILING       REGION
,2P3E14.4,14X,1PE14.4)
C 9730 FORMAT(//1X,28(1H*) ///3X,24HSUM     OF    ALL     REGIONS
,2P5E14.4 )
 9700 FORMAT(1H0,///' STEADY STATE PRESSURE DROPS (KG/CM2)' ,10X,
     1   'FLOW RATE=',1PE13.5,' G/S CM2',
     1///30X,  'DENSITY  HEAD',4X,8HFRICTION   ,4X,12HACCELERATION
,2X,
     2        14HEXPANSION-IRR ,2X,   5HLOCAL,  3X,15HCONTRACTION-
IRR, 4X,
     2       11HCONTRACTION ,6X, 5HTOTAL   )
 9710                            FORMAT(//3X,2A4,2X,14HCONFIGURATION
,2P2E14.4,56X,1P2E14.4)
 9720                              FORMAT(//3X,2A4,A1,1X,14HBOILING
REGION,2P6E14.4,14X,1PE14.4)
 9730 FORMAT(//1X,28(1H*) ///3X,24HSUM     OF     ALL     REGIONS
,2P8E14.4 )
C LAPUR6 END
      RETURN
```

Subroutine STEADY

In LAPUR 6, subroutines FRICT and DELTP are functions of the individual channel type.

```
C LAPUR6 M:2
C MODIFICATION
C       CALL FRICT
C       CALL DELTP
      CALL FRICT(IX)
      CALL DELTP(IX)
C LAPUR6 END
```

2.7. MODIFICATIONS IN LAPURW 6.0 RELATED TO THERMAL HYDRAULICS

This section presents the modifications made in the LAPURW (frequency domain) relating to thermal hydraulics.

2.7.1. Energy Conservation—LAPUR 6.0 Nonboiling Region Coefficients

The energy conservation equation in the nonboiling region is

$$\frac{Q'}{w_0} = \frac{\rho_l}{\rho_F}\frac{1}{u_0}\frac{A(z)}{A_0}\frac{\partial h_l}{\partial t} + y\frac{\partial h_l}{\partial z} \tag{162}$$

where Q' is the energy per unit length supply by the fuel and y is the normalized mass flow rate.

Linearizing this conservation equation around the steady-state point and Laplace transforming the resulting equation yields:

$$\frac{\delta\overline{Q}'}{w_0} = \frac{\rho_{l,0}}{\rho_F}\frac{1}{u_0}\frac{A(Z)}{A_0} s\,\delta\overline{h}_l + \frac{\partial}{\partial z}\left(\delta\overline{h}_l\right) + \frac{Q'_0}{w_0}\delta\overline{y} \tag{163}$$

The total perturbation of the heat flux from the fuel to the coolant, $\delta\overline{Q}'$, can be expressed in function of the fuel transfer functions by:

$$\delta\overline{Q}' = Q_0\left(CB_q\,\delta\overline{q}' + CC_q\,\delta\overline{T}_l + CA_q\,\delta\overline{y}\right) \tag{164}$$

where $\delta\overline{q}'$ is the normalized total power generation perturbation in the fuel, $\delta\overline{T}_l$ is the liquid coolant temperature perturbation, and $\delta\overline{y}$ is the normalized coolant flow rate perturbation.

We define

$$S = \frac{h_l}{h_{z1} - h_0} = \frac{h_l}{\Delta h_0} \tag{165}$$

where Δh_0 is the enthalpy rise in the nonboiling region.

Integrating equation (163) over the length of the i-th node, and using equation (165) and the total perturbation of the heat flux from the fuel to the coolant along the channel, we obtain:

$$\delta\overline{S}_{i+1} = e^{-d_{1,i}\,\Delta z_i}\ \delta\overline{S}_i + \left(1 - e^{-d_{1,i}\,\Delta z_i}\right)\frac{\delta\overline{g}_i}{d_{1,i}} \tag{166}$$

where

$$\delta\overline{g} = \frac{1}{\Delta h_0\, w_0}\left[Q'_0\left(CB_q\,\delta\overline{q}' + \left(CA_q - 1\right)\delta\overline{y}\right)\right] \tag{167}$$

The new coefficient is $d_{1,i}$ = CTAUNBV(I), used in subroutine COEFIW

$$d_{1,i} = \frac{\Delta z_i\, s\, \tau_1}{ZNB}\,\frac{A_{a,i}}{A_0} - FQ_i\,\frac{\Delta h_0}{c_{p,av}}\,CC_{q,i} \tag{168}$$

where FQ_i is the relative power of node i, and $c_{p.av}$ is the average specific heat of water in the NBR.

One subroutine, COEFIW, is modified

2.7.1.1. LAPUR modifications

Subroutine COEFIW

```
C LAPUR6 I:6
C NEW LINES
                 CTAUNBV(I)=                                   (ZCOM(I+1)-
ZCOM(I))*CSS*TAU1/ZNB*(AVNBL(I)/A0)
      >                         -FQ(I)*DELH0/CPAVG*CCQ(I)
C
                 IF(FLOW_AREA_VAR.EQ.1)THEN
                  CQ1    = CTAUNBV(I)
                 ENDIF
C LAPUR6 END
```

2.7.2. Mass and Energy Conservation—LAPUR 6.0 Boiling Region Coefficients

2.7.2.1. Mass conservation

The normalized conservation mass equation in the boiling region is given by:

$$\frac{A_0}{A(z)}\frac{\partial y}{\partial z} = \frac{\eta}{u_0}\frac{\partial \alpha}{\partial t} \tag{169}$$

Linearizing this conservation equation around the steady-state point and Laplace transforming the resulting equation yields

$$\frac{A_0}{A(z)}\frac{\partial}{\partial z}\delta\overline{y} = \frac{\eta}{u_0}\, s\,\delta\overline{\alpha} \tag{170}$$

Integrating (170) over the length of the j-th node yields:

$$\delta\bar{y}_j = \delta\bar{y}_{a,j} - \frac{1}{\left[\frac{A_0}{A(z_{j+1})} + \frac{A_0}{A(z_j)}\right]} \frac{\eta}{u_0} s\,\Delta z_j\,\delta\bar{\alpha}_{a,j} \qquad \text{for } j = 1, N_{BR} \tag{171}$$

where

$$\delta\bar{y}_{a,j} = \frac{\delta\bar{y}_j + \delta\bar{y}_{j+1}}{2} \tag{172}$$

The new coefficient for the *Mass Conservation*, used in subroutine COEFIW, is

$$CDV1_j = -\frac{\frac{\eta}{u_0} s\,\Delta z_j}{\left[\frac{A_0}{A(z_{j+1})} + \frac{A_0}{A(z_j)}\right]} \tag{173}$$

2.7.2.2. Energy conservation

Total fluid

The normalized conservation energy equation for the total fluid in the boiling region is given by:

$$\frac{\eta}{(1-\eta)h_{fg}\,w_0} Q' = \frac{\partial}{\partial z}\left[y\left\{\sigma - H\left(\frac{1}{1-\eta} - \sigma\right)\right\}\right] - \frac{\eta}{(1-\eta)}\frac{1}{u_0}\frac{\partial}{\partial t}\left[H(1-\alpha)\frac{A(z)}{A_0}\right] \tag{174}$$

where H is the normalized degree of subcooling

$$H = \frac{h_F - h_l}{h_{fg}} \tag{175}$$

Linearizing this conservation equation around the steady-state point and Laplace transforming the resulting equation yields:

$$\begin{aligned}\left[\frac{\eta}{(1-\eta)w_0\,h_{fg}}\right]_0 \delta\bar{Q}' = {} & \frac{\partial}{\partial z}\left\{\left[\sigma - H\left(\frac{1}{1-\eta} - \sigma\right)\right]_0 \delta\bar{y}\right\} - \frac{\partial}{\partial z}\left\{\left[\frac{1}{1-\eta} - \sigma\right]_0 \delta\bar{H}\right\} \\ & + \left[\frac{\eta}{1-\eta}\frac{1}{u_0}\right]_0 \frac{A(Z)}{A_0} s\left[-\left\{[1-\alpha]_0\,\delta\bar{H}\right\} + H_0\,\delta\bar{\alpha}\right] \\ & + \frac{\partial}{\partial z}\left\{\left[\frac{\eta}{1-\eta}(1+H)\frac{\partial X}{\partial H}\right]_0 \delta\bar{H}\right\} + \frac{\partial}{\partial z}\left\{\left[\frac{\eta}{1-\eta}(1+H)\frac{\partial X}{\partial \alpha}\right]_0 \delta\bar{\alpha}\right\}\end{aligned} \tag{176}$$

where

$$\sigma = 1 + \frac{\eta}{1-\eta} X \tag{177}$$

and

$$X = \frac{\alpha\,\gamma\left(1-\eta\right)}{1-\alpha\left[1-\gamma\left(1-\eta\right)\right]} \tag{178}$$

Inserting into equation (176) the total perturbation of the heat flux from the fuel to the coolant, equation (164), and integrating over the length of the j-th node yields:

$$CD_{5,j}\,\delta\overline{y}_{a,j} + CDV_{6,j}\,\delta\overline{\alpha}_{a,j} + CDV_{7,j}\,\delta\overline{H}_{a,j} = CEV_{3,j} \tag{179}$$

with

$$CEV_{3,j} = CD_{14,j}\,\delta\overline{y}_{j} + CDV_{15,j}\,\delta\overline{\alpha}_{j} + CDV_{16,j}\,\delta\overline{H}_{j} + CD_{18,j}\,\delta\overline{q}_{a,j} \tag{180}$$

and

$$\delta\overline{y}_{a,j} = \frac{\delta\overline{y}_{j} + \delta\overline{y}_{j+1}}{2} \tag{181}$$

$$\delta\overline{\alpha}_{a,j} = \frac{\delta\overline{\alpha}_{j} + \delta\overline{\alpha}_{j+1}}{2} \tag{182}$$

$$\delta\overline{H}_{a,j} = \frac{\delta\overline{H}_{j} + \delta\overline{H}_{j+1}}{2} \tag{183}$$

and the coefficients are given by:

$$CD_{5,j} = \left\{ 2\left[\sigma - H\left(\frac{1}{1-\eta} - \sigma\right)\right]_{0,j+1} - \left[\frac{\eta}{\left(1-\eta\right)w_0\,h_{fg}}\right]\Delta z_j\,Q'_{0,j}\,CA_{q,j} \right\} \tag{184}$$

$$CDV_{6,j} = \left\{ \frac{\eta}{1-\eta}\,2\left(1+H\right)_{0,j+1}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j+1} + \frac{\eta}{1-\eta}\,\frac{1}{u_0}\,s\,\frac{A_{a,j}}{A_0}\,H_{0,a,j}\,\Delta z_j \right\} \tag{185}$$

$$\begin{aligned} CDV_{7,j} = \Bigg\{ & -2\left[\frac{1}{1-\eta} - \sigma\right]_{0,j+1} - \frac{\eta}{1-\eta}\,\frac{1}{u_0}\,s\,\frac{A_{a,j}}{A_0}\left(1-\alpha_0\right)_{a,j}\Delta z_j \\ & + \frac{\eta}{1-\eta}\,2\left(1+H\right)_{0,j+1}\left(\frac{\partial X}{\partial H}\right)_{0,j+1} + \left[\frac{\eta}{\left(1-\eta\right)w_0\,h_{fg}}\right]\Delta z_j\,Q'_{0,j}\,CC_{q,j}\,\frac{h_{fg}}{c_p} \Bigg\} \end{aligned} \tag{186}$$

$$CD_{14,j} = \left\{ \left[\sigma - H\left(\frac{1}{1-\eta} - \sigma\right)\right]_{0,j+1} + \left[\sigma - H\left(\frac{1}{1-\eta} - \sigma\right)\right]_{0,j} \right\} \tag{187}$$

$$CDV_{15,j} = \left\{ \frac{\eta}{1-\eta}\left(1+H\right)_{0,j+1}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j+1} + \frac{\eta}{1-\eta}\left(1+H\right)_{0,j}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j} + \frac{\eta}{1-\eta}\,\frac{s}{u_0}\,\frac{A_{a,j}}{A_0}\,\frac{\left(H_{0,j+1} - H_{0,j}\right)}{2}\,\Delta z_j \right\} \tag{188}$$

$$CDV_{16,j} = \left\{ -\left[\frac{1}{1-\eta} - \sigma\right]_{0,j+1} - \left[\frac{1}{1-\eta} - \sigma\right]_{0,j} + \frac{\eta}{1-\eta}\frac{s}{u_0}\frac{A_{a,j}}{A_0}\frac{\left(\alpha_{0,j+1} - \alpha_{0,j}\right)}{2}\Delta z_j \right.$$
$$\left. + \frac{\eta}{1-\eta}\left[(1+H)_{0,j+1}\left(\frac{\partial X}{\partial H}\right)_{0,j+1} + (1+H)_{0,j}\left(\frac{\partial X}{\partial H}\right)_{0,j}\right]\right\} \tag{189}$$

$$CD_{18,j} = \left\{\left[\frac{\eta}{(1-\eta)w_0\, h_{fg}}\right] Q'_{0,j}\, CB_{q,j}\, \Delta z_j\right\} \tag{190}$$

The new coefficients for *Energy Conservation*, used in subroutine COEFIW, are:

$$CDV_{6,j} = \left\{\frac{\eta}{1-\eta} 2(1+H)_{0,j+1}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j+1} + \frac{\eta}{1-\eta}\frac{1}{u_0} s \frac{A_{a,j}}{A_0} H_{0,a,j}\, \Delta z_j\right\} \tag{191}$$

$$CDV_{7,j} = \left\{ -2\left[\frac{1}{1-\eta} - \sigma\right]_{0,j+1} - \frac{\eta}{1-\eta}\frac{1}{u_0} s \frac{A_{a,j}}{A_0}(1-\alpha_0)_{a,j}\, \Delta z_j \right.$$
$$\left. + \frac{\eta}{1-\eta} 2(1+H)_{0,j+1}\left(\frac{\partial X}{\partial H}\right)_{0,j+1} + \left[\frac{\eta}{(1-\eta)w_0\, h_{fg}}\right]\Delta z_j\, Q'_{0,j}\, CC_{q,j}\frac{h_{fg}}{c_p}\right\} \tag{192}$$

$$CDV_{15,j} = \left\{\frac{\eta}{1-\eta}(1+H)_{0,j+1}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j+1} + \frac{\eta}{1-\eta}(1+H)_{0,j}\left(\frac{\partial X}{\partial \alpha}\right)_{0,j} + \frac{\eta}{1-\eta}\frac{s}{u_0}\frac{A_{a,j}}{A_0}\frac{\left(H_{0,j+1} - H_{0,j}\right)}{2}\Delta z_j\right\} \tag{193}$$

$$CDV_{16,j} = \left\{ -\left[\frac{1}{1-\eta} - \sigma\right]_{0,j+1} - \left[\frac{1}{1-\eta} - \sigma\right]_{0,j} + \frac{\eta}{1-\eta}\frac{s}{u_0}\frac{A_{a,j}}{A_0}\frac{\left(\alpha_{0,j+1} - \alpha_{0,j}\right)}{2}\Delta z_j \right.$$
$$\left. + \frac{\eta}{1-\eta}\left[(1+H)_{0,j+1}\left(\frac{\partial X}{\partial H}\right)_{0,j+1} + (1+H)_{0,j}\left(\frac{\partial X}{\partial H}\right)_{0,j}\right]\right\} \tag{194}$$

Steam phase

The normalized conservation energy equation for the steam phase in the boiling region is given by:

$$\frac{\eta F_s}{(1-\eta)h_{fg}\, w_0} Q = \lambda_s \frac{\eta}{u_0}\alpha\frac{A_0}{A_0} + \frac{\partial y\sigma}{\partial z} \tag{195}$$

where F_s is the fraction of energy invested in steam formation, and λ_s is the bubble decay constant.

Linearizing this conservation equation around the steady-state point and Laplace transforming the resulting equation yields:

$$\left\{\left[\frac{\eta Q'}{(1-\eta)w_0 h_{fg}}\frac{\partial F_s}{\partial H}\right]_0 - \left[\frac{\eta}{u_0}\frac{A(Z)}{A_0}\alpha\frac{\partial \lambda_s}{\partial H}\right]_0\right\}\delta\overline{H} =$$

$$-\left[\frac{\eta F_s}{(1-\eta)w_0 h_{fg}}\right]_0 \delta\overline{Q}' + \left[\frac{\eta}{u_0}\frac{A(z)}{A_0}\alpha\frac{\partial \lambda_s}{\partial y}\right]_0 \delta\overline{y} + \frac{\partial}{\partial z}\left\{\sigma_{\upsilon}\,\delta\overline{y}\right\} \tag{196}$$

$$+\frac{\partial}{\partial z}\left\{\left[\left(\frac{\eta}{1-\eta}\right)\frac{\partial X}{\partial H}\right]_0 \delta\overline{H}\right\} + \left[\frac{\eta}{u_0}\lambda_s\frac{A(z)}{A_0}\right]_0 \delta\overline{\alpha} + \frac{\partial}{\partial z}\left\{\left[\left(\frac{\eta}{1-\eta}\right)\frac{\partial X}{\partial \alpha}\right]_0 \delta\overline{\alpha}\right\} = 0$$

Inserting into equation (196) the total perturbation of the heat flux from the fuel to the coolant, equation (164), and integrating over the length of the j-th node yields:

$$\mathrm{CDV}_{2,j}\,\delta\overline{y}_{a,j} + \mathrm{CDV}_{3,j}\,\delta\overline{\alpha}_{a,j} + \mathrm{CDV}_{4,j}\,\delta\overline{H}_{a,j} = \mathrm{CEV}_{2,j} \tag{197}$$

with

$$\mathrm{CEV}_{2,j} = \mathrm{CDV}_{11,j}\,\delta\overline{y}_j + \mathrm{CDV}_{12,j}\,\delta\overline{\alpha}_j + \mathrm{CDV}_{13,j}\,\delta\overline{H}_j + \mathrm{CD}_{17,j}\,\delta\overline{q}_{a,j} \tag{198}$$

and the coefficients are given by:

$$\mathrm{CDV}_{2,j} = \left\{-\left(\frac{\eta}{1-\eta}\right)\left(\frac{Q'_0}{w_0 h_{fg}}\right)\mathrm{CA}_{q,a,j}\,\Delta z_j\,\frac{\left(2F_s(j+1)+F_s(j)\right)_0}{3}\right.$$

$$\left. + \frac{A_{a,j}}{A_0}\frac{\eta}{u_0}\Delta z_j\,\alpha_{j+1}\,1.6\,\lambda_{s,j+1} + 2\,\sigma_{0,j+1}\right\} \tag{199}$$

$$\mathrm{CDV}_{3,j} = \left\{\frac{A_{a,j}}{A_0}\frac{\eta}{u_0}\Delta z_j\,\lambda_{s,j+1} + 2\left(\frac{\eta}{1-\eta}\right)\left(\frac{\partial X}{\partial \alpha}\right)_{0,j+1}\right\} \tag{200}$$

$$\mathrm{CDV}_{4,j} = \left\{\left(\frac{\eta}{1-\eta}\right)\left(\frac{Q'_0}{w_0 h_{fg}}\right)\frac{h_{fg}}{c_p}\mathrm{CC}_{q,a,j}\,\Delta z_j\,\frac{\left(2F_s(j+1)+F_s(j)\right)_0}{3} + \frac{A_{a,j}}{A_0}\frac{\eta}{u_0}\Delta z_j\,\alpha_{j+1}\,2\,\frac{\lambda_{s,j+1}}{H_{j+1}}\right.$$

$$\left. + \left(\frac{\eta}{1-\eta}\right)\left(\frac{Q'_0}{w_0 h_{fg}}\right)\Delta z_j\,\frac{f_{p,j+1}}{(1-\eta)}F^2_{s,j+1} + 2\left(\frac{\eta}{1-\eta}\right)\left(\frac{\partial X}{\partial H}\right)_{0,j+1}\right\} \tag{201}$$

$$\mathrm{CDV}_{11,j} = \left\{\frac{A_{a,j}}{A_0}\frac{\eta}{u_0}\frac{\Delta z_j}{2}\left[\alpha_{0,j+1}\,1.6\,\lambda_{s,0,j+1} - \alpha_{0,j}\,1.6\,\lambda_{s,0,j}\right] + \left(\sigma_{0,j+1} + \sigma_{0,j}\right)\right.$$

$$\left. - \left(\frac{\eta}{1-\eta}\right)\left(\frac{Q'_0}{w_0 h_{fg}}\right)\mathrm{CA}_{q,a,j}\,\Delta z_j\,\frac{\left(F_s(j+1)-F_s(j)\right)_0}{6}\right\} \tag{202}$$

$$CDV_{12,j} = \left\{ \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \frac{\Delta z_j}{2} \left[\lambda_{s,j} - \lambda_{s,j+1} \right]_0 + \left(\frac{\eta}{1-\eta} \right) \left[\left(\frac{\partial X}{\partial \alpha} \right)_{0,j+1} + \left(\frac{\partial X}{\partial \alpha} \right)_{0,j} \right] \right\} \tag{203}$$

$$\begin{aligned} CDV_{13,j} = & \left\{ \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \Delta z_j \left[\alpha_{j+1} \frac{\lambda_{s,j+1}}{H_{j+1}} - \alpha_j \frac{\lambda_{s,j}}{H_j} \right]_0 - \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) \frac{\Delta z_j}{2} \left[\frac{f_{p,j} \, F_{s,j}^2 - f_{p,j+1} \, F_{s,j+1}^2}{1-\eta} \right]_0 \right. \\ & \left. + \left(\frac{\eta}{1-\eta} \right) \left[\left(\frac{\partial X}{\partial H} \right)_{0,j+1} + \left(\frac{\partial X}{\partial H} \right)_{0,j} \right] + \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) \frac{h_{fg}}{c_p} CC_{q,a,j} \, \Delta z_j \left[\frac{\left(F_s(j+1) - F_s(j) \right)_0}{6} \right] \right\} \end{aligned} \tag{204}$$

$$CD_{17,j} = \left\{ \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) \left[F_{s,a,j} \, CB_{q,a,j} \, \Delta z_j \right] \right\} \tag{205}$$

where f_p is an adjustable factor for the fraction of power invested in steam production,

The new coefficients for *Energy Conservation*, used in subroutine COEFIW, are:

$$\begin{aligned} CDV_{2,j} = & \left\{ - \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) CA_{q,a,j} \, \Delta z_j \, \frac{2 F_s(j+1) + F_s(j)}{3} \right. \\ & \left. + \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \Delta z_j \, \alpha_{j+1} \, 1.6 \, \lambda_{s,j+1} + 2 \sigma_{0,j+1} \right\} \end{aligned} \tag{206}$$

$$CDV_{3,j} = \left\{ \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \Delta z_j \, \lambda_{s,j+1} + 2 \left(\frac{\eta}{1-\eta} \right) \left(\frac{\partial X}{\partial \alpha} \right)_{0,j+1} \right\} \tag{207}$$

$$\begin{aligned} CDV_{4,j} = & \left\{ \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) \frac{h_{fg}}{c_p} CC_{q,a,j} \, \Delta z_j \, \frac{\left(2 F_s(j+1) + F_s(j) \right)_0}{3} + \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \Delta z_j \, \alpha_{j+1} \, 2 \frac{\lambda_{s,j+1}}{H_{j+1}} \right. \\ & \left. + \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) \Delta z_j \frac{f_{p,j+1}}{(1-\eta)} F_{s,j+1}^2 + 2 \left(\frac{\eta}{1-\eta} \right) \left(\frac{\partial X}{\partial H} \right)_{0,j+1} \right\} \end{aligned} \tag{208}$$

$$\begin{aligned} CDV_{11,j} = & \left\{ \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \frac{\Delta z_j}{2} \left[\alpha_{j+1} \, 1.6 \, \lambda_{s,j+1} - \alpha_j \, 1.6 \, \lambda_{s,j} \right] + \left(\sigma_{0,j+1} + \sigma_{0,j} \right) \right. \\ & \left. - \left(\frac{\eta}{1-\eta} \right) \left(\frac{Q'_0}{w_0 \, h_{fg}} \right) CA_{q,a,j} \, \Delta z_j \, \frac{F_s(j+1) - F_s(j)}{6} \right\} \end{aligned} \tag{209}$$

$$CDV_{12,j} = \left\{ \frac{A_{a,j}}{A_0} \frac{\eta}{u_0} \frac{\Delta z_j}{2} \left[\lambda_{s,j} - \lambda_{s,j+1} \right] + \left(\frac{\eta}{1-\eta} \right) \left[\left(\frac{\partial X}{\partial \alpha} \right)_{0,j+1} + \left(\frac{\partial X}{\partial \alpha} \right)_{0,j} \right] \right\} \tag{210}$$

$$
\begin{aligned}
CDV_{13,j} = \Bigg\{ & \frac{A_{a,j}}{A_0}\frac{\eta}{u_0}\Delta z_j\left[\alpha_{j+1}\frac{\lambda_{s,j+1}}{H_{j+1}} - \alpha_j\frac{\lambda_{s,j}}{H_j}\right] - \left(\frac{\eta}{1-\eta}\right)\left(\frac{Q'_0}{w_0\,h_{fg}}\right)\frac{\Delta z_j}{2}\left[\frac{f_{p,j}F_{s,j}^2 - f_{p,j+1}F_{s,j+1}^2}{1-\eta}\right] \\
& + \left(\frac{\eta}{1-\eta}\right)\left[\left(\frac{\partial X}{\partial H}\right)_{0,j+1} + \left(\frac{\partial X}{\partial H}\right)_{0,j}\right] + \left(\frac{\eta}{1-\mu}\right)\left(\frac{Q'_0}{w_0\,h_{fg}}\right)\frac{h_{fg}}{c_p}CC_{q,a,j}\,\Delta z_j\left[\frac{F_s(j+1) - F_s(j)}{6}\right]\Bigg\}
\end{aligned}
\tag{211}
$$

2.7.2.3. LAPUR modifications

One subroutine, COEFIW, is modified.

Subroutine COEFIW

```
C LAPUR6 I:34
C NEW LINES
                QA = AVL(J)/A0
                QB = A0/AVCL(J)
                QB1= A0/AVCL(J1)
C
                CDV1  (J)  = -CSS*TAUA*2/(QB1+QB)
                CDV2  (J)  = -CB16(J) + Q8*B9(J)*QA + 2.*V0(J1)
                CDV3  (J)  = Q8*B5(J)*QA + 2.*DVDB0(J1)
                CDV4  (J)  = CB15(J) + Q8*B7(J)*QA - COPP(J)*B3(J)
     >                       + 2.*DVDH0(J1)
                CDV6  (J)  = 2.*Q6*DVDB0(J1) + Q3/Q2*CSS*B13(J)*QA
                CDV7    (J)    =    2.*V0(J1)    -    2./Q2    -
Q3/Q2*CSS*B11(J)*QA
     >                         + COPP(J)*CCQ(I)*Q7 + 2.*Q6*DVDH0(J1)
+2.*XI
                CDV11(J)   =  Q3*B10(J)*QA   +  V0(J1)   +  V0(J)   -
Q9*CAQ(I)
                CDV12(J)  = Q8*B6(J)*QA + DVDB0(J1) + DVDB0(J)
                CDV13(J)    =    Q8*B8(J)*QA    -    COPP(J)*B4(J)    +
DVDH0(J1)
     >                       + DVDH0(J) + Q9*Q7*CCQ(I)
                CDV15(J)  = Q6*DVDB0(J1) + Q5*DVDB0(J)
     >                       + Q3*CSS*B14(J)/Q2*QA
                CDV16(J)  = V0(J1) + V0(J) - Q3*CSS*B12(J)/Q2*QA
     >                         + Q6*DVDH0(J1) + Q5*DVDH0(J) - 2./Q2
+2.*XI
C
              IF(FLOW_AREA_VAR.EQ.1)THEN
             CD1  (J)  = CDV1  (J)
             CD2  (J)  = CDV2  (J)
             CD3  (J)  = CDV3  (J)
```

```
                CD4  (J)  = CDV4  (J)
                CD6  (J)  = CDV6  (J)
                CD7  (J)  = CDV7  (J)
                CD11(J)  = CDV11(J)
                CD12(J)  = CDV12(J)
                CD13(J)  = CDV13(J)
                CD15(J)  = CDV15(J)
                CD16(J)  = CDV16(J)
                 ENDIF
C LAPUR6 END
```

2.7.3. Momentum Conservation—LAPUR 6.0 Boiling Region Coefficients

The momentum conservation equations used by LAPUR 6.0 are explained in Sect. 2.5.2.

The new coefficient τV_j, equation (112), is used in the frequency domain (subroutine FREQ):

$$\tau V_j = \frac{u_0}{gL_0}\Delta z_j \frac{A_0}{A_{a,j}} = \text{TAUIPV(J)} \qquad (212)$$

One subroutine, FREQ, is modified.

2.7.3.1. LAPUR 6.0 modifications

Subroutine FREQ

```
C LAPUR6 I:1
C NEW LINE
      COMMON/PERTH/CDBA
C LAPUR6 END
```

....

```
C LAPUR6 I:4
C NEW LINES
             IF(FLOW_AREA_VAR.EQ.1)THEN
              CDP(K)  = CDP(K+1)  +  (CSS*TAUIPV(J)+C13(J))*CDYA(K)
     >           + C14(J)*CDBA(K)  - C15(J)*CDY(K)  - C16(J)*CDB(K)
             ENDIF
C LAPUR6 END
```

....

```
C LAPUR6 I:5
C NEW LINES
             IF(FLOW_AREA_VAR.EQ.1)THEN
              CDP(J)  = CDP(J+1)  +  (CSS*TAUIPV(J)+C13(J))*CDYA(J)
     1           + C14(J)*CDBA(J)  - C15(J)*CDY(J)  - C16(J)*CDB(J)
     2           + C21(J)*CDHA(J)  - C22(J)*CDH(J)
             ENDIF
C LAPUR6 END
```

2.8. OTHER MODIFICATIONS TO LAPURW 6.0

This section presents other modifications to LAPURW.

Subroutine MAIN—LAPUR 6.0 Version

```
      C     LAPURW6.1BETA
.........
      C LAPUR6 M:1
      C MODIFICATION
      C    WRITE(*,'('' LAPUR5W RUN TITLE :''/'' ** '',18A4,'' ** '')')
            WRITE(*,'(''  LAPUR6W  RUN  TITLE  :''/''  **  '',18A4,''  **
      '')')
      C LAPUR6 END
.........
      C LAPUR6 M:1
      C MODIFICATION
      C        WRITE(6,'(''1'',18A4,''*** LAPUR5W *** '',24X
                WRITE(6,'(''1'',18A4,''*** LAPUR6W ***'',24X
      C LAPUR6 END
.........
      C LAPUR6 M:1
      C MODIFICATION
      C        WRITE (*,'(/'' ** USING RESULTS FROM LAPUR5X RUN :''
                WRITE (*,'(/'' ** USING RESULTS FROM LAPUR6X RUN :''
      C LAPUR6 END
```

Subroutine COEFIW—Variable flow area

```
      C LAPUR6 I:2
      C NEW LINES
            INTEGER FLOW_AREA_VAR
            DATA FLOW_AREA_VAR/ 1 /
      C LAPUR6 END
```

Subroutine DRUMR1—New commons used; Intermediate storage

```
            EQUIVALENCE  (XDL1(1),DPIN1),(XFRI(1),IFFM(1))
           >             ,(XFR3(1),IFF),(XCTP(1),TPFM(1))
.........
            DIMENSION    XDL1(N_DLTP1)
            DIMENSION    XFRI(N_FRICC)
            DIMENSION    XFR3(N_FRIC1)
            DIMENSION    XCTP(N_CTPFM)
.........
            READ (NDISK1)  XDL1
            READ (NDISK1)  XFRI
            READ (NDISK1)  XFR3
            READ (NDISK1)  XCTP
```

Subroutine FREQ—If FLOW_AREA_VAR is defined as 1, the variable flow area formalism is used.

```
C LAPUR6 I:2
C NEW LINES
      INTEGER FLOW_AREA_VAR
      DATA FLOW_AREA_VAR/ 1 /
C LAPUR6 END
```

Subroutine INPUTW—LAPUR 6.0 version

```
C LAPUR6 M:1
C MODIFICATION
C      WRITE(6,'('' ERROR.  LAPUR5 CAN NOT HANDLE MULTICORE
CASES''
        WRITE(6,'('' ERROR.  LAPUR6 CAN NOT HANDLE MULTICORE
CASES''
C LAPUR6 END
```

Subroutine TRANS—LAPUR 6.0 version

```
C LAPUR6 M:4
C MODIFICATION
C                 WRITE(*,'('' RERUN LAPUR5W WITH TIGHTER
FREQUENCY''
C     >           '' SPACING AROUND'', F6.2,'' Hz'')') W(IW)/6.2835
C                 WRITE(6,'('' RERUN LAPUR5W WITH TIGHTER
FREQUENCY''
C     >           '' SPACING AROUND'', F6.2,'' Hz'')') W(IW)/6.2835
                    WRITE(*,'('' RERUN LAPUR6W WITH TIGHTER
FREQUENCY''
     >                            '' SPACING AROUND'', F6.2,'' Hz'')')
W(IW)/6.2835
                    WRITE(6,'('' RERUN LAPUR6W WITH TIGHTER
FREQUENCY''
     >                            '' SPACING AROUND'', F6.2,'' Hz'')')
W(IW)/6.2835
C LAPUR6 END
```

2.9. MODIFICATIONS IN SHARED FILES

This section presents the modifications made in the shared files (param.fi, XW_com.fi, W_com.fi) relative to thermal hydraulic improvements.

File Param.fi

```
C LAPUR6 I:4
C NEW LINES
      PARAMETER (NVAMAX  = 10) ! Max # of variable area channels
(>=10)
      PARAMETER (NOVAMAX = 90) ! Max # of axial intervals channel
(  90)
      PARAMETER (NLLMAX  = 10) ! Max # of local loss channel types
(>=10)
      PARAMETER (NOLLMAX = 90) ! Max # of axial intervals ll-
channel(  90)
C LAPUR6 END
.........
C LAPUR6 M:1
C MODIFICATION
C      PARAMETER (N_CEF2 = 5 + NCENMAX + NOBMAX1)
      PARAMETER (N_CEF2 = 5 + NCENMAX + NOBMAX1 + NOBMAX)
C LAPUR6 END
.........
C LAPUR6 M:1
C MODIFICATION
C     >                     + NCEMAX + 4*NCEMAX*NCENMAX)
     >                     + NCEMAX + 4*NCEMAX*NCENMAX
C LAPUR6 END
C LAPUR6 I:2
C NEW LINES
     >                     + 2 + 2*NCHMAX + NVAMAX + 3*NVAMAX*NOVAMAX
     >                     + NLLMAX + 2*NLLMAX*NOLLMAX)
C LAPUR6 END
.........
C LAPUR6 M:1
C MODIFICATION
C      PARAMETER (N_NOHD = 2*NOTMAX1 + 4*NOBMAX1 + NOBMAX)
      PARAMETER (N_NOHD = 2*NOTMAX1 + 4*NOBMAX1 + NOBMAX
C LAPUR6 END
C LAPUR6 I:2
C NEW LINES
     >                     + 15*NOBMAX + NOBMAX1 + 16*NNBMAX
     >                     + 2*NNBMAX1)
C LAPUR6 END
.........
C LAPUR6 M:1
C MODIFICATION
```

```
C     >                    + 4*NCENMAX)
     >                    + 4*NCENMAX
C LAPUR6 END
C LAPUR6 I:1
C NEW LINE
     >                    + 2 + 3*NOVAMAX + 2*NOLLMAX)
C LAPUR6 END
.........
C LAPUR6 I:4
C NEW LINES
      PARAMETER (N_DLTP1 = 48 + 6*NOBMAX + 16*NNBMAX)
      PARAMETER (N_FRICC = 10*NFRMAX)
      PARAMETER (N_FRIC1 = 10)
      PARAMETER (N_CTPFM = 8*NOBMAX1)
C LAPUR6 END
```

File XW_com.fi

```
C LAPUR6 I:1
C NEW LINE
     >              ,TAUIPV(NOBMAX)
C LAPUR6 END
.........
C LAPUR6 I:17
C NEW LINES
      COMMON /DLTP1/ DPIN1          ,DPDHIN1        ,DPFRIN1
     >              ,DPNB2          ,DPDHNB2        ,DPFRNB2
     >              ,DPACNB2        ,DPEXNB2        ,DPLLNB2
     >              ,DPCONB2        ,DPSB1          ,DPDHSB1
     >              ,DPFRSB1        ,DPACSB1        ,DPEXSB
     >              ,DPLLSB         ,DPCOSB         ,DPBB1
     >              ,DPDHBB1        ,DPFRBB1        ,DPACBB1
     >              ,DPEXBB         ,DPLLBB         ,DPCOBB
     >              ,DPR1           ,DPDHR1         ,DPFRR1
     >              ,DPDH1          ,DPFR1          ,DPAC1
     >              ,DPLL           ,DPEX           ,DPCO
     >              ,DPCON1         ,DPCONR1        ,DPCONT1
     >              ,EKCP1          ,DPTOT1         ,DPDHP1(NOBMAX1)
     >              ,DPFRP1(NOBMAX1),DPACP1(NOBMAX1),EKCRP1(10)
     >              ,DPDHNB1(NNBMAX),DPFRNB1(NNBMAX),DPACNB1(NNBMAX)
     >              ,DPEXNB(NNBMAX) ,DPEXP(NOBMAX1) ,DPLLNB(NNBMAX)
     >              ,DPLLP(NOBMAX1) ,DPCONB(NNBMAX) ,DPCOP(NOBMAX1)
C LAPUR6 END
.........
C LAPUR6 I:6
C NEW LINES
     >              ,NTDV                   ,NDIMV(NCHMAX)
     >              ,NODV(NVAMAX)           ,DZVM(NVAMAX,NOVAMAX)
     >              ,AVM(NVAMAX,NOVAMAX)    ,DEVM(NVAMAX,NOVAMAX)
     >              ,NTDLL                  ,NDIMLL(NCHMAX)
     >              ,NODLL(NLLMAX)          ,DZLLM(NLLMAX,NOLLMAX)
```

```
     >              ,EKLLM(NLLMAX,NOLLMAX)
C LAPUR6 END
```

....

```
C LAPUR6 I:16
C NEW LINES
     >              ,DEVL(NOBMAX)     ,AVL(NOBMAX)
     >              ,HVL(NOBMAX)      ,TVL(NOBMAX)   ,EMUVL(NOBMAX)
     >              ,RHOVL(NOBMAX)    ,UVL(NOBMAX)   ,REVL(NOBMAX)
     >              ,DEVNBL(NNBMAX)   ,AVNBL(NNBMAX)
     >              ,HVNBL(NNBMAX)    ,TVNBL(NNBMAX) ,EMUVNBL(NNBMAX)
     >              ,RHOVNBL(NNBMAX)  ,UVNBL(NNBMAX) ,REVNBL(NNBMAX)
     >              ,EKFNBL(NNBMAX)
     >              ,AVNBCL(NNBMAX1)  ,AVCL(NOBMAX1)
     >              ,DEVNBCL(NNBMAX1),DEVCL(NOBMAX1)
     >              ,EKLLNBL(NNBMAX)  ,EKLLL(NOBMAX)
     >              ,FNBL1(NNBMAX)    ,FNBL2(NNBMAX) ,FNBL(NNBMAX)
     >              ,FL1(NOBMAX)      ,FL2(NOBMAX)   ,FFL(NOBMAX)
     >              ,A2NBL1(NNBMAX)   ,A2NBL2(NNBMAX),A2NBL(NNBMAX)
     >              ,A2L1(NOBMAX)     ,A2L2(NOBMAX)  ,A2L(NOBMAX)
     >              ,RHOVNBCL(NNBMAX1)
     >              ,EKLFNB(NNBMAX)   ,EKLF(NOBMAX)
C LAPUR6 END
```

....

```
C LAPUR6 I:3
C NEW LINES
     >              ,NV
     >              ,DZV(NOVAMAX)     ,AV(NOVAMAX)   ,DEV(NOVAMAX)
     >              ,NLL              ,DZLL(NOLLMAX) ,EKLL(NOLLMAX)
C LAPUR6 END
```

....

```
C LAPUR6 I:13
C NEW LINES
      COMMON /FRICC/ IFFM(NFRMAX)     ,ANM(NFRMAX)   ,BNM(NFRMAX)
     >              ,CNM(NFRMAX)      ,DNM(NFRMAX)   ,RRM(NFRMAX)
     >              ,IFMM(NFRMAX)          ,AJUSTAC1M(NFRMAX)
     >              ,AJUSTAA1M(NFRMAX)     ,AJUSTAB1M(NFRMAX)
      COMMON /FRIC1/ IFF              ,AN            ,BN
     >              ,CN               ,DN            ,RR
     >              ,IFM                   ,AJUSTAC1
     >              ,AJUSTAA1              ,AJUSTAB1
      COMMON /CTPFM/ TPFM(NOBMAX1)
     >              ,DTPFMDY0(NOBMAX1),DTPFMDH0(NOBMAX1)
     >              ,DTPFMDB0(NOBMAX1),DOMDH01(NOBMAX1)
     >              ,HM0(NOBMAX1)
     >              ,DHMDB0(NOBMAX1)   ,DHMDH0(NOBMAX1)
C LAPUR6 END
```

File W_com.fi

```
C LAPUR6 I:5
C NEW LINES
```

```
     >                  ,CTAUNBV(NOBMAX)
     >                  ,CDV1(NOBMAX)     ,CDV2(NOBMAX)    ,CDV3(NOBMAX)
     >                  ,CDV4(NOBMAX)     ,CDV6(NOBMAX)    ,CDV7(NOBMAX)
     >                  ,CDV11(NOBMAX)    ,CDV12(NOBMAX)   ,CDV13(NOBMAX)
     >                  ,CDV15(NOBMAX)    ,CDV16(NOBMAX)   ,CDV22(NOBMAX)
C LAPUR6 END
```

....

```
C LAPUR6 I:2
C NEW LINES
     >            ,CTAUNBV,CDV1,CDV2,CDV3,CDV4,CDV6,CDV7
     >            ,CDV11,CDV12,CDV13,CDV15,CDV16,CDV22
C LAPUR6 END
```

CHAPTER 3. PROGRAMMING ERRORS

3.1. PROGRAMMING ERRORS CORRECTED IN VERSION 5.2

The programming errors found in LAPUR 5.1 and corrected in LAPUR 5.2 are:

Subroutine W_ONECOR.for

Wrong CBD and CCD calculation

Old Logic:

```
CBD=CAD+NCH(IX)*( CDYX(IX)*CMX(IX)+CDQX(IX) )*Q1
CCD=CAD+NCH(IX)*( CDYX(IX)*CNX(IX)+CDTX(IX) )*Q1
```

Corrected Logic:

```
CBD=CBD+NCH(IX)*( CDYX(IX)*CMX(IX)+CDQX(IX) )*Q1
CCD=CCD+NCH(IX)*( CDYX(IX)*CNX(IX)+CDTX(IX) )*Q1
```

3.2. PROGRAMMING ERRORS CORRECTED IN VERSION 6.0

Three miscellaneous errors were found in the subroutine COEFIW (W_coef.for) of LAPUR 5.2 and were corrected in version 6.0.

Subroutine COEFIW

```
C LAPUR6 M:1
C MODIFICATION
C Miscellaneous error
C              Q8 = (2.*FS02(J) + FS01(J))/3.*COPP(J)
                Q18= (2.*FS02(J) + FS01(J))/3.*COPP(J)
C LAPUR6 END
```

…….

```
C LAPUR6 M:2
C MODIFICATION
C Miscellaneous error
C              CB15(J) = Q8*CCQ(I)*Q7
C              CB16(J) = Q8*CAQ(I)
                CB15(J) = Q18*CCQ(I)*Q7
                CB16(J) = Q18*CAQ(I)
C LAPUR6 END
```

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NOMENCLATURE

A	flow area
a_2	Reynolds's number constant
c_p	*specific heat capacity at constant pressure*
$c_{p.av}$	average specific heat of water in the NBR
D_H	hydraulic diameter
DZ	cell length
f	friction factor
f_M	Moody friction factor
f_p	adjustable factor for the fraction of power invested in steam production
F_s	fraction of energy invested in steam formation
G	mass flux
g	gravitational acceleration
$H = \frac{h_F - h_l}{h_{fg}}$	normalized degree of sub-cooling
h	enthalpy
h_{fg}	vaporization enthalpy
K_C	contraction coefficient for pipes (input user data card 43)
K_{cc}	contraction coefficient at the inlet of the channels (input user data card 10)
K_F	crud-deposition friction multiplier
K_L	local-loss coefficient
L	channel length
m	cell
N	total boiling cells
n	cell edge
NNB	total nonboiling cells
N_{con}	total number of contractions in the channel
N_{exp}	total number of expansions in the channel
N_{NB}	total nonboiling cells
P	pressure
P_w	wet perimeter
Q'	energy per unit lenght supply by the fuel
R_r	relative roughness
Re	Reynolds number
s	Laplace transform
t	time
u	velocity
w	mass flow rate
XF	flow quality used in the Chisholm-Baroczy two-phase friction multiplier
x	*steam quality*
$y = \frac{w}{w_0}$	normalized mass flow rate
z	*height*
ZNB	nonboiling bulk-boiling boundary location

Greek symbols

α	void fraction
Δz	cell length
Δ	increment operator
δ^{Kr}	Kronecker delta
ϕ^2_{CB}	Chisholm-Baroczy two-phase friction multiplier
ϕ^2_{MN}	Martinelli-Nelson two-phase friction multiplier
λ_s	bubble decay constant
$\Pi = \frac{P}{g\rho_F L}$	normalized pressure
γ	slip ratio
μ	dynamic viscosity
ρ	density
Ω	Jones two-phase friction multiplier correction factor
$\eta = 1 - \frac{\rho_g}{\rho_F}$	relative density decrement in the evaporation process
θ	angle
$\delta\overline{q}'$	normalized total power generation perturbation in the fuel
$\delta\overline{T}_l$	liquid coolant temperature perturbation
$\delta\overline{y}$	normalized coolant flow rate perturbation

Subscripts

0	steady-state or reference conditions
a	averaged value
F	saturated conditions
g	steam phase
i	nonboiling cell
in	inlet conditions
j	boiling cell
l	liquid phase
NB	nonboiling region
ZNB	nonboiling bulk-boiling boundary location
Z1	nonboiling bulk-boiling boundary location

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Dr. T. L. Huang, Project Manager

11. ABSTRACT *(200 words or less)*

This report documents a series of programming upgrades to Version 6.0 of the LAPUR code. LAPUR, a computer program in FORTRAN, is a mathematical description of the core of a boiling water reactor. Its two linked modules, LAPURX and LAPURW, respectively solve the steady-state governing equations for the coolant and fuel and the dynamic equations for the coolant, fuel, and neutron field in the frequency domain. The main upgrade in LAPUR 6 is the ability to model part-length fuel rods and fuel spacers explicitly. General implementation descriptions are followed by a detailed description of input and output parameters of LAPURX and LAPURW. Sample inputs are included and stability benchmarks are noted.

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BWR Stability

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