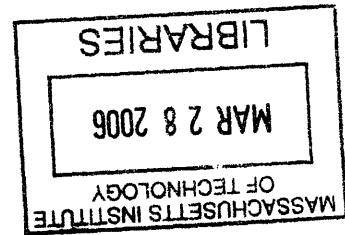


# Design of Annular Fuel for High Power Density BWRs

by

**Paolo Morra**

Laurea in Ingegneria Nucleare  
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Submitted to the Department of Nuclear Engineering  
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Submitted to the Department of Nuclear Engineering on December 17, 2004, in partial fulfillment of the Requirements for the Degree of Master of Science at the Massachusetts Institute of Technology

## **ABSTRACT**

Enabling high power density in the core of Boiling Water Reactors (BWRs) is economically profitable for existing or new reactors. In this work, we examine the potential for increasing the power density in BWR plants by switching from the current solid fuel to annular fuel cooled both on its inside and outside surfaces. The GE 8x8 bundle dimensions and fuel to moderator ratio are preserved as a reference to enable applications in existing reactors. A methodology is developed and VIPRE code calculations are performed to select the best annular fuel bundle design on the basis of its Critical Power Ratio (CPR) performance. Within the limits applied to the reference solid fuel, the CPR margin in the 5x5 and 6x6 annular fuel bundles is traded for an increase in power density. It is found that the power density increase with annular fuel in BWRs may be limited to 23%. This is smaller than possible for PWRs due to the different mechanisms that control the critical thermal conditions of the two reactors. The annular fuel could still be a profitable alternative to the solid fuel due to neutronic and thermal advantages.

Thesis Supervisor: Mujid S. Kazimi

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But in particular I would like to dedicate this work to my grandfather Roccantonio Morra. I will never forget you.

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# Chapter 1

## Introduction and Scope of Work

There is a close correlation between the energy consumed per capita and the quality of life in any society. One of the biggest challenges of modern times is to provide a longer and better life to the increasing world population; the energy needed for such a goal cannot be sustained in the long term simply by increasing energy efficiency nor can it be reasonably achieved using the current fuel mix. The increasing tension in the oil-rich Middle East and the depletion of fossil fuel resources in the rest of the world foretell a future where energy is going to be more and more expensive. Thus the average quality of life of the world population may suffer if there is no change or innovation in energy technology and policy.

Currently, worldwide research is exploring many directions to find a solution for sustainable energy, and most of the probable alternatives involve a larger role for nuclear power in modern societies. This will be hard to achieve through building of new nuclear power units due to the resistance of a significant segment of the population to nuclear energy. Eventually the situation may change, but as a short to medium term solution, the global nuclear industries are pursuing relicensing and power uprating of already existing nuclear power plants. Due to the high capital cost of nuclear plants, either extending the life of a plant or raising its power output would be economic, since most of the added energy is obtained with a smaller investment, if any, in capital costs.

Power uprating of existing Nuclear Power Plants (NPPs) has been thoroughly studied and extensively applied by improving the methods to evaluate the conservative margin between the operating and limiting condition, or by increasing the capability of the secondary coolant circuit. One way to raise the power in a major way is to change the fuel design in the reactor core. If the more efficient fuel design can be accommodated in

the existing plants, upgrading can be considered. Alternatively, the increased power density of the core can be the basis for new power plants.

A new fuel design for Pressurized Water Reactors (PWR) has been proposed and studied at MIT. The fuel employs annular geometry with internal as well as external cooling, to be able to lower the cladding heat flux and thus achieve higher safety margins than the normal solid fuel. These larger margins allow raising the power of the plant without compromising its safety in case of accidents. The PWR annular fuel study shows promising results [1]. It is reasonable to expect a substantial power density increase to have a significant impact on the revenues of the nuclear industry even considering the higher manufacturing costs of the annular fuel.

The very promising results obtained for the PWR annular fuel naturally led to the proposal to investigate the possibility of a power density upgrade in the Boiling Water Reactor (BWR) plants using the same technique. There is no other study that we are aware of examining the annular fuel for BWR application. So the scope of this work is to provide a first estimate of the possibility of using the annular fuel in BWR plants and to find what the most promising designs are. To identify the power uprate potential, it is necessary to quantify safety margins of the core with annular fuel. The Critical Power Ratio (CPR) is used to quantify the safety margin during steady state operation and transients, as is current practice for the solid fuel in BWR plants.

First, we will examine the possible designs of the BWR bundle with the goal of maximizing the advantage given by the annular fuel (in particular the heat transfer area). Two layouts will be studied in particular, a 5x5 and a 6x6 fuel bundle, but under the constraint of fixed bundle size equal to the GE 8x8 solid fuel bundle. The constraints on the design, especially the minimum gap between rods, the same assembly size as existing BWRs, and a minimum allowable diameter of the internal channel, combine to limit considerably the number of possible designs.

The methodology and analysis tool are described in Chapter 2. The possible correlations for CPR calculation, will be adapted to annular fuel, and implemented in the VIPRE01mod02 code (Chapter 2). Then on the basis of their thermal hydraulic characteristics (especially the heat transfer surface and the tightness of the pitch) we will select the most promising designs for a more in-depth study (Chapter 3). In this work, the coolant flow in the core is assumed to increase in proportion to the power density increase. We will also compare the annular fuel design to the solid fuel design and calculate the maximum power density upgrade achievable keeping the same safety margin as the solid fuel (Chapter 4). Finally, the work will be summarized and suggestions are made for future work (Chapter 5). Details of the code handling are given in the Appendices.

# Chapter 2

## Methodology and Analysis Tools

### 2.1 Methodology

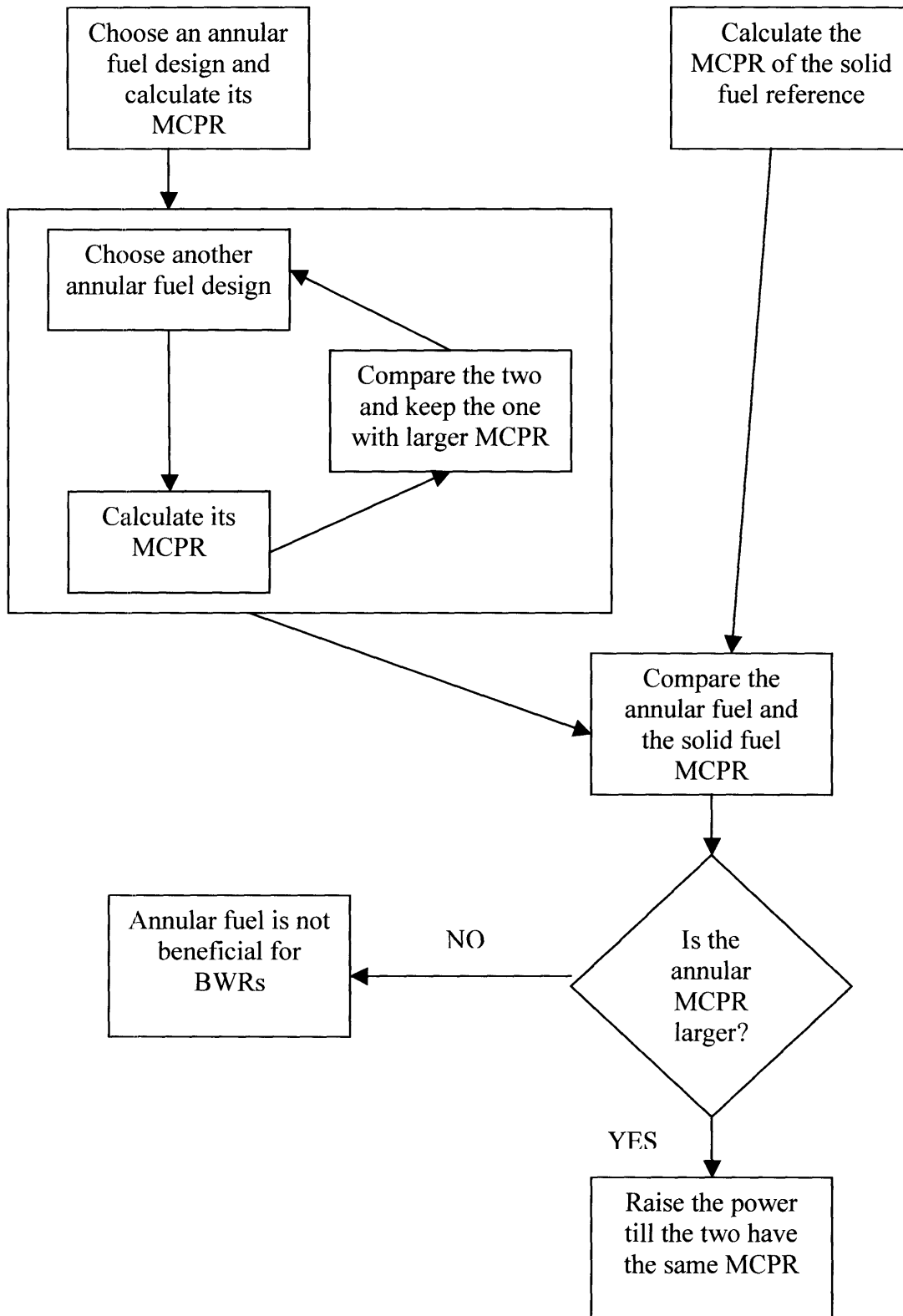
Our objective, as stated in Chapter 1, is to show that switching to annular fuel in existing BWR cores can allow us to eventually raise the power with relatively small modifications to the plant, or at least to show that this possibility is interesting enough to be worth studying more in depth.

First we will consider that the limiting factor in the fuel assembly design is the CHF (Critical Heat Flux), and in particular, in the BWR case, the CPR (Critical Power Ratio) [2]. Thus we will evaluate the performance of the fuel designs on the basis of their CPR values, considering a fuel design better than another if its CPR is higher. By ‘better’ we mean that a fuel design with higher CPR than another will allow us to get a larger power increase. To maintain the same thermal environment under which the materials operate in the core as well as in the hot region of the vessel, we assume that the core flow will increase proportionally with the power, so that the steam flow rates (or quality) and pressure conditions of the hot assembly and the upper core regions are not altered. Also, for safety reasons, we will not allow the CPR of the annular fuel to be lower than the solid fuel value, following the reasoning that experience has shown the solid fuel to be reliable and safe and thus the annular fuel should be at least as good as the solid (at least in steady state) if it respects the same CPR constraint. This is further discussed in Section 2.4.

To reach our objective we have decided to use a well-established thermal hydraulic code, VIPRE, to analyze the core of a BWR using annular fuel and to do the same analysis for

a BWR using normal (solid) fuel. After calculating the thermal hydraulic parameters, we can use them and a CPR (Critical Power Ratio) correlation to obtain the Minimum Critical Power Ratio (MCPR) of the two systems. We can also iterate on the possible designs of annular fuel to get the maximum possible power while keeping the MCPR equal or higher than that of the solid fuel.

If the MCPR of the annular fuel is larger than the solid fuel we can raise the power (and the mass flow rate by the same ratio) of the annular fuel till we reach the same MCPR of the solid fuel. This will give us an idea of how much we can improve the power in existing BWRs by switching to annular fuel. As expected, we will see in Chapter 4 that there exist annular fuel designs that have larger MCPR than the solid's, so we can obtain a power density increase. This process is shown in flow chart form in Figure 2.1.



**Figure 2.1: Flow chart of the fuel comparison**

Now we would like to discuss in-depth the various parts of our methodology. First of all we note that while the whole process is once-through, it involves at least two large iteration loops, one to choose the best annular fuel design and the second to determine how much we can increase the power till we get the same MCPR as the solid fuel case. We will discuss in Section 2.3 why and how we are using the CPR as the main parameter in our analysis.

The iteration to choose the best annular fuel design is explained in-depth in Chapter 3. The possible designs are infinite, due to the fact that the geometrical variables in play are continuous. However with an intelligent choice of the parameters to explore and considering the many constraints we have to impose to get a fuel design that is viable from the mechanical, vibration, thermal hydraulic and neutronic points of view, we can limit our search to a few main designs. Also, we want to enable the fuel use by existing BWR plants and this forces more constraints on us.

The choice of the solid fuel reference arrangement and operating conditions is also shown in Chapter 3. In Chapter 4 we show the MCPR calculation for annular and solid fuel and the fact that annular fuel design that has higher MCPR than the solid can also satisfy the applied constraints. The power upgrade calculation is also shown in Chapter 4.

There is an additional feature that we wish to discuss here. In general to have an accurate thermal analysis the entire core should be modeled to have a complete thermal hydraulic picture of the flow and consider the MCPR calculations reliable. In the BWR case though, we can resort to model only a bundle due to the fact that bundles are encased and share the same inlet and outlet plena. As a consequence we can consider the pressure drop the same for all bundles. This observation and the fact that there is no cross flow among the bundles allow us to calculate the MCPR of the BWR core using just two bundle models in the following way.

First we divide the total reactor flow, a commonly known data [2], by the number of bundles in the core (after considering that some of the flow will bypass the bundles) thus

getting the flow in an average bundle. Then, we use the model to calculate the pressure drop in the average bundle that, by the argument discussed before is going to be the same in every bundle. So, knowing the pressure drop we can apply the calculated pressure drop to the hot bundle model, this time to calculate the flow and all the other thermal hydraulic parameters. With these we can calculate the CPR of the hot bundle that will be the MCPR of the core. We use this method for both the annular and solid fuel and obtain the power density to match the MCPR of the two.

We want to underline that we developed two inputs for every design, one for the hot bundle and one for the average bundle. They have the same geometry and differ only in the power, the inlet pressure drop and the fact that they are used for different purposes in our method.

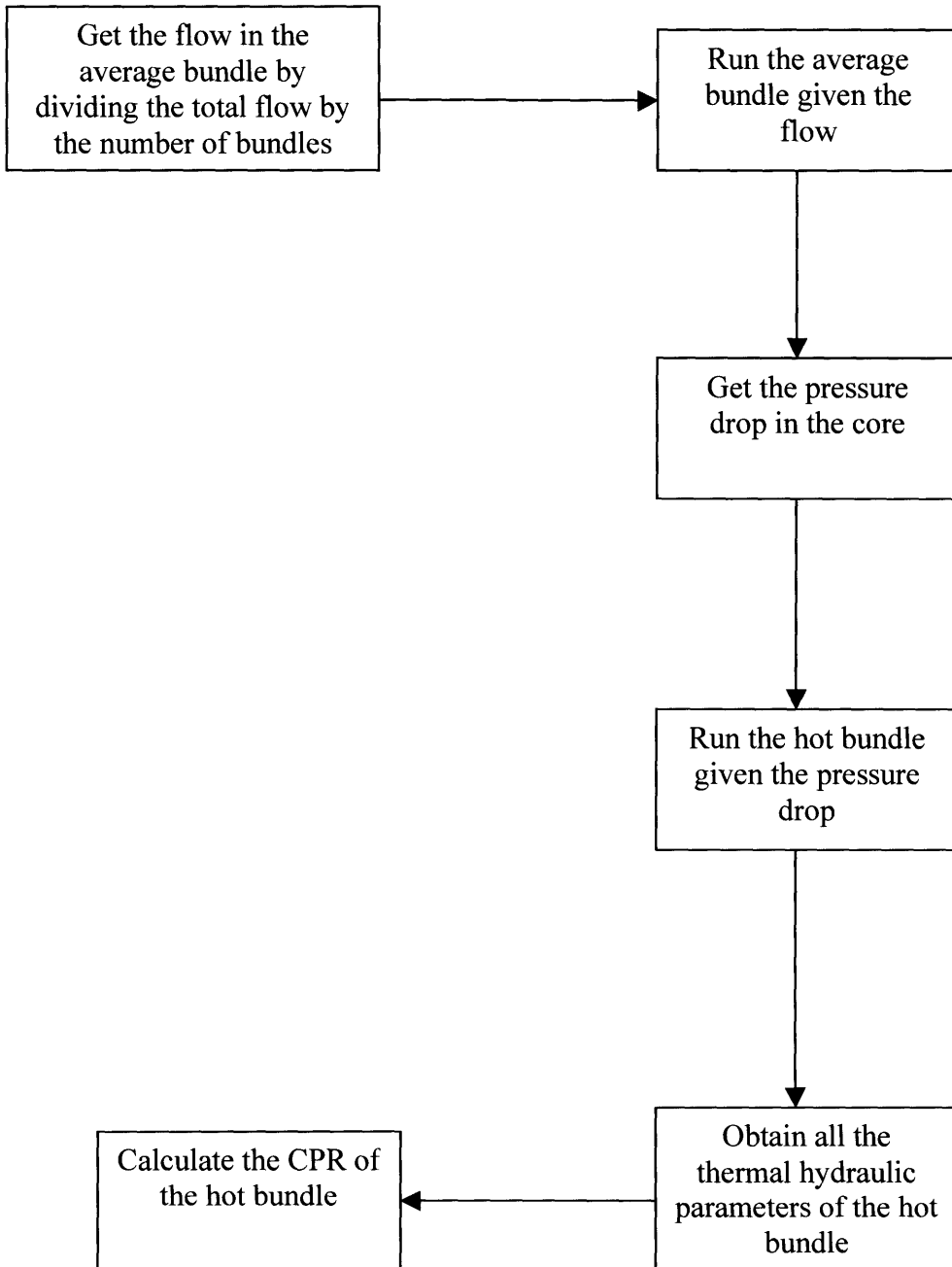


Figure 2.2: Flow chart of the iterative method for the thermal hydraulic calculations

## 2.2 Analysis Tools

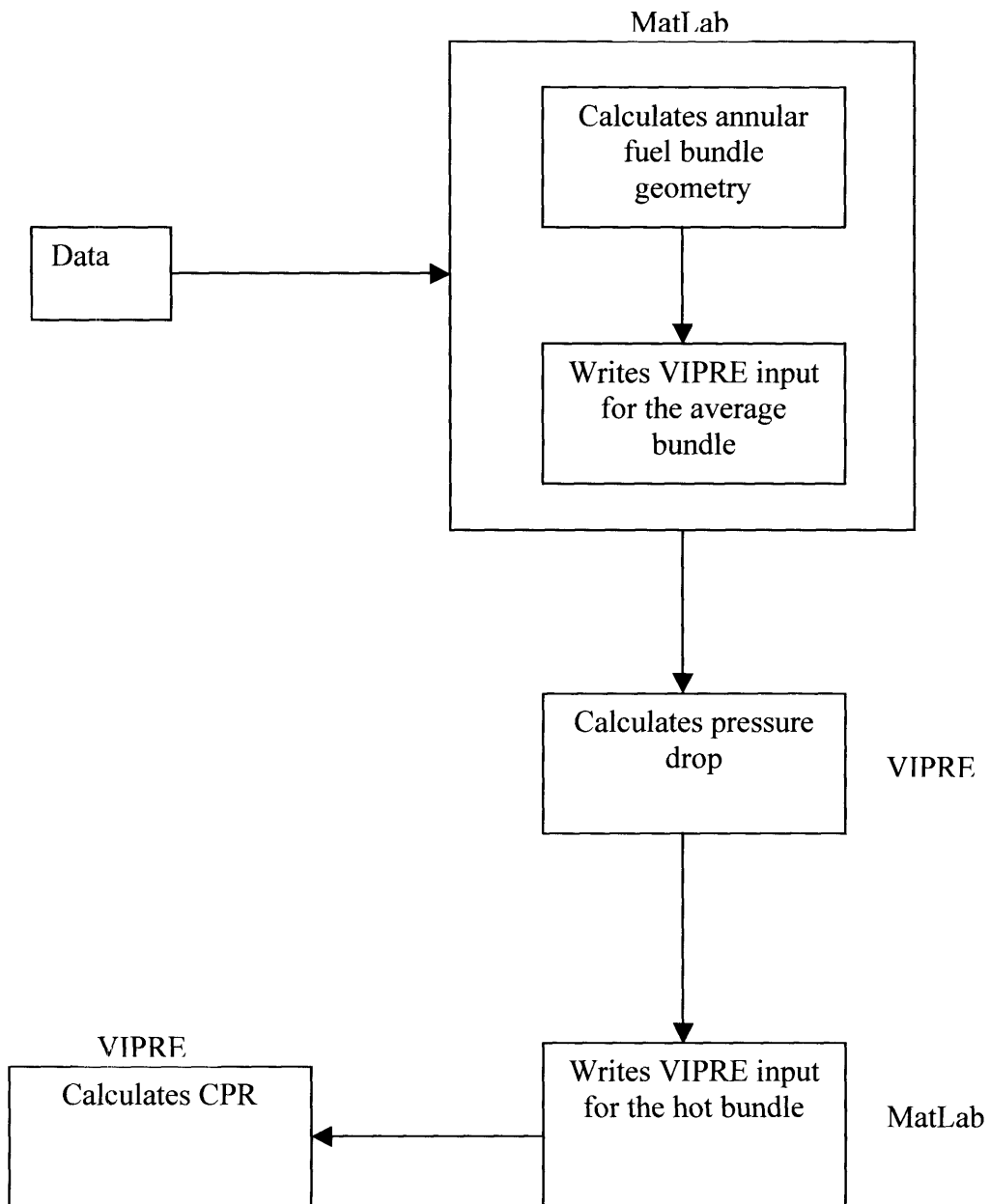
As discussed in Section 2.1 it is important to choose a reliable thermal hydraulic code to do the calculations we have described. We need a code that has the following characteristics:

- has a robust thermal hydraulic model
- widely accepted in the nuclear field
- able to calculate the thermal hydraulic parameters we need
- allow change of the geometry of the fuel from solid to annular
- numerically stable
- should have the possibility to calculate the CPR of the system
- should have updated CPR correlations
- must be available to us
- should be fast
- extensively documented

We have found that among the alternatives available to us, the VIPRE code fulfills better these characteristics. We had the VIPRE01mod02 available and we decided to use it for this analysis since it meets all the above requirements and there was already some experience in its use in our department.

We have obtained good results with VIPRE, even if we had some problems with its convergence, especially in the annular fuel case. The code shows a tendency of not converging for a high number of axial nodes and there are peculiar zones where we cannot achieve convergence even with a lower number of axial nodes. It seems that the code has some problems in handling our model from the numerical point of view, because the principal cause of no convergence is due to the fact that the error keeps oscillating between the iterations and thus the code stops after it reaches the maximum number of set iterations. This problem is discussed thoroughly in Appendix A.

To implement the model explained in Section 2.1 we have scripted in MatLab a program (Appendices C and D) that calculates the fuel geometry and writes automatically the input for VIPRE (Appendix B). The MatLab script is able to write the input for both the average and hot bundles, thus we need to iterate between MatLab and VIPRE to get the MCPR of the design, as shown in Figure 2.3 below.



**Figure 2.3: Flow chart of the code interactions**

## 2.3 VIPRE thermal hydraulic model and correlation choices

VIPRE thermal hydraulic two phase flow model is essentially a homogeneous equilibrium model with an added set of void-drift correlations that help it better simulate the two phase effects. In fact the basic equations are written using the homogeneous formulation, and then the empirical correlations are added to refine the result.

The main assumptions are [3]:

- The flow has sufficiently low velocity such that kinetic and potential energies are small compared to internal thermal energy
- Work done by body forces and shear stresses in the energy equation is small compared to surface heat transfer and convective energy transport
- Heat conduction through the fluid surface is small compared to convective energy transport and heat transfer from solid surfaces
- The phases are in thermal equilibrium (except for subcooled boiling, see Section 2.3.1)
- Gravity is the only significant body force in the momentum equation
- Viscous shear stresses between fluid elements are small compared to the drag force on solid surfaces
- The fluid is incompressible (with respect to pressure) but thermally expandable; this means that the density and transport properties vary only with the local temperature, not with the pressure.

The above assumptions allow the conservation equations to be written in a simpler form but to get closer to reality the developers of the code inserted some correlations that allow them to close the mathematical system and to model more complicate situations with good accuracy.

## 2.3.1 The flow model

VIPRE 01 originally used the homogeneous model for two phase flow. This means that it considered the two phase flow to be a single fluid with the properties (density, viscosity, etc.) of the mixture, and the same phasic velocity for both the liquid and the vapor. This is a fairly reasonable approximation of the flow field at high pressures and high mass velocities, but is less satisfactory at lower pressures and mass velocities. The homogeneous model was modified in VIPRE01 mod 2.0 by the following correlations:

- Two phase friction multiplier

The momentum equation can be modified by this correlation that takes into account the nonhomogeneities in the two phase flow field and its influence on the pressure drop.

Here we use the EPRI correlation as suggested in the manual

- Subcooled void correlation

This correlation is used to model the nonequilibrium transition from single phase liquid to two-phase boiling flow with heat transfer from a hot wall. The correlation calculates the actual flowing quality for the two-phase mixture and the bulk liquid temperature which could still be subcooled.

Again we choose the EPRI correlation as suggested in the manual

- Bulk void relation

This correlation takes the local quality from the previous correlation and uses it to predict the subcooled void.

Even here we choose the EPRI correlation as suggested in the manual

For all three types of correlations the EPRI ones were the most recently available and covered wider ranges of application, thus they were selected in all three cases. Also the

combination of the three EPRI correlations was shown to achieve the best results over the full range of void fractions [4].

## 2.3.2 Heat transfer correlations

The code uses the following correlations to calculate the heat transfer coefficient between the hot wall and the fluid. We must specify a correlation for each part of the boiling curve.

- Single phase forced convection  
Here we choose the Dittus-Boelter correlation due to the fact that it covers our range of applications and requires one parameter less than the default correlation (EPRI)
- Subcooled nucleate boiling  
Here the only two available correlations that are valid for annulus are the Thom and Chen correlations. The Chen correlation was selected due to its wider applicability range. In any case both were tested and gave very similar results.
- Saturated nucleate boiling  
Again the Chen correlation was selected for the same reasons as above
- Critical heat flux correlation  
This correlation is used to define the peak of the boiling curve. The default (EPRI) correlation was selected. The correlation used for determination of CPR is different and will be discussed in the following Section.
- Transition boiling correlation  
We use the default choice (Condie-Bengtson).

- Film boiling correlation

We use the default correlation (Groeneveld 5.7)

All the correlations selected were checked to be applicable to our case or at least to be the closest to our conditions. Special attention has been given in selecting the correlations to be valid for annular geometry whenever possible.

## 2.4 CPR correlations

The phenomenon variously known as critical heat flux, departure from nucleate boiling, dryout or burnout is defined by Hewitt [5] as the condition where, for a relatively small increase in the heat flux, the heat transfer surface exhibits an inordinate increase in temperature.

However one chooses to define it, the critical heat flux (CHF) represents the sharp pinnacle of the boiling curve (by that we mean the curve that plots heat flux versus wall temperature), to the left of which is efficient stable nucleate boiling heat transfer and to the right of which is an inefficient unstable transition boiling region followed by film boiling leading to high surface temperatures. The point where this occurs in a particular two phase flow situation appears to depend on at least four distinct and nominally independent parameters: the geometry of the flow channel (usually taken into account through the hydraulic diameter), the pressure, the mass flow rate, and the quality (usually the equilibrium quality). These four parameters can be correlated from CHF test data to develop an equation defining the critical heat flux.

For CHF in forced convective channel flow, two different kinds of boiling crisis are most common in nuclear applications. In the subcooled or low steam quality region, a boiling crisis occurs by the transition from nucleate boiling to film boiling or departure from

nucleate boiling (DNB). This phenomenon is most common in Pressurized Water Reactors (PWRs). In the higher steam quality region, mostly annular flow, the boiling crisis originates from depletion of the liquid film (film dryout). This is most common in Boiling Water Reactors (BWRs), and is the phenomenon we will concentrate upon.

In annular flow there is a thin liquid film in contact with the heated surface and in the middle of the channel there is vapor, usually with some liquid drops suspended in it, if the quality is not already very high. The flow rate of the liquid film is determined by evaporation, droplet entrainment (due to drops of liquid being suspended in the vapor that flows faster than the film thus creating film surface oscillation that allow some of the crests to become captured in the vapor) and droplet deposition back on the film. The first phenomenon is due to the heat flux coming from the solid surface, while the other two are originated by the mass exchange between the two phases due to the mechanical effect of the vapor on the liquid film.

After this description it is easy to see that the CHF corresponds to the condition in which the flow rate of the liquid film falls to zero. In this situation the solid wall 'dries out' of liquid and is forced to exchange heat directly with the vapor. Even if there will be liquid droplets suspended in it (because the quality is still less than 1), the heat transfer coefficient will diminish considerably compared to the boiling situation when the liquid film was still in contact with the wall. As a consequence, since the heat flux is constant during this process, the temperature difference will rise and the situation can become dangerous for the wall materials due to loss of strength at high temperatures or even approaching the melting point.

In DNB analysis for PWRs, the characteristic parameters are the critical heat flux (CHF), and the minimum departure from nucleate boiling ratio (MDNBR), which is equal to the minimum heat flux ratio (MCHFR).

Basically a correlation gives us the critical heat flux for the local thermal hydraulic parameters  $\dot{q}''_{CHF}$  and we also know the local heat flux  $\dot{q}''$ , thus we can get the minimum value of the ratio of the two:

$$\frac{\dot{q}''}{\dot{q}''_{CHF}} \quad (2.1)$$

This approach was originally used for BWRs as well. Today though in the most widely used approach for analysis of the boiling transition in BWRs, the characteristic parameters are the critical quality, the critical power and the critical power ratio (CPR).

VIPRE offers two correlations to calculate the thermal margin in a BWR, namely, the Hench-Levy correlation [3] and the Hench-Gillis correlation [3, 6]. The Hench-Levy correlation uses the older, less precise approach of calculating the MCHFR (the only difference being that it uses bundle average conditions to calculate the critical heat flux). Thus the Hench-Gillis correlation was selected since it uses the more modern CPR approach.

The Hench-Gillis correlation is used in iteration on bundle enthalpy rise to determine the critical bundle power. The bundle-average flow and enthalpy are used to calculate a critical quality value  $x_{CHF}$  at every axial elevation along the boiling length. The critical quality is compared then to the local bundle average quality  $x_{avg}$  to define the minimum thermal margin (TM).

$$\frac{x_{CHF}}{x_{avg}} \quad (2.2)$$

where

- = factor function of the radial peaking
- = Pressure
- = Mass flux
- = boiling length

- = critical quality calculated with the correlation at the boiling length corresponding to the axial location  $z$
- $\bar{q}$  = bundle average quality at axial location  $z$
- $\Delta T_{in}$  = inlet subcooling for the bundle
- $h_{fg}$  = latent heat of vaporization at the system pressure

When the critical quality is equal to the local quality the equation is an exact balance and we have  $TM=1$ . In general the conditions will not be at critical power though, so the code will have to iterate on the average enthalpy till it strikes the right balance. The iteration will stop when  $TM=1$  and then the enthalpy calculated will be used to compute the critical power. Then we can define:

$$\text{---} \tag{2.3}$$

It should be noted that the iterations are carried out only on the enthalpy rise of the bundle; the flow solution is not recomputed for the new power. This is consistent with the derivation of most critical quality correlations [3].

## 2.5 CPR correlation modification

The Hench Gillis correlation has the form [6]:

$$\text{---} \tag{2.4}$$

where the J-factor is principally a function of the radial power peaking. A and B are empirical functions of the mass flux (G), and:

$$\text{---} \tag{2.5}$$

where (D) is the diameter of the rods and (n) the number of rods.

This ‘Z’ is the definition of the nondimensional boiling length that Hench and Gillis chose for their study. Since most of the parameters in the correlation are bundle-averaged, and thus similar if not identical both in the annular and solid fuel, it is evident that any advantage of the annular fuel will come from the ‘heat transfer area’ term in the nondimensional boiling length.

Although VIPRE allows us to define tubes in the core and we use this option to simulate annular fuel, the CPR correlation uses only the external diameter to calculate the heat transfer area. This way in many cases we would have an even *lower* heat transfer area in the annular fuel case, thus eliminating any advantage that the annular fuel could present. Our solution was to include the internal diameter in the nondimensional boiling length calculation so that it would look as:

$$\frac{D_o}{D_i} \quad (2.6)$$

where  $D_o$  is the external diameter of the annular fuel and  $D_i$  the internal. While logical, this modification needs experimental verification.

We then created a new routine for CPR calculation in the VIPRE source code that is identical to the old routine besides the calculation of the heat transfer area. Using Equation 2.6 to calculate the nondimensional boiling length, we have the advantage of being able to consider all the heat transfer area in the annular fuel case, while the equation works as before for the solid fuel.

We consider our change of the correlation in line with the original idea of its development, since we have followed its theoretical aim: to consider the whole heat transfer area in Equation 2.5.

The Hench-Gillis correlation was originally evaluated for 7x7 solid fuel assemblies in a limited number of conditions [6]. Later though it was applied and then verified even for conditions outside its initial field of applicability, such as the 8x8 assemblies used by

modern BWRs. It is important to note that it is a purely empirical correlation and thus should not be applied to conditions outside the range of validation data. We are perfectly aware that our change of the correlation for the annular fuel has no rigorous basis without extensive experimental testing. We are confident though that for our aim of giving an idea of the possible advantages of the annular fuel over the solid fuel it can help us form an informed opinion about the desirability of studying more in depth the use of annular fuel for BWRs

# Chapter 3: Fuel Modeling

## 3.1 Solid fuel bundle geometry

In this work we propose to model both the solid and annular fuel bundles and compare the results. We are aware that the numbers we obtain are associated with uncertainties that we cannot firmly establish, but we are confident that the comparison to the solid fuel bundle can give us an indication on how good the annular fuel could be as an alternative.

The model we have used did not describe the conditions of a particular plant. We have tried to be as close as possible to the characteristics given in the open literature about the BWR plants now in operation (BWR-5) but we acknowledge the fact that no particular plant was the basis for it.

### 3.1.1 Geometrical data

We have chosen to test our designs using the flow conditions of the GE BWR5 plant, with the warning given above about the fact that we didn't have access to the characteristics of any particular plant. For this reason the BWR5 bundle was modeled generically using the VIPRE thermal hydraulic code, and we used that as a reference. The data we used as a reference for the GE BWR5 8x8 bundle are:

**Table 3.1: Design parameters of the GE BWR 8x8 bundle**

<b><u>Parameters</u></b>	<b><u>Values</u></b>
Core thermal power (MWth)	3293
Number of fuel assemblies in the core	764
Active fuel height (cm)	367
Fuel assembly pitch (cm)	15.24
Bundle lattice	8×8
Lattice pin pitch (cm)	1.62
Clad thickness (cm)	0.085
Gap thickness (cm)	0.01
Number of fuel rods	62
Number of water rods	2
Inner distance between box walls (cm)	13.4
Fuel rod OD (cm)	1.23
Water rod OD (cm)	1.50
Water rod ID (cm)	1.32

Most of the geometrical data we have used can be extrapolated from the data of Table 3.1. These data are mostly from the BWR whole core sample input given in the VIPRE manual [7]. However that input is explicitly declared as a mix of BWR5 and BWR6 data, and was not referenced for a particular plant. This should not affect our work which does not aim to license the annular fuel but to quantify the possible power density increase relative to the solid fuel design.

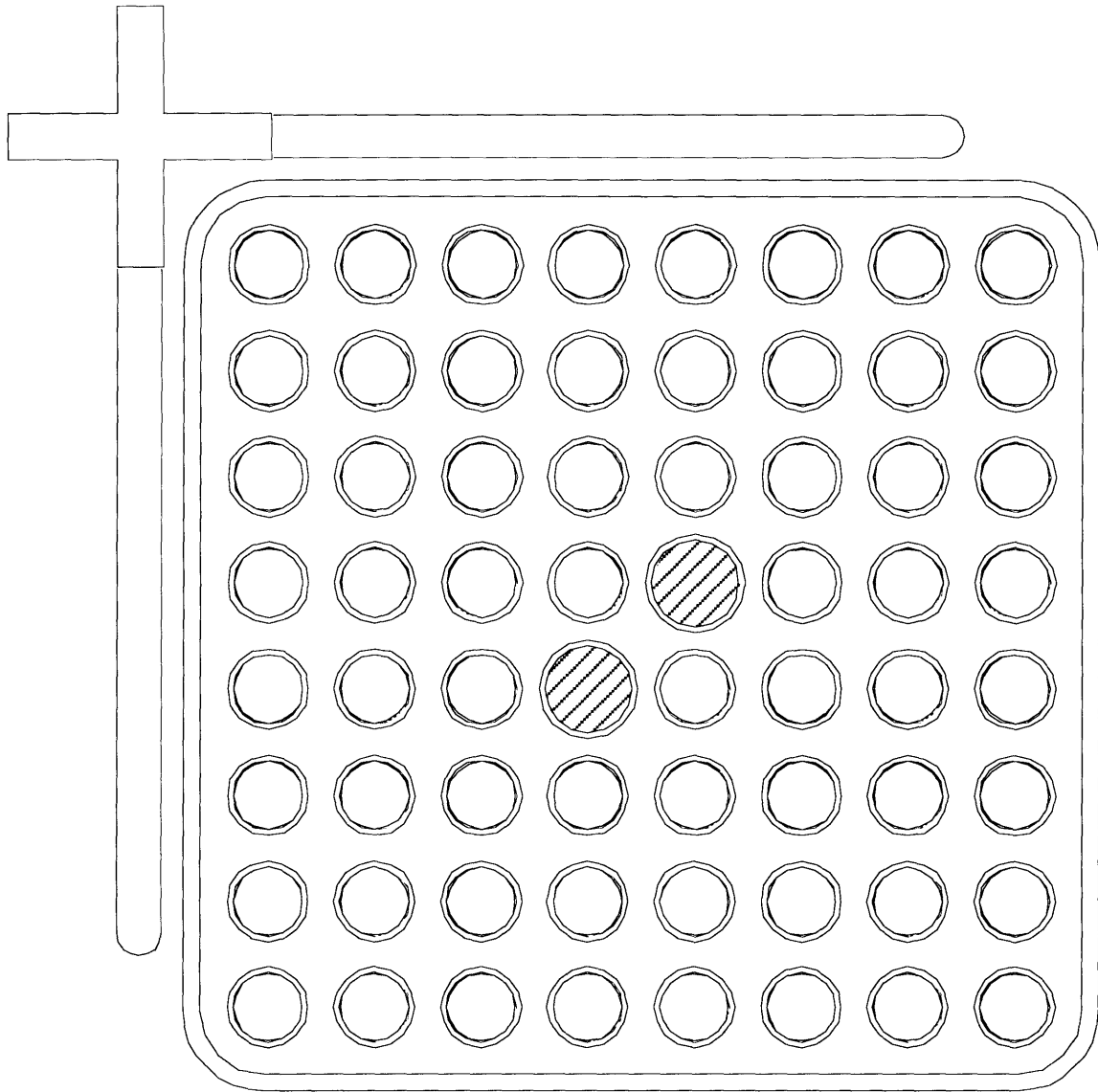
**Table 3.2: Core conditions of the GE BWR 8x8 bundle**

<b><u>Parameters</u></b>	<b><u>Values</u></b>
Fraction of power generated in the coolant	5%
Gap conductance (W/m <sup>2</sup> K)	6000
System Pressure (MPa)	7.2
Inlet Temperature (°C)	279
Core Mass Flow Rate (kg/s)	13400
Core Bypass	5%

We need to comment on some of the data in Table 3.2, and point out where assumptions have been made. In particular the constant gap conductance has been chosen for coherence with the annular fuel. The model for the dynamic gap conductance for annular fuel is still under study, so we couldn't include it for the solid fuel without creating a considerable difference between the parameters of the two designs.

The bypass has been chosen as 5% arbitrarily. We have been able to find some values between 5% and 10% in the literature as a possible range, and 5% was chosen as more likely in modern plant designs. As long as we keep the same value for both the solid and annular bundle models we don't expect much of a consequence from the choice.

We show in Figure 3.1 the typical two dimensional layout of the GE BWR 8x8 bundle.



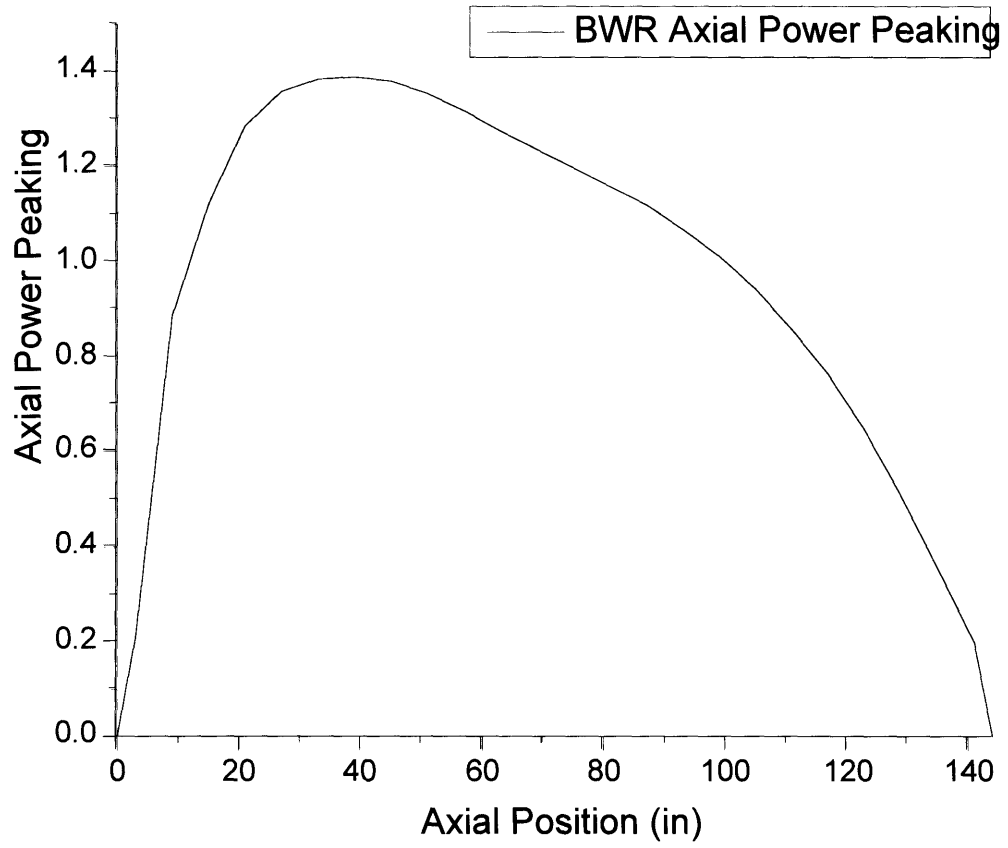
**Figure 3.1: 2D view of a typical BWR-5 8x8 bundle**

### 3.1.2 Other data

The above geometrical data are not enough to run the code. VIPRE requires many other input parameters like the radial and axial power peaking. Since we were not modeling a particular plant, and thus we could not refer to any available data, we had to reconstruct most of them.

#### Axial power peaking

As axial power peaking we have used a single profile for the bundle extracted from the VIPRE manual. The profile represents the usual lower core peaking expected in a BWR core. The peak to average axial power value is 1.39, as seen in Figure 3.2.



**Figure 3.2: Solid fuel axial power peaking**

### Radial power peaking

To obtain a representative radial power peaking, MCNP was used to model a bundle to obtain representative values. Figure 3.3 summarizes the pin peaking factors within the bundle. The actual calculation of this peaking will not be addressed in this report. The details can be found in [8].

0.994								
1.016	0.355							
1.073	0.995	0.996						
1.112	1.086	1.010	1.070					
<b>1.113</b>	1.090	1.038	0.000	1.069				
1.074	1.000	1.013	1.038	1.009	0.995			
1.016	0.356	0.999	1.089	1.084	0.993	0.355		
0.993	1.015	1.072	1.111	1.110	1.071	1.013	0.991	

**Figure 3.3: BWR-5 8x8 radial power peaking**

### Core pressure drop

We don't have access to data about the local core pressure drops such as at grids, the entrance and the exit. We extracted it from the VIPRE manual sample input as said above. The data we were able to get are summarized in Table 3.3

**Table 3.3: Local pressure drop coefficients**

<u>Location</u>	<u>Coefficient</u>
Orifice (average bundle)	24.28
Orifice (hot bundle)	23.37
Entrance plate	6.63
Grids	1.5
Exit plate	1.46

We would like to comment in particular on the orifice coefficients. The lowest inlet pressure drop coefficient reported in the sample input for was taken as the hot bundle one while the one that gives the right inlet pressure drop (see Figure 4.4) is taken as the average bundle orifice pressure drop coefficient. This last one is also the most common in the core modeled by the sample input.

### Materials

The materials that we need to define in the code for our VIPRE model are two, fuel and cladding. For the cladding we have taken the standard Zircalloy property table that has been used in the PWR case [1]. Although Zircalloy-2, the cladding material used in BWRs, differs from Zircalloy-4, the cladding material used in PWRs, the difference is very small in the properties that interest us, in particular the thermal ones. For the fuel we have used the uranium oxide properties from the same reference [1].

## 3.2 Annular fuel design

### 3.2.1 Criteria for the bundle design

The first step is to design a possible annular fuel lattice for BWR reactors to fit the same bundle side dimensions. This constraint is very important because it will assure that the annular fuel we design will have the possibility to be used even by existing BWRs. Also this constraint limits the possible lattice choices, since the annular fuel will have obviously to be of larger diameter than the solid fuel if we want to accommodate a reasonable volume of fuel in the bundle and keep a sufficiently large internal channel diameter. As for now, both the 5x5 and 6x6 lattices could be interesting for our research, while both a smaller and larger lattice would probably give either hydraulic problems (channels too small), mechanical problems (fretting) or thermal problems (surface area too small).

There are two fundamental parameters to be decided, and they will identify unambiguously the fuel design:

- The ratio between the internal diameter of the annular fuel pin and the hydraulic diameter of the solid fuel bundle internal channels.
- The ratio between the total fuel volume in the solid and the annular bundle.

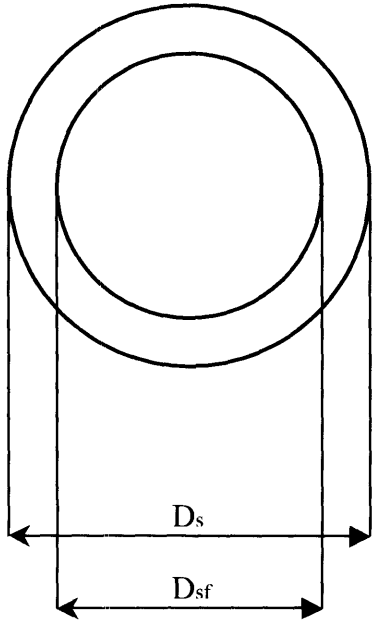
After some checks on the possible configurations we decided to accept to have only 90% of the fuel present in the reference in our annular fuel bundle. This will allow better thermal hydraulic performance of the core and eliminate a degree of freedom of the design at the expense of the neutronics of the design. Also it is the same choice made in the PWR case [1].

The following dimensions were taken to be the same for the annular and solid fuel bundles:

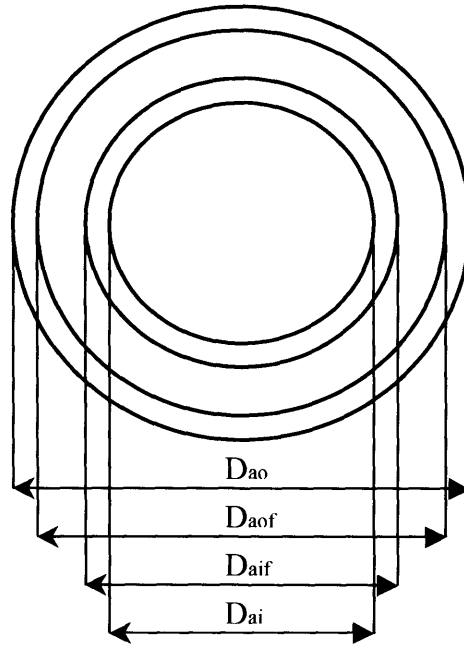
- We will keep the assembly side length equal to that of the solid for retrofittability,
- Clad thickness the same as the reference solid fuel pin,
- Internal clad thickness the same as the external clad thickness,
- Gap dimension and conductance the same as solid,
- Internal gap the same as external gap,
- Water rod modeled as if it was composed only by the external clad of a fuel rod and with the same thickness,
- Water rod outer diameter the same as the fuel rod,

These assumptions and constraints are all based on thermal hydraulic, neutronic and vibrational considerations. In addition to these we need another constraint to get a unique solution given the above parameters. We chose to keep constant (at the same value as in the solid bundle) the ratio between the gap between rods and the gap between a corner rod and the bundle wall ( $\frac{g_{rod-rod}}{g_{rod-wall}}$ ), this allows us to keep a reasonable ratio between the hydraulic diameters in various parts of the bundle.

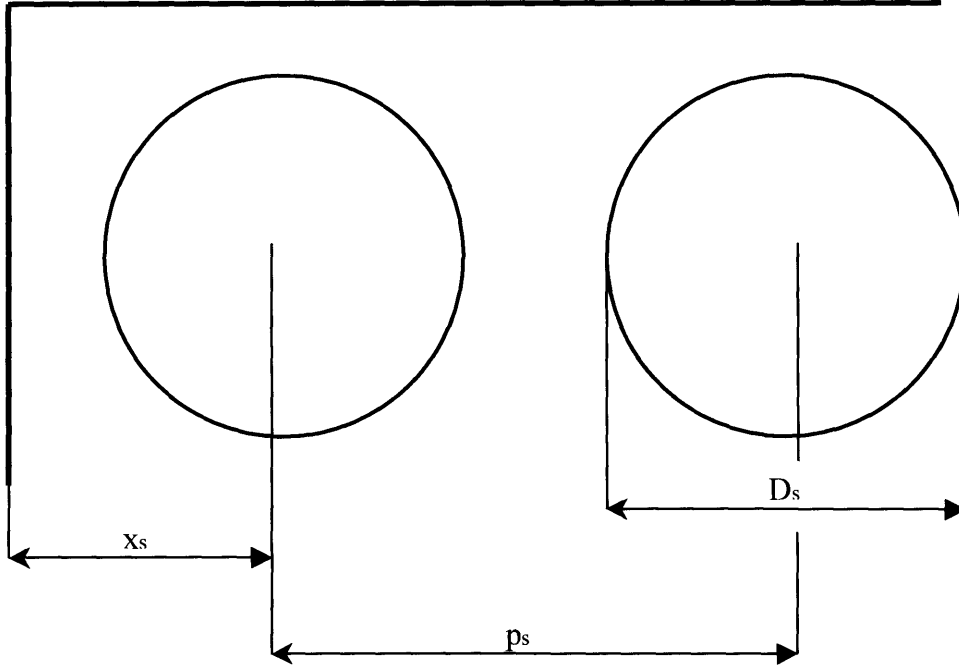
Below we show a section of a solid (Figure 3.5) and an annular rod (Figure 3.4) and introduce the typical dimensions (Figures 3.6 and 3.7). The figures are not to scale.



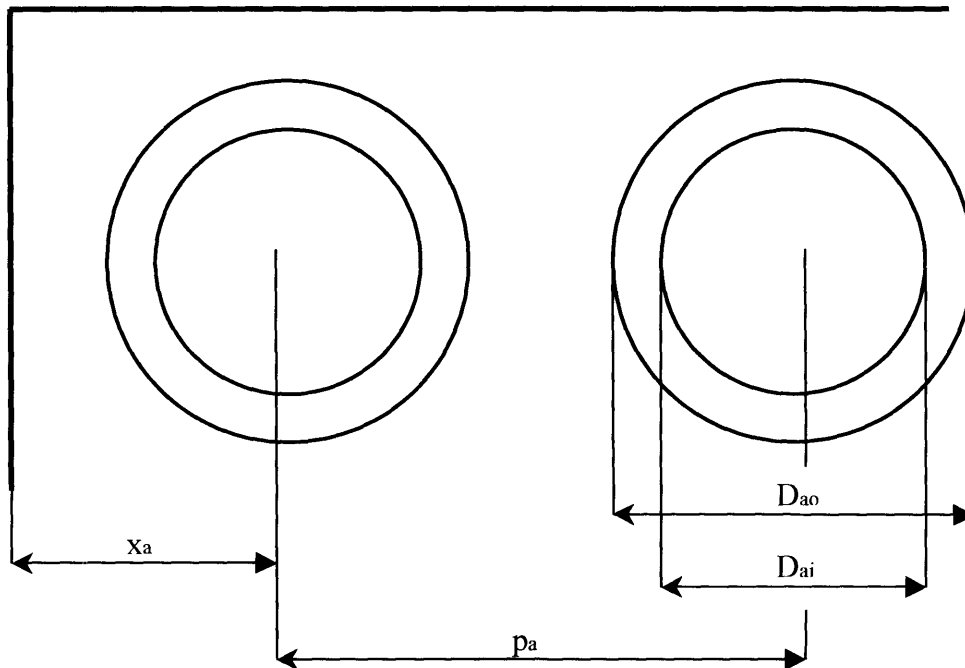
**Figure 3.4: Solid fuel rod section**



**Figure 3.5: Annular fuel rod section**



**Figure 3.6: Solid fuel rods layout in respect to the bundle wall**



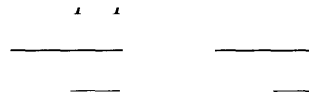
**Figure 3.7: Annular fuel rods layout in respect to the bundle wall**

The procedure followed to design the annular fuel bundle is:

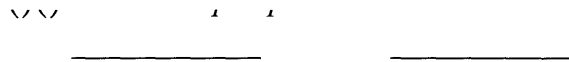
1. Choose the internal diameter of a pin  
This is done indirectly choosing the ratio between the internal diameter of the annular fuel and the hydraulic diameter of the solid fuel
2. Calculate the external diameter of the annular fuel pin knowing the ratio between the total fuel in the solid and the annular bundles

where  $N_a$  is the number of pins in the annular assembly (24 or 34) and  $N_s$  the number of pins in a solid assembly (62). The suffix 'f' added to the geometrical parameters means that they are referred to the actual fuel within the pin.

3. Calculate the pitch of the annular fuel pins assuming that the ratio of the distance between the corner rod and the bundle wall and between the internal rods is the same both for the annular and the solid fuel bundle:



where



The above assumption basically tries to keep the flow as similar as possible in the two designs.

With all the above assumptions, data and calculations the bundle is uniquely defined.

Also for the design to be accepted, it has to respect the following parameters:

1. The ratio between the internal diameter of the annular fuel and the hydraulic diameter of the solid fuel must be reasonable (between 0.7 and 1.1)
2. The distance of the corner rods from the wall and the distance between rods must be at least 1 mm
3. The moderator to fuel ratio of the annular fuel bundle must be close to the one of the solid fuel bundle (within 10%)

Every design that passes all the checks is considered viable and can be tested for the maximum power upgrade achievable.

## 3.2.2 Geometric data

We have explored many designs in the above illustrated parameters space. Here we will show only the ones that we considered more promising. The designs were chosen ultimately for their CPR performance but we had to take into consideration even the flow quality imbalance between the channels and other thermal hydraulic considerations. Also, we had to discard the designs for which the VIPRE code didn't converge for a reasonable number of axial nodes, since in that case we felt that we couldn't trust the code's CPR calculations.

### 3.2.2.1 The 5x5 bundle

On Tables 3.4 and 3.5 we show a comparative list of the important geometrical characteristics of the most promising designs.

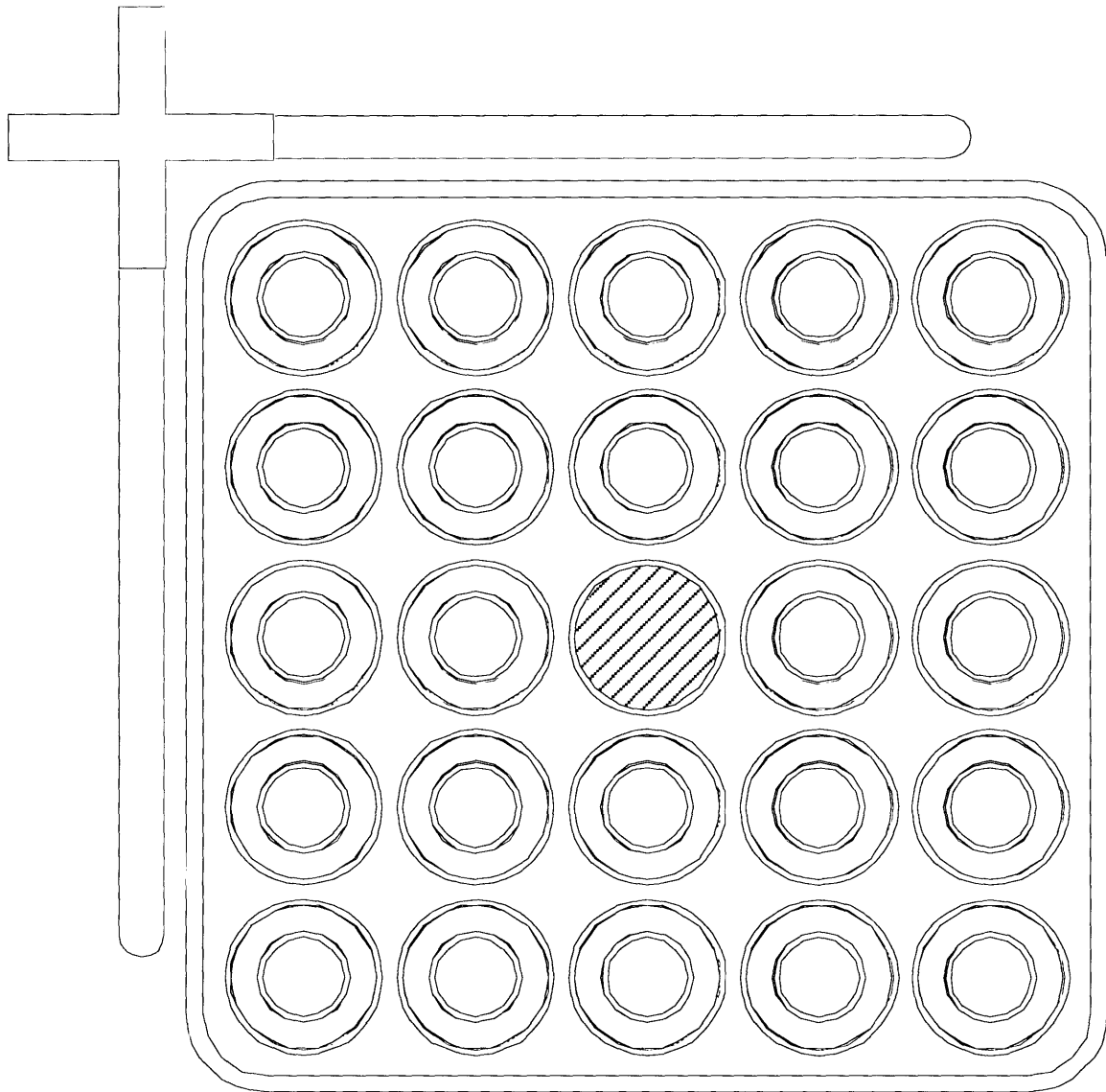
**Table 3.4: Annular fuel 5x5 possible designs**

Design	Internal Diameter (solid hydraulic diameter=100%)	Fuel volume (solid=100%)	Bundle lattice
Annular 1	100%	90%	5x5
<b>Annular 2</b>	90%	90%	5x5
Annular 3	85%	90%	5x5
Annular 4	80%	90%	5x5

**Table 3.5: Geometrical parameters of the Annular fuel 5x5 possible designs**

	GE BWR/5	Annular 1	<b>Annular 2</b>	Annular 3	Annular 4
Bundle lattice	8x8	5x5	5x5	5x5	5x5
Number of fuel rods	62	24	24	24	24
Number of Water rods	2	1	1	1	1
Clad thickness (cm)	0.085				
Gap (cm)	0.01				
Inner distance between box walls (cm)	13.4				
Pellet OD (cm)	1.04	2.308	2.202	2.151	2.102
Pellet ID (cm)	-	1.677	1.528	1.454	1.379
Fuel Rod OD (cm)	1.23	2.498	2.392	2.341	2.292
Fuel Rod ID (cm)	-	1.487	1.338	1.264	1.189
Water Rod OD (cm)	1.50	2.498	2.392	2.341	2.292
Water Rod ID (cm)	1.32	2.318	2.212	2.161	2.112
Corner Hydraulic Diameter (cm)	1.010	0.632	0.811	0.897	0.980
Border Hydraulic Diameter (cm)	1.210	0.775	0.972	1.068	1.163
External Hydraulic Diameter (cm)	1.487	1.072	1.281	1.385	1.489
Internal Hydraulic Diameter (cm)	-	1.487	1.338	1.264	1.189

These are the most promising 5x5 designs. Annular 1 was discarded because it showed a large imbalance of flow qualities between the internal and external channels and in addition is slightly out of range of the tolerance we fixed for the fuel/moderator ratio. We discarded Annular 4 due to poor code convergence for this design. We chose the Annular 2 design due to better CPR performance compared to the Annular 3 design. From now on we will consider Annular 2 as the reference 5x5 annular bundle, and we show in Figure 3.8 below a possible 2D section of the bundle.



**Figure 3.8: 2D view of the annular fuel 5x5 bundle**

### 3.2.2.2 The 6x6 bundle

For the 6x6 bundle case there is less freedom in the design, since this design presents a more tightly packed bundle. This is due to the fact that we have now to fit 44% more rods than the 5x5 design in the same area, in order to keep the important feature of being able to use this fuel in existing BWR plants.

As described before in Section 3.2.1 we have many constraints in the design, so we cannot vary the internal diameter too much without either losing a good moderator to fuel ratio or placing the rods too close and thus risking vibration problems. As a consequence there is a smaller range of designs that respect all the constraints than the 5x5 bundle. Two designs have been chosen with parameters described in Tables 3.6 and 3.7 and Figure 3.9 shows a possible 2D section of the 6x6 bundle.

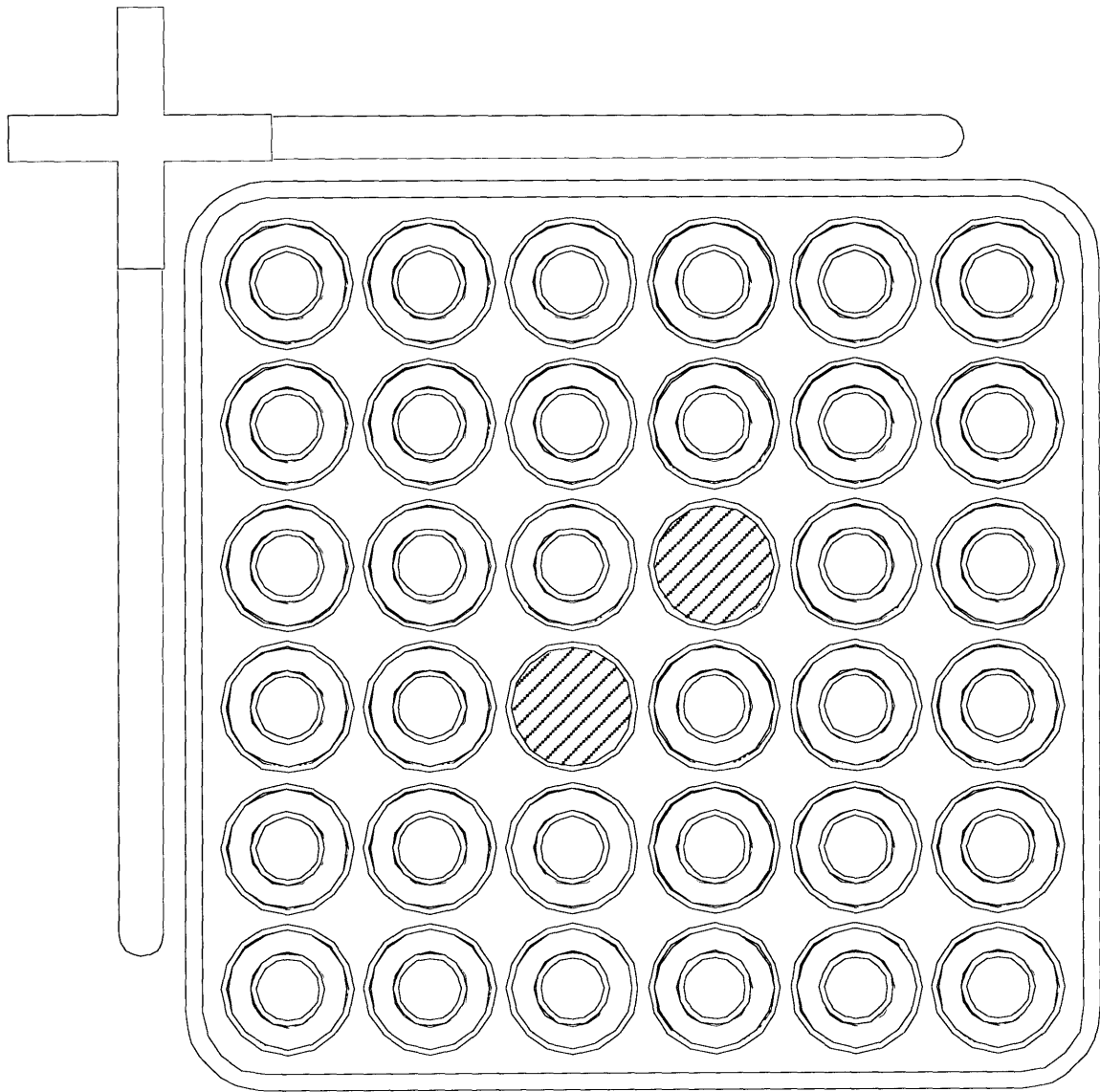
The Annular 5 design actually gives better thermal hydraulic characteristics and more open channels over the other candidate (Annular 6). Additionally it achieves a slightly better pressure drop for the same reason, and thus it is our selected design.

**Table 3.6: Annular fuel 6x6 possible designs**

Design	Internal Diameter (solid hydraulic diameter=100%)	Fuel volume (solid=100%)	Bundle lattice
<b>Annular 5</b>	80%	90%	6x6
Annular 6	75%	90%	6x6

**Table 3.7: Geometrical parameters of the Annular fuel 6x6 possible designs**

	GE BWR/5	<b>Annular 5</b>	Annular 6
Bundle lattice	8x8	6x6	6x6
Number of fuel rods	62	36	36
Number of Water rods	2	2	2
Clad thickness (cm)	0.085		
Gap (cm)	0.01		
Inner distance between box walls (cm)	13.4		
Pellet OD (cm)	1.04	1.918	1.865
Pellet ID (cm)	-	1.379	1.305
Fuel Rod OD (cm)	1.23	2.108	2.055
Fuel Rod ID (cm)	-	1.189	1.115
Water Rod OD (cm)	1.50	2.108	2.055
Water Rod ID (cm)	1.32	1.928	1.875
Spacing rod-rod (cm)	0.390	0.106	0.150
Spacing rod-bundle wall (cm)	0.415	0.112	0.160
Lattice pin pitch (cm)	1.62	2.213	2.205
Corner Hydraulic Diameter (cm)	1.010	0.490	0.582
Border Hydraulic Diameter (cm)	1.210	0.606	0.706
External Hydraulic Diameter (cm)	1.487	0.852	0.958
Internal Hydraulic Diameter (cm)	-	1.189	1.115



**Figure 3.9: 2D view of the annular fuel 6x6 bundle**

### 3.2.3 Other data

#### Axial power peaking

We have chosen to use the same axial power profile as the solid fuel case.

#### Radial power peaking

For this case the data were obtained from a MCNP model since there are no experimental data available for annular fuel. The actual calculation of this peaking will not be addressed in this report, but can be found in [8]. The radial power peaking used is shown in Figure 3.10 for the 5x5 bundle and in Figure 3.11 for the 6x6 bundle.

1.030				
<b>1.217</b>	0.369			
1.140	1.031	0.000		
1.216	0.369	1.031	0.369	
1.029	1.215	1.139	1.215	1.028

**Figure 3.10: Radial power peaking for the 5x5 annular fuel bundle**

1.102						
1.085	0.377					
1.099	1.016	<b>1.129</b>				
1.103	1.068	0.000	<b>1.129</b>			
1.088	0.381	1.067	1.016	0.377		
1.102	1.087	1.102	1.097	1.083	1.098	

**Figure 3.11: Radial power peaking for the 6x6 annular fuel bundle**

### Core pressure drop

We investigated the pressure drop for annular fuel. From preliminary calculations we have seen that for most designs the limiting factor is the quality imbalance between the inner and outer channels, due to the fact that those do not communicate. We can force more flow into the internal channel, and thus address this problem, in two ways: by enlarging the internal channel diameter (and thus changing design) or by increasing the grid pressure drop.

The technique we adopted consists of exploring all the parameters space. For a specific design (and thus an internal channel diameter), we progressively increased the grid pressure drop to force more flow in the internal channel. This allowed us to maximize the CPR for each design considered at the expense of the core pressure drop.

## Materials

To allow a more precise comparison between annular and solid fuel bundles, the material properties of both the cladding and the fuel itself were kept the same as in the reference design.

### 3.3 Differences between the 5x5 and the 6x6 design

The 5x5 bundle allows more freedom in choosing the geometrical parameters due to the fact that we can fit 25 rods in the bundle in more ways than we can fit 36. This leads to larger hydraulic diameters and lower pressure drops. On the other side this 5x5 design does not increase much the heat transfer surface and has other constraints from the neutronic point of view, since we can adjust the burnable poison in very few rods.

A comparison between some geometrical parameters of the best 5x5 and 6x6 designs chosen for future analysis is given in Table 3.8 below:

**Table 3.8: Comparison between the 5x5 and the 6x6 annular designs**

	GE BWR/5	Annular 5x5	Annular 6x6
Fuel to Moderator volumetric ratio (normalized)	1.000	0.889	0.955
Fuel Volume (normalized)	1.00	0.900	0.900
Moderator Volume (normalized)	1.00	1.012	0.942
Cladding Volume (normalized)	1.00	1.269	1.606
Heated surface/fuel volume (normalized)	1.00	1.304	1.633

We want to underline the fact that the moderator volume is proportional to the flow area, thus the normalized flow area would give the same result as the normalized moderator volume.

As we can see the 6x6 annular fuel bundle shows a remarkably higher heated surface than the 5x5 design. Thus it is more promising for the goal of this work, the power uprate of

BWR nuclear power plants. Also it shows a closer moderator to fuel ratio to the reference and thus it has potentially better neutronics, or at least closer to the solid fuel's. We see that we pay for those improvements with the higher amount of cladding in the fuel and higher pressure drop (in the 6x6 case) due to the smaller flow area and larger surface area, as given in Table 4.2 in the next chapter.

# Chapter 4: Results and Analysis

## 4.1 Validation of the model

First of all we want to validate the method we used by showing agreement of the reference data in literature with our solid fuel model. As discussed in Chapter 2 we will compare our single bundle output obtained using the VIPRE code with the data available in the open literature for BWR cores.

It is difficult to base our model on BWR fuel operating and limiting thermal conditions in a particular plant, both because the data is proprietary and because of the variability of the BWR cores built. So, we will use as reference typical range of values. Most of the reference data we select is obtained from reference [9].

### 4.1.1 Void fraction

Axial distributions of quality and void fraction for a typical BWR [6] are shown in Figure 4.1

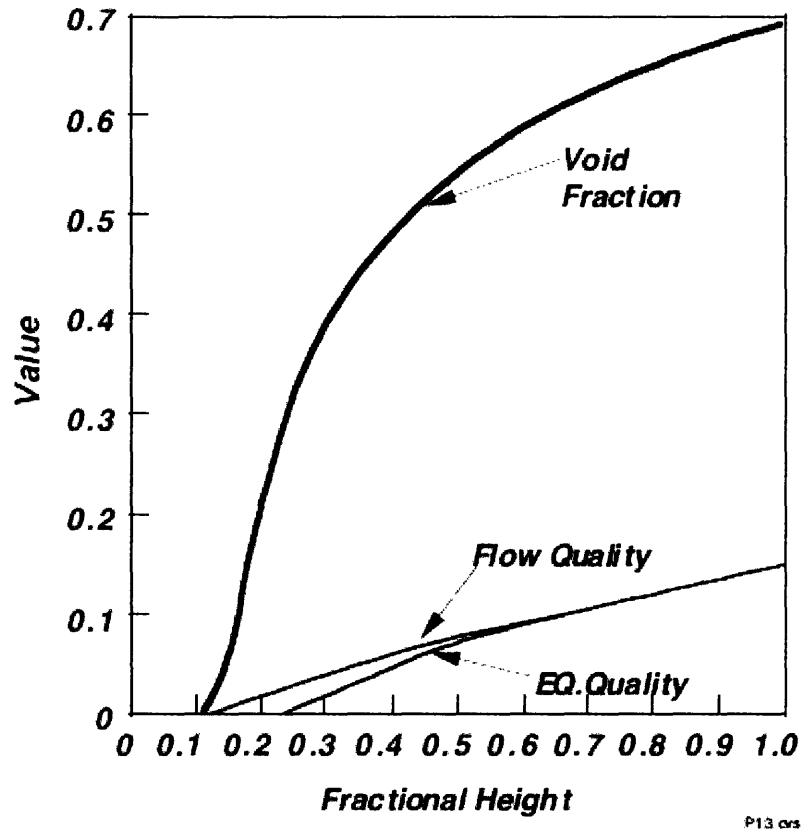


Figure 4.1: Void fraction and quality in a typical BWR [9]

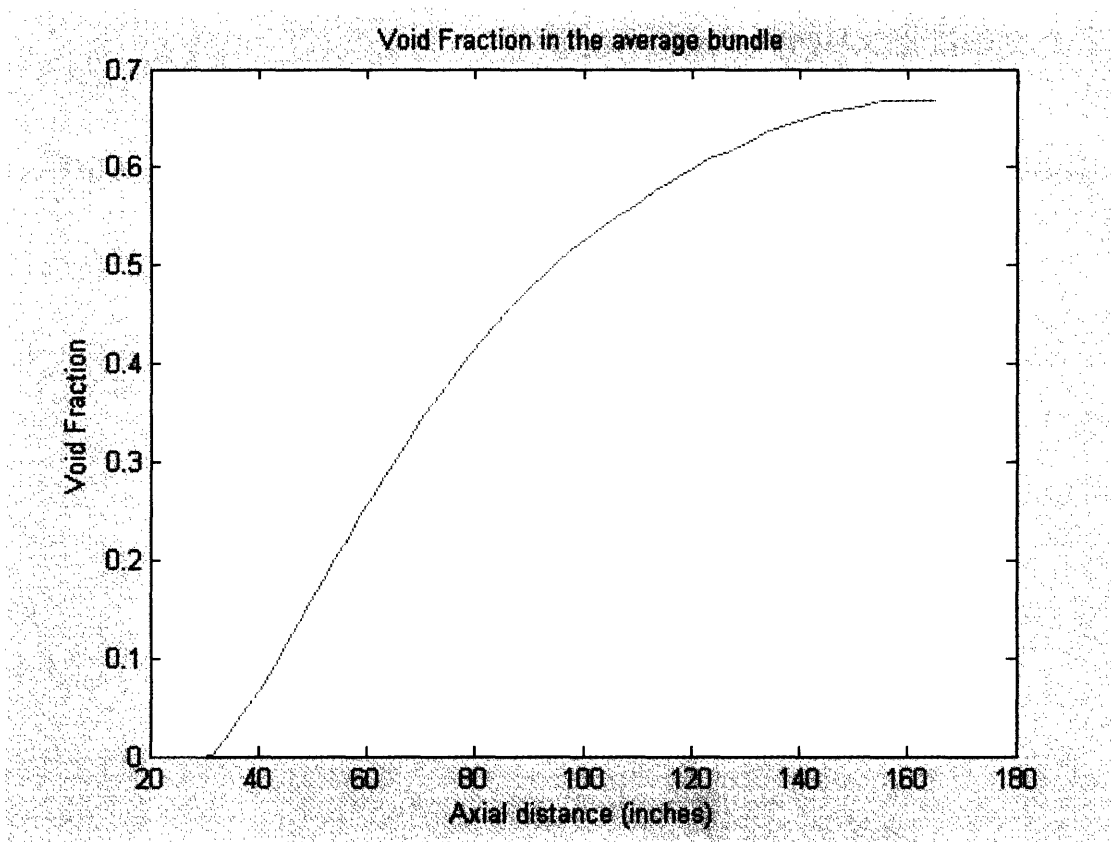


Figure 4.2: Void fraction in the solid fuel model

The results calculated with our model for the solid fuel are shown in Figures 4.2 and 4.3. As we can see in Figure 4.2 the plane averaged exit void fraction for the average bundle of the solid fuel calculated by VIPRE is 67%, which agrees very well with the reference value for the whole core 70%. Also the calculated axial average is 38.66% again for the average bundle while the reference core average is 40%. As a reminder, the heated section in the channel extends from position 13.5 inches to 157.5 inches.

## 4.1.2 Quality

We can see in Figure 4.3 below the equilibrium quality calculated with our solid fuel model

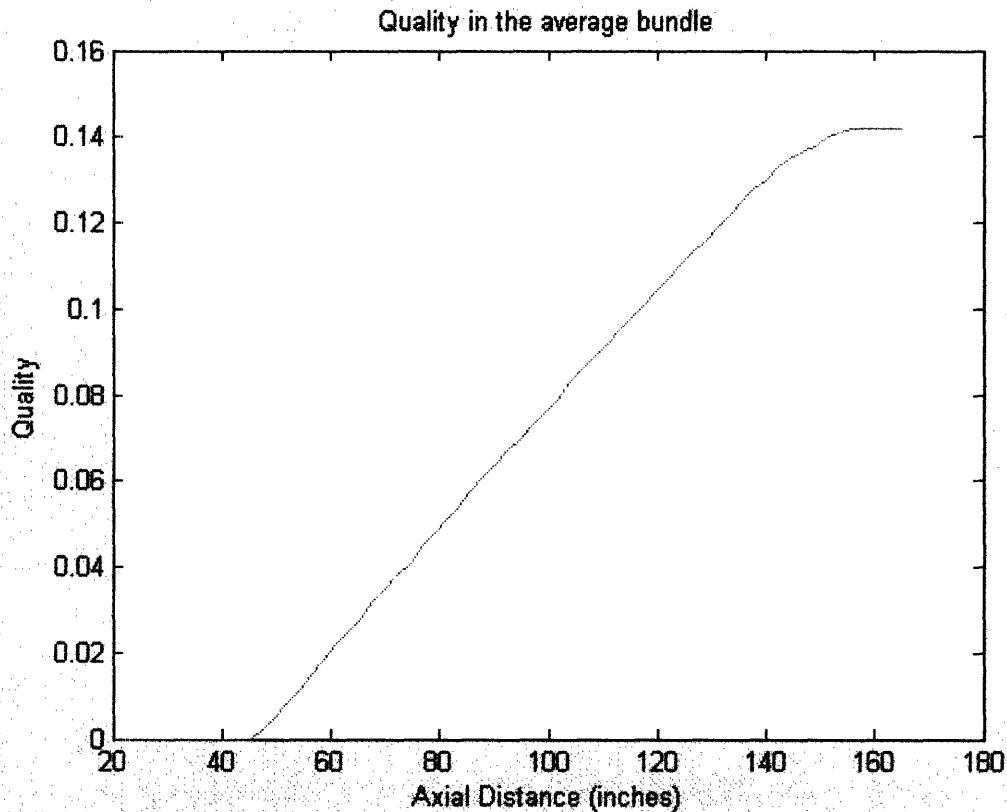


Figure 4.3: Equilibrium quality in the solid fuel model

From Figure 4.3, the plane averaged exit quality for the average bundle of the solid fuel calculated by VIPRE is 14.2%, again a value that agrees very well with the whole core average of 15% given by the reference.

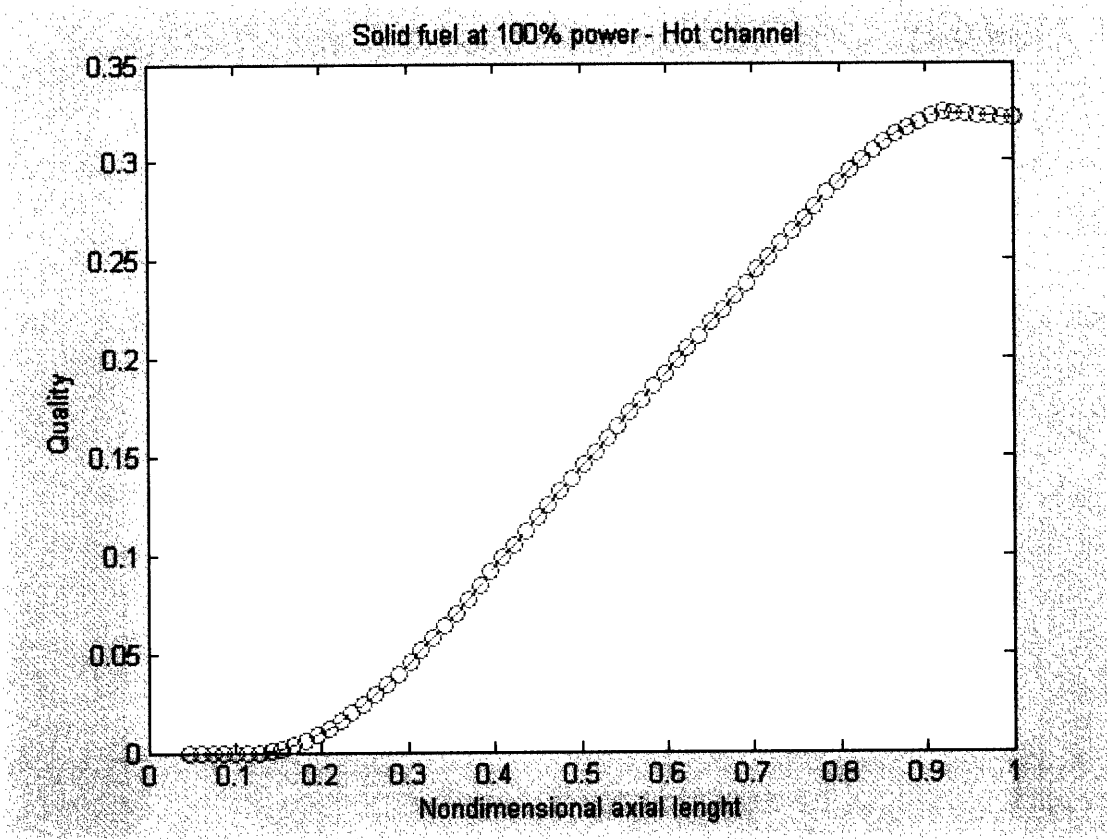


Figure 4.4: Quality in the hot channel of the solid fuel model

Figure 4.4 shows the axial quality profile of the hottest channel in the core. We can see that the exit quality reaches 32%, about double that of the average. The hottest channel in this case is the side channel adjacent to the hot rod (see Figure 3.3). Since in our model the corner and side channels are smaller than the internal channels, those are the most likely to reach the highest quality. So, if the hot rod is also in contact with a corner or border channel this will probably become the hottest, like what happened in this case.

Also for the way VIPRE models the bundle we could have shown four channels around the hot rod. Here we have decided to show only the one that reaches the highest exit quality. The other channels in contact with the hot rod reach exit quality level 7% (relative value) lower at the most and thus are very close to the channel shown.

### 4.1.3 Pressure drop

We now compare the pressure drop shown in Figure 4.4 for a typical BWR [9] with the calculated pressure drop in the average bundle shown in Figure 4.5

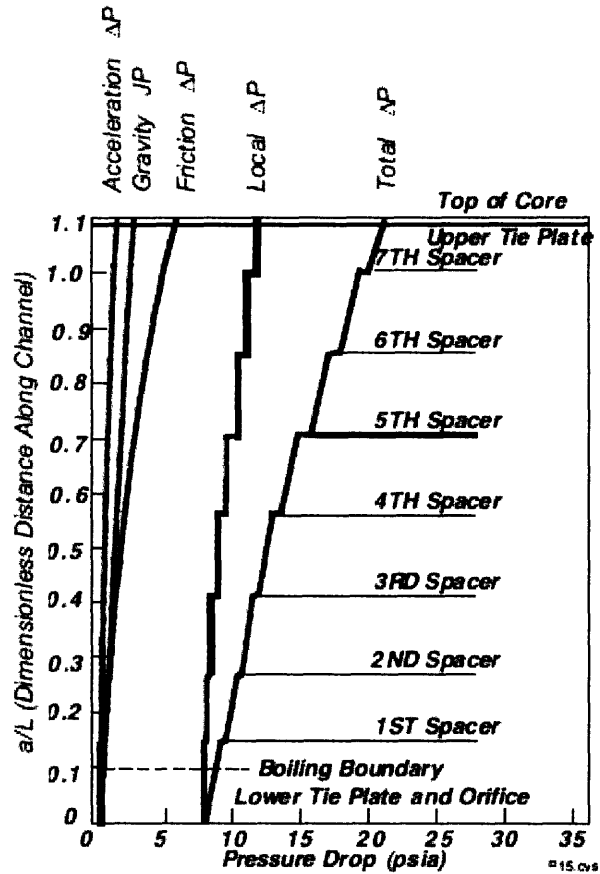
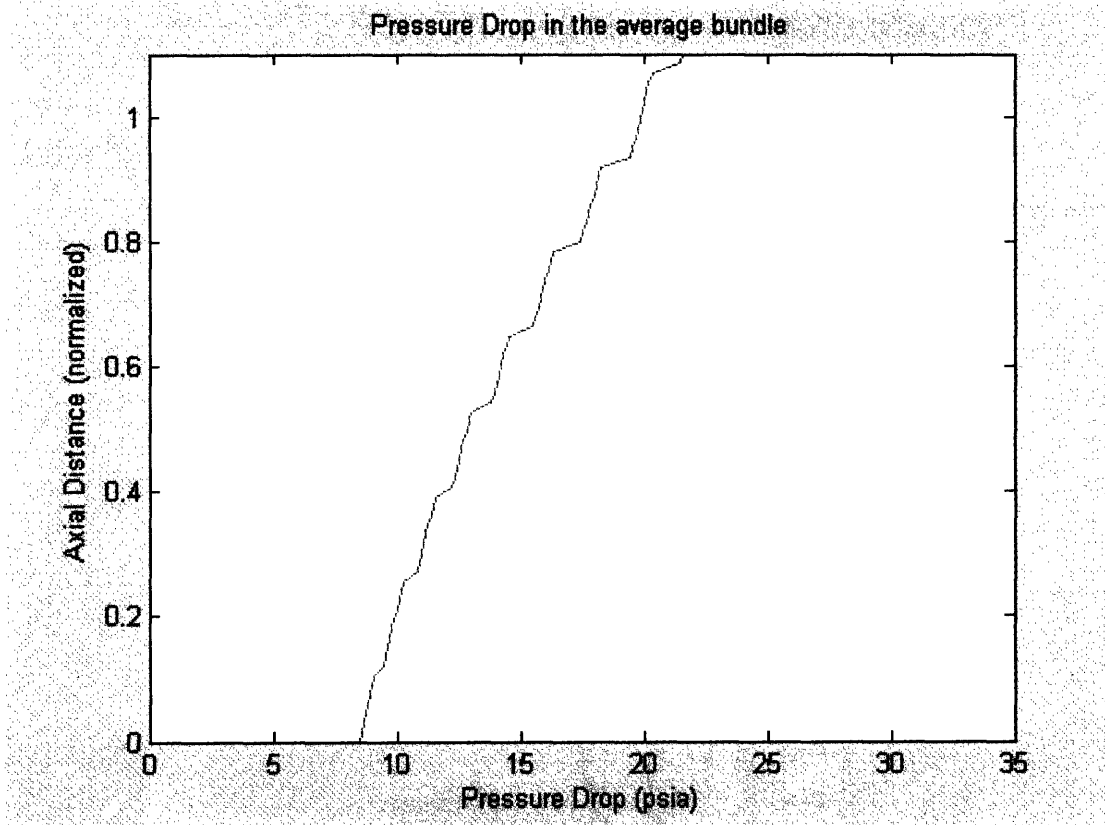


Figure 4.5: Pressure drop in a typical BWR [9]



**Figure 4.6: Pressure drop in the solid fuel model**

Again we can see the good agreement between the data. Our calculated core pressure drop is 21.6 psia, about the same value given in reference [9].

## 4.1.4 MCPR

Reference [9] shows an indicative table for the Minimum Critical Power Ratio (MCPR) in BWR reactors. This is a key parameter since we intend to compare the performance of our annular fuel to the solid fuel on the basis of this quantity. Also this parameter is closely related to the safety of the reactor since if  $MCPR < 1$  then by definition we will encounter a thermal crisis (dryout) somewhere in the reactor with subsequent damage of the fuel and possible release of radioactive material in the primary loop, as discussed in Chapter 2. This is especially undesirable in BWR reactors since part of the coolant goes directly in the turbine and thus is present even outside the containment.

It is not enough to keep the MCPR just above one, since we have to allow a margin for uncertainties, transients and operation.

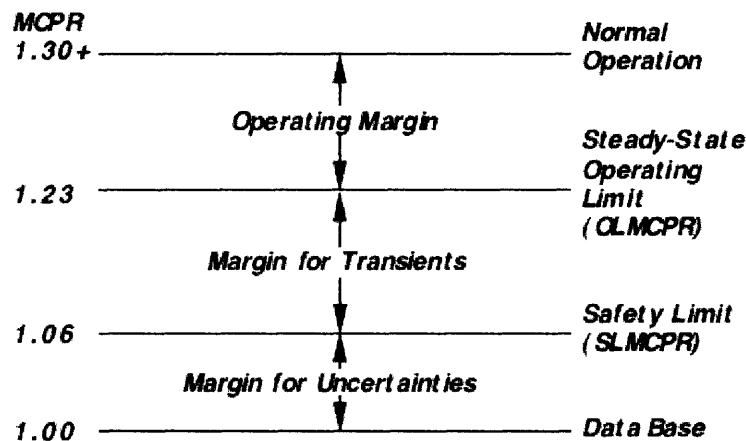


Figure 4.7: MCPR in a typical BWR reactor

As we can see from Figure 4.7 the MCPR must be 1.30+. There are studies about the possibility to operate with lower MCPR, between 1.2 and 1.26, but we are working with old data and our determination of the CPR is a best-estimate, since we didn't introduce any conservatism, so we shall take 1.3 as our lower bound.

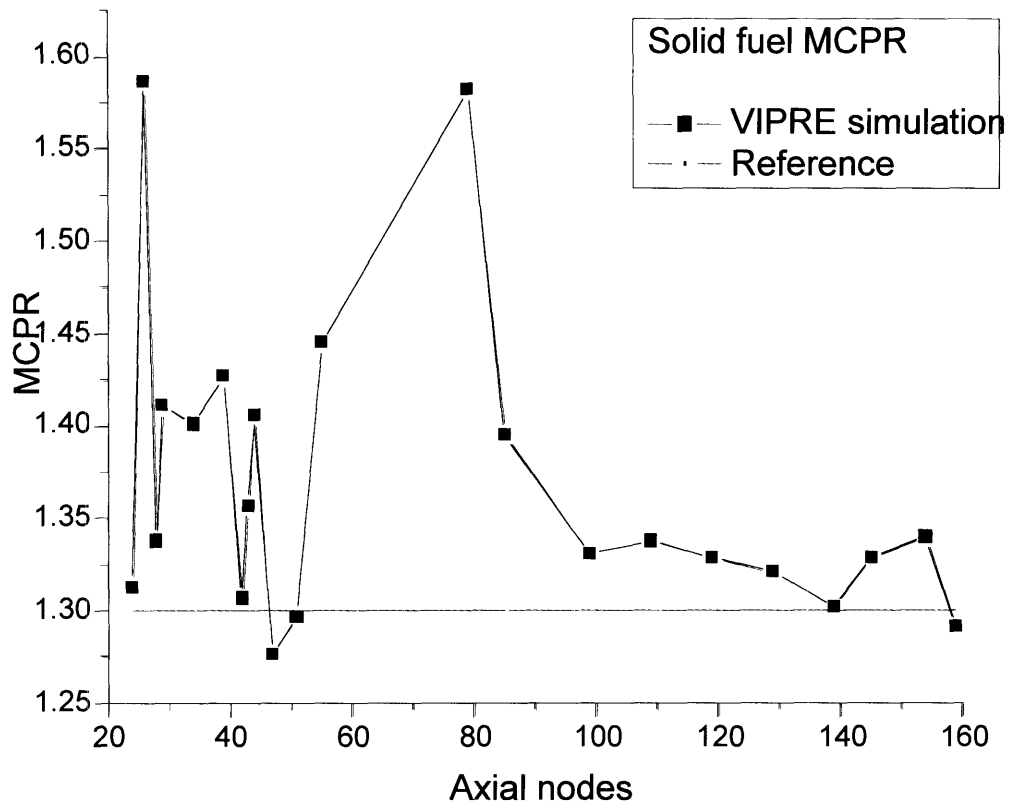
It is more demanding to validate our results for the MCPR since they show a dependence on the number of axial nodes used to model the bundle.

VIPRE is a computer code and thus it relies on its ability to compute the solution of the original system of differential equation that describes the physical reality by discretizing it. The differential equations are transformed in finite differences so that they can be solved using the high computational power of the computer. This discretization applies to all variables but is especially evident for the spatial ones (and time, in transients). To be able to use the discrete model, the code has to divide space in meshes and it concentrates the variables that apply to a mesh in its center, the node (usually).

VIPRE allows the user to choose the number of axial nodes to model his system. Usually using a very low number of axial nodes is not recommended since a coarse mesh means smearing over variation within each node and more errors in the solution of the system, because the code would lump too many different zones together. Also a very fine mesh is usually not a good idea since it increases the computational time and memory needs. Furthermore, it eventually will arrive to a point where other errors will become more important than the ones related to discretization and thus the result will not be improved any more by refining the mesh. Also, there may be internal limits depending on the code in use.

So, there is usually a window of mesh sizes that should be used and if the code is reliable the results obtained for all these possible values should be consistent in the sense that there should be a steady refining of the result toward the 'true value'. By the nature of the discretization process we understand that the finer the mesh the closer we should be to the 'true value', provided that the limits of the code have not been exceeded or other errors become more important.

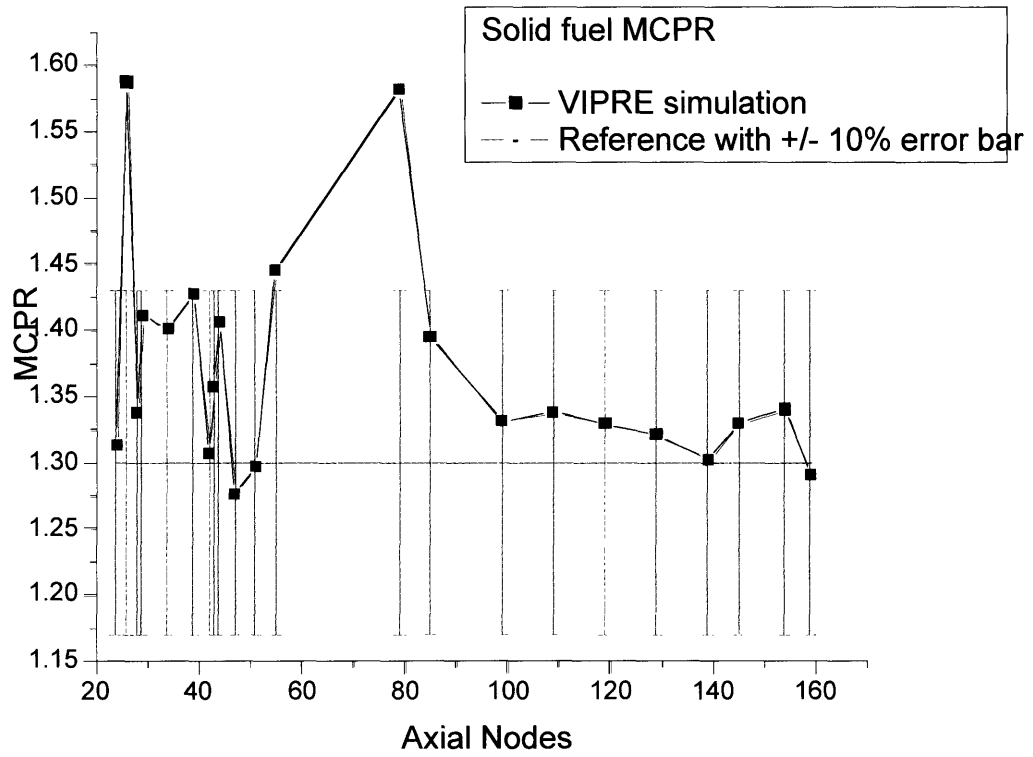
As seen in Figure 4.8, we get a reasonably good convergence toward a value as we increase the number of axial nodes, but we didn't achieve convergence for all the possible numbers of axial nodes in our 'mesh window'.



**Figure 4.8: MCPR in the solid fuel model**

Even if we didn't achieve convergence for all the possible values of axial nodes, it is already evident that the MCPR is converging toward a definite value, around 1.3.

We can easily show that by plotting a 10% error band (see Figure 4.9):



**Figure 4.9: MCPR comparison with reference (10% error bar)**

Also, if we look only to the higher number of axial nodes, we can see from Figure 4.10 that all the results are inside a 5% error from the suggested value of 1.3, thus strengthening our belief that the code is actually converging to that.

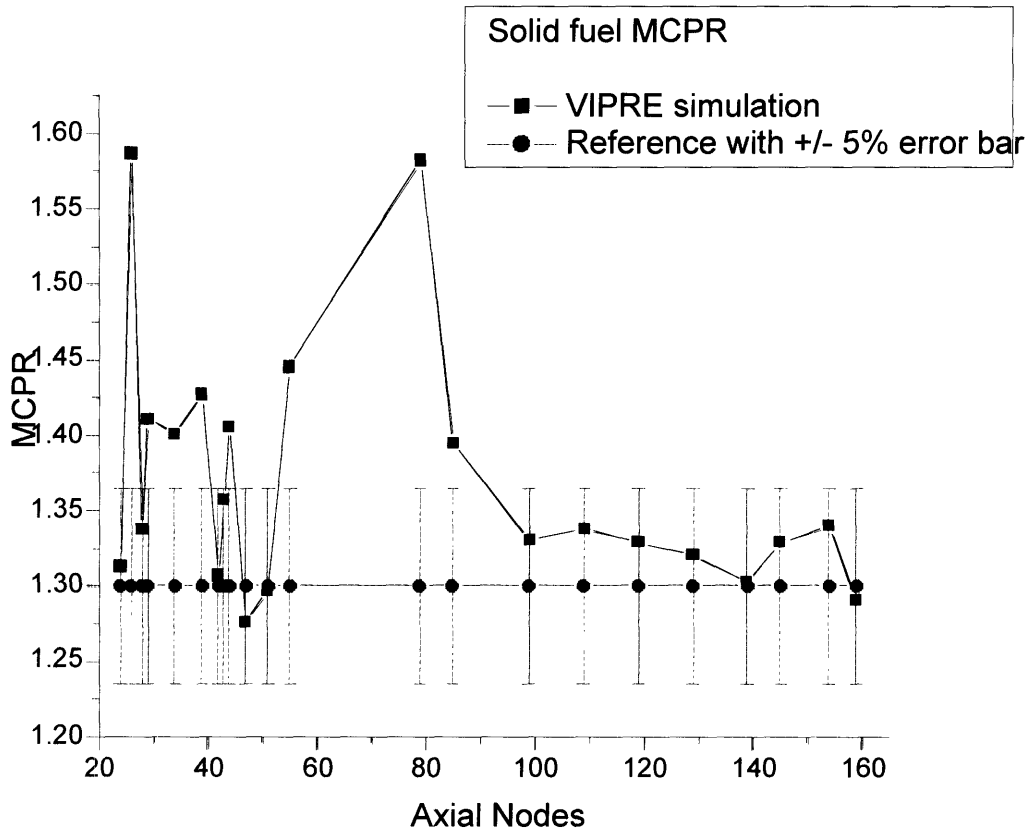


Figure 4.10: MCPR comparison with reference (5% error bar)

The results we show look reasonable, since the oscillation for the smaller number of axial nodes shows that the calculation with a coarse mesh is not precise enough. With a finer mesh we get values that are very close to each other and definitively inside the error band we would expect from the correlation. We also achieved relative convergence on almost all values of axial nodes in the range considered, but the reason of not achieving absolute convergence for all values must be studied more; we look into this in Appendix A.

We stopped at 160 axial nodes for computational time reasons and because we think that in a system like ours it is meaningless to use even a higher number, not for an internal limit of the code.

## 4.2 Data presentation

We will first evaluate the thermal hydraulic conditions of the new design and compare them to the solid fuel reference. Then we will calculate the MCPR for each design and compare it to the solid fuel MCPR to check if there is any margin. We will then try to trade that margin for a power density increase, as described in Chapter 2, by raising proportionally flow and power of the annular fuel bundle until its MCPR matches the one calculated in Section 4.1.4 for the solid fuel reference.

### 4.2.1 Annular 5x5

As discussed in Chapter 3, the design chosen was Annular 2 in Table 3.5.

#### 4.2.1.1 Thermal hydraulic parameters

As we can see from Table 4.1, the values obtained for the new design at the 100% power level match very well both the reference values and the values obtained by our model for the solid fuel at 100% power. About the quality and void fraction, these are bundle average quantities and since the power and the flow are the same for all designs, this is not a surprising result but underlines that the model is behaving correctly.

**Table 4.1: Thermal hydraulic comparison for the 5x5 annular fuel design**

(all at 100% power)	Solid Fuel	5x5 annular fuel	Reference
Exit Quality	14.2%	14.5%	~15%
Exit Void Fraction	67%	65.6%	~70%
Average Void Fraction	38.66%	37.67%	~40%
Pressure Drop	21.6 psia	20.2 psia	~21 psia

In Table 4.2 we show the maximum and average temperature for the hottest section of the hot rod both for the annular and solid fuel. These data illustrate one of the most important advantages of the annular fuel: its temperatures are considerably lower than the solid fuel's due to the fact that it is cooled on both sides and thus the heat flux is split between the two. Also in the same table we show the relative mass flux in the hot channel for the two designs. The value for the external channel of the 5x5 design is considerably smaller than the one for the internal because the hottest channel is in this case a border channel (on the side of the bundle) and thus it has smaller hydraulic diameter than an interior channel.

**Table 4.2: Thermal hydraulic comparison for the worse conditions (5x5 annular fuel)**

(Hot Rod)	Solid Fuel	5x5 annular fuel	
		External	Internal
Power Density	100%	116%	
Mass flow rate	100%	116%	
Mass flux	100%	111%	152%
Pressure Drop	100%	120.8%	
Maximum fuel Temperature (hot rod)	1608.61 C	774.39 C	
Average fuel Temperature (hot rod)	1043.26 C	540.98 C	

We also show the quality profile along the hot rod at 100% power (Figure 4.11) and at 116% power (Figure 4.12). As can be seen, they are very similar, because we are raising the flow and the power by the same ratio. The imbalance among the internal and external channel is not too large, and the highest quality is reached in the internal channel. This happens because the 5x5 design is a very open one and the external channels have the advantage to be able to mix flows among each other. The hottest channel of the hot bundle (the internal channel of the hot rod in this case) reaches about the same exit quality as the solid fuel. As in the solid fuel case we have plotted only the worst of the four external channels around the rod, since the others reach an exit quality very close to it.

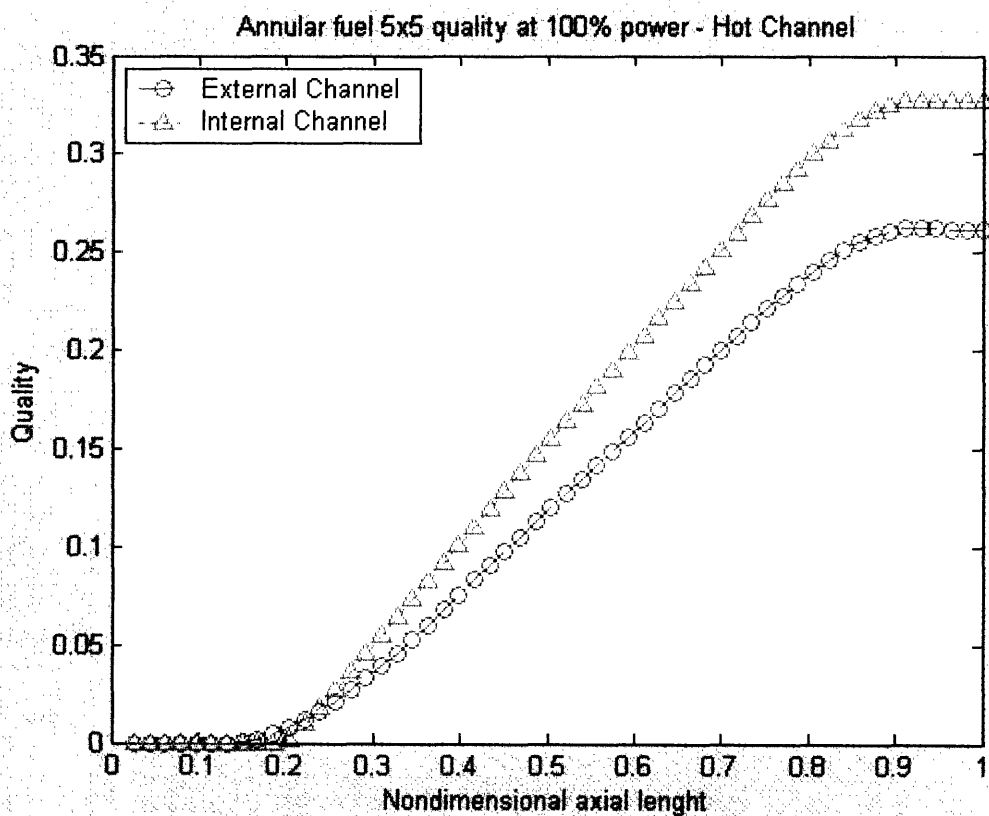


Figure 4.11: Hot channel quality axial profile for annular 5x5 design at 100% power

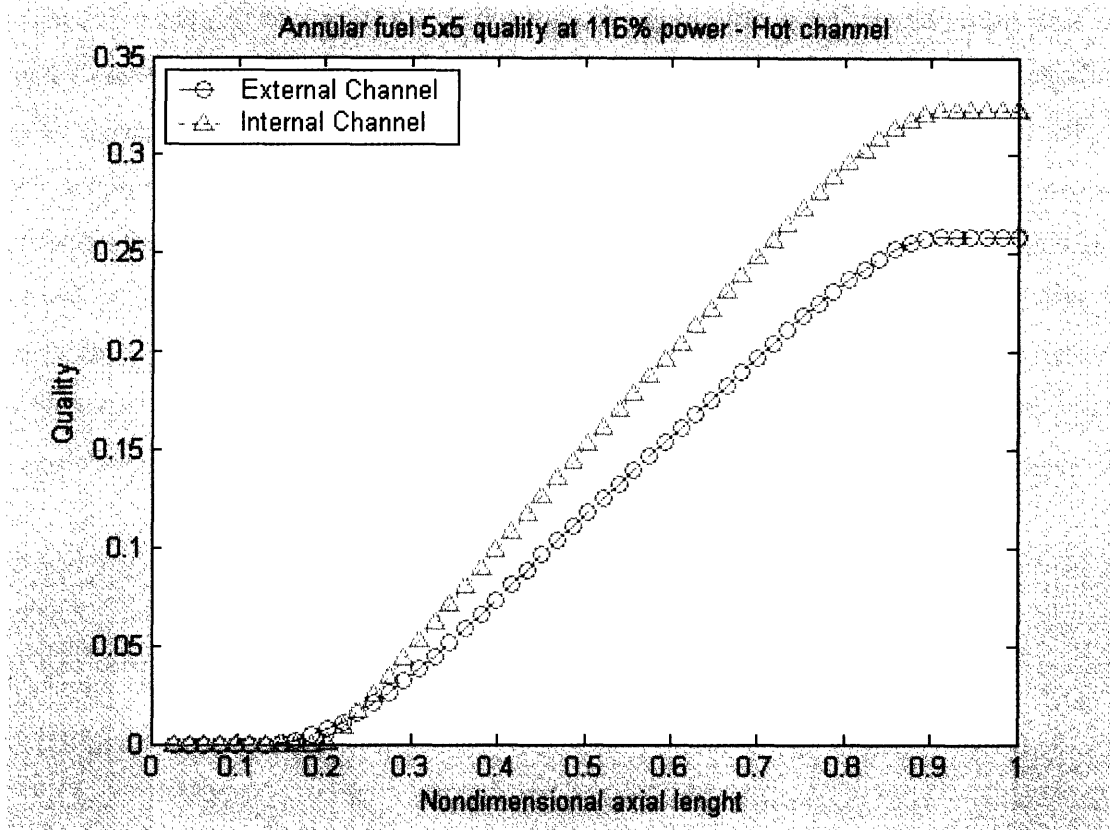


Figure 4.12: Hot channel quality axial profile for annular 5x5 design at 116% power

Our calculated core pressure drop at 100% power is 20.2 psia, about 1 psia less than the solid fuel design thanks to the more open layout. However, for a power increase of 16% the core pressure drop is 26 psia, about 20% more than the solid fuel design at 100% power as a result of the higher flow rate necessary for the power increase, as seen in Figure 4.13. We have to underline that the total pressure drop in all the internal and external channels of the same bundle is the same since they are communicating at the ends.

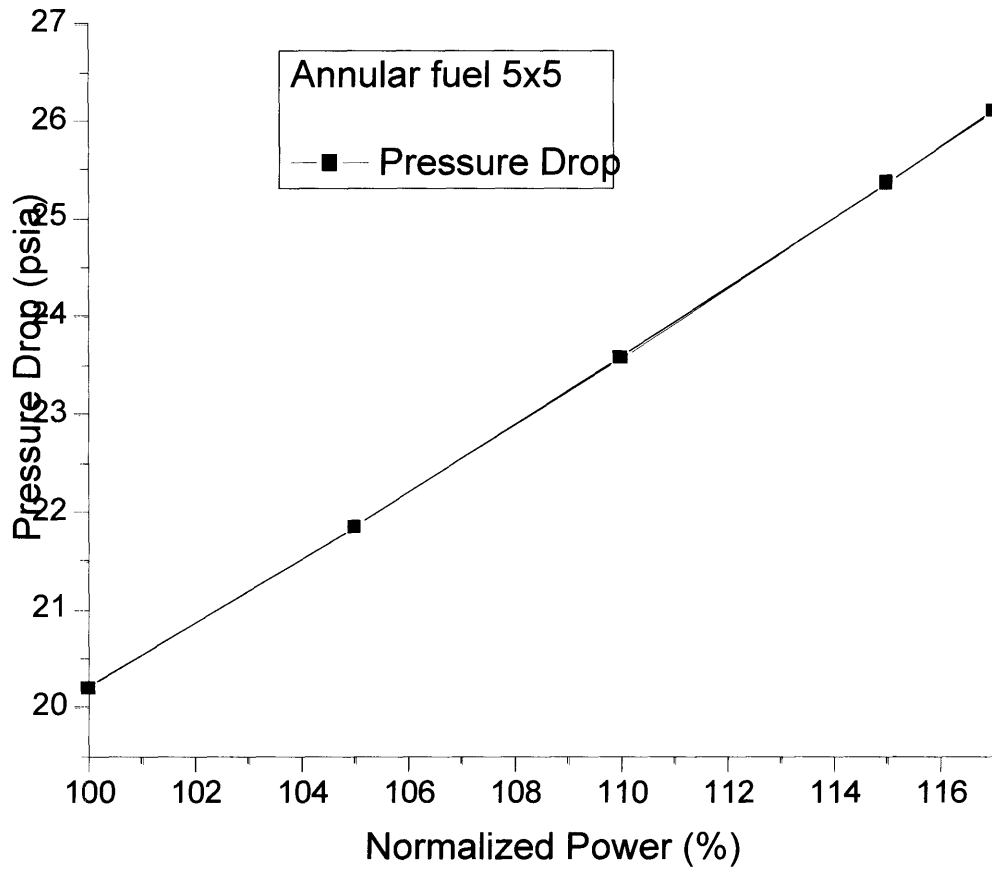


Figure 4.13: Pressure drop increase with power for annular fuel 5x5

### 4.2.1.2 MCPR

It is seen in Figure 4.14 that the values of MCPR for the hot bundle of the annular fuel design 5x5 are heading towards a certain value when increasing the number of axial nodes. As explained in Appendix A we will take as representative of the final result the value we obtain for the highest number of axial nodes (59), 1.467.

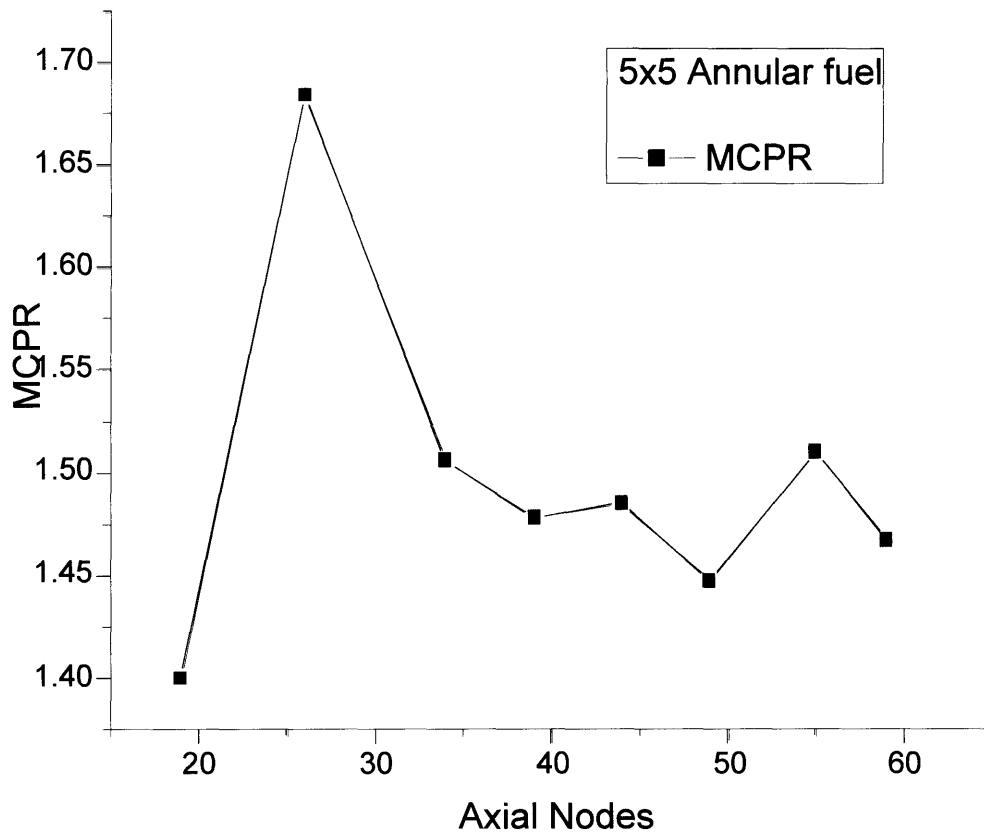


Figure 4.14: MCPR for the annular fuel 5x5

Following the method outlined in Chapter 2 we increase the power and the mass flow rate by the same percentage till we can achieve the same MCPR as that for the solid fuel reference. It can be observed in Figure 4.15 that we can increase the power up to 16% if we use the 5x5 annular fuel in the existing BWR cores.

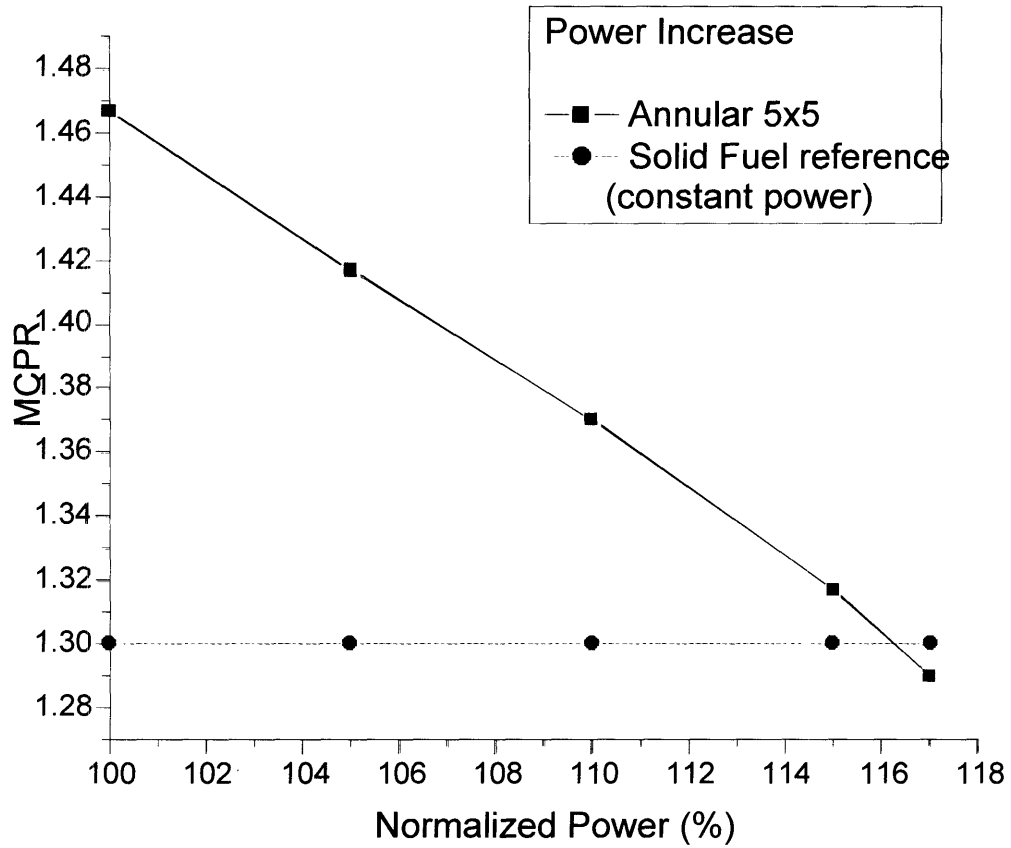


Figure 4.15: Power increase for annular fuel 5x5

## 4.2.2 Annular 6x6

As discussed in Chapter 3, the design chosen was Annular 5 in Table 3.7.

### 4.2.2.1 Thermal hydraulic Parameters

We obtain relatively similar results to the solid fuel case for Quality and Void fraction. Again at 100% power, all parameters are compared in Table 4.3.

**Table 4.3: Thermal hydraulic comparison for the 6x6 annular fuel design**

(all at 100% power)	Solid Fuel	5x5 annular fuel	6x6 annular fuel	Reference
Exit Quality	14.2%	14.5%	14.5%	~15%
Exit Void Fraction	67%	65.6%	65.3%	~70%
Average Void Fraction	38.66%	37.67%	37.57%	~40%
Pressure Drop	21.6 psia	20.2 psia	25.1 psia	~21 psia

**Table 4.4: Thermal hydraulic comparison for the worse conditions (6x6 annular fuel)**

(Hot Rod)	Solid Fuel	5x5 annular fuel		6x6 annular fuel	
		External	Internal	External	Internal
Power Density	100%	116%		123%	
Mass flow rate	100%	116%		123%	
Mass flux (hot channel)	100%	111%	152%	102.6%	190%
Pressure Drop	100%	120.8%		163.8%	
Maximum fuel Temperature (hot rod)	1608.61 C	774.39 C		618.33 C	
Average fuel Temperature (hot rod)	1043.26 C	540.98 C		470.19 C	

In Table 4.4 above we show the relative mass flux for the three designs. As discussed below, the hottest channel in the 6x6 case is not the one adjacent to the hot rod. Here we reported the values for the hottest channel, which is a corner channel in this case. This explains why the mass flux for the external channel is considerably smaller than the internal, since the corner channels have smaller flow area and hydraulic diameters.

From the data about the fuel temperature in Table 4.4 we can see that the advantage of the annular fuel over the solid is even larger for the 6x6 case, exactly as expected since the smaller pins mean lower thermal resistance and larger heat exchange surface, and thus better cooling. We compare the temperature radial profile of the hottest section of the hot rod of the three designs in Figure 4.16.

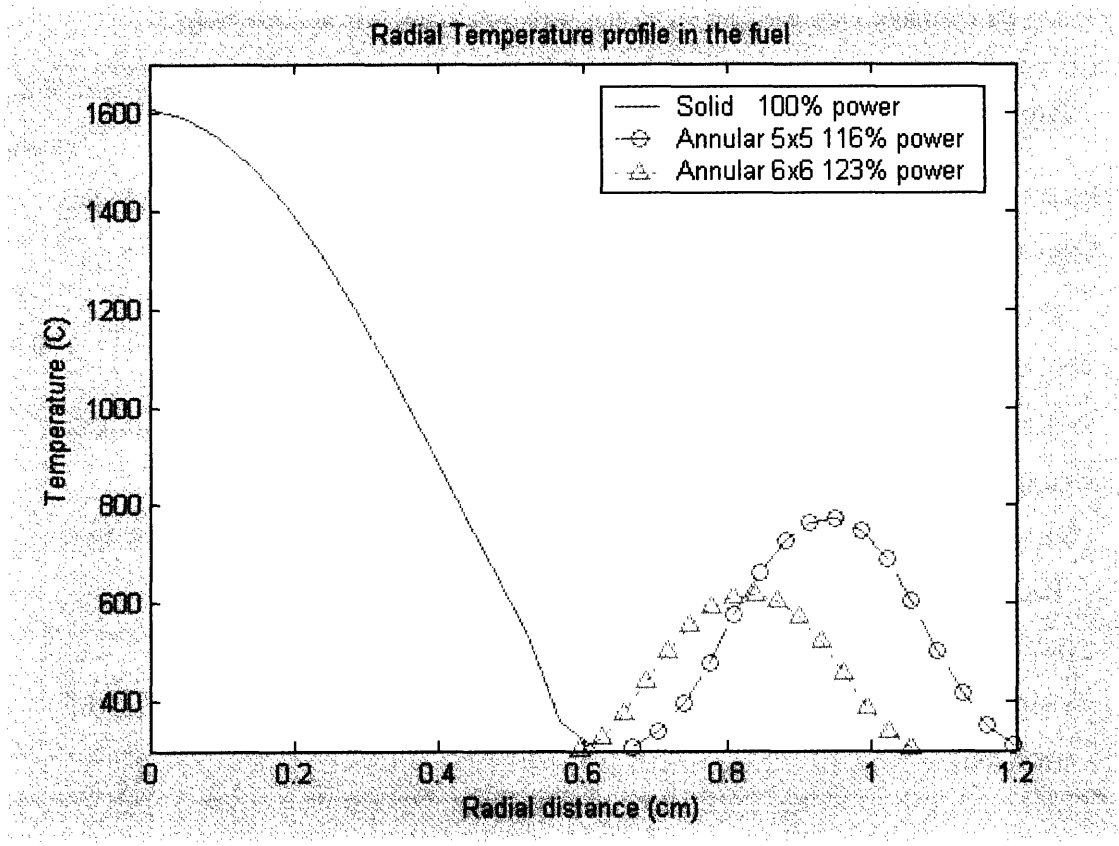
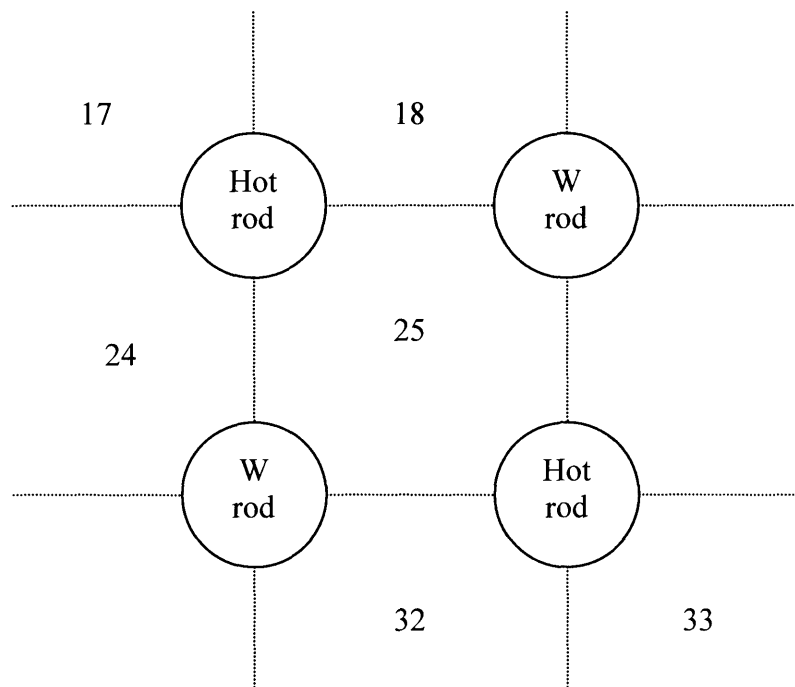


Figure 4.16: Hot rod temperature comparison

We show the annular fuel quality profile along the hot rod at 100% (Figure 4.18) and at 123% power (Figure 4.19). As seen, the external and internal channels are inverted compared to the annular 5x5 case, since now the hottest channel is the external one. This happens because the 6x6 design has a tighter lattice, with very small external channels, in order to keep the internal channels of a sufficient dimension for manufacturing purposes and to avoid channel blocking due to debris. In this case we couldn't say that all the external channels around the hot rod achieve similar quality. We can see in Figure 4.17 that the hot rods (there are two rods with the same radial power peaking in the 6x6 design, see Figure 3.11) are the ones close to the water rods.



**Figure 4.17: Part of the 6x6 bundle layout**

In Figures 4.18 and 4.19 we have plotted the quality in channel 33 as the external hot channel (since it was the hottest) but channel 25 (labeled as ‘cold channel’) achieves a much lower quality than the hottest channel, as we can see in the Figures. This is because it is in contact with both the water rods and thus receives much less heat than the other channels.

Also there is an interesting feature of the 6x6 bundle. As we can see in Figure 3.11 the hot rod in this case is not along the border of the channel. This means that the hot rod is surrounded by full-size internal channels only. As we have said in Section 4.2.1.1 the border and corner channels have lower flow area and thus are more likely to have a higher exit quality. In fact, in this design the hottest channel is actually the corner channel for all values of power considered, as we can see in Figures 4.20 and 4.21, not only because the corner channel is the smallest in the design, but even the radial power peaking of the corner rod is very close to the one of the hot rod. If we look at this channel and we compare it to the hot channels of the annular 5x5 and the solid design, again we can see that we reach similar quality values. The hottest internal channel is still the one

belonging to the hot rod, even if the inner channel of the corner rod reaches almost the same exit quality.

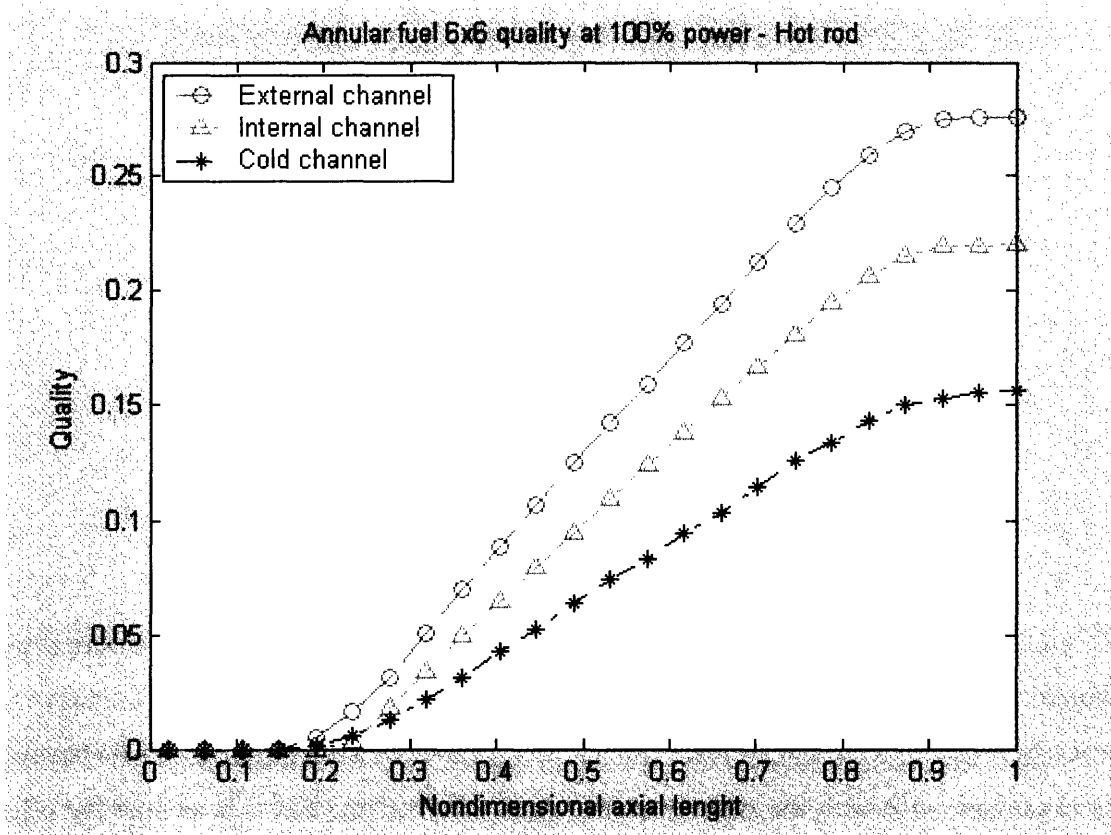


Figure 4.18: Hot rod channels quality axial profile for annular 6x6 design at 100% power

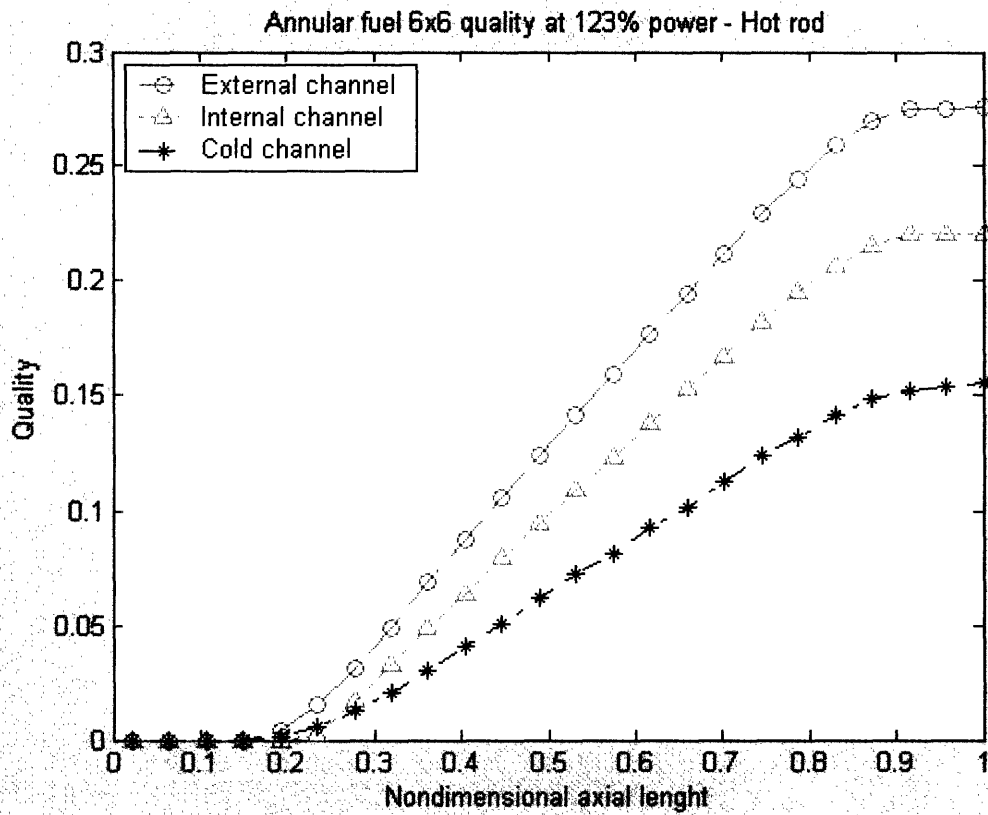


Figure 4.19: Hot rod channels quality axial profile for annular 6x6 design at 123% power

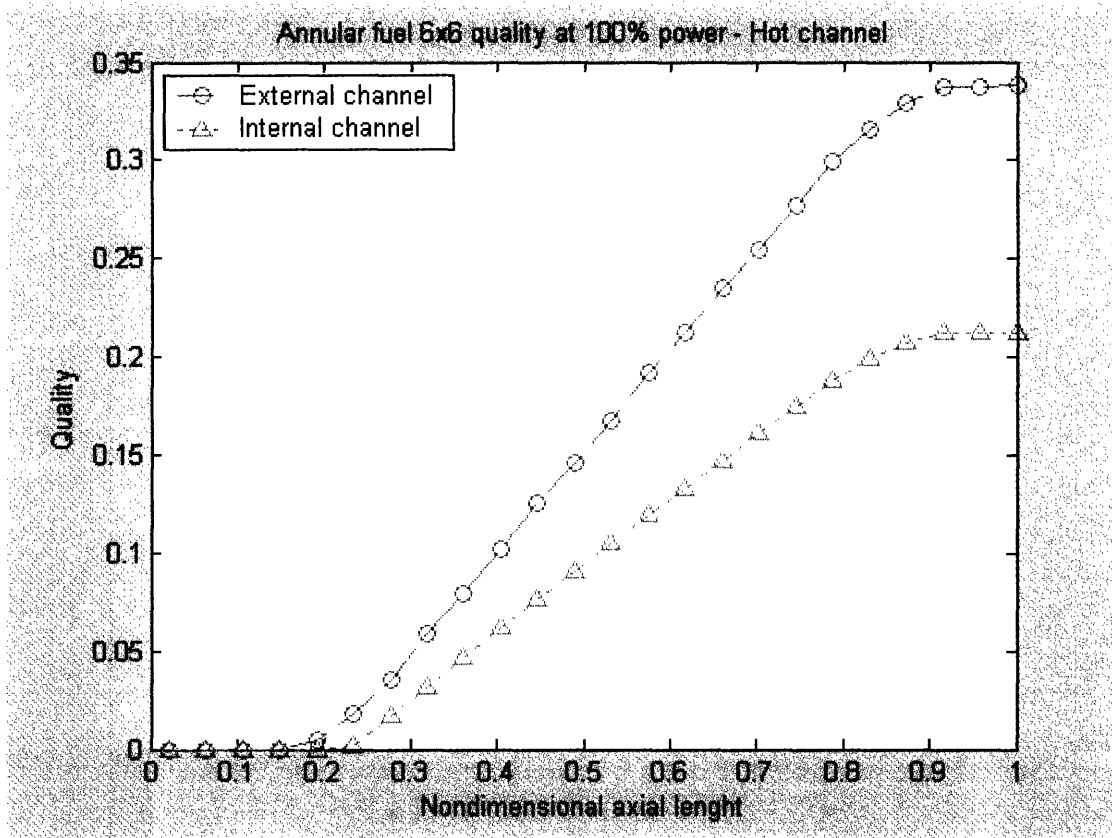


Figure 4.20: Hot channel (corner) quality axial profile for annular 6x6 design at 100% power

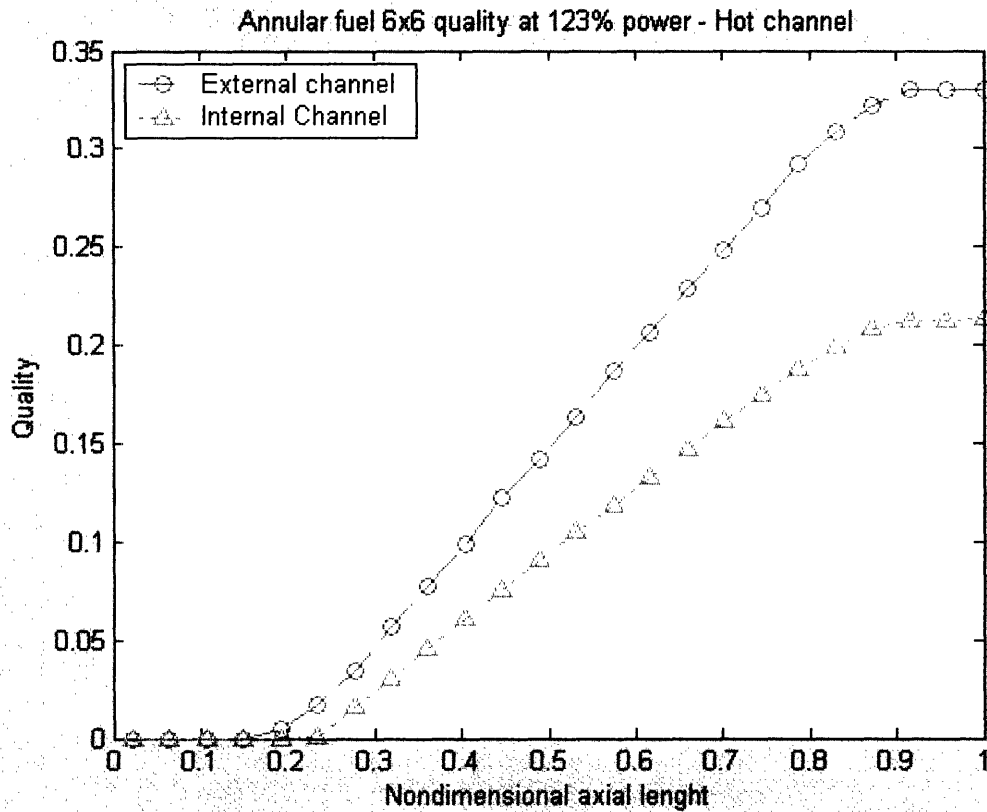


Figure 4.21: Hot channel (corner) quality axial profile for annular 6x6 design at 123% power

As seen in Figure 4.22, for the 6x6 design the pressure drop at 100% power is already higher than the solid fuel (25.1 psia). In addition, for a power increase of 23% we obtain a pressure drop of 35.39 psia, about 60% more than the solid fuel at 100% power (see Table 4.4). This means that in the case the annular fuel was adopted, more powerful recirculation pumps would be necessary.

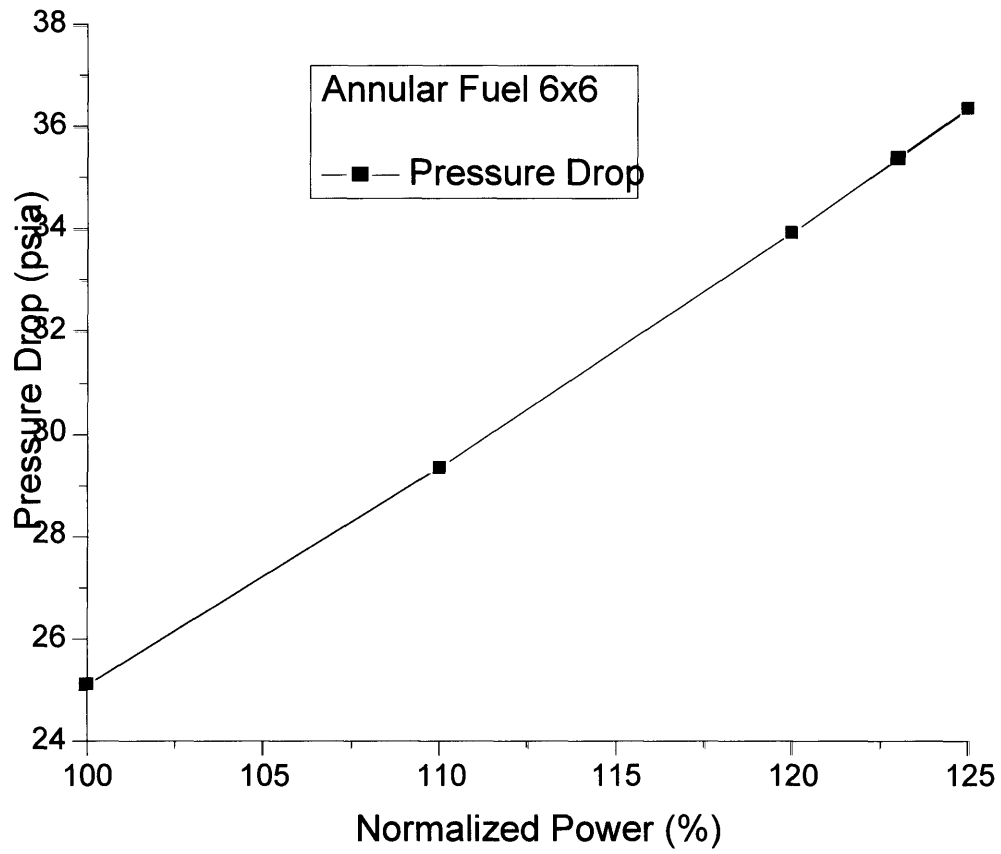


Figure 4.22: Pressure drop increase with power for annular fuel 6x6

#### 4.2.2.2 MCPR

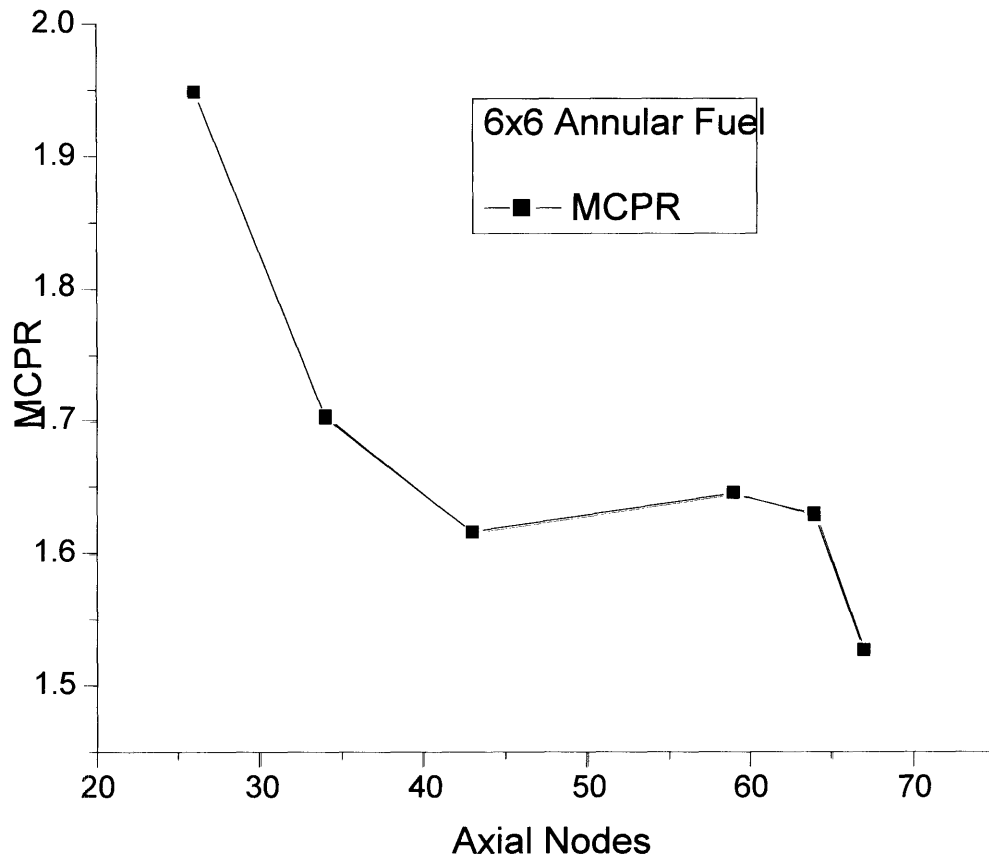


Figure 4.23: MCPR for the annular fuel 6x6

In the 6x6 we obtain less convergence points due to the tighter lattice. It has already been reported, even with different geometry and flow conditions, that VIPRE has convergence problems in tighter lattices with annular fuel [9], so this result was expected. In any case we still are able to obtain a few convergence points and, following the criteria outlined in Appendix A, we choose as representative MCPR the one we obtained with the highest number of axial nodes (67), which is 1.526, as can be seen in Figure 4.23. In this case this MCPR has the virtue of being the lowest obtained, and thus the more conservative.

Again following the method outlined in Chapter 2 we increase the power and the mass flow rate by the same percentage until we can achieve the same MCPR as the solid fuel reference. Figure 4.24 shows that we can increase the power up to 23% if we use 6x6 annular fuel in the existing BWR cores.

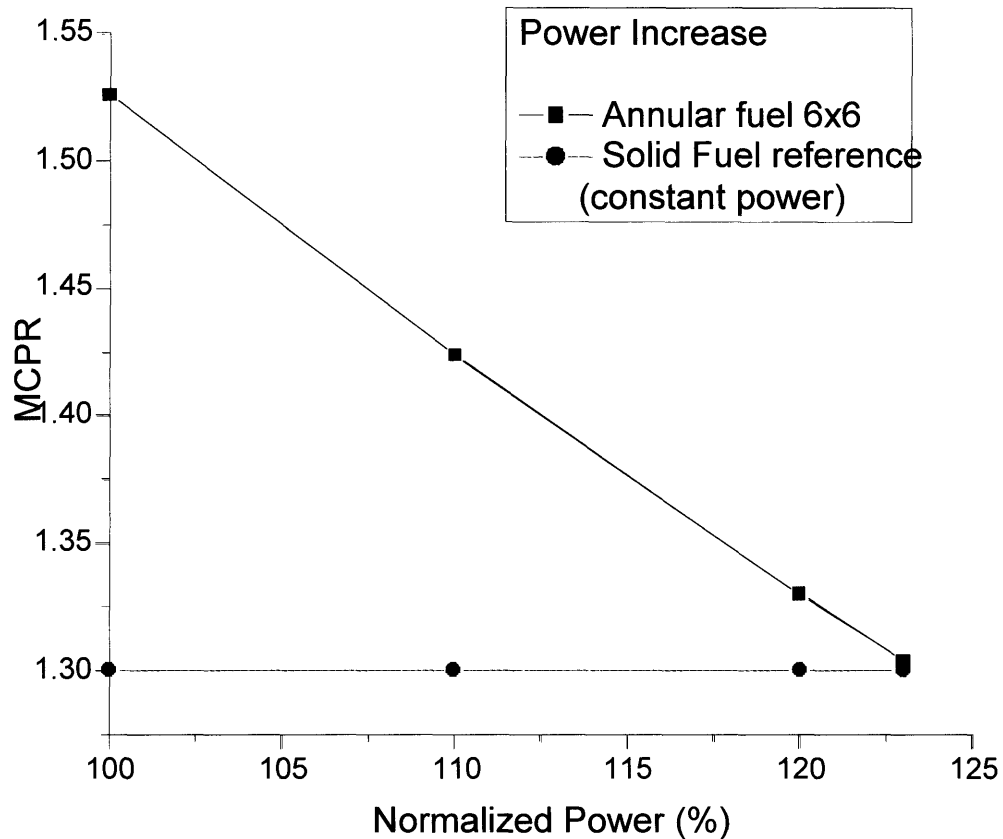


Figure 4.24: Power increase for annular fuel 6x6

## 4.3 Analysis of the results

As we have seen there is good agreement between the solid and annular fuel regarding the fundamental thermalhydraulic variables. This is very important because it shows that, even considering the uncertainties inherent in the model, the fuels we considered are interchangeable and this achieves one of the targets of the present work: the possibility to use annular fuel in the existing BWR nuclear power plants.

We have shown that both annular fuel designs allow an appreciable power uprate in the existing BWR nuclear power plants. However the magnitude of the uprate is less than was achieved in the PWR case.

It is important to remember the convergence issues we have encountered. As shown in Section 4.2 we achieved convergence with careful choice of axial nodes, especially with annular fuel. In any case we believe that the MCPR is actually converging to the value calculated for the higher number of nodes. As mentioned before, we decided always to consider the value of the CPR obtained for the highest number of nodes. This value has also the characteristic of being the lowest or very close to the lowest value obtained for all nodes, thus providing a conservative estimation.

We can compare the designs from the point of view of the heat transfer surface and achievable power density in Table 4.5.

**Table 4.5: Fuel design comparison**

	solid	5x5 Annular	6x6 Annular
Power (normalized)	100%	116%	123%
Heated surface/fuel volume (normalized)	100%	139.3%	163.3%
Pressure drop (normalized)	100%	120.4%	163.8%

As we can see, the power increase requires an increase in pressure drop. These two things together mean that the recirculation pumps will have to be increased to overcome the higher pressure drop. In addition, forces that lift the assemblies would be increased and a new design for holding them down would be needed.

### 4.3.1 Theoretical expectations on CPR

As discussed in Chapter 2, the process that leads to dryout is the depletion of the liquid film in contact with the heated surface. In a high quality environment, like the one we find in BWR reactors, the most common flow regime is annular; in this situation there is a thin liquid film in contact with the heated surface and in the middle of the channel there is vapor, usually with some liquid drops suspended in it, if the quality is not already very high.

The flow rate of the liquid film is determined by evaporation, droplet entrainment (due to drops of liquid suspended in the vapor that are captured in the film) and droplet deposition. The first phenomenon is due to the heat flux coming from the solid surface, while the other two are originated by the mass exchange between the two phases due to the mechanical effect of the vapor on the liquid film.

The CHF corresponds to the condition in which the flow rate of the liquid film falls to zero. In this situation the solid wall ‘dries out’ of liquid and is forced to exchange heat directly with the vapor. Even if there will be liquid droplets suspended in the vapor (because the quality is still less than 1), the heat transfer coefficient will diminish considerably compared to the boiling situation when the liquid film was still in contact with the wall. As a consequence, since the heat flux is constant during this process, the temperature difference will rise and the situation can become dangerous for the wall materials.

From the above explanation it is easy to understand why a higher heat transfer surface should change the CHF phenomenon. It can be shown too [2] that for high quality CHF the critical channel power is not sensitive to the distribution of the heat flux along a fixed length.

For PWR reactors, the local values of CHF dominate. The CHF correlations in low quality environment (DNB) are based on the comparison between the local heat flux and the critical heat flux, thus we can see that the most important parameter is the heat flux itself and especially its local distribution. So, following our discussion, a larger surface means lower heat flux and as a consequence better MDNBR. Furthermore, as the flow velocity is increased bubbles are swept away from the wall which reduces the chances of vapor film formation. Thus, increased flow increases the CHF.

The CPR correlation, instead, as seen in Section 2.4, consists of the ratio between critical bundle power and actual bundle power and is strongly dependent on average conditions. This does not help the annular fuel whose advantage is exactly in splitting the heat flux

on two separate cooled surfaces. The only advantage is the presence of the heat transfer area in the nondimensional boiling length term, as seen in Section 2.5, but the effect is not as strong as the direct dependence we have in the DNB case.

There is also another effect that we should consider. When we raise the power, we also need to raise the mass flow. This preserves the quality distribution along the axis. However, the higher absolute steam mass flux tends to strip faster the liquid film from the wall, which means it will develop the dryout condition at a lower value of the flow quality,  $x$ . On the other hand though, the higher mass flux will tend to lower the flow quality,  $x$ . Remembering that the CPR is a ratio of the critical quality,  $x_c$ , to the actual quality of the bundle (Sections 2.4 and 2.5) we can see that this actually could raise the CPR due to lowering  $x$ , or lowering the CPR due to lowering the  $x_c$ . Only the relative magnitude of the change will decide if the CPR actually decreases or increases. Thus in general we cannot foresee a priori what will be the effect of an increased mass flux on the system.

# Chapter 5: Summary and Conclusions

## 5.1 Summary

Our objective was to examine whether an annular fuel design would be a viable alternative for a higher power density core compared to the solid fuel design, currently used in BWRs.

The fundamental analysis tool used was VIPRE01mod02 thermal hydraulic code as discussed in Chapter 2. By recognizing that the fuel bundles in BWRs are enclosed in channel boxes, we were able to avoid modeling the whole core. Instead, we run just an average bundle to calculate the core pressure drop first, and then use that pressure drop as an input data to run the hot bundle, thus obtaining the Minimum Critical Power Ratio (MCPR) of a particular design. To model the annular fuel we used the code capability to model an annular tube with internal cooling, which was used already before in an effort to analyze the PWR performance with annular fuel.

We reviewed the available data on the solid fuel bundles of BWRs and decided to examine annular 5x5 and 6x6 bundle designs which provide larger heat transfer surface area, as discussed in Chapter 3. After establishing the important hydraulic and neutronic constraints, especially the ones derived from the fact that we would like to retrofit the existing BWRs using the annular fuel, we identified the most promising annular fuel designs. All the designs that satisfied the thermal hydraulic, neutronic and mechanical constraints were examined and judged from the point of view of their CPR.

The best annular fuel designs from the CPR point of view were compared to the solid fuel (Chapter 4). Since the CPR for the annular fuel was higher than that for the solid fuel, one could achieve a wider safety margin which could be traded for a power density

upgrade. The power density upgrade that reduces the annular fuel MCPR to the solid fuel level has been calculated and the results are shown and discussed in Chapter 4.

As a result we found that with the designs analyzed we can get a maximum uprate of 23% in an existing BWR plant with the 6x6 bundle. While this is not a negligible number it is inferior to the uprate that a PWR with annular fuel is able to achieve [1]. The nature of this difference is addressed in Section 4.3.1.

## 5.2 Conclusions

From the calculations presented in Chapter 4, we conclude that an appreciable power density increase is possible using the proposed 6x6 annular fuel design. A power increase of 23% that is significant although smaller than the PWR case. For a PWR the annular fuel allows a rise of power density up to 50% [1].

It should also be remembered that the flow rate is also assumed to be increased in proportion to the power. Thus the pressure drop across the core will rise by about 60% and as a consequence this will require a substantial increase of the power of the recirculation pumps.

We are conscious of the limitations of our calculations, especially due to our adaptation of the Hench-Gillis CPR correlation for the annular fuel, without having an experimental base for validation. We feel that further studies are needed before one can strongly recommend the annular fuel for BWR application. It is possible that a more in-depth study with an up-to-date CPR correlation, and possibly developed specifically for annular fuel, would yield better results. In any case, for reasons inherent to the mechanism of dryout which controls the critical power condition, as discussed in Chapter 4, it is not expected to arrive at the same level of power density upgrade as we can expect in the case of PWRs.

However, there are other advantages of annular fuel: the lower temperature in the fuel helps reduce the effects of transients and fission gas release during high burnup [8], and its larger fuel pins add mechanical rigidity. This might be enough to assure its competitiveness in the market, even for BWRs.

## 5.3 Future studies

The most important approximation that should be relaxed is related to the CPR correlation. The Hench-Gillis correlation is relatively old and, since it was developed for solid fuel, it is theoretically not applicable to the annular one.

As a first step we think we could refine the calculation by considering the inner and outer channels separately, each with its own CHF correlation. This is a necessary step since the inner and outer channels do not communicate. The EPRI correlation which was developed for both BWRs and PWRs is the first possible choice. The ultimate step would be to develop an experimentally based CPR correlation for the annular fuel. Eventually one would like to model the whole core to calculate the bypass flow more accurately and may wish to use a full 3D calculation with a newer thermal hydraulic code such as TRACE.

Larger pressure drop and power could raise the issue of stability against density wave oscillations. This issue must also be analyzed to identify the stability-imposed limit on power uprate. For a wider study of the applicability of annular fuel, the examination of the flow split between internal and external channels at various levels of power and flow as well as consideration of mechanical issues such as vibrations and lift off forces would be advisable. Also, considerations of transients such as LOFA and LOCA should be addressed to complete the thermal margin evaluations.

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# **Appendix A:**

## **Convergence and Comparison Criteria**

### **A.1 Convergence**

As we have seen in Chapter 4 we don't achieve convergence for every possible value of axial nodes both in the annular and solid fuel case. Ideally we would get convergence for all the cases and the parameter calculated would converge smoothly, or oscillate around, a well defined value.

We have seen that, even if the results are not unsatisfactory, they are very different from the ideal we have defined. We want to discuss the reason for this in this Appendix.

The situation of the annular fuel and the solid fuel is very different convergence-wise. While the solid fuel achieves convergence for most of the possible values of axial nodes, the annular fuel convergence is more sporadic. In the rest of the Appendix we will concentrate on the convergence problems that we find in running the annular fuel, since these are the ones that concern us the most.

Table A.1 provides the data we get from running the average rod for the 6x6 design.

**Table A.1: Convergence of the 6x6 average bundle**

Axial Nodes	Pressure Drop (psia)	CPR
16	25.2978	1.972
19	H	H
24	25.2079	C
26	H	H
34	25.1432	1.954
39	H	H
43	H	H
44	25.0634	2.375
49	25.0826	C
50	25.098	2.507
51	H	H
55	H	H
59	H	H
61	XH	XH
64	H	H
69	H	H
79	H	H
89	X	X
99	XH	XH
109	XH	XH
119	X	X
129	XH	XH
139	S	S
149	S	S
159	S	S

All the spaces where the numbers are not shown mean that the code has not converged.

We have used the following index for the not-converged cases:

- H: error on the heat transfer coefficient calculation
- X: numerical error (the code does not converge after the maximum number of iterations)
- S: the code stops due to an infinite (very large) error
- C: the code is not able to find the boiling length and thus to calculate the CPR but calculates the thermal hydraulic parameters normally

More than one letter in the same place means that the code gave both errors at the same time.

We could actually show many tables like that, with more or less converged points, and not-convergence due to a different combination of the above 4 reasons. As said before there is a difference though between the annular and the solid fuel. As we can see in chapter 4 we obtain more converged runs in the solid case.

First of all we want to underline how the convergence becomes sporadic with increasing the number of axial nodes, for the annular fuel design. This is an unexpected result because a computer code should actually achieve better precision, if it is stable. But considering that the VIPRE code is not certified for use for annular fuel, it is probably a consequence of the fact that we stretched its capabilities.

Another thing we can note from Table A.1 is that the difference between the pressure drop calculated using different number of axial nodes is very little, around 1% at most, while the fluctuation of the CPR is much higher.

To try to understand the reasons behind this problem we need to review how VIPRE calculates the parameters of interest.

First of all VIPRE has 3 different possible numerical methods to solve the system:

➤ Direct

The direct solution is the easiest to implement in the code and the less robust. It basically tries to directly invert the matrix and is not useful for our complicated system. Its main advantage is that, when it works, it is faster.

➤ Iterative

The iterative solution solves the same equations as the direct method but does it in an iterative way, thus using more computational time but allowing convergence in more cases. This is the solution we used.

➤ Recirculation

The recirculation solution is completely different from the previous two, since it modifies the system of equations to allow better results in some cases. It is especially useful in cases involving reverse flow.

We have tried to use both the second and the third solution method but the Recirculation solution gives convergence only for some annular fuel designs and even in those few cases only for 16 axial nodes and thus was discarded. We have done all our calculations with the Iterative solution.

Having specified the numerical method, we have now to remind the reader that VIPRE first calculates the thermalhydraulic parameters and then uses these results to calculate the CPR. As a consequence, if the thermalhydraulic calculation does not converge, automatically the CPR cannot be calculated. As we have seen, it is possible to have cases where the thermalhydraulic calculation is successful but the CPR cannot be calculated. This is very important because we can see that the fluctuation in the thermalhydraulic parameters with the number of axial nodes is actually very small, what changes in a not negligible manner is the CPR. Since the CPR calculation happens after the thermalhydraulic calculation, we can be confident that the problem is actually in the CPR routine.

Also, if we follow the method proposed in Chapter 2, if the thermalhydraulic calculation of the average bundle does not converge, we cannot run the calculation of the hot bundle at all, since we don't have a pressure drop for the core.

We have run all the cases between 16 and 160 axial nodes due to computational time issues, but we believe that the range is wide enough to start clarifying what is happening.

The thermalhydraulic calculation becomes more and more unstable with increasing number of axial nodes, especially for the average bundle. So we believe that it is a numerical problem on the pressure drop calculation. This is very evident for the annular case and less worrying but still present for the solid fuel case. The CPR calculation instead tends to be unstable for the lower number of axial nodes due to the more difficulty for the code in identifying the boiling point in a coarse grid. These two things together should originate a window of convergence that is more or less what we observe (see Chapter 4).

## A.2 Comparison Criteria

Since we don't get a single answer from the code for the CPR and the pressure drop but an answer that is a function of the number of axial nodes, the next step is to try to decide what are actually the pressure drop and the CPR that we can assign to the design.

First of all we have to remember that the pressure drop and the other thermal hydraulic parameters are not a problem, since they do not fluctuate more than few percent in all the cases we have run. This suggests a way to get more convergence than what we would get simply using the method illustrated in Chapter 2. The method is the same as what we illustrated in Figure 2.2, only now we run first the average bundle for all the possible number of axial nodes and get the pressure drop of the bundle (with an error of 1% or less) and then run the hot bundle with the pressure drop obtained, again for all the possible number of axial nodes. With this method we can do more runs and thus obtain more converged points for the hot bundle than before, when we could not run the hot bundle if the average did not converge for the same number of axial nodes.

The CPR value remains a problem, since we get very different results for the different number of axial nodes. There are many possible criteria to compare the solid and annular fuel CPR. Choosing the criterion must be done carefully since the CPR is heavily dependent on the number of axial nodes we use and convergence is sporadic.

Some possible criteria are:

1. Compare the minimum CPR for both annular and solid
2. Compare the maximum
3. Compare the average
4. Compare the CPRs corresponding to the same number of axial nodes
5. Compare the CPRs corresponding to the maximum number of axial nodes for which we achieve convergence

Criteria number 1 and 2 have the disadvantage of taking the peaks of the convergence curve. As we discussed in Chapter 4 the CPR oscillates with the number of axial nodes and should, theoretically, go to an asymptotic value for a very large number of axial nodes. This asymptotic value is not observed due to the fact that we don't achieve convergence for a very large number of axial nodes but we can see the tendency from the graphs. If we knew *how* the CPR goes to the asymptotic (real) value, we could choose the criteria 1 or 2 with some success, but since we don't know, we risk actually using the value with the largest error.

Criterion number 3 cannot reasonably be used if we cannot show that the CPR oscillates around the true value with the increase of the number of axial nodes. If it actually went to the real value from above or below, for example, this criterion would give a completely wrong result.

Criterion number 4 is relatively safe but has the disadvantage that we don't have a value for axial nodes for which all the design converge, thus we cannot use it. Also even if we had one, it has the downside of theoretically allowing more than one value for the CPR if the designs all converged for more than one value of axial nodes.

Criterion number 5 is probably the safest. Since theoretically the code should converge to the true value if we increase the number of axial nodes, choosing the CPR corresponding to the maximum number of axial nodes for which we achieve convergence should get us as close as possible to the real value of the CPR

In any case we have two comforting results. First, the solid fuel actually seems to be converging to a value and thus it is possible that even the annular could have if we had enough converged points. Second, the CPR corresponding to the highest number of axial nodes for which we obtain convergence (Criterion 5) and the lowest CPR (Criterion 3) are almost always the same, showing that we can use them interchangeably. For these reasons we believe that the best we can do is to compare the designs using Criterion 5.

# Appendix B: VIPRE Inputs

## B.1 Solid fuel-average bundle input

```
*
* 1 assembly, 8x8 annular pins, using BWR power distribution
* SOLID FUEL
*
*****
1,0,0,
*vipre.1
Bwr solid fuel
*
geom,83,83,52,0,0,0, *normal geometry input , check last 0---- BWR
normal geom input Oo *geom.1
*
178.5,0.0,0.5, *geom.2
*
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\*  
\*  
rods,1,66,1,2,1,0,0,0,0,1,0 \*three material types,one type of geo.  
\*rods.1

```

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*
26
*rods3
*Normal rod (rods.4)
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49,1,0.999,1,57,0.25,58,0.25,66,0.25,67,0.25,
50,1,1.089,1,58,0.25,59,0.25,67,0.25,68,0.25,
51,1,1.084,1,59,0.25,60,0.25,68,0.25,69,0.25,
52,1,0.993,1,60,0.25,61,0.25,69,0.25,70,0.25,
53,1,0.355,1,61,0.25,62,0.25,70,0.25,71,0.25,
54,1,1.013,1,62,0.25,63,0.25,71,0.25,72,0.25,
55,1,0.993,1,64,0.25,65,0.25,73,0.25,74,0.25,
56,1,1.015,1,65,0.25,66,0.25,74,0.25,75,0.25,
57,1,1.072,1,66,0.25,67,0.25,75,0.25,76,0.25,
58,1,1.111,1,67,0.25,68,0.25,76,0.25,77,0.25,
59,1,1.11,1,68,0.25,69,0.25,77,0.25,78,0.25,
60,1,1.071,1,69,0.25,70,0.25,78,0.25,79,0.25,
61,1,1.013,1,70,0.25,71,0.25,79,0.25,80,0.25,
62,1,0.991,1,71,0.25,72,0.25,80,0.25,81,0.25,
63,2,0,1,40,0.25,41,0.25,49,0.25,50,0.25,
rod (ext)
-63,2,0,1,83,1,
rod (int)
64,2,0,1,32,0.25,33,0.25,41,0.25,42,0.25,
rod (ext)
-64,2,0,1,82,1,
rod (int)
*
0
*rods.9
*
1,2,3,4,5,6,7,8,
9,10,11,12,13,14,15,16,

```

\*Water

\*Water

\*Water

\*Water

\*rods.57

```

17,18,19,20,21,22,23,24,
25,26,27,28,64,29,30,31,
32,33,34,63,35,36,37,38,
39,40,41,42,43,44,45,46,
47,48,49,50,51,52,53,54,
55,56,57,58,59,60,61,62,

*blank line above necessary /rods.57 -HG CPR corr
64,0.6378,0.4055,0.484252,16.2893659,          *rods.58
0                                                *rods.59
*
*fuel
1,nucl,0.484252,0.4094488,12,0.0,0.0334646
*rods.62
0,0,0,0,0,1056.66,0.92,0,
*rods 63
*constant radial power in the pellet, no power in the clad
*
*water tube
2,tube,0.59055,0.519685,1
*rods.68
3,1,0.0354331,1.0,
*rods.69
*
1,18,409.0,clad,
*table for cladding
*rods.70
0.0,0.0671,7.3304509,?
25,0.0671,7.3304509,
50,0.0671,7.33045093,?
65,0.0671,7.33045093,
80.33,0.0671,7.33045093,?
260.33,0.07212,8.11585329,
692.33,0.07904,9.80167423,?
1502.33,0.08955,13.2923,
1507.73,0.11988,13.3211893,?
1543.73,0.14089,13.51665,
1579.73,0.14686,13.717249,?
1615.73,0.1717,13.923198,
1651.73,0.1949,14.1347101,?
1687.73,0.18388,14.351998,
1723.73,0.1478,14.5752746,?
1759.73,0.112,14.804753,
1786.73,0.085,14.9810589,?
2240.33,0.085,18.5665964,
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0,
*oper.1 /flow is specified
-1.0,0.0,2.0,0.005,
*oper.2 *first word to be changed if you change BC
0
*oper.3 *only if first w above is not 0.0
1044.28,534.2,36.73,69.52,0.0
*oper.5

```

```

*13400 kg/s ,5%bypass and splitted evenly
*Rod power got from total power divided total number of rods
0,          *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,      *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
hneh,
*corr 18 , Hench-Gillis
*****
grid,0,5,
*grid.1
24.280,6.630,1.500,1.460,20000,
*grid.2
*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
81,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5
17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,
49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,
65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,
81,
*grid.5
*3.0,1,13.5,2,34.5,3,58.5,3,76.5,3,94.5,3,118.5,3,136.5,3,
*154.5,3,175.5,3,          *grid
loc. *grid.6
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,          *grid
loc. *grid.6
2,1
82,83,
0.0,5,
0,
*****
cont,
*cont.1
0.0,0,750,50,3,0,      *iterative solution
*cont.2
0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd

```

```
*
*end of data input
0
```

## B.2 Solid fuel-hot bundle input

```
*
* 1 assembly, 8x8 annular pins, using BWR power distribution
* SOLID FUEL
*
*****
1,0,0,
*vipre.1
Bwr solid fuel
*vipre.2
*
geom,83,83,52,0,0,0, *normal geometry input , check last 0---- BWR
normal geom input Oo *geom.1
*
178.5,0.0,0.5, *geom.2
*
1,0.1184,1.1914,0.38033,2,2,0.16339,0.52165,10,0.16339,0.52165,
2,0.16655,1.3985,0.76066,2,3,0.16339,0.6378,11,0.15354,0.52165,
3,0.16655,1.3985,0.76066,2,4,0.16339,0.6378,12,0.15354,0.52165,
4,0.16655,1.3985,0.76066,2,5,0.16339,0.6378,13,0.15354,0.52165,
5,0.16655,1.3985,0.76066,2,6,0.16339,0.6378,14,0.15354,0.52165,
6,0.16655,1.3985,0.76066,2,7,0.16339,0.6378,15,0.15354,0.52165,
7,0.16655,1.3985,0.76066,2,8,0.16339,0.6378,16,0.15354,0.52165,
8,0.16655,1.3985,0.76066,2,9,0.16339,0.52165,17,0.15354,0.52165,
9,0.1184,1.1914,0.38033,1,18,0.16339,0.52165,
10,0.16655,1.3985,0.76066,2,11,0.15354,0.52165,19,0.16339,0.6378,
11,0.22261,1.5213,1.5213,2,12,0.15354,0.6378,20,0.15354,0.6378,
12,0.22261,1.5213,1.5213,2,13,0.15354,0.6378,21,0.15354,0.6378,
13,0.22261,1.5213,1.5213,2,14,0.15354,0.6378,22,0.15354,0.6378,
14,0.22261,1.5213,1.5213,2,15,0.15354,0.6378,23,0.15354,0.6378,
15,0.22261,1.5213,1.5213,2,16,0.15354,0.6378,24,0.15354,0.6378,
16,0.22261,1.5213,1.5213,2,17,0.15354,0.6378,25,0.15354,0.6378,
17,0.22261,1.5213,1.5213,2,18,0.15354,0.52165,26,0.15354,0.6378,
18,0.16655,1.3985,0.76066,1,27,0.16339,0.6378,
19,0.16655,1.3985,0.76066,2,20,0.15354,0.52165,28,0.16339,0.6378,
20,0.22261,1.5213,1.5213,2,21,0.15354,0.6378,29,0.15354,0.6378,
21,0.22261,1.5213,1.5213,2,22,0.15354,0.6378,30,0.15354,0.6378,
22,0.22261,1.5213,1.5213,2,23,0.15354,0.6378,31,0.15354,0.6378,
23,0.22261,1.5213,1.5213,2,24,0.15354,0.6378,32,0.15354,0.6378,
24,0.22261,1.5213,1.5213,2,25,0.15354,0.6378,33,0.15354,0.6378,
25,0.22261,1.5213,1.5213,2,26,0.15354,0.6378,34,0.15354,0.6378,
26,0.22261,1.5213,1.5213,2,27,0.15354,0.52165,35,0.15354,0.6378,
27,0.16655,1.3985,0.76066,1,36,0.16339,0.6378,
28,0.16655,1.3985,0.76066,2,29,0.15354,0.52165,37,0.16339,0.6378,
29,0.22261,1.5213,1.5213,2,30,0.15354,0.6378,38,0.15354,0.6378,
```

30,0.22261,1.5213,1.5213,2,31,0.15354,0.6378,39,0.15354,0.6378,  
31,0.22261,1.5213,1.5213,2,32,0.15354,0.6378,40,0.15354,0.6378,  
32,0.20017,1.6048,1.141,2,33,0.10039,0.6378,41,0.10039,0.6378,  
33,0.20017,1.6048,1.141,2,34,0.15354,0.6378,42,0.10039,0.6378,  
34,0.22261,1.5213,1.5213,2,35,0.15354,0.6378,43,0.15354,0.6378,  
35,0.22261,1.5213,1.5213,2,36,0.15354,0.52165,44,0.15354,0.6378,  
36,0.16655,1.3985,0.76066,1,45,0.16339,0.6378,  
37,0.16655,1.3985,0.76066,2,38,0.15354,0.52165,46,0.16339,0.6378,  
38,0.22261,1.5213,1.5213,2,39,0.15354,0.6378,47,0.15354,0.6378,  
39,0.22261,1.5213,1.5213,2,40,0.15354,0.6378,48,0.15354,0.6378,  
40,0.20017,1.6048,1.141,2,41,0.10039,0.6378,49,0.10039,0.6378,  
41,0.20017,1.6048,1.141,2,42,0.10039,0.6378,50,0.10039,0.6378,  
42,0.20017,1.6048,1.141,2,43,0.15354,0.6378,51,0.15354,0.6378,  
43,0.22261,1.5213,1.5213,2,44,0.15354,0.6378,52,0.15354,0.6378,  
44,0.22261,1.5213,1.5213,2,45,0.15354,0.52165,53,0.15354,0.6378,  
45,0.16655,1.3985,0.76066,1,54,0.16339,0.6378,  
46,0.16655,1.3985,0.76066,2,47,0.15354,0.52165,55,0.16339,0.6378,  
47,0.22261,1.5213,1.5213,2,48,0.15354,0.6378,56,0.15354,0.6378,  
48,0.22261,1.5213,1.5213,2,49,0.15354,0.6378,57,0.15354,0.6378,  
49,0.20017,1.6048,1.141,2,50,0.10039,0.6378,58,0.15354,0.6378,  
50,0.20017,1.6048,1.141,2,51,0.15354,0.6378,59,0.15354,0.6378,  
51,0.22261,1.5213,1.5213,2,52,0.15354,0.6378,60,0.15354,0.6378,  
52,0.22261,1.5213,1.5213,2,53,0.15354,0.6378,61,0.15354,0.6378,  
53,0.22261,1.5213,1.5213,2,54,0.15354,0.52165,62,0.15354,0.6378,  
54,0.16655,1.3985,0.76066,1,63,0.16339,0.6378,  
55,0.16655,1.3985,0.76066,2,56,0.15354,0.52165,64,0.16339,0.6378,  
56,0.22261,1.5213,1.5213,2,57,0.15354,0.6378,65,0.15354,0.6378,  
57,0.22261,1.5213,1.5213,2,58,0.15354,0.6378,66,0.15354,0.6378,  
58,0.22261,1.5213,1.5213,2,59,0.15354,0.6378,67,0.15354,0.6378,  
59,0.22261,1.5213,1.5213,2,60,0.15354,0.6378,68,0.15354,0.6378,  
60,0.22261,1.5213,1.5213,2,61,0.15354,0.6378,69,0.15354,0.6378,  
61,0.22261,1.5213,1.5213,2,62,0.15354,0.6378,70,0.15354,0.6378,  
62,0.22261,1.5213,1.5213,2,63,0.15354,0.52165,71,0.15354,0.6378,  
63,0.16655,1.3985,0.76066,1,72,0.16339,0.6378,  
64,0.16655,1.3985,0.76066,2,65,0.15354,0.52165,73,0.16339,0.52165,  
65,0.22261,1.5213,1.5213,2,66,0.15354,0.6378,74,0.15354,0.52165,  
66,0.22261,1.5213,1.5213,2,67,0.15354,0.6378,75,0.15354,0.52165,  
67,0.22261,1.5213,1.5213,2,68,0.15354,0.6378,76,0.15354,0.52165,  
68,0.22261,1.5213,1.5213,2,69,0.15354,0.6378,77,0.15354,0.52165,  
69,0.22261,1.5213,1.5213,2,70,0.15354,0.6378,78,0.15354,0.52165,  
70,0.22261,1.5213,1.5213,2,71,0.15354,0.6378,79,0.15354,0.52165,  
71,0.22261,1.5213,1.5213,2,72,0.15354,0.52165,80,0.15354,0.52165,  
72,0.16655,1.3985,0.76066,1,81,0.16339,0.52165,  
73,0.1184,1.1914,0.38033,1,74,0.16339,0.52165,  
74,0.16655,1.3985,0.76066,1,75,0.16339,0.6378,  
75,0.16655,1.3985,0.76066,1,76,0.16339,0.6378,  
76,0.16655,1.3985,0.76066,1,77,0.16339,0.6378,  
77,0.16655,1.3985,0.76066,1,78,0.16339,0.6378,  
78,0.16655,1.3985,0.76066,1,79,0.16339,0.6378,  
79,0.16655,1.3985,0.76066,1,80,0.16339,0.6378,  
80,0.16655,1.3985,0.76066,1,81,0.16339,0.52165,  
81,0.1184,1.1914,0.38033,  
82,0.21211,1.6326,1.6326,  
83,0.21211,1.6326,1.6326,  
\*geom.4  
prop,0,1,2,1 \*internal EPRI functions \*prop.1

```

*
*
rods,1,66,1,2,1,0,0,0,0,1,0 *three material types,one type of geo.
*rods.1
144.0,13.513,0,0
*rods.2
*
26
*rods3
*Normal rod (rods.4)
0.,0.,?
3.,0.11769,?
9.,0.60128,?
15.,0.82226,
21.,0.9944,?
27.,1.1257,?
33.,1.20176,?
39.,1.23379,
45.,1.23859,?
51.,1.22898,?
57.,1.21297,?
63.,1.19376,
69.,1.17454,?
75.,1.15853,?
81.,1.14732,?
87.,1.14171,
93.,1.13931,?
99.,1.14171,?
105.,1.14412,?
111.,1.13211,
117.,1.08006,?
123.,0.98559,?
129.,0.83106,?
135.,0.61329,
141.,0.34508,?
144.,0.,
*
*
*****rods geometry input
*rods.9
1,1,0.994,1,1,0.25,2,0.25,10,0.25,11,0.25,
2,1,1.016,1,2,0.25,3,0.25,11,0.25,12,0.25,
3,1,1.073,1,3,0.25,4,0.25,12,0.25,13,0.25,
4,1,1.112,1,4,0.25,5,0.25,13,0.25,14,0.25,
5,1,1.113,1,5,0.25,6,0.25,14,0.25,15,0.25,
6,1,1.074,1,6,0.25,7,0.25,15,0.25,16,0.25,
7,1,1.016,1,7,0.25,8,0.25,16,0.25,17,0.25,
8,1,0.993,1,8,0.25,9,0.25,17,0.25,18,0.25,
9,1,1.016,1,10,0.25,11,0.25,19,0.25,20,0.25,
10,1,0.355,1,11,0.25,12,0.25,20,0.25,21,0.25,
11,1,0.995,1,12,0.25,13,0.25,21,0.25,22,0.25,
12,1,1.086,1,13,0.25,14,0.25,22,0.25,23,0.25,
13,1,1.09,1,14,0.25,15,0.25,23,0.25,24,0.25,
14,1,1,1,15,0.25,16,0.25,24,0.25,25,0.25,
15,1,0.356,1,16,0.25,17,0.25,25,0.25,26,0.25,
16,1,1.015,1,17,0.25,18,0.25,26,0.25,27,0.25,

```

17,1,1.073,1,19,0.25,20,0.25,28,0.25,29,0.25,  
18,1,0.995,1,20,0.25,21,0.25,29,0.25,30,0.25,  
19,1,0.996,1,21,0.25,22,0.25,30,0.25,31,0.25,  
20,1,1.01,1,22,0.25,23,0.25,31,0.25,32,0.25,  
21,1,1.038,1,23,0.25,24,0.25,32,0.25,33,0.25,  
22,1,1.013,1,24,0.25,25,0.25,33,0.25,34,0.25,  
23,1,0.999,1,25,0.25,26,0.25,34,0.25,35,0.25,  
24,1,1.072,1,26,0.25,27,0.25,35,0.25,36,0.25,  
25,1,1.112,1,28,0.25,29,0.25,37,0.25,38,0.25,  
26,1,1.086,1,29,0.25,30,0.25,38,0.25,39,0.25,  
27,1,1.01,1,30,0.25,31,0.25,39,0.25,40,0.25,  
28,1,1.07,1,31,0.25,32,0.25,40,0.25,41,0.25,  
29,1,1.038,1,33,0.25,34,0.25,42,0.25,43,0.25,  
30,1,1.089,1,34,0.25,35,0.25,43,0.25,44,0.25,  
31,1,1.111,1,35,0.25,36,0.25,44,0.25,45,0.25,  
32,1,1.113,1,37,0.25,38,0.25,46,0.25,47,0.25,  
33,1,1.09,1,38,0.25,39,0.25,47,0.25,48,0.25,  
34,1,1.038,1,39,0.25,40,0.25,48,0.25,49,0.25,  
35,1,1.069,1,41,0.25,42,0.25,50,0.25,51,0.25,  
36,1,1.009,1,42,0.25,43,0.25,51,0.25,52,0.25,  
37,1,1.084,1,43,0.25,44,0.25,52,0.25,53,0.25,  
38,1,1.11,1,44,0.25,45,0.25,53,0.25,54,0.25,  
39,1,1.074,1,46,0.25,47,0.25,55,0.25,56,0.25,  
40,1,1,1,47,0.25,48,0.25,56,0.25,57,0.25,  
41,1,1.013,1,48,0.25,49,0.25,57,0.25,58,0.25,  
42,1,1.038,1,49,0.25,50,0.25,58,0.25,59,0.25,  
43,1,1.009,1,50,0.25,51,0.25,59,0.25,60,0.25,  
44,1,0.995,1,51,0.25,52,0.25,60,0.25,61,0.25,  
45,1,0.993,1,52,0.25,53,0.25,61,0.25,62,0.25,  
46,1,1.071,1,53,0.25,54,0.25,62,0.25,63,0.25,  
47,1,1.016,1,55,0.25,56,0.25,64,0.25,65,0.25,  
48,1,0.356,1,56,0.25,57,0.25,65,0.25,66,0.25,  
49,1,0.999,1,57,0.25,58,0.25,66,0.25,67,0.25,  
50,1,1.089,1,58,0.25,59,0.25,67,0.25,68,0.25,  
51,1,1.084,1,59,0.25,60,0.25,68,0.25,69,0.25,  
52,1,0.993,1,60,0.25,61,0.25,69,0.25,70,0.25,  
53,1,0.355,1,61,0.25,62,0.25,70,0.25,71,0.25,  
54,1,1.013,1,62,0.25,63,0.25,71,0.25,72,0.25,  
55,1,0.993,1,64,0.25,65,0.25,73,0.25,74,0.25,  
56,1,1.015,1,65,0.25,66,0.25,74,0.25,75,0.25,  
57,1,1.072,1,66,0.25,67,0.25,75,0.25,76,0.25,  
58,1,1.111,1,67,0.25,68,0.25,76,0.25,77,0.25,  
59,1,1.11,1,68,0.25,69,0.25,77,0.25,78,0.25,  
60,1,1.071,1,69,0.25,70,0.25,78,0.25,79,0.25,  
61,1,1.013,1,70,0.25,71,0.25,79,0.25,80,0.25,  
62,1,0.991,1,71,0.25,72,0.25,80,0.25,81,0.25,  
63,2,0,1,40,0.25,41,0.25,49,0.25,50,0.25,  
rod (ext) \*Water  
-63,2,0,1,83,1, \*Water  
rod (int)  
64,2,0,1,32,0.25,33,0.25,41,0.25,42,0.25,  
rod (ext) \*Water  
-64,2,0,1,82,1, \*Water  
rod (int)  
\*

```

0
*rods.9
*
1,2,3,4,5,6,7,8,
9,10,11,12,13,14,15,16,
17,18,19,20,21,22,23,24,
25,26,27,28,64,29,30,31,
32,33,34,63,35,36,37,38,
39,40,41,42,43,44,45,46,
47,48,49,50,51,52,53,54,
55,56,57,58,59,60,61,62,
*rods.57

*blank line above necessary /rods.57 -HG CPR corr
64,0.6378,0.4055,0.484252,16.2893659,
0
*rods.58
*rods.59
*
*fuel
1,nucl,0.484252,0.4094488,12,0.0,0.0334646
*rods.62
0,0,0,0,0,1056.66,0.92,0,
*rods 63
*constant radial power in the pellet, no power in the clad
*
*water tube
2,tube,0.59055,0.519685,1
*rods.68
3,1,0.0354331,1.0,
*rods.69
*
1,18,409.0,clad,
*table for cladding
*rods.70
0.0,0.0671,7.3304509,?
25,0.0671,7.3304509,
50,0.0671,7.33045093,?
65,0.0671,7.33045093,
80.33,0.0671,7.33045093,?
260.33,0.07212,8.11585329,
692.33,0.07904,9.80167423,?
1502.33,0.08955,13.2923,
1507.73,0.11988,13.3211893,?
1543.73,0.14089,13.51665,
1579.73,0.14686,13.717249,?
1615.73,0.1717,13.923198,
1651.73,0.1949,14.1347101,?
1687.73,0.18388,14.351998,
1723.73,0.1478,14.5752746,?
1759.73,0.112,14.804753,
1786.73,0.085,14.9810589,?
2240.33,0.085,18.5665964,
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0,
*oper.1 /flow is specified

```

```

21.6081,0.0,2.0,0.005,
*oper.2  *first word to be changed if you change BC
0
*oper.3  *only if first w above is not 0.0
1044.28,534.2,36.73,97.328,0.0
*oper.5
*13400 kg/s ,5%bypass and splitted evenly
*Rod power got from total power divided total number of rods
0,          *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,      *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
hnch,
*corr 18 , Hensch-Gillis
*****
grid,0,5,
*grid.1
23.37,6.630,1.500,1.460,20000,
*grid.2
*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
81,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5
17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,
49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,
65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,
81,
*grid.5
*3.0,1,13.5,2,34.5,3,58.5,3,76.5,3,94.5,3,118.5,3,136.5,3,
*154.5,3,175.5,3,          *grid
loc. *grid.6
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,          *grid
loc. *grid.6
2,1
82,83,
0.0,5,
0,
*****
cont,
*cont.1
0.0,0,750,50,3,0,      *iterative solution
*cont.2

```

```

0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd
*
*end of data input
0

```

## B.3 Annular 5x5-average bundle input

```

*****
*
* 1 assembly, 5x5 annular pins, using BWR power distribution *
*      AVERAGE      ROD
*
*      one axial profile and approximate radial profile
*
*      parDi: 0.90
*      parfuel: 0.90
*      Superpower: 1.00
*      MODIFIED HG correlation for CPR
*      ITERATIVE solution
*****
1,0,0,
*vipre.1
Bwr annular fuel
*vipre.2
*
geom,61,61,50,0,0,0,      *normal geometry input
*geom.1
*
178.5,0.0,0.5,
*geom.2
*
1,0.14993,1.87825,0.73968,2,2,0.09839,0.80177,7,0.09839,0.80177,
2,0.24047,2.51362,1.47936,2,3,0.09839,1.03425,8,0.09246,0.80177,
3,0.24047,2.51362,1.47936,2,4,0.09839,1.03425,9,0.09246,0.80177,
4,0.24047,2.51362,1.47936,2,5,0.09839,1.03425,10,0.09246,0.80177,
5,0.24047,2.51362,1.47936,2,6,0.09839,0.80177,11,0.09246,0.80177,
6,0.14993,1.87825,0.73968,1,12,0.09839,0.80177,
7,0.24047,2.51362,1.47936,2,8,0.09246,0.80177,13,0.09839,1.03425,
8,0.37306,2.95873,2.95873,2,9,0.09246,1.03425,14,0.09246,1.03425,
9,0.37306,2.95873,2.95873,2,10,0.09246,1.03425,15,0.09246,1.03425,
10,0.37306,2.95873,2.95873,2,11,0.09246,1.03425,16,0.09246,1.03425,
11,0.37306,2.95873,2.95873,2,12,0.09246,0.80177,17,0.09246,1.03425,
12,0.24047,2.51362,1.47936,1,18,0.09839,1.03425,
13,0.24047,2.51362,1.47936,2,14,0.09246,0.80177,19,0.09839,1.03425,

```

14,0.37306,2.95873,2.95873,2,15,0.09246,1.03425,20,0.09246,1.03425,  
15,0.37306,2.95873,2.21905,2,16,0.09246,1.03425,21,0.09246,1.03425,  
16,0.37306,2.95873,2.21905,2,17,0.09246,1.03425,22,0.09246,1.03425,  
17,0.37306,2.95873,2.95873,2,18,0.09246,0.80177,23,0.09246,1.03425,  
18,0.24047,2.51362,1.47936,1,24,0.09839,1.03425,  
19,0.24047,2.51362,1.47936,2,20,0.09246,0.80177,25,0.09839,1.03425,  
20,0.37306,2.95873,2.95873,2,21,0.09246,1.03425,26,0.09246,1.03425,  
21,0.37306,2.95873,2.21905,2,22,0.09246,1.03425,27,0.09246,1.03425,  
22,0.37306,2.95873,2.21905,2,23,0.09246,1.03425,28,0.09246,1.03425,  
23,0.37306,2.95873,2.95873,2,24,0.09246,0.80177,29,0.09246,1.03425,  
24,0.24047,2.51362,1.47936,1,30,0.09839,1.03425,  
25,0.24047,2.51362,1.47936,2,26,0.09246,0.80177,31,0.09839,0.80177,  
26,0.37306,2.95873,2.95873,2,27,0.09246,1.03425,32,0.09246,0.80177,  
27,0.37306,2.95873,2.95873,2,28,0.09246,1.03425,33,0.09246,0.80177,  
28,0.37306,2.95873,2.95873,2,29,0.09246,1.03425,34,0.09246,0.80177,  
29,0.37306,2.95873,2.95873,2,30,0.09246,0.80177,35,0.09246,0.80177,  
30,0.24047,2.51362,1.47936,1,36,0.09839,0.80177,  
31,0.14993,1.87825,0.73968,1,32,0.09839,0.80177,  
32,0.24047,2.51362,1.47936,1,33,0.09839,1.03425,  
33,0.24047,2.51362,1.47936,1,34,0.09839,1.03425,  
34,0.24047,2.51362,1.47936,1,35,0.09839,1.03425,  
35,0.24047,2.51362,1.47936,1,36,0.09839,0.80177,  
36,0.14993,1.87825,0.73968,

\*Internal subchannels

37,0.21794,1.65489,1.65489,  
38,0.21794,1.65489,1.65489,  
39,0.21794,1.65489,1.65489,  
40,0.21794,1.65489,1.65489,  
41,0.21794,1.65489,1.65489,  
42,0.21794,1.65489,1.65489,  
43,0.21794,1.65489,1.65489,  
44,0.21794,1.65489,1.65489,  
45,0.21794,1.65489,1.65489,  
46,0.21794,1.65489,1.65489,  
47,0.21794,1.65489,1.65489,  
48,0.21794,1.65489,1.65489,  
49,0.21794,1.65489,1.65489,  
50,0.21794,1.65489,1.65489,  
51,0.21794,1.65489,1.65489,  
52,0.21794,1.65489,1.65489,  
53,0.21794,1.65489,1.65489,  
54,0.21794,1.65489,1.65489,  
55,0.21794,1.65489,1.65489,  
56,0.21794,1.65489,1.65489,  
57,0.21794,1.65489,1.65489,  
58,0.21794,1.65489,1.65489,  
59,0.21794,1.65489,1.65489,  
60,0.21794,1.65489,1.65489,  
61,0.59573,2.73610,2.73610,

\*geom.4

prop,0,1,2,1 \*internal EPRI functions \*prop.1

\*

rods,1,50,1,2,4,0,0,0,0,1,0, \*three material types,one type of geo.

\*rods.1

144.0,13.513,0,0,

\*rods.2

26

\*rods3

\*One axial profile only (rods.4)

0.,0.,?  
3.,0.11769,?  
9.,0.60128,?  
15.,0.82226,  
21.,0.9944,?  
27.,1.1257,?  
33.,1.20176,?  
39.,1.23379,  
45.,1.23859,?  
51.,1.22898,?  
57.,1.21297,?  
63.,1.19376,  
69.,1.17454,?  
75.,1.15853,?  
81.,1.14732,?  
87.,1.14171,  
93.,1.13931,?  
99.,1.14171,?  
105.,1.14412,?  
111.,1.13211,  
117.,1.08006,?  
123.,0.98559,?  
129.,0.83106,?  
135.,0.61329,  
141.,0.34508,?  
144.,0.,

\*

\*

\*\*\*\*\*rods geomatry input

\*rods.9

1,1,1.030,1,1,0.25,2,0.25,7,0.25,8,0.25,  
-1,1,1.030,1,37,1,  
2,1,1.217,1,2,0.25,3,0.25,8,0.25,9,0.25,  
-2,1,1.217,1,38,1,  
3,1,1.140,1,3,0.25,4,0.25,9,0.25,10,0.25,  
-3,1,1.140,1,39,1,  
4,1,1.216,1,4,0.25,5,0.25,10,0.25,11,0.25,  
-4,1,1.216,1,40,1,  
5,1,1.029,1,5,0.25,6,0.25,11,0.25,12,0.25,  
-5,1,1.029,1,41,1,  
6,1,1.217,1,7,0.25,8,0.25,13,0.25,14,0.25,  
-6,1,1.217,1,42,1,  
7,1,0.369,1,8,0.25,9,0.25,14,0.25,15,0.25,  
-7,1,0.369,1,43,1,  
8,1,1.031,1,9,0.25,10,0.25,15,0.25,16,0.25,  
-8,1,1.031,1,44,1,  
9,1,0.369,1,10,0.25,11,0.25,16,0.25,17,0.25,  
-9,1,0.369,1,45,1,  
10,1,1.215,1,11,0.25,12,0.25,17,0.25,18,0.25,  
-10,1,1.215,1,46,1,  
11,1,1.140,1,13,0.25,14,0.25,19,0.25,20,0.25,  
-11,1,1.140,1,47,1,  
12,1,1.031,1,14,0.25,15,0.25,20,0.25,21,0.25,  
-12,1,1.031,1,48,1,

```

13,1,1.031,1,16,0.25,17,0.25,22,0.25,23,0.25,
-13,1,1.031,1,49,1,
14,1,1.139,1,17,0.25,18,0.25,23,0.25,24,0.25,
-14,1,1.139,1,50,1,
15,1,1.216,1,19,0.25,20,0.25,25,0.25,26,0.25,
-15,1,1.216,1,51,1,
16,1,0.369,1,20,0.25,21,0.25,26,0.25,27,0.25,
-16,1,0.369,1,52,1,
17,1,1.031,1,21,0.25,22,0.25,27,0.25,28,0.25,
-17,1,1.031,1,53,1,
18,1,0.369,1,22,0.25,23,0.25,28,0.25,29,0.25,
-18,1,0.369,1,54,1,
19,1,1.215,1,23,0.25,24,0.25,29,0.25,30,0.25,
-19,1,1.215,1,55,1,
20,1,1.029,1,25,0.25,26,0.25,31,0.25,32,0.25,
-20,1,1.029,1,56,1,
21,1,1.215,1,26,0.25,27,0.25,32,0.25,33,0.25,
-21,1,1.215,1,57,1,
22,1,1.139,1,27,0.25,28,0.25,33,0.25,34,0.25,
-22,1,1.139,1,58,1,
23,1,1.215,1,28,0.25,29,0.25,34,0.25,35,0.25,
-23,1,1.215,1,59,1,
24,1,1.028,1,29,0.25,30,0.25,35,0.25,36,0.25,
-24,1,1.028,1,60,1,
25,2,0.0,1,15,0.25,16,0.25,21,0.25,22,0.25,
rod
-25,2,0.0,1,-61,1,
*water rod
0
*rods.9
*
1,2,3,4,5,
6,7,8,9,10,
11,12,25,13,14,
15,16,17,18,19,
20,21,22,23,24,

*blank line above necessary /rods.57 -HG CPR corr
25,1.034255,0.098389,0.941793,16.242377,
0
*rods.58,
*rods.59
*
*fuel
1,tube,0.941793,0.526769,5,
*rods.68
*
2,1,0.033465,0.0,? *inner cladding
*rods.69
2,2,0.003937,0.0,? *inner gap
*rods.69
8,3,0.132709,1.0,? *fuel ring
*rods.69
2,4,0.003937,0.0, *outer gap
*rods.69
2,1,0.033465,0.0, *outer cladding
*rods.69
*
*water tube

```

2,tube,0.941793,0.870927,1  
3,1,0.035433,0.0,  
\*

\*rods.68  
\*rods.69

1,18,409.0,clad,  
\*table for cladding  
\*rods.70  
0.0,0.0671,7.3304509,?  
25,0.0671,7.3304509,  
50,0.0671,7.33045093,?  
65,0.0671,7.33045093,  
80.33,0.0671,7.33045093,?  
260.33,0.07212,8.11585329,  
692.33,0.07904,9.80167423,?  
1502.33,0.08955,13.2923,  
1507.73,0.11988,13.3211893,?  
1543.73,0.14089,13.51665,  
1579.73,0.14686,13.717249,?  
1615.73,0.1717,13.923198,  
1651.73,0.1949,14.1347101,?  
1687.73,0.18388,14.351998,  
1723.73,0.1478,14.5752746,?  
1759.73,0.112,14.804753,  
1786.73,0.085,14.9810589,?  
2240.33,0.085,18.5665964,  
\*

\*gap  
2,1,0.025,igap,  
\*rods.70  
1,1.240834,0.346679, \*Cp=5195J/kg-K \*gap=6000  
\*rods.71  
\*

\*fuel  
3,22,650.617,FUO2,  
\*rods.70  
86,0.05677357,4.73275874,?  
176,0.06078589,4.2991726,  
266,0.06366347,3.93877428,?  
356,0.06581210,3.6345405,  
446,0.06747631,3.37435643,?  
536,0.06880819,3.1493668,  
626,0.06990545,2.95294976,?  
716,0.07083283,2.78005572,  
806,0.07163441,2.62676801,?  
896,0.07234099,2.49000319,  
986,0.07297458,2.36730189,?  
1076,0.07355124,2.25667975,  
1166,0.07408294,2.1565193,?  
1256,0.07457886,2.06549023,  
1346,0.07504628,1.98248979,?  
1436,0.07549123,1.90659753,  
1526,0.0759191,1.83704065,?  
1616,0.07633503,1.77316713,  
1706,0.0767443,1.7144247,?  
1796,0.07715268,1.66034425,  
1886,0.07756663,1.61052668,?

```

1976,0.07799351,1.5646323,
*rods.71
*
*outer gap
4,1,0.025,ogap,
*rods.70
1,1.240834,0.34667666,      *Cp=5195J/kg-K *gap=6000
*rods.71
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0
*oper.1
-1.0,0.0,2.0,0.005,                      *oper.2   *first
word to be changed if you change BC
0                                           *oper.3   *only if first w above is
not 0.0
1044.27,534.2,36.730000,179.590000,0.0,
*oper.5
*13400 kg/s ,5*Rod power got from total power divided total number of
rods
0,                                           *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,          *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
mine,
*corr 18 , Hench-Gillis
*****
grid,0,5,
*grid.1
24.280,6.63,1.50,1.46,20000,
*grid.2
*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
36,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5
17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,
*grid.5
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,                      *grid
loc. *grid.6
24,3
37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,
53,54,55,56,57,58,59,60,

```

```

1.0,1,12.263,2,31.225,3,
1,1,
61,
1.0,5,
0,
*****
cont,
*cont.1
0.0,0,50,50,3,0,
*cont.2
0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd
*
*end of data input
0

```

## B.4 Annular 5x5-hot bundle input

```

*****
*
* 1 assembly, 5x5 annular pins, using BWR power distribution
* HOT ROD
* one axial profile and approximate radial profile
*
* parDi: 0.90
* parfuel: 0.90
* Superpower: 1.00
* MODIFIED HG correlation for CPR
* ITERATIVE solution
*****
1,0,0,
*vipre.1
Bwr annular fuel
*vipre.2
*
geom,61,61,50,0,0,0, *normal geometry input
*geom.1
*
178.5,0.0,0.5,
*geom.2
*
1,0.14993,1.87825,0.73968,2,2,0.09839,0.80177,7,0.09839,0.80177,
2,0.24047,2.51362,1.47936,2,3,0.09839,1.03425,8,0.09246,0.80177,
3,0.24047,2.51362,1.47936,2,4,0.09839,1.03425,9,0.09246,0.80177,
4,0.24047,2.51362,1.47936,2,5,0.09839,1.03425,10,0.09246,0.80177,

```

5,0.24047,2.51362,1.47936,2,6,0.09839,0.80177,11,0.09246,0.80177,  
6,0.14993,1.87825,0.73968,1,12,0.09839,0.80177,  
7,0.24047,2.51362,1.47936,2,8,0.09246,0.80177,13,0.09839,1.03425,  
8,0.37306,2.95873,2.95873,2,9,0.09246,1.03425,14,0.09246,1.03425,  
9,0.37306,2.95873,2.95873,2,10,0.09246,1.03425,15,0.09246,1.03425,  
10,0.37306,2.95873,2.95873,2,11,0.09246,1.03425,16,0.09246,1.03425,  
11,0.37306,2.95873,2.95873,2,12,0.09246,0.80177,17,0.09246,1.03425,  
12,0.24047,2.51362,1.47936,1,18,0.09839,1.03425,  
13,0.24047,2.51362,1.47936,2,14,0.09246,0.80177,19,0.09839,1.03425,  
14,0.37306,2.95873,2.95873,2,15,0.09246,1.03425,20,0.09246,1.03425,  
15,0.37306,2.95873,2.21905,2,16,0.09246,1.03425,21,0.09246,1.03425,  
16,0.37306,2.95873,2.21905,2,17,0.09246,1.03425,22,0.09246,1.03425,  
17,0.37306,2.95873,2.95873,2,18,0.09246,0.80177,23,0.09246,1.03425,  
18,0.24047,2.51362,1.47936,1,24,0.09839,1.03425,  
19,0.24047,2.51362,1.47936,2,20,0.09246,0.80177,25,0.09839,1.03425,  
20,0.37306,2.95873,2.95873,2,21,0.09246,1.03425,26,0.09246,1.03425,  
21,0.37306,2.95873,2.21905,2,22,0.09246,1.03425,27,0.09246,1.03425,  
22,0.37306,2.95873,2.21905,2,23,0.09246,1.03425,28,0.09246,1.03425,  
23,0.37306,2.95873,2.95873,2,24,0.09246,0.80177,29,0.09246,1.03425,  
24,0.24047,2.51362,1.47936,1,30,0.09839,1.03425,  
25,0.24047,2.51362,1.47936,2,26,0.09246,0.80177,31,0.09839,0.80177,  
26,0.37306,2.95873,2.95873,2,27,0.09246,1.03425,32,0.09246,0.80177,  
27,0.37306,2.95873,2.95873,2,28,0.09246,1.03425,33,0.09246,0.80177,  
28,0.37306,2.95873,2.95873,2,29,0.09246,1.03425,34,0.09246,0.80177,  
29,0.37306,2.95873,2.95873,2,30,0.09246,0.80177,35,0.09246,0.80177,  
30,0.24047,2.51362,1.47936,1,36,0.09839,0.80177,  
31,0.14993,1.87825,0.73968,1,32,0.09839,0.80177,  
32,0.24047,2.51362,1.47936,1,33,0.09839,1.03425,  
33,0.24047,2.51362,1.47936,1,34,0.09839,1.03425,  
34,0.24047,2.51362,1.47936,1,35,0.09839,1.03425,  
35,0.24047,2.51362,1.47936,1,36,0.09839,0.80177,  
36,0.14993,1.87825,0.73968,  
\*Internal subchannels  
37,0.21794,1.65489,1.65489,  
38,0.21794,1.65489,1.65489,  
39,0.21794,1.65489,1.65489,  
40,0.21794,1.65489,1.65489,  
41,0.21794,1.65489,1.65489,  
42,0.21794,1.65489,1.65489,  
43,0.21794,1.65489,1.65489,  
44,0.21794,1.65489,1.65489,  
45,0.21794,1.65489,1.65489,  
46,0.21794,1.65489,1.65489,  
47,0.21794,1.65489,1.65489,  
48,0.21794,1.65489,1.65489,  
49,0.21794,1.65489,1.65489,  
50,0.21794,1.65489,1.65489,  
51,0.21794,1.65489,1.65489,  
52,0.21794,1.65489,1.65489,  
53,0.21794,1.65489,1.65489,  
54,0.21794,1.65489,1.65489,  
55,0.21794,1.65489,1.65489,  
56,0.21794,1.65489,1.65489,  
57,0.21794,1.65489,1.65489,  
58,0.21794,1.65489,1.65489,  
59,0.21794,1.65489,1.65489,

```

60,0.21794,1.65489,1.65489,
61,0.59573,2.73610,2.73610,
*geom.4
prop,0,1,2,1  *internal EPRI functions *prop.1
*
rods,1,50,1,2,4,0,0,0,0,1,0,  *three material types,one type of geo.
*rods.1
144.0,13.513,0,0,
*rods.2
26
*rods3
*One axial profile only (rods.4)
0.,0.,?
3.,0.11769,?
9.,0.60128,?
15.,0.82226,
21.,0.9944,?
27.,1.1257,?
33.,1.20176,?
39.,1.23379,
45.,1.23859,?
51.,1.22898,?
57.,1.21297,?
63.,1.19376,
69.,1.17454,?
75.,1.15853,?
81.,1.14732,?
87.,1.14171,
93.,1.13931,?
99.,1.14171,?
105.,1.14412,?
111.,1.13211,
117.,1.08006,?
123.,0.98559,?
129.,0.83106,?
135.,0.61329,
141.,0.34508,?
144.,0.,
*
*
*****rods geomatry input                                *rods.9
1,1,1.030,1,1,0.25,2,0.25,7,0.25,8,0.25,
-1,1,1.030,1,37,1,
2,1,1.217,1,2,0.25,3,0.25,8,0.25,9,0.25,
-2,1,1.217,1,38,1,
3,1,1.140,1,3,0.25,4,0.25,9,0.25,10,0.25,
-3,1,1.140,1,39,1,
4,1,1.216,1,4,0.25,5,0.25,10,0.25,11,0.25,
-4,1,1.216,1,40,1,
5,1,1.029,1,5,0.25,6,0.25,11,0.25,12,0.25,
-5,1,1.029,1,41,1,
6,1,1.217,1,7,0.25,8,0.25,13,0.25,14,0.25,
-6,1,1.217,1,42,1,
7,1,0.369,1,8,0.25,9,0.25,14,0.25,15,0.25,
-7,1,0.369,1,43,1,
8,1,1.031,1,9,0.25,10,0.25,15,0.25,16,0.25,

```

```

-8,1,1.031,1,44,1,
9,1,0.369,1,10,0.25,11,0.25,16,0.25,17,0.25,
-9,1,0.369,1,45,1,
10,1,1.215,1,11,0.25,12,0.25,17,0.25,18,0.25,
-10,1,1.215,1,46,1,
11,1,1.140,1,13,0.25,14,0.25,19,0.25,20,0.25,
-11,1,1.140,1,47,1,
12,1,1.031,1,14,0.25,15,0.25,20,0.25,21,0.25,
-12,1,1.031,1,48,1,
13,1,1.031,1,16,0.25,17,0.25,22,0.25,23,0.25,
-13,1,1.031,1,49,1,
14,1,1.139,1,17,0.25,18,0.25,23,0.25,24,0.25,
-14,1,1.139,1,50,1,
15,1,1.216,1,19,0.25,20,0.25,25,0.25,26,0.25,
-15,1,1.216,1,51,1,
16,1,0.369,1,20,0.25,21,0.25,26,0.25,27,0.25,
-16,1,0.369,1,52,1,
17,1,1.031,1,21,0.25,22,0.25,27,0.25,28,0.25,
-17,1,1.031,1,53,1,
18,1,0.369,1,22,0.25,23,0.25,28,0.25,29,0.25,
-18,1,0.369,1,54,1,
19,1,1.215,1,23,0.25,24,0.25,29,0.25,30,0.25,
-19,1,1.215,1,55,1,
20,1,1.029,1,25,0.25,26,0.25,31,0.25,32,0.25,
-20,1,1.029,1,56,1,
21,1,1.215,1,26,0.25,27,0.25,32,0.25,33,0.25,
-21,1,1.215,1,57,1,
22,1,1.139,1,27,0.25,28,0.25,33,0.25,34,0.25,
-22,1,1.139,1,58,1,
23,1,1.215,1,28,0.25,29,0.25,34,0.25,35,0.25,
-23,1,1.215,1,59,1,
24,1,1.028,1,29,0.25,30,0.25,35,0.25,36,0.25,
-24,1,1.028,1,60,1,
25,2,0.0,1,15,0.25,16,0.25,21,0.25,22,0.25,
rod
-25,2,0.0,1,-61,1,
*water rod
0
*rods.9
*
1,2,3,4,5,
6,7,8,9,10,
11,12,25,13,14,
15,16,17,18,19,
20,21,22,23,24,

*blank line above necessary /rods.57 -HG CPR corr
25,1.034255,0.098389,0.941793,16.242377,
0
*rods.58,
*rods.59
*
*fuel
1,tube,0.941793,0.526769,5,
*rods.68
*
2,1,0.033465,0.0,? *inner cladding
*rods.69

```

```

2,2,0.003937,0.0,? *inner gap
*rods.69
8,3,0.132709,1.0,? *fuel ring
*rods.69
2,4,0.003937,0.0, *outer gap
*rods.69
2,1,0.033465,0.0, *outer cladding
*rods.69
*
*water tube
2,tube,0.941793,0.870927,1 *rods.68
3,1,0.035433,0.0, *rods.69
*
1,18,409.0,clad,
*table for cladding
*rods.70
0.0,0.0671,7.3304509,?
25,0.0671,7.3304509,
50,0.0671,7.33045093,?
65,0.0671,7.33045093,
80.33,0.0671,7.33045093,?
260.33,0.07212,8.11585329,
692.33,0.07904,9.80167423,?
1502.33,0.08955,13.2923,
1507.73,0.11988,13.3211893,?
1543.73,0.14089,13.51665,
1579.73,0.14686,13.717249,?
1615.73,0.1717,13.923198,
1651.73,0.1949,14.1347101,?
1687.73,0.18388,14.351998,
1723.73,0.1478,14.5752746,?
1759.73,0.112,14.804753,
1786.73,0.085,14.9810589,?
2240.33,0.085,18.5665964,
*
*gap
2,1,0.025,igap,
*rods.70
1,1.240834,0.346679, *Cp=5195J/kg-K *gap=6000
*rods.71
*
*fuel
3,22,650.617,FUO2,
*rods.70
86,0.05677357,4.73275874,?
176,0.06078589,4.2991726,
266,0.06366347,3.93877428,?
356,0.06581210,3.6345405,
446,0.06747631,3.37435643,?
536,0.06880819,3.1493668,
626,0.06990545,2.95294976,?
716,0.07083283,2.78005572,
806,0.07163441,2.62676801,?
896,0.07234099,2.49000319,
986,0.07297458,2.36730189,?
1076,0.07355124,2.25667975,

```

```

1166,0.07408294,2.1565193,?
1256,0.07457886,2.06549023,
1346,0.07504628,1.98248979,?
1436,0.07549123,1.90659753,
1526,0.0759191,1.83704065,?
1616,0.07633503,1.77316713,
1706,0.0767443,1.7144247,?
1796,0.07715268,1.66034425,
1886,0.07756663,1.61052668,?
1976,0.07799351,1.5646323,
*rods.71
*
*outer gap
4,1,0.025,ogap,
*rods.70
1,1.240834,0.34667666,      *Cp=5195J/kg-K *gap=6000
*rods.71
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0
*oper.1
20.020000,0.0,2.0,0.005,      *oper.2   *first word to be
changed if you change BC
0                                *oper.3   *only if
first w above is not 0.0
1044.27,534.2,36.730000,251.426000,0.0,
*oper.5
*13400 kg/s ,5*Rod power got from total power divided total number of
rods
0,                                *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,      *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
mine,
*corr 18 , Hensch-Gillis
*****
grid,0,5,
*grid.1
23.370,6.63,1.50,1.46,20000,
*grid.2
*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
36,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5

```

```

17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,
*grid.5
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,                                *grid
loc. *grid.6
24,3
37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,
53,54,55,56,57,58,59,60,
1.0,1,12.263,2,31.225,3,
1,1,
61,
1.0,5,
0,
*****
cont,
*cont.1
0.0,0,50,50,3,0,
*cont.2
0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd
*
*end of data input
0

```

## B.5 Annular 6x6-average bundle input

```

*****
*
* 1 assembly, 6x6 annular pins, using BWR power distribution *
*   AVERAGE   ROD
*
*   one axial profile and approximate radial profile
*
*   parDi: 0.80 *
*   parfuel: 0.90 *
*   Superpower: 1.00 *
*   MODIFIED HG correlation for CPR *
*   ITERATIVE solution *
*****
1,0,0,
*vipre.1

```

```

Bwr annular fuel
*vipre.2
*
geom,85,85,50,0,0,0,      *normal geometry input
*geom.1
*
178.5,0.0,0.5,
*geom.2
*
1,0.07566,1.57013,0.65173,2,2,0.04430,0.66532,8,0.04430,0.66532,
2,0.12976,2.17490,1.30346,2,3,0.04430,0.87144,9,0.04163,0.66532,
3,0.12976,2.17490,1.30346,2,4,0.04430,0.87144,10,0.04163,0.66532,
4,0.12976,2.17490,1.30346,2,5,0.04430,0.87144,11,0.04163,0.66532,
5,0.12976,2.17490,1.30346,2,6,0.04430,0.87144,12,0.04163,0.66532,
6,0.12976,2.17490,1.30346,2,7,0.04430,0.66532,13,0.04163,0.66532,
7,0.07566,1.57013,0.65173,1,14,0.04430,0.66532,
8,0.12976,2.17490,1.30346,2,9,0.04163,0.66532,15,0.04430,0.87144,
9,0.21859,2.60692,2.60692,2,10,0.04163,0.87144,16,0.04163,0.87144,
10,0.21859,2.60692,2.60692,2,11,0.04163,0.87144,17,0.04163,0.87144,
11,0.21859,2.60692,2.60692,2,12,0.04163,0.87144,18,0.04163,0.87144,
12,0.21859,2.60692,2.60692,2,13,0.04163,0.87144,19,0.04163,0.87144,
13,0.21859,2.60692,2.60692,2,14,0.04163,0.66532,20,0.04163,0.87144,
14,0.12976,2.17490,1.30346,1,21,0.04430,0.87144,
15,0.12976,2.17490,1.30346,2,16,0.04163,0.66532,22,0.04430,0.87144,
16,0.21859,2.60692,2.60692,2,17,0.04163,0.87144,23,0.04163,0.87144,
17,0.21859,2.60692,2.60692,2,18,0.04163,0.87144,24,0.04163,0.87144,
18,0.21859,2.60692,1.95519,2,19,0.04163,0.87144,25,0.04163,0.87144,
19,0.21859,2.60692,1.95519,2,20,0.04163,0.87144,26,0.04163,0.87144,
20,0.21859,2.60692,2.60692,2,21,0.04163,0.66532,27,0.04163,0.87144,
21,0.12976,2.17490,1.30346,1,28,0.04430,0.87144,
22,0.12976,2.17490,1.30346,2,23,0.04163,0.66532,29,0.04430,0.87144,
23,0.21859,2.60692,2.60692,2,24,0.04163,0.87144,30,0.04163,0.87144,
24,0.21859,2.60692,1.95519,2,25,0.04163,0.87144,31,0.04163,0.87144,
25,0.21859,2.60692,1.95519,2,26,0.04163,0.87144,32,0.04163,0.87144,
26,0.21859,2.60692,1.95519,2,27,0.04163,0.87144,33,0.04163,0.87144,
27,0.21859,2.60692,2.60692,2,28,0.04163,0.66532,34,0.04163,0.87144,
28,0.12976,2.17490,1.30346,1,35,0.04430,0.87144,
29,0.12976,2.17490,1.30346,2,30,0.04163,0.66532,36,0.04430,0.87144,
30,0.21859,2.60692,2.60692,2,31,0.04163,0.87144,37,0.04163,0.87144,
31,0.21859,2.60692,1.95519,2,32,0.04163,0.87144,38,0.04163,0.87144,
32,0.21859,2.60692,1.95519,2,33,0.04163,0.87144,39,0.04163,0.87144,
33,0.21859,2.60692,2.60692,2,34,0.04163,0.87144,40,0.04163,0.87144,
34,0.21859,2.60692,2.60692,2,35,0.04163,0.66532,41,0.04163,0.87144,
35,0.12976,2.17490,1.30346,1,42,0.04430,0.87144,
36,0.12976,2.17490,1.30346,2,37,0.04163,0.66532,43,0.04430,0.66532,
37,0.21859,2.60692,2.60692,2,38,0.04163,0.87144,44,0.04163,0.66532,
38,0.21859,2.60692,2.60692,2,39,0.04163,0.87144,45,0.04163,0.66532,
39,0.21859,2.60692,2.60692,2,40,0.04163,0.87144,46,0.04163,0.66532,
40,0.21859,2.60692,2.60692,2,41,0.04163,0.87144,47,0.04163,0.66532,
41,0.21859,2.60692,2.60692,2,42,0.04163,0.66532,48,0.04163,0.66532,
42,0.12976,2.17490,1.30346,1,49,0.04430,0.66532,
43,0.07566,1.57013,0.65173,1,32,0.04430,0.66532,
44,0.12976,2.17490,1.30346,1,33,0.04430,0.87144,
45,0.12976,2.17490,1.30346,1,34,0.04430,0.87144,
46,0.12976,2.17490,1.30346,1,35,0.04430,0.87144,
47,0.12976,2.17490,1.30346,1,36,0.04430,0.87144,

```

```

48,0.12976,2.17490,1.30346,1,36,0.04430,0.66532,
49,0.07566,1.57013,0.65173,
*Internal subchannels
50,0.17220,1.47102,1.47102,
51,0.17220,1.47102,1.47102,
52,0.17220,1.47102,1.47102,
53,0.17220,1.47102,1.47102,
54,0.17220,1.47102,1.47102,
55,0.17220,1.47102,1.47102,
56,0.17220,1.47102,1.47102,
57,0.17220,1.47102,1.47102,
58,0.17220,1.47102,1.47102,
59,0.17220,1.47102,1.47102,
60,0.17220,1.47102,1.47102,
61,0.17220,1.47102,1.47102,
62,0.17220,1.47102,1.47102,
63,0.17220,1.47102,1.47102,
64,0.17220,1.47102,1.47102,
65,0.17220,1.47102,1.47102,
66,0.17220,1.47102,1.47102,
67,0.17220,1.47102,1.47102,
68,0.17220,1.47102,1.47102,
69,0.17220,1.47102,1.47102,
70,0.17220,1.47102,1.47102,
71,0.17220,1.47102,1.47102,
72,0.17220,1.47102,1.47102,
73,0.17220,1.47102,1.47102,
74,0.17220,1.47102,1.47102,
75,0.17220,1.47102,1.47102,
76,0.17220,1.47102,1.47102,
77,0.17220,1.47102,1.47102,
78,0.17220,1.47102,1.47102,
79,0.17220,1.47102,1.47102,
80,0.17220,1.47102,1.47102,
81,0.17220,1.47102,1.47102,
82,0.17220,1.47102,1.47102,
83,0.17220,1.47102,1.47102,
84,0.45239,2.38429,2.38429,
85,0.45239,2.38429,2.38429,
*geom.4
prop,0,1,2,1 *internal EPRI functions *prop.1
*
rods,1,72,1,2,4,0,0,0,0,1,0, *three material types,one type of geo.
*rods.1
144.0,13.513,0,0,
*rods.2
26
*rods3
*One axial profile only (rods.4)
0.,0.,?
3.,0.11769,?
9.,0.60128,?
15.,0.82226,
21.,0.9944,?
27.,1.1257,?
33.,1.20176,?

```

39.,1.23379,  
45.,1.23859,?  
51.,1.22898,?  
57.,1.21297,?  
63.,1.19376,  
69.,1.17454,?  
75.,1.15853,?  
81.,1.14732,?  
87.,1.14171,  
93.,1.13931,?  
99.,1.14171,?  
105.,1.14412,?  
111.,1.13211,  
117.,1.08006,?  
123.,0.98559,?  
129.,0.83106,?  
135.,0.61329,  
141.,0.34508,?  
144.,0.,

\*

\*

\*\*\*\*\*rods geomatry input

\*rods.9

1,1,1.102,1,1,0.25,2,0.25,8,0.25,9,0.25,  
-1,1,1.102,1,50,1,  
2,1,1.085,1,2,0.25,3,0.25,9,0.25,10,0.25,  
-2,1,1.085,1,51,1,  
3,1,1.099,1,3,0.25,4,0.25,10,0.25,11,0.25,  
-3,1,1.099,1,52,1,  
4,1,1.103,1,4,0.25,5,0.25,11,0.25,12,0.25,  
-4,1,1.103,1,53,1,  
5,1,1.088,1,5,0.25,6,0.25,12,0.25,13,0.25,  
-5,1,1.088,1,54,1,  
6,1,1.102,1,6,0.25,7,0.25,13,0.25,14,0.25,  
-6,1,1.102,1,55,1,  
7,1,1.085,1,8,0.25,9,0.25,15,0.25,16,0.25,  
-7,1,1.085,1,56,1,  
8,1,0.377,1,9,0.25,10,0.25,16,0.25,17,0.25,  
-8,1,0.377,1,57,1,  
9,1,1.016,1,10,0.25,11,0.25,17,0.25,18,0.25,  
-9,1,1.016,1,58,1,  
10,1,1.068,1,11,0.25,12,0.25,18,0.25,19,0.25,  
-10,1,1.068,1,59,1,  
11,1,0.381,1,12,0.25,13,0.25,19,0.25,20,0.25,  
-11,1,0.381,1,60,1,  
12,1,1.087,1,13,0.25,14,0.25,20,0.25,21,0.25,  
-12,1,1.087,1,61,1,  
13,1,1.099,1,15,0.25,16,0.25,22,0.25,23,0.25,  
-13,1,1.099,1,62,1,  
14,1,1.016,1,16,0.25,17,0.25,23,0.25,24,0.25,  
-14,1,1.016,1,63,1,  
15,1,1.129,1,17,0.25,18,0.25,24,0.25,25,0.25,  
-15,1,1.129,1,64,1,  
16,1,1.067,1,19,0.25,20,0.25,26,0.25,27,0.25,  
-16,1,1.067,1,65,1,  
17,1,1.102,1,20,0.25,21,0.25,27,0.25,28,0.25,  
-17,1,1.102,1,66,1,

```

18,1,1.103,1,22,0.25,23,0.29,28,0.25,30,0.25,
-18,1,1.103,1,67,1,
19,1,1.068,1,23,0.25,24,0.25,30,0.25,31,0.25,
-19,1,1.068,1,68,1,
20,1,1.129,1,25,0.25,26,0.25,32,0.25,33,0.25,
-20,1,1.129,1,69,1,
21,1,1.016,1,26,0.25,27,0.25,33,0.25,34,0.25,
-21,1,1.016,1,70,1,
22,1,1.097,1,27,0.25,28,0.25,34,0.25,35,0.25,
-22,1,1.097,1,71,1,
23,1,1.088,1,29,0.25,30,0.25,36,0.25,37,0.25,
-23,1,1.088,1,72,1,
24,1,0.381,1,30,0.25,31,0.25,37,0.25,38,0.25,
-24,1,0.381,1,73,1,
25,1,1.067,1,31,0.25,32,0.25,38,0.25,39,0.25,
-25,1,1.067,1,74,1,
26,1,1.016,1,32,0.25,33,0.25,39,0.25,40,0.25,
-26,1,1.016,1,75,1,
27,1,0.377,1,33,0.25,34,0.25,40,0.25,41,0.25,
-27,1,0.377,1,76,1,
28,1,1.083,1,34,0.25,35,0.25,41,0.25,42,0.25,
-28,1,1.083,1,77,1,
29,1,1.102,1,36,0.25,37,0.25,43,0.25,44,0.25,
-29,1,1.102,1,78,1,
30,1,1.087,1,37,0.25,38,0.25,44,0.25,45,0.25,
-30,1,1.087,1,79,1,
31,1,1.102,1,38,0.25,39,0.25,45,0.25,46,0.25,
-31,1,1.102,1,80,1,
32,1,1.097,1,39,0.25,40,0.25,46,0.25,47,0.25,
-32,1,1.097,1,81,1,
33,1,1.083,1,40,0.25,41,0.25,47,0.25,48,0.25,
-33,1,1.083,1,82,1,
34,1,1.098,1,41,0.25,42,0.25,48,0.25,49,0.25,
-34,1,1.098,1,83,1,
35,2,0.0,1,18,0.25,19,0.25,25,0.25,26,0.25,
rod *water
-35,2,0.0,1,-84,1,
*water rod
36,2,0.0,1,24,0.25,25,0.25,31,0.25,32,0.25,
rod *water
-36,2,0.0,1,-85,1,
*water rod
0
*rods.9
*
1,2,3,4,5,6,
7,8,9,10,11,12,
13,14,15,35,16,17,
18,19,36,20,21,22,
23,24,25,26,27,28,
29,30,31,32,33,34,

*blank line above necessary /rods.57 -HG CPR corr
36,0.871438,0.044296,0.829810,15.122049, *rods.58,
0 *rods.59
*
```

```

*fuel
1,tube,0.829810,0.468239,5,
*
2,1,0.033465,0.0,? *inner cladding
*rods.69
2,2,0.003937,0.0,? *inner gap
*rods.69
8,3,0.105982,1.0,? *fuel ring
*rods.69
2,4,0.003937,0.0, *outer gap
*rods.69
2,1,0.033465,0.0, *outer cladding
*rods.69
*
*water tube
2,tube,0.829810,0.758944,1
3,1,0.035433,0.0,
*
1,18,409.0,clad,
*table for cladding
*rods.70
0.0,0.0671,7.3304509,?
25,0.0671,7.3304509,
50,0.0671,7.33045093,?
65,0.0671,7.33045093,
80.33,0.0671,7.33045093,?
260.33,0.07212,8.11585329,
692.33,0.07904,9.80167423,?
1502.33,0.08955,13.2923,
1507.73,0.11988,13.3211893,?
1543.73,0.14089,13.51665,
1579.73,0.14686,13.717249,?
1615.73,0.1717,13.923198,
1651.73,0.1949,14.1347101,?
1687.73,0.18388,14.351998,
1723.73,0.1478,14.5752746,?
1759.73,0.112,14.804753,
1786.73,0.085,14.9810589,?
2240.33,0.085,18.5665964,
*
*gap
2,1,0.025,igap,
*rods.70
1,1.240834,0.346679, *Cp=5195J/kg-K *gap=6000
*rods.71
*
*fuel
3,22,650.617,FUO2,
*rods.70
86,0.05677357,4.73275874,?
176,0.06078589,4.2991726,
266,0.06366347,3.93877428,?
356,0.06581210,3.6345405,
446,0.06747631,3.37435643,?
536,0.06880819,3.1493668,
626,0.06990545,2.95294976,?

```

```

716,0.07083283,2.78005572,
806,0.07163441,2.62676801,?
896,0.07234099,2.49000319,
986,0.07297458,2.36730189,?
1076,0.07355124,2.25667975,
1166,0.07408294,2.1565193,?
1256,0.07457886,2.06549023,
1346,0.07504628,1.98248979,?
1436,0.07549123,1.90659753,
1526,0.0759191,1.83704065,?
1616,0.07633503,1.77316713,
1706,0.0767443,1.7144247,?
1796,0.07715268,1.66034425,
1886,0.07756663,1.61052668,?
1976,0.07799351,1.5646323,
*rods.71
*
*outer gap
4,1,0.025,ogap,
*rods.70
1,1.240834,0.34667666,      *Cp=5195J/kg-K *gap=6000
*rods.71
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0
*oper.1
-1.0,0.0,2.0,0.005,          *oper.2   *first
word to be changed if you change BC
0                               *oper.3   *only if first w above is
not 0.0
1044.27,534.2,36.730000,126.770000,0.0,
*oper.5
*13400 kg/s ,5*Rod power got from total power divided total number of
rods
0,                               *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,      *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
mine,
*corr 18 , Hench-Gillis
*****
grid,0,5,
*grid.1
24.280,6.63,1.50,1.46,20000,
*grid.2

```

```

*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
49,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5
17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,
49,
*grid.5
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,
*grid
loc. *grid.6
34,3,
50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,
66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,
82,83,
1.0,1,12.263,2,31.225,3,
2,1,
84,85,
1.0,5,
0,
*****
cont,
*cont.1
0.0,0,50,50,3,0,
*cont.2
0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd
*
*end of data input
0

```

## B.6 Annular 6x6-hot bundle input

```

*****
*
* 1 assembly, 6x6 annular pins, using BWR power distribution *
*      HOT      ROD *
*      one axial profile and approximate radial profile *
*
*      parDi: 0.80 *
*      parfuel: 0.90 *
*      Superpower: 1.00 *
*      MODIFIED HG correlation for CPR *
*      ITERATIVE solution *
*****

```

```

1,0,0,
*vipre.1
Bwr annular fuel
*vipre.2
*
geom,85,85,50,0,0,0,      *normal geometry input
*geom.1
*
178.5,0.0,0.5,
*geom.2
*
1,0.07566,1.57013,0.65173,2,2,0.04430,0.66532,8,0.04430,0.66532,
2,0.12976,2.17490,1.30346,2,3,0.04430,0.87144,9,0.04163,0.66532,
3,0.12976,2.17490,1.30346,2,4,0.04430,0.87144,10,0.04163,0.66532,
4,0.12976,2.17490,1.30346,2,5,0.04430,0.87144,11,0.04163,0.66532,
5,0.12976,2.17490,1.30346,2,6,0.04430,0.87144,12,0.04163,0.66532,
6,0.12976,2.17490,1.30346,2,7,0.04430,0.66532,13,0.04163,0.66532,
7,0.07566,1.57013,0.65173,1,14,0.04430,0.66532,
8,0.12976,2.17490,1.30346,2,9,0.04163,0.66532,15,0.04430,0.87144,
9,0.21859,2.60692,2.60692,2,10,0.04163,0.87144,16,0.04163,0.87144,
10,0.21859,2.60692,2.60692,2,11,0.04163,0.87144,17,0.04163,0.87144,
11,0.21859,2.60692,2.60692,2,12,0.04163,0.87144,18,0.04163,0.87144,
12,0.21859,2.60692,2.60692,2,13,0.04163,0.87144,19,0.04163,0.87144,
13,0.21859,2.60692,2.60692,2,14,0.04163,0.66532,20,0.04163,0.87144,
14,0.12976,2.17490,1.30346,1,21,0.04430,0.87144,
15,0.12976,2.17490,1.30346,2,16,0.04163,0.66532,22,0.04430,0.87144,
16,0.21859,2.60692,2.60692,2,17,0.04163,0.87144,23,0.04163,0.87144,
17,0.21859,2.60692,2.60692,2,18,0.04163,0.87144,24,0.04163,0.87144,
18,0.21859,2.60692,1.95519,2,19,0.04163,0.87144,25,0.04163,0.87144,
19,0.21859,2.60692,1.95519,2,20,0.04163,0.87144,26,0.04163,0.87144,
20,0.21859,2.60692,2.60692,2,21,0.04163,0.66532,27,0.04163,0.87144,
21,0.12976,2.17490,1.30346,1,28,0.04430,0.87144,
22,0.12976,2.17490,1.30346,2,23,0.04163,0.66532,29,0.04430,0.87144,
23,0.21859,2.60692,2.60692,2,24,0.04163,0.87144,30,0.04163,0.87144,
24,0.21859,2.60692,1.95519,2,25,0.04163,0.87144,31,0.04163,0.87144,
25,0.21859,2.60692,1.95519,2,26,0.04163,0.87144,32,0.04163,0.87144,
26,0.21859,2.60692,1.95519,2,27,0.04163,0.87144,33,0.04163,0.87144,
27,0.21859,2.60692,2.60692,2,28,0.04163,0.66532,34,0.04163,0.87144,
28,0.12976,2.17490,1.30346,1,35,0.04430,0.87144,
29,0.12976,2.17490,1.30346,2,30,0.04163,0.66532,36,0.04430,0.87144,
30,0.21859,2.60692,2.60692,2,31,0.04163,0.87144,37,0.04163,0.87144,
31,0.21859,2.60692,1.95519,2,32,0.04163,0.87144,38,0.04163,0.87144,
32,0.21859,2.60692,1.95519,2,33,0.04163,0.87144,39,0.04163,0.87144,
33,0.21859,2.60692,2.60692,2,34,0.04163,0.87144,40,0.04163,0.87144,
34,0.21859,2.60692,2.60692,2,35,0.04163,0.66532,41,0.04163,0.87144,
35,0.12976,2.17490,1.30346,1,42,0.04430,0.87144,
36,0.12976,2.17490,1.30346,2,37,0.04163,0.66532,43,0.04430,0.66532,
37,0.21859,2.60692,2.60692,2,38,0.04163,0.87144,44,0.04163,0.66532,
38,0.21859,2.60692,2.60692,2,39,0.04163,0.87144,45,0.04163,0.66532,
39,0.21859,2.60692,2.60692,2,40,0.04163,0.87144,46,0.04163,0.66532,
40,0.21859,2.60692,2.60692,2,41,0.04163,0.87144,47,0.04163,0.66532,
41,0.21859,2.60692,2.60692,2,42,0.04163,0.66532,48,0.04163,0.66532,
42,0.12976,2.17490,1.30346,1,49,0.04430,0.66532,
43,0.07566,1.57013,0.65173,1,32,0.04430,0.66532,
44,0.12976,2.17490,1.30346,1,33,0.04430,0.87144,
45,0.12976,2.17490,1.30346,1,34,0.04430,0.87144,

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46,0.12976,2.17490,1.30346,1,35,0.04430,0.87144,
47,0.12976,2.17490,1.30346,1,36,0.04430,0.87144,
48,0.12976,2.17490,1.30346,1,36,0.04430,0.66532,
49,0.07566,1.57013,0.65173,
*Internal subchannels
50,0.17220,1.47102,1.47102,
51,0.17220,1.47102,1.47102,
52,0.17220,1.47102,1.47102,
53,0.17220,1.47102,1.47102,
54,0.17220,1.47102,1.47102,
55,0.17220,1.47102,1.47102,
56,0.17220,1.47102,1.47102,
57,0.17220,1.47102,1.47102,
58,0.17220,1.47102,1.47102,
59,0.17220,1.47102,1.47102,
60,0.17220,1.47102,1.47102,
61,0.17220,1.47102,1.47102,
62,0.17220,1.47102,1.47102,
63,0.17220,1.47102,1.47102,
64,0.17220,1.47102,1.47102,
65,0.17220,1.47102,1.47102,
66,0.17220,1.47102,1.47102,
67,0.17220,1.47102,1.47102,
68,0.17220,1.47102,1.47102,
69,0.17220,1.47102,1.47102,
70,0.17220,1.47102,1.47102,
71,0.17220,1.47102,1.47102,
72,0.17220,1.47102,1.47102,
73,0.17220,1.47102,1.47102,
74,0.17220,1.47102,1.47102,
75,0.17220,1.47102,1.47102,
76,0.17220,1.47102,1.47102,
77,0.17220,1.47102,1.47102,
78,0.17220,1.47102,1.47102,
79,0.17220,1.47102,1.47102,
80,0.17220,1.47102,1.47102,
81,0.17220,1.47102,1.47102,
82,0.17220,1.47102,1.47102,
83,0.17220,1.47102,1.47102,
84,0.45239,2.38429,2.38429,
85,0.45239,2.38429,2.38429,
*geom.4
prop,0,1,2,1 *internal EPRI functions *prop.1
*
rods,1,72,1,2,4,0,0,0,0,1,0, *three material types,one type of geo.
*rods.1
144.0,13.513,0,0,
*rods.2
26
*rods3
*One axial profile only (rods.4)
0.,0.,?
3.,0.11769,?
9.,0.60128,?
15.,0.82226,
21.,0.9944,?

```

27.,1.1257,?  
 33.,1.20176,?  
 39.,1.23379,  
 45.,1.23859,?  
 51.,1.22898,?  
 57.,1.21297,?  
 63.,1.19376,  
 69.,1.17454,?  
 75.,1.15853,?  
 81.,1.14732,?  
 87.,1.14171,  
 93.,1.13931,?  
 99.,1.14171,?  
 105.,1.14412,?  
 111.,1.13211,  
 117.,1.08006,?  
 123.,0.98559,?  
 129.,0.83106,?  
 135.,0.61329,  
 141.,0.34508,?  
 144.,0.,  
 \*

\*

\*\*\*\*\*rods geomatry input

\*rods.9

1,1,1.102,1,1,0.25,2,0.25,8,0.25,9,0.25,  
 -1,1,1.102,1,50,1,  
 2,1,1.085,1,2,0.25,3,0.25,9,0.25,10,0.25,  
 -2,1,1.085,1,51,1,  
 3,1,1.099,1,3,0.25,4,0.25,10,0.25,11,0.25,  
 -3,1,1.099,1,52,1,  
 4,1,1.103,1,4,0.25,5,0.25,11,0.25,12,0.25,  
 -4,1,1.103,1,53,1,  
 5,1,1.088,1,5,0.25,6,0.25,12,0.25,13,0.25,  
 -5,1,1.088,1,54,1,  
 6,1,1.102,1,6,0.25,7,0.25,13,0.25,14,0.25,  
 -6,1,1.102,1,55,1,  
 7,1,1.085,1,8,0.25,9,0.25,15,0.25,16,0.25,  
 -7,1,1.085,1,56,1,  
 8,1,0.377,1,9,0.25,10,0.25,16,0.25,17,0.25,  
 -8,1,0.377,1,57,1,  
 9,1,1.016,1,10,0.25,11,0.25,17,0.25,18,0.25,  
 -9,1,1.016,1,58,1,  
 10,1,1.068,1,11,0.25,12,0.25,18,0.25,19,0.25,  
 -10,1,1.068,1,59,1,  
 11,1,0.381,1,12,0.25,13,0.25,19,0.25,20,0.25,  
 -11,1,0.381,1,60,1,  
 12,1,1.087,1,13,0.25,14,0.25,20,0.25,21,0.25,  
 -12,1,1.087,1,61,1,  
 13,1,1.099,1,15,0.25,16,0.25,22,0.25,23,0.25,  
 -13,1,1.099,1,62,1,  
 14,1,1.016,1,16,0.25,17,0.25,23,0.25,24,0.25,  
 -14,1,1.016,1,63,1,  
 15,1,1.129,1,17,0.25,18,0.25,24,0.25,25,0.25,  
 -15,1,1.129,1,64,1,  
 16,1,1.067,1,19,0.25,20,0.25,26,0.25,27,0.25,  
 -16,1,1.067,1,65,1,

```

17,1,1.102,1,20,0.25,21,0.25,27,0.25,28,0.25,
-17,1,1.102,1,66,1,
18,1,1.103,1,22,0.25,23,0.29,28,0.25,30,0.25,
-18,1,1.103,1,67,1,
19,1,1.068,1,23,0.25,24,0.25,30,0.25,31,0.25,
-19,1,1.068,1,68,1,
20,1,1.129,1,25,0.25,26,0.25,32,0.25,33,0.25,
-20,1,1.129,1,69,1,
21,1,1.016,1,26,0.25,27,0.25,33,0.25,34,0.25,
-21,1,1.016,1,70,1,
22,1,1.097,1,27,0.25,28,0.25,34,0.25,35,0.25,
-22,1,1.097,1,71,1,
23,1,1.088,1,29,0.25,30,0.25,36,0.25,37,0.25,
-23,1,1.088,1,72,1,
24,1,0.381,1,30,0.25,31,0.25,37,0.25,38,0.25,
-24,1,0.381,1,73,1,
25,1,1.067,1,31,0.25,32,0.25,38,0.25,39,0.25,
-25,1,1.067,1,74,1,
26,1,1.016,1,32,0.25,33,0.25,39,0.25,40,0.25,
-26,1,1.016,1,75,1,
27,1,0.377,1,33,0.25,34,0.25,40,0.25,41,0.25,
-27,1,0.377,1,76,1,
28,1,1.083,1,34,0.25,35,0.25,41,0.25,42,0.25,
-28,1,1.083,1,77,1,
29,1,1.102,1,36,0.25,37,0.25,43,0.25,44,0.25,
-29,1,1.102,1,78,1,
30,1,1.087,1,37,0.25,38,0.25,44,0.25,45,0.25,
-30,1,1.087,1,79,1,
31,1,1.102,1,38,0.25,39,0.25,45,0.25,46,0.25,
-31,1,1.102,1,80,1,
32,1,1.097,1,39,0.25,40,0.25,46,0.25,47,0.25,
-32,1,1.097,1,81,1,
33,1,1.083,1,40,0.25,41,0.25,47,0.25,48,0.25,
-33,1,1.083,1,82,1,
34,1,1.098,1,41,0.25,42,0.25,48,0.25,49,0.25,
-34,1,1.098,1,83,1,
35,2,0.0,1,18,0.25,19,0.25,25,0.25,26,0.25,
rod *water
-35,2,0.0,1,-84,1,
*water rod
36,2,0.0,1,24,0.25,25,0.25,31,0.25,32,0.25,
rod *water
-36,2,0.0,1,-85,1,
*water rod
0
*rods.9
*
1,2,3,4,5,6,
7,8,9,10,11,12,
13,14,15,35,16,17,
18,19,36,20,21,22,
23,24,25,26,27,28,
29,30,31,32,33,34,

*blank line above necessary /rods.57 -HG CPR corr
36,0.871438,0.044296,0.829810,15.122049, *rods.58,

```

```

0
*
*fuel
1,tube,0.829810,0.468239,5,
*
2,1,0.033465,0.0,? *inner cladding
*rods.69
2,2,0.003937,0.0,? *inner gap
*rods.69
8,3,0.105982,1.0,? *fuel ring
*rods.69
2,4,0.003937,0.0, *outer gap
*rods.69
2,1,0.033465,0.0, *outer cladding
*rods.69
*
*water tube
2,tube,0.829810,0.758944,1
3,1,0.035433,0.0,
*
1,18,409.0,clad,
*table for cladding
*rods.70
0.0,0.0671,7.3304509,?
25,0.0671,7.3304509,
50,0.0671,7.33045093,?
65,0.0671,7.33045093,
80.33,0.0671,7.33045093,?
260.33,0.07212,8.11585329,
692.33,0.07904,9.80167423,?
1502.33,0.08955,13.2923,
1507.73,0.11988,13.3211893,?
1543.73,0.14089,13.51665,
1579.73,0.14686,13.717249,?
1615.73,0.1717,13.923198,
1651.73,0.1949,14.1347101,?
1687.73,0.18388,14.351998,
1723.73,0.1478,14.5752746,?
1759.73,0.112,14.804753,
1786.73,0.085,14.9810589,?
2240.33,0.085,18.5665964,
*
*gap
2,1,0.025,igap,
*rods.70
1,1.240834,0.346679, *Cp=5195J/kg-K *gap=6000
*rods.71
*
*fuel
3,22,650.617,FUO2,
*rods.70
86,0.05677357,4.73275874,?
176,0.06078589,4.2991726,
266,0.06366347,3.93877428,?
356,0.06581210,3.6345405,
446,0.06747631,3.37435643,?

```

```

536,0.06880819,3.1493668,
626,0.06990545,2.95294976,?
716,0.07083283,2.78005572,
806,0.07163441,2.62676801,?
896,0.07234099,2.49000319,
986,0.07297458,2.36730189,?
1076,0.07355124,2.25667975,
1166,0.07408294,2.1565193,?
1256,0.07457886,2.06549023,
1346,0.07504628,1.98248979,?
1436,0.07549123,1.90659753,
1526,0.0759191,1.83704065,?
1616,0.07633503,1.77316713,
1706,0.0767443,1.7144247,?
1796,0.07715268,1.66034425,
1886,0.07756663,1.61052668,?
1976,0.07799351,1.5646323,
*rods.71
*
*outer gap
4,1,0.025,ogap,
*rods.70
1,1.240834,0.34667666,      *Cp=5195J/kg-K *gap=6000
*rods.71
*
*****
*P,T
oper,1,1,0,1,0,1,0,0,0
*oper.1
25.098000,0.0,2.0,0.005,      *oper.2  *first word to be
changed if you change BC
0      *oper.3  *only if
first w above is not 0.0
1044.27,534.2,36.730000,177.478000,0.0,
*oper.5
*13400 kg/s ,5*Rod power got from total power divided total number of
rods
0,      *no forcing functions
*oper.12
*****
*correlations
corr,-2,2,0,
*corr.1
epri,epri,epri,none,
*corr.2
0.2,
*corr.3
ditb,chen,chen,epri,cond,g5.7,      *correlation for boiling curve
*corr.6
1,0,0.0,
*corr.16,for epri
mine,
*corr 18 , Hench-Gillis
*****
grid,0,5,
*grid.1

```

```

23.370,6.63,1.50,1.46,20000,
*grid.2
*pressure drop is 24.28 for the average rod and 23.37 for the hot rod
49,10,
*grid.4
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
*grid.5
17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,
49,
*grid.5
1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,
153.203,3,175.445,4,
loc. *grid.6
34,3,
50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,
66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,
82,83,
1.0,1,12.263,2,31.225,3,
2,1,
84,85,
1.0,5,
0,
*****
cont,
*cont.1
0.0,0,50,50,3,0,
*cont.2
0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,
*cont.3
5,0,0,0,0,0,1,1,0,0,0,1,1,0,
*cont.6
5000.,0.0,0.0,0.0,0.0,0.0,
*cont.7
endd
*
*end of data input
0

```

# Appendix C

## MatLab Input for Solid Fuel Design

```

-----
function solid8x8PRINT2(nothing);

%Solid fuel, reference, BWR-5 8x8, whole assembly
%PRINTS EXACTLY VIPRE INPUT (channels and rods)

%all in cm

D=1.23; %diameter
L=13.4; %length of the assembly
p=1.62; %pin pitch
Nf=62; %number of fuel rods
Nw=2; %number of water rods
n=8; %bundle lattice
t=0.085; %clad thickness
Diw=1.32; %water rod inner D
Dow=1.50; %water rod outer D

%conversion: cm/k=in
k=2.540;

D=D/k; %diameter
L=L/k; %length of the assembly
p=p/k; %pin pitch
t=t/k; %clad thickness
Diw=Diw/k; %water rod inner D
Dow=Dow/k; %water rod outer D

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

x=(L-(n-1)*p)/2; %side of the corner channel

%calculation

Aa=(x*x-(pi*D*D)/16); %corner
Pwa=(2*x+((pi*D)/4));
Pha=((pi*D)/4);

Ab=(p*x-((pi*D*D)/8)); %border
Pwb=(p+((pi*D)/2));

```

```

Phb=((pi*D)/2);

Ac=(p*p-((pi*D*D)/4)); %normal
Pwc=(pi*D);
Phc=(pi*D);

Ad=((p*p)-((3/4)*(pi*D*D/4))-((pi*Dow*Dow)/16)); %external water rod
Pwd=((3/4)*(pi*D)+(pi*Dow/4));
Phd=((3/4)*pi*D);

Ae=((pi*Diw*Diw)/4); %internal water rod
Pwe=(pi*Diw);
Phe=Pwe; %VIPRE requirement

%connection between: (already converted)

conn1=x-(D/2);      %a<->b ; b<->b
conn2=p-D;         %b<->c ; c<->c ; c<->d
conn3=p-(D/2)-(Dow/2); %d<->d

dist1=(x/2)+(p/2); %a<->b ; b<->c
dist2=p;          %b<->b ; c<->c ; c<->d ; d<->d

%checks
% CheckA=4*Aa+28*Ab+42*Ac+7*Ad+2*Ae;
% CheckA2=L*L-(62*pi*D*D/4)-2*pi/4*(Dow*Dow-Diw*Diw);
% CheckA-CheckA2;

%print
%1)Erase all the 123456789 (replace all with space)
%2)put commas at the end of all the lines
CANC=123456789;

m=[1 Aa Pwa Pha 2 2 conn1 dist1 10 conn1 dist1;
  2 Ab Pwb Phb 2 3 conn1 dist2 11 conn2 dist1;
  3 Ab Pwb Phb 2 4 conn1 dist2 12 conn2 dist1;
  4 Ab Pwb Phb 2 5 conn1 dist2 13 conn2 dist1;
  5 Ab Pwb Phb 2 6 conn1 dist2 14 conn2 dist1;
  6 Ab Pwb Phb 2 7 conn1 dist2 15 conn2 dist1;
  7 Ab Pwb Phb 2 8 conn1 dist2 16 conn2 dist1;
  8 Ab Pwb Phb 2 9 conn1 dist1 17 conn2 dist1;
  9 Aa Pwa Pha 1 18 conn1 dist1 CANC CANC CANC;
  10 Ab Pwb Phb 2 11 conn2 dist1 19 conn1 dist2;
  11 Ac Pwc Phc 2 12 conn2 dist2 20 conn2 dist2;
  12 Ac Pwc Phc 2 13 conn2 dist2 21 conn2 dist2;

```

13 Ac Pwc Phc 2 14 conn2 dist2 22 conn2 dist2;  
14 Ac Pwc Phc 2 15 conn2 dist2 23 conn2 dist2;  
15 Ac Pwc Phc 2 16 conn2 dist2 24 conn2 dist2;  
16 Ac Pwc Phc 2 17 conn2 dist2 25 conn2 dist2;  
17 Ac Pwc Phc 2 18 conn2 dist1 26 conn2 dist2;  
18 Ab Pwb Phb 1 27 conn1 dist2 CANC CANC CANC;  
19 Ab Pwb Phb 2 20 conn2 dist1 28 conn1 dist2;  
20 Ac Pwc Phc 2 21 conn2 dist2 29 conn2 dist2;  
21 Ac Pwc Phc 2 22 conn2 dist2 30 conn2 dist2;  
22 Ac Pwc Phc 2 23 conn2 dist2 31 conn2 dist2;  
23 Ac Pwc Phc 2 24 conn2 dist2 32 conn2 dist2;  
24 Ac Pwc Phc 2 25 conn2 dist2 33 conn2 dist2;  
25 Ac Pwc Phc 2 26 conn2 dist2 34 conn2 dist2;  
26 Ac Pwc Phc 2 27 conn2 dist1 35 conn2 dist2;  
27 Ab Pwb Phb 1 36 conn1 dist2 CANC CANC CANC;  
28 Ab Pwb Phb 2 29 conn2 dist1 37 conn1 dist2;  
29 Ac Pwc Phc 2 30 conn2 dist2 38 conn2 dist2;  
30 Ac Pwc Phc 2 31 conn2 dist2 39 conn2 dist2;  
31 Ac Pwc Phc 2 32 conn2 dist2 40 conn2 dist2;  
32 Ad Pwd Phd 2 33 conn3 dist2 41 conn3 dist2;  
33 Ad Pwd Phd 2 34 conn2 dist2 42 conn3 dist2;  
34 Ac Pwc Phc 2 35 conn2 dist2 43 conn2 dist2;  
35 Ac Pwc Phc 2 36 conn2 dist1 44 conn2 dist2;  
36 Ab Pwb Phb 1 45 conn1 dist2 CANC CANC CANC;  
37 Ab Pwb Phb 2 38 conn2 dist1 46 conn1 dist2;  
38 Ac Pwc Phc 2 39 conn2 dist2 47 conn2 dist2;  
39 Ac Pwc Phc 2 40 conn2 dist2 48 conn2 dist2;  
40 Ad Pwd Phd 2 41 conn3 dist2 49 conn3 dist2;  
41 Ad Pwd Phd 2 42 conn3 dist2 50 conn3 dist2;  
42 Ad Pwd Phd 2 43 conn2 dist2 51 conn2 dist2;  
43 Ac Pwc Phc 2 44 conn2 dist2 52 conn2 dist2;  
44 Ac Pwc Phc 2 45 conn2 dist1 53 conn2 dist2;  
45 Ab Pwb Phb 1 54 conn1 dist2 CANC CANC CANC;  
46 Ab Pwb Phb 2 47 conn2 dist1 55 conn1 dist2;  
47 Ac Pwc Phc 2 48 conn2 dist2 56 conn2 dist2;  
48 Ac Pwc Phc 2 49 conn2 dist2 57 conn2 dist2;  
49 Ad Pwd Phd 2 50 conn3 dist2 58 conn2 dist2;  
50 Ad Pwd Phd 2 51 conn2 dist2 59 conn2 dist2;  
51 Ac Pwc Phc 2 52 conn2 dist2 60 conn2 dist2;  
52 Ac Pwc Phc 2 53 conn2 dist2 61 conn2 dist2;  
53 Ac Pwc Phc 2 54 conn2 dist1 62 conn2 dist2;  
54 Ab Pwb Phb 1 63 conn1 dist2 CANC CANC CANC;  
55 Ab Pwb Phb 2 56 conn2 dist1 64 conn1 dist2;  
56 Ac Pwc Phc 2 57 conn2 dist2 65 conn2 dist2;  
57 Ac Pwc Phc 2 58 conn2 dist2 66 conn2 dist2;  
58 Ac Pwc Phc 2 59 conn2 dist2 67 conn2 dist2;

```

59 Ac Pwc Phc 2 60 conn2 dist2 68 conn2 dist2;
60 Ac Pwc Phc 2 61 conn2 dist2 69 conn2 dist2;
61 Ac Pwc Phc 2 62 conn2 dist2 70 conn2 dist2;
62 Ac Pwc Phc 2 63 conn2 dist1 71 conn2 dist2;
63 Ab Pwb Phb 1 72 conn1 dist2 CANC CANC CANC;
64 Ab Pwb Phb 2 65 conn2 dist1 73 conn1 dist1;
65 Ac Pwc Phc 2 66 conn2 dist2 74 conn2 dist1;
66 Ac Pwc Phc 2 67 conn2 dist2 75 conn2 dist1;
67 Ac Pwc Phc 2 68 conn2 dist2 76 conn2 dist1;
68 Ac Pwc Phc 2 69 conn2 dist2 77 conn2 dist1;
69 Ac Pwc Phc 2 70 conn2 dist2 78 conn2 dist1;
70 Ac Pwc Phc 2 71 conn2 dist2 79 conn2 dist1;
71 Ac Pwc Phc 2 72 conn2 dist1 80 conn2 dist1;
72 Ab Pwb Phb 1 81 conn1 dist1 CANC CANC CANC;
73 Aa Pwa Pha 1 74 conn1 dist1 CANC CANC CANC;
74 Ab Pwb Phb 1 75 conn1 dist2 CANC CANC CANC;
75 Ab Pwb Phb 1 76 conn1 dist2 CANC CANC CANC;
76 Ab Pwb Phb 1 77 conn1 dist2 CANC CANC CANC;
77 Ab Pwb Phb 1 78 conn1 dist2 CANC CANC CANC;
78 Ab Pwb Phb 1 79 conn1 dist2 CANC CANC CANC;
79 Ab Pwb Phb 1 80 conn1 dist2 CANC CANC CANC;
80 Ab Pwb Phb 1 81 conn1 dist1 CANC CANC CANC;
81 Aa Pwa Pha CANC CANC CANC CANC CANC CANC CANC;
82 Ae Pwe Phe CANC CANC CANC CANC CANC CANC CANC; %int water rod
83 Ae Pwe Phe CANC CANC CANC CANC CANC CANC CANC;]; %int water rod

```

```
%csvwrite('C:\Documents and Settings\Administrator\Desktop\provamatsolid.txt',m);
```

```
%rods
```

```
r=zeros(66,12);
```

```
i=0;
```

```
j=0;
```

```
%radial power factor
```

```
rpf=zeros(1,66);
```

```
rpf=[0.994,1.016,1.073,1.112,1.113,1.074,1.016,0.993,...
```

```
1.016,0.355,0.995,1.086,1.09,1.,0.356,1.015,...
```

```
1.073,0.995,0.996,1.01,1.038,1.013,0.999,1.072,...
```

```
1.112,1.086,1.01,1.070,1.038,1.089,1.111,... %without the water rod
```

```
1.113,1.090,1.038,1.069,1.009,1.084,1.11,... %without the water rod
```

```
1.074,1.,1.013,1.038,1.009,0.995,0.993,1.071,...
```

```
1.016,0.356,0.999,1.089,1.084,0.993,0.355,1.013,...
```

```
0.993,1.015,1.072,1.111,1.11,1.071,1.013,0.991,...
```

```
0,0,0,0]; %water rod internal and external
```

```

for i=1:66
    r(i,1)=i;
    r(i,2)=1;
    r(i,3)=rpf(1,i);
    r(i,4)=2;    %axial power profile for the border/besides water rods

    if (i<=8)
        r(i,5)=i;

    elseif ((i>8) & (i<=16))
        r(i,5)=i+1;

    elseif ((i>16) & (i<=24))
        r(i,5)=i+2;

    elseif ((i>24) & (i<=28))
        r(i,5)=i+3;

    elseif ((i>28) & (i<=31))
        r(i,5)=i+4;

    elseif ((i>31) & (i<=34))
        r(i,5)=i+5;

    elseif ((i>34) & (i<=38))
        r(i,5)=i+6;

    elseif ((i>38) & (i<=46))
        r(i,5)=i+7;

    elseif ((i>46) & (i<=54))
        r(i,5)=i+8;

    else
        r(i,5)=i+9;
    end

    r(i,6)=0.25;
    r(i,7)=r(i,5)+1;
    r(i,8)=0.25;
    r(i,9)=r(i,5)+9;
    r(i,10)=0.25;
    r(i,11)=r(i,9)+1;
    r(i,12)=0.25;
end

```

```

%modify rod 63/64/-63/-64 ...water rods

for i=63:66
    r(i,2)=2;
    r(i,3)=0;
    r(63,5)=40;
    r(64,5)=32;
    r(i,7)=r(i,5)+1;
    r(i,9)=r(i,5)+9;
    r(i,11)=r(i,9)+1;
end

for i=65:66
    r(i,1)=-i+2;
    r(65,5)=83;
    r(66,5)=82;
    r(i,6)=1;
    for j=7:12
        r(i,j)=CANC;
    end
end

%modify the axial power profile for the not-normal rods
%normal rods
for i=10:15
    r(i,4)=3;
end

r(18,4)=3;
r(19,4)=3;
r(23,4)=3;
r(26,4)=3;
r(30,4)=3;
r(33,4)=3;
r(37,4)=3;
r(40,4)=3;
r(44,4)=3;
r(45,4)=3;

for i=48:53
    r(i,4)=3;
end

%corner rods
r(1,4)=1;
r(8,4)=1;

```

```
r(55,4)=1;  
r(62,4)=1;
```

```
%inversion of lines  
temp=0;  
for j=1:12  
    temp=r(64,j);  
    r(64,j)=r(65,j);  
    r(65,j)=temp;  
end
```

```
%REMEMBER TO ADD A ZERO AT THE END!
```

```
csvwrite('C:\Documents and Settings\Administrator\Desktop\provamatsolid.txt',r);
```

---

# Appendix D

## MatLab Inputs for Annular Fuel Design

### D.1 Annular 5x5

---

```
function annular5x5PRINTtuttoflow2(parDi,superpow,tag,pressdrop,corx,sol);

% parDi=0.9;
% superpow=1;
% tag=1;
% pressdrop=20.19;
% corx=1;
% sol=0;

parfuel=0.9;
axialnodes=50; %79;
%parDi=Dai/Dhs --suggested 90% (ratio between the internal diameter of the
%annular on the hydraulic diameter of the solid)
%parfuel=Afa/Afs ----suggested 100%
%superpow=power upgrade besides the hot rod factor (1.4), 1 is normal
%tag=if it is hot or average rod. Hot rod=1, average=0
%corx chooses the correlation. 0=hench-gillis, all else, mine
%sol=0 iterative, 1=direct, 2=recirculation

%Calculation sheet for dimensions of BWR annular fuel
%Annular - 5x5
%Reference Solid: BWR-5 8x8
%FINAL DESIGN / keeping the fuel volume instead

%NOTE: MODIFIED to include gaps
%Neglected the cladding of the water rods and control rods

%PRINTS EXACTLY ALL VIPRE INPUT

%NOTE:
%1) The flow is uprated as the power is (we want constant quality)
%2) One axial profile
%3) radial profile 'provvisorio'
```

```

%CHECKS
if (parDi<0.7)
    'warning'
elseif (parDi>1)
    'warning>1'
end

if (parfuel<0.9)
    'low fuel'
elseif (parfuel>1)
    'high fuel'
end

if (superpow<1)
    'superpow'
end

if ((tag~=0) & (tag~=1))
    'tag'
end

if ((pressdrop==0) & (tag~=0))
    'pressure drop'
end

%all in cm
L=13.4; % width of the assembly
t=0.085; %clad thickness

%number of rods
Ns=62; %solid --- 2 water rods
Na=24; %ann --- 1 water rod
na=5; %number of annular rods per side
ns=8; %number of solid rods per side

%solid
Ds=1.23; %solid D
Dsf=1.04; %solid fuel D
g=(Ds/2)-t-(Dsf/2); %gap in the solid fuel= gap in the annular fuel (but it has 2 of them)
p=1.62;
guide=(1.50-1.32)/2; %thickness of the guide tube in the reference design / I use the
same

Ap=p*p-((pi*Ds*Ds)/4); %flow area in a subchannel
Pw=pi*Ds; %wetted perimeter

```

$D_h = 4 \cdot A_p / P_w$ ;      %Hydraulic D /solid, RELATED TO int for annular fuel

$A_{ms} = L \cdot L - ((N_s + 2) \cdot \pi \cdot D_s \cdot D_s / 4)$ ;    %area of moderator

$A_{fs} = N_s \cdot \pi \cdot D_{sf} \cdot D_{sf} / 4$ ;      %area of fuel /RELATED

$c = A_{fs} / A_{ms}$ ;              %RATIO, not the same for both

%annular

$D_{ai} = \text{parDi} \cdot D_h$ ; %internal D of ann function of hydr D of solid

$D_{aif} = D_{ai} + (2 \cdot (t + g))$ ; %internal D of ann fuel

$t_g = t + g$ ;

%External fuel diameter calculation

$D_{aof} = \sqrt{((N_s / (N_a / \text{parfuel})) \cdot D_{sf} \cdot D_{sf}) + (D_{aif} \cdot D_{aif})}$ ;

$D_{ao} = D_{aof} + (2 \cdot (t + g))$ ;              %external diameter of annular rod

%verification

$A_{ma} = L \cdot L - ((N_a) \cdot \pi \cdot (D_{ao} \cdot D_{ao} - D_{ai} \cdot D_{ai}) / 4) - (\pi \cdot (D_{ao} \cdot D_{ao} - ((D_{ao} - 2 \cdot \text{guide}) \cdot (D_{ao} - 2 \cdot \text{guide}))) / 4)$ ;

% $A_{ma} = L \cdot L - ((N_a + 1) \cdot \pi \cdot (D_{ao} \cdot D_{ao} - D_{ai} \cdot D_{ai}) / 4)$ ;

$A_{fa} = N_a \cdot \pi \cdot (D_{aof} \cdot D_{aof} - D_{aif} \cdot D_{aif}) / 4$ ;

$\text{appoc} = A_{fa} / A_{ma}$ ;

if  $((\text{abs}(\text{appoc}/c) < 0.9) \mid (\text{abs}(\text{appoc}/c) > 1.1))$

  'Vf/Vm ratio is wrong'

  appoc

  c

  appoc/c

$\text{abs}((\text{appoc} - c) / c)$

else

  'giusto Vf/Vm'

% appoc

% c

% appoc/c

%  $\text{abs}((\text{appoc} - c) / c)$

end

if  $((L - n_a \cdot D_{ao}) / (n_a + 1)) < 0.1$

  'average spacing is less than 0.1'

else

  'correct average spacing'

end

```

%tests
% c
% appoc
% appoc/c
% (abs(c-appoc))/c
% Afs/Afa
% Ams/Ama

%end calculation

%conversion: cm/k=in
k=2.540;
%k=1; %just for printing

%measure of the distance rod-bundle (solid)

x=(L-(ns-1)*p)/2; %distance from the center of the corner rod to the bundle wall
delta=x-p;

%pitch of the annular fuel (pa)
%we impose that the ratio (p-D)/x is the same for both
delta=(p-Ds)/(x-(Ds/2));
pa=(delta*L/2-delta*Dao/2+Dao)/(1+(delta/2)*(na-1));
xp=(L-(na-1)*pa)/2; %distance from the center of the corner rod to the bundle wall

distwall=xp-(Dao/2);
if (distwall<0.1)
    'the distance from the wall is too little'
else
    'distwall OK'
end

%*****
****

%CHECKS
% pa-Dao
% xp-(Dao/2)
% (pa-Dao)/(xp-(Dao/2))
% p-Ds
% x-(Ds/2)
% (p-Ds)/(x-(Ds/2))

% (L-Dao*na)/(na+1)
% (L-Ds*ns)/(ns+1)

```

0%\*\*\*\*\*  
\*\*\*\*

%Flow area Ax , x is the type (see yellow paper)  
%a: corner 1/6/31/36  
%b: border 2/3/4/5/7/12/13/18/19/24/25/30/32/33/34/35  
%c: middle 8/9/10/11/14/17/20/23/26/27/28/29  
%d: water 15/16/21/22  
%e: internal 37->60  
%w: water tube 61

$Aa = xp * xp - (\pi * Dao * Dao / 16);$   
 $Pwa = 2 * xp + (\pi * Dao / 4);$   
 $Pha = \pi * Dao / 4;$

$Ab = (pa * xp) - (\pi * Dao * Dao / 8);$   
 $Pwb = pa + (\pi * Dao / 2);$   
 $Phb = \pi * Dao / 2;$

$Ac = pa * pa - (\pi * Dao * Dao / 4);$   
 $Pwc = \pi * Dao;$   
 $Phc = Pwc;$

$Ad = pa * pa - (\pi * Dao * Dao / 4);$   
 $Pwd = \pi * Dao;$   
 $Phd = 3 * \pi * Dao / 4;$

$Ae = \pi * Dai * Dai / 4;$   
 $Pwe = \pi * Dai;$   
 $Phe = Pwe;$

%guide=(1.50-1.32)/2; %thickness of the guide tube in the reference design / I use the same  
 $Aw = \pi * (Dao - 2 * guide) * (Dao - 2 * guide) / 4;$   
 $Pww = \pi * (Dao - 2 * guide);$   
 $Phw = Pww;$  %VIPRE requirement

%connections  
%a<->b, b<->b  
 $conn1 = xp - (Dao / 2);$   
%b<->c, c<->c, c<->d, d<->d  
 $conn2 = pa - Dao;$

%distance of centroids

```

%b<->b, c<->c, c<->d, d<->d
dist1=pa;
%a<->b, b<->c
dist2=(xp/2)+(pa/2);

%((pa-Dao)/(xp-(Dao/2))) %spacing ratio
% 4*(x*x-(pi*Ds*Ds/16))/((2*x)+(pi*Ds/4)) %corner Dh for solid
% 4*(x*p-(pi*Ds*Ds/8))/(p+(pi*Ds/2)) %border Dh for solid

%plots
%cladding volume
Acs=Ns*(pi/4)*(Ds*Ds-(Ds-2*t)*(Ds-2*t))+(pi/4)*(1.50*1.50-1.32*1.32);
Aca=Na*(pi/4)*((Dao*Dao-(Dao-2*t)*(Dao-2*t))+(Dai+2*t)*(Dai+2*t)-
Dai*Dai)+(pi/4)*(Dao*Dao-(Dao-2*guide)*(Dao-2*guide));
%heated surface on fuel volume ratio
SVs=Ns*pi*Ds/Afs;
SVa=Na*(pi*Dao+pi*Dai)/Afa;

%Na*pi*(Dao)/(Na*pi*(Dao+Dai))
%Dao/(Dao+Dai)

% Aca/Acs
% SVa/SVs

% Daof
% Daif
% Dao
% Dai
% Dao-(2*guide)

% pa
% 4*Aa/Pwa
% 4*Ab/Pwb
% 4*Ac/Pwc
% 4*Ae/Pwe
% Afa
% appoc

% Afa/Afs
% Ama/Ams
% Afa
% Afs

% pa-Dao
% xp-(Dao/2)

```

```

% appoc/c

%gap conductance calculation

%igap
hg=6000; %W/(m2K)
%from report 1: kg=hg*Ravg*ln(Ro/Ri)
kgi=hg*(((Dai/2)+t+(g/2))/100)*log((Daif/2)/((Dai/2)+t)); %converted in meters---kg->
W/mK
%outer gap
kgo=hg*(((Daof/2)+(g/2))/100)*log(((Daof/2)+g)/(Daof/2));
kth=1.73073; %divide by this to go from W/mK to Btu/hrftF

%conversion to inches
%areas ->divide by k*k
Aa=Aa/(k*k);
Ab=Ab/(k*k);
Ac=Ac/(k*k);
Ad=Ad/(k*k);
Ae=Ae/(k*k);
Aw=Aw/(k*k);
%lengths: divide by k
Pwa=Pwa/k;
Pha=Pha/k;
Pwb=Pwb/k;
Phb=Phb/k;
Pwc=Pwc/k;
Phc=Phc/k;
Pwd=Pwd/k;
Phd=Phd/k;
Pwe=Pwe/k;
Phe=Phe/k;
Pww=Pww/k;
Phw=Phw/k;
conn1=conn1/k;
conn2=conn2/k;
dist1=dist1/k;
dist2=dist2/k;

%other stuff useful for the input
pa=pa/k;
distwall=distwall/k;
Dao=Dao/k;
Dai=Dai/k;
Ama=Ama/(k*k); %area
Spessore=(Daof-Daif)/2/k;

```

```

g=g/k;
t=t/k;
guide=guide/k;
Daiw=Dao-2*(guide);
power=179.59; %kW/rod
flow=36.73; %lbm/s

%'rods' construction
ii=0;

%first word: channel number
% chn=ones(50,1);
% for ii=2:50
%   chn(ii,1)=ceil(ii/2);
%   if (chn(ii,1)==chn((ii-1),1))
%       chn(ii,1)=-chn(ii,1);
%   end
% end

%Second word: rod geometry type
% rgt=ones(50,1);
% rgt(49,1)=2;
% rgt(50,1)=2;

%Third word: radial power factor
%rpf=ones(24,1);

rpf=[1.030,1.217,1.140,1.216,1.029,...
      1.217,0.369,1.031,0.369,1.215,...
      1.140,1.031,...
      1.031,1.139,...
      1.216,0.369,1.031,0.369,1.215...
      1.029,1.215,1.139,1.215,1.028];

rpf=rpf';

% rpfpr=zeros(48,1);
% for ii=1:48
%   rpfpr(ii,1)=rpf(ceil(ii/2));
% end

%Fourth word: axial profiles
ax=ones(24,1);
%definisci ax!!!!
% for ii=1:24
%   ax(ii,1)=2;

```

```

% end
% ax(7,1)=3;
% ax(9,1)=3;
% ax(16,1)=3;
% ax(18,1)=3;
% ax(1,1)=1;
% ax(5,1)=1;
% ax(20,1)=1;
% ax(24,1)=1;
%double the axial profile for internal channels
% axpp=zeros(48,1);
% for ii=1:48
%   axpp(ii,1)=ax(ceil(ii/2));
% end

%scrivo
%fid=fopen('C:\VIPRE\input','w');
fid=fopen('C:\Vipre2\input','w');

%%%%%%%%%%
%%%%%%%%%%
%%%%%%%%%%

fprintf(fid,'*****\n');
fprintf(fid,'*                               *\n');
fprintf(fid,'* 1 assembly, 5x5 annular pins, using BWR power distribution *\n');

if (tag==1)
    fprintf(fid,'*      HOT ROD                               *\n');
else
    fprintf(fid,'*      AVERAGE ROD                               *\n');
end
fprintf(fid,'*      one axial profile and approximate radial profile *\n');
fprintf(fid,'*      parDi: %2.2f                               *\n',parDi);
fprintf(fid,'*      parfuel: %2.2f                               *\n',parfuel);
fprintf(fid,'*      Superpower: %2.2f                               *\n',superpow);
if (corx==0)
    fprintf(fid,'*      HENCH GILLIS correlation for CPR *\n');
else
    fprintf(fid,'*      MODIFIED HG correlation for CPR *\n');
end
if (sol==0)
    fprintf(fid,'*      ITERATIVE solution *\n');

```

```

elseif (sol==1)
    fprintf(fid,'*    DIRECT solution                *\n');
else
    fprintf(fid,'*    RECIRCULATION solution            *\n');
end
fprintf(fid,'*****\n');
fprintf(fid,'*This input is under construction                \n');
fprintf(fid,'1,0,0,                                *vipre.1\n');
fprintf(fid,'Bwr annular fuel                        *vipre.2\n');
fprintf(fid,'*                                \n');
fprintf(fid,'geom,61,61,%u,0,0,0,    *normal geometry input
*geom.1\n',axialnodes);
fprintf(fid,'*                                \n');
fprintf(fid,'178.5,0.0,0.5,                        *geom.2\n');
fprintf(fid,'*                                \n');
fprintf(fid,'1,%6.5f,%6.5f,%6.5f,2,2,%6.5f,%6.5f,7,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,dist2,conn1,dist2);
fprintf(fid,'2,%6.5f,%6.5f,%6.5f,2,3,%6.5f,%6.5f,8,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1,conn2,dist2);
fprintf(fid,'3,%6.5f,%6.5f,%6.5f,2,4,%6.5f,%6.5f,9,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1,conn2,dist2);
fprintf(fid,'4,%6.5f,%6.5f,%6.5f,2,5,%6.5f,%6.5f,10,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1,conn2,dist2);
fprintf(fid,'5,%6.5f,%6.5f,%6.5f,2,6,%6.5f,%6.5f,11,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist2,conn2,dist2);
fprintf(fid,'6,%6.5f,%6.5f,%6.5f,1,12,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,dist2);
fprintf(fid,'7,%6.5f,%6.5f,%6.5f,2,8,%6.5f,%6.5f,13,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn2,dist2,conn1,dist1);
fprintf(fid,'8,%6.5f,%6.5f,%6.5f,2,9,%6.5f,%6.5f,14,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2,dist1,conn2,dist1);
fprintf(fid,'9,%6.5f,%6.5f,%6.5f,2,10,%6.5f,%6.5f,15,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2,dist1,conn2,dist1);
fprintf(fid,'10,%6.5f,%6.5f,%6.5f,2,11,%6.5f,%6.5f,16,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2,dist1,conn2,dist1);
fprintf(fid,'11,%6.5f,%6.5f,%6.5f,2,12,%6.5f,%6.5f,17,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2,dist2,conn2,dist1);
fprintf(fid,'12,%6.5f,%6.5f,%6.5f,1,18,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'13,%6.5f,%6.5f,%6.5f,2,14,%6.5f,%6.5f,19,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn2,dist2,conn1,dist1);
fprintf(fid,'14,%6.5f,%6.5f,%6.5f,2,15,%6.5f,%6.5f,20,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2,dist1,conn2,dist1);
fprintf(fid,'15,%6.5f,%6.5f,%6.5f,2,16,%6.5f,%6.5f,21,%6.5f,%6.5f,\n',Ad,Pwd,Phd,conn2,dist1,conn2,dist1);
fprintf(fid,'16,%6.5f,%6.5f,%6.5f,2,17,%6.5f,%6.5f,22,%6.5f,%6.5f,\n',Ad,Pwd,Phd,conn2,dist1,conn2,dist1);

```

```

fprintf(fid,'17,%6.5f,%6.5f,%6.5f,2,18,%6.5f,%6.5f,23,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'18,%6.5f,%6.5f,%6.5f,1,24,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
%fprintf(fid,'19,%6.5f,%6.5f,%6.5f,1???,20,%6.5f,%6.5f,25,%6.5f,%6.5f,\n',Ab,P
%wb,Phb,conn2,dist2,conn1,dist1); ???
fprintf(fid,'19,%6.5f,%6.5f,%6.5f,2,20,%6.5f,%6.5f,25,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist1);
fprintf(fid,'20,%6.5f,%6.5f,%6.5f,2,21,%6.5f,%6.5f,26,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'21,%6.5f,%6.5f,%6.5f,2,22,%6.5f,%6.5f,27,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'22,%6.5f,%6.5f,%6.5f,2,23,%6.5f,%6.5f,28,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'23,%6.5f,%6.5f,%6.5f,2,24,%6.5f,%6.5f,29,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'24,%6.5f,%6.5f,%6.5f,1,30,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
%fprintf(fid,'25,%6.5f,%6.5f,%6.5f,1???,26,%6.5f,%6.5f,31,%6.5f,%6.5f,\n',Ab,P
%wb,Phb,conn2,dist2,conn1,dist2); ???
fprintf(fid,'25,%6.5f,%6.5f,%6.5f,2,26,%6.5f,%6.5f,31,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist2);
fprintf(fid,'26,%6.5f,%6.5f,%6.5f,2,27,%6.5f,%6.5f,32,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'27,%6.5f,%6.5f,%6.5f,2,28,%6.5f,%6.5f,33,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'28,%6.5f,%6.5f,%6.5f,2,29,%6.5f,%6.5f,34,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'29,%6.5f,%6.5f,%6.5f,2,30,%6.5f,%6.5f,35,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist2);
fprintf(fid,'30,%6.5f,%6.5f,%6.5f,1,36,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist2);
fprintf(fid,'31,%6.5f,%6.5f,%6.5f,1,32,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,dist2);
fprintf(fid,'32,%6.5f,%6.5f,%6.5f,1,33,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'33,%6.5f,%6.5f,%6.5f,1,34,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'34,%6.5f,%6.5f,%6.5f,1,35,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'35,%6.5f,%6.5f,%6.5f,1,36,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist2);
fprintf(fid,'36,%6.5f,%6.5f,%6.5f,\n',Aa,Pwa,Pha);
fprintf(fid,'*Internal subchannels \n');
fprintf(fid,'37,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'38,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'39,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'40,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'41,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'42,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'43,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'44,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'45,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'46,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);

```

```

fprintf(fid,'47,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'48,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'49,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'50,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'51,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'52,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'53,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'54,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'55,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'56,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'57,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'58,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'59,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'60,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'61,%6.5f,%6.5f,%6.5f,\n',Aw,Pww,Phw);
fprintf(fid,'*geom.4\n');
fprintf(fid,'prop,0,1,2,1 *internal EPRI functions *prop.1\n');
fprintf(fid,'*      \n');
fprintf(fid,'rods,1,50,1,2,4,0,0,0,1,0, *three material types,one type of geo. *rods.1\n');
fprintf(fid,'144.0,13.513,0,0,          *rods.2\n');
fprintf(fid,'26                          *rods3\n');
fprintf(fid,'*One axial profile only (rods.4)\n');
fprintf(fid,'0.,0.,?\n');
fprintf(fid,'3.,0.11769,?\n');
fprintf(fid,'9.,0.60128,?\n');
fprintf(fid,'15.,0.82226,\n');
fprintf(fid,'21.,0.9944,?\n');
fprintf(fid,'27.,1.1257,?\n');
fprintf(fid,'33.,1.20176,?\n');
fprintf(fid,'39.,1.23379,\n');
fprintf(fid,'45.,1.23859,?\n');
fprintf(fid,'51.,1.22898,?\n');
fprintf(fid,'57.,1.21297,?\n');
fprintf(fid,'63.,1.19376,\n');
fprintf(fid,'69.,1.17454,?\n');
fprintf(fid,'75.,1.15853,?\n');
fprintf(fid,'81.,1.14732,?\n');
fprintf(fid,'87.,1.14171,\n');
fprintf(fid,'93.,1.13931,?\n');
fprintf(fid,'99.,1.14171,?\n');
fprintf(fid,'105.,1.14412,?\n');
fprintf(fid,'111.,1.13211,\n');
fprintf(fid,'117.,1.08006,?\n');
fprintf(fid,'123.,0.98559,?\n');
fprintf(fid,'129.,0.83106,?\n');
fprintf(fid,'135.,0.61329,\n');

```

```

fprintf(fid,'141.,0.34508,?\n');
fprintf(fid,'144.,0.,\n');
fprintf(fid,'*\n');
fprintf(fid,'*\n');
fprintf(fid,'*****rods geomatry input                *rods.9\n');
fprintf(fid,'1,1,%1.3f,%d,1,0.25,2,0.25,7,0.25,8,0.25,\n',rpf(1,1),ax(1,1));
fprintf(fid,'-1,1,%1.3f,%d,37,1,\n',rpf(1,1),ax(1,1));
fprintf(fid,'2,1,%1.3f,%d,2,0.25,3,0.25,8,0.25,9,0.25,\n',rpf(2,1),ax(2,1));
fprintf(fid,'-2,1,%1.3f,%d,38,1,\n',rpf(2,1),ax(2,1));
fprintf(fid,'3,1,%1.3f,%d,3,0.25,4,0.25,9,0.25,10,0.25,\n',rpf(3,1),ax(3,1));
fprintf(fid,'-3,1,%1.3f,%d,39,1,\n',rpf(3,1),ax(3,1));
fprintf(fid,'4,1,%1.3f,%d,4,0.25,5,0.25,10,0.25,11,0.25,\n',rpf(4,1),ax(4,1));
fprintf(fid,'-4,1,%1.3f,%d,40,1,\n',rpf(4,1),ax(4,1));
fprintf(fid,'5,1,%1.3f,%d,5,0.25,6,0.25,11,0.25,12,0.25,\n',rpf(5,1),ax(5,1));
fprintf(fid,'-5,1,%1.3f,%d,41,1,\n',rpf(5,1),ax(5,1));
fprintf(fid,'6,1,%1.3f,%d,7,0.25,8,0.25,13,0.25,14,0.25,\n',rpf(6,1),ax(6,1));
fprintf(fid,'-6,1,%1.3f,%d,42,1,\n',rpf(6,1),ax(6,1));
fprintf(fid,'7,1,%1.3f,%d,8,0.25,9,0.25,14,0.25,15,0.25,\n',rpf(7,1),ax(7,1));
fprintf(fid,'-7,1,%1.3f,%d,43,1,\n',rpf(7,1),ax(7,1));
fprintf(fid,'8,1,%1.3f,%d,9,0.25,10,0.25,15,0.25,16,0.25,\n',rpf(8,1),ax(8,1));
fprintf(fid,'-8,1,%1.3f,%d,44,1,\n',rpf(8,1),ax(8,1));
fprintf(fid,'9,1,%1.3f,%d,10,0.25,11,0.25,16,0.25,17,0.25,\n',rpf(9,1),ax(9,1));
fprintf(fid,'-9,1,%1.3f,%d,45,1,\n',rpf(9,1),ax(9,1));
fprintf(fid,'10,1,%1.3f,%d,11,0.25,12,0.25,17,0.25,18,0.25,\n',rpf(10,1),ax(10,1));
fprintf(fid,'-10,1,%1.3f,%d,46,1,\n',rpf(10,1),ax(10,1));
fprintf(fid,'11,1,%1.3f,%d,13,0.25,14,0.25,19,0.25,20,0.25,\n',rpf(11,1),ax(11,1));
fprintf(fid,'-11,1,%1.3f,%d,47,1,\n',rpf(11,1),ax(11,1));
fprintf(fid,'12,1,%1.3f,%d,14,0.25,15,0.25,20,0.25,21,0.25,\n',rpf(12,1),ax(12,1));
fprintf(fid,'-12,1,%1.3f,%d,48,1,\n',rpf(12,1),ax(12,1));
fprintf(fid,'13,1,%1.3f,%d,16,0.25,17,0.25,22,0.25,23,0.25,\n',rpf(13,1),ax(13,1));
fprintf(fid,'-13,1,%1.3f,%d,49,1,\n',rpf(13,1),ax(13,1));
fprintf(fid,'14,1,%1.3f,%d,17,0.25,18,0.25,23,0.25,24,0.25,\n',rpf(14,1),ax(14,1));
fprintf(fid,'-14,1,%1.3f,%d,50,1,\n',rpf(14,1),ax(14,1));
fprintf(fid,'15,1,%1.3f,%d,19,0.25,20,0.25,25,0.25,26,0.25,\n',rpf(15,1),ax(15,1));
fprintf(fid,'-15,1,%1.3f,%d,51,1,\n',rpf(15,1),ax(15,1));
fprintf(fid,'16,1,%1.3f,%d,20,0.25,21,0.25,26,0.25,27,0.25,\n',rpf(16,1),ax(16,1));
fprintf(fid,'-16,1,%1.3f,%d,52,1,\n',rpf(16,1),ax(16,1));
fprintf(fid,'17,1,%1.3f,%d,21,0.25,22,0.25,27,0.25,28,0.25,\n',rpf(17,1),ax(17,1));
fprintf(fid,'-17,1,%1.3f,%d,53,1,\n',rpf(17,1),ax(17,1));
fprintf(fid,'18,1,%1.3f,%d,22,0.25,23,0.25,28,0.25,29,0.25,\n',rpf(18,1),ax(18,1));
fprintf(fid,'-18,1,%1.3f,%d,54,1,\n',rpf(18,1),ax(18,1));
fprintf(fid,'19,1,%1.3f,%d,23,0.25,24,0.25,29,0.25,30,0.25,\n',rpf(19,1),ax(19,1));
fprintf(fid,'-19,1,%1.3f,%d,55,1,\n',rpf(19,1),ax(19,1));
fprintf(fid,'20,1,%1.3f,%d,25,0.25,26,0.25,31,0.25,32,0.25,\n',rpf(20,1),ax(20,1));
fprintf(fid,'-20,1,%1.3f,%d,56,1,\n',rpf(20,1),ax(20,1));
fprintf(fid,'21,1,%1.3f,%d,26,0.25,27,0.25,32,0.25,33,0.25,\n',rpf(21,1),ax(21,1));

```

```

fprintf(fid,'-21,1,%1.3f,%d,57,1,\n',rpf(21,1),ax(21,1));
fprintf(fid,'22,1,%1.3f,%d,27,0.25,28,0.25,33,0.25,34,0.25,\n',rpf(22,1),ax(22,1));
fprintf(fid,'-22,1,%1.3f,%d,58,1,\n',rpf(22,1),ax(22,1));
fprintf(fid,'23,1,%1.3f,%d,28,0.25,29,0.25,34,0.25,35,0.25,\n',rpf(23,1),ax(23,1));
fprintf(fid,'-23,1,%1.3f,%d,59,1,\n',rpf(23,1),ax(23,1));
fprintf(fid,'24,1,%1.3f,%d,29,0.25,30,0.25,35,0.25,36,0.25,\n',rpf(24,1),ax(24,1));
fprintf(fid,'-24,1,%1.3f,%d,60,1,\n',rpf(24,1),ax(24,1));
fprintf(fid,'25,2,0.0,1,15,0.25,16,0.25,21,0.25,22,0.25,          *water rod\n');
fprintf(fid,'-25,2,0.0,1,-61,1,          *water rod\n');
fprintf(fid,'0          *rods.9\n');
fprintf(fid,'*\n');
fprintf(fid,'1,2,3,4,5,\n');
fprintf(fid,'6,7,8,9,10,\n');
fprintf(fid,'11,12,25,13,14,\n');
fprintf(fid,'15,16,17,18,19,\n');
fprintf(fid,'20,21,22,23,24,\n');
fprintf(fid,'          \n');
fprintf(fid,'*blank line above necessary /rods.57 -HG CPR corr\n');
fprintf(fid,'25,%6.6f,%6.6f,%6.6f,%6.6f,          *rods.58,\n',pa,distwall,Dao,Ama);
fprintf(fid,'0          *rods.59\n');
fprintf(fid,'* \n');
fprintf(fid,'*fuel \n');
fprintf(fid,'1,tube,%6.6f,%6.6f,5,          *rods.68\n',Dao,Dai);
fprintf(fid,'* \n');
fprintf(fid,'2,1,%6.6f,0.0,? *inner cladding          *rods.69\n',t);
fprintf(fid,'2,2,%6.6f,0.0,? *inner gap          *rods.69\n',g);
fprintf(fid,'8,3,%6.6f,1.0,? *fuel ring          *rods.69\n',Spessore);
fprintf(fid,'2,4,%6.6f,0.0, *outer gap          *rods.69\n',g);
fprintf(fid,'2,1,%6.6f,0.0, *outer cladding          *rods.69\n',t);
fprintf(fid,'* \n');
fprintf(fid,'*water tube\n');
fprintf(fid,'2,tube,%6.6f,%6.6f,1          *rods.68\n',Dao,Daiw);
fprintf(fid,'3,1,%6.6f,0.0,          *rods.69\n',guide); %I put 0.0 rpf
instead of 1.0
fprintf(fid,'* \n');
fprintf(fid,'1,18,409.0,clad,\n');
fprintf(fid,'*table for cladding          *rods.70\n');
fprintf(fid,'0.0,0.0671,7.3304509,?\n');
fprintf(fid,'25,0.0671,7.3304509,\n');
fprintf(fid,'50,0.0671,7.33045093,?\n');
fprintf(fid,'65,0.0671,7.33045093,\n');
fprintf(fid,'80.33,0.0671,7.33045093,?\n');
fprintf(fid,'260.33,0.07212,8.11585329,\n');
fprintf(fid,'692.33,0.07904,9.80167423,?\n');
fprintf(fid,'1502.33,0.08955,13.2923,\n');
fprintf(fid,'1507.73,0.11988,13.3211893,?\n');

```

```

fprintf(fid,'1543.73,0.14089,13.51665,\n');
fprintf(fid,'1579.73,0.14686,13.717249,?\n');
fprintf(fid,'1615.73,0.1717,13.923198,\n');
fprintf(fid,'1651.73,0.1949,14.1347101,?\n');
fprintf(fid,'1687.73,0.18388,14.351998,\n');
fprintf(fid,'1723.73,0.1478,14.5752746,?\n');
fprintf(fid,'1759.73,0.112,14.804753,\n');
fprintf(fid,'1786.73,0.085,14.9810589,?\n');
fprintf(fid,'2240.33,0.085,18.5665964,\n');
fprintf(fid,'* \n');
fprintf(fid,'*gap\n');
fprintf(fid,'2,1,0.025,igap, *rods.70\n');
fprintf(fid,'1,1.240834,0.346679, *Cp=5195J/kg-K *gap=6000 *rods.71\n');
fprintf(fid,'* \n');
fprintf(fid,'*fuel\n');
fprintf(fid,'3,22,650.617,FUO2, *rods.70\n');
fprintf(fid,'86,0.05677357,4.73275874,?\n');
fprintf(fid,'176,0.06078589,4.2991726,\n');
fprintf(fid,'266,0.06366347,3.93877428,?\n');
fprintf(fid,'356,0.06581210,3.6345405,\n');
fprintf(fid,'446,0.06747631,3.37435643,?\n');
fprintf(fid,'536,0.06880819,3.1493668,\n');
fprintf(fid,'626,0.06990545,2.95294976,?\n');
fprintf(fid,'716,0.07083283,2.78005572,\n');
fprintf(fid,'806,0.07163441,2.62676801,?\n');
fprintf(fid,'896,0.07234099,2.49000319,\n');
fprintf(fid,'986,0.07297458,2.36730189,?\n');
fprintf(fid,'1076,0.07355124,2.25667975,\n');
fprintf(fid,'1166,0.07408294,2.1565193,?\n');
fprintf(fid,'1256,0.07457886,2.06549023,\n');
fprintf(fid,'1346,0.07504628,1.98248979,?\n');
fprintf(fid,'1436,0.07549123,1.90659753,\n');
fprintf(fid,'1526,0.0759191,1.83704065,?\n');
fprintf(fid,'1616,0.07633503,1.77316713,\n');
fprintf(fid,'1706,0.0767443,1.7144247,?\n');
fprintf(fid,'1796,0.07715268,1.66034425,\n');
fprintf(fid,'1886,0.07756663,1.61052668,?\n');
fprintf(fid,'1976,0.07799351,1.5646323, *rods.71\n');
fprintf(fid,'* \n');
fprintf(fid,'*outer gap\n');
fprintf(fid,'4,1,0.025,ogap, *rods.70\n');
fprintf(fid,'1,1.240834,0.34667666, *Cp=5195J/kg-K *gap=6000
*rods.71\n');
fprintf(fid,'* \n');
fprintf(fid,'*****\n');
fprintf(fid,'*P,T\n');

```

```

fprintf(fid,'oper,1,1,0,1,0,1,0,0,0                                *oper.1\n');

if (tag==1)
fprintf(fid,'%6.6f,0.0,2.0,0.005,                                *oper.2 *first word to be changed if you
change BC\n',pressdrop);
fprintf(fid,'0                                                *oper.3 *only if first w above is not 0.0\n');
else
fprintf(fid,'-1.0,0.0,2.0,0.005,                                *oper.2 *first word to be changed if
you change BC\n');
fprintf(fid,'0                                                *oper.3 *only if first w above is not 0.0\n');
end
%oper 2 va a -1.0 !!!!!!!
power=power*superpow;
flow=36.73*superpow;

if (tag==1)
    power=power*1.4;
end

fprintf(fid,'1044.27,534.2,%6.6f,%6.6f,0.0,                        *oper.5\n',flow,power);

fprintf(fid,'*13400 kg/s ,5%bypass and splitted evenly\n');
fprintf(fid,'*Rod power got from total power divided total number of rods\n');
fprintf(fid,'0,                *no forcing functions                *oper.12\n');
fprintf(fid,'*****\n');
fprintf(fid,'*correlations \n');
fprintf(fid,'corr,-2,2,0,                                *corr.1\n');
fprintf(fid,'epri,epri,epri,none,                        *corr.2 \n');
fprintf(fid,'0.2,                                *corr.3 \n');
%fprintf(fid,'ditb,thsp,thsp,epri,cond,g5.7, *correlation for boiling curve *corr.6 \n');
fprintf(fid,'ditb,chen,chen,epri,cond,g5.7, *correlation for boiling curve *corr.6 \n');
fprintf(fid,'1,0,0.0,                                *corr.16,for epri\n');

if (corx==0)
fprintf(fid,'hnch,                                *corr 18 , Hench-Gillis \n');
else
fprintf(fid,'mine,                                *corr 18 , Hench-Gillis \n');
end

fprintf(fid,'*****\n');

perdita1=24.28;
if (tag==1)
    perdita1=23.37;
end
end

```

```

fprintf(fid,'grid,0,5,                                *grid.1\n');
fprintf(fid,'%3.3f,6.63,1.50,1.46,20000,
*grid.2\n',perdita1);
fprintf(fid,'*pressure drop is 24.28 for the average rod and 23.37 for the hot rod\n');
fprintf(fid,'36,10,                                *grid.4\n');
fprintf(fid,'1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,        *grid.5\n');
fprintf(fid,'17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32, \n');
fprintf(fid,'33,34,35,36,                            *grid.5\n');
fprintf(fid,'1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,\n');
fprintf(fid,'153.203,3,175.445,4,                    *grid loc. *grid.6\n');
fprintf(fid,'24,3\n');
fprintf(fid,'37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,\n');
fprintf(fid,'53,54,55,56,57,58,59,60,\n');
fprintf(fid,'1.0,1,12.263,2,31.225,3,\n');
fprintf(fid,'1,1,\n');
fprintf(fid,'61,\n');
fprintf(fid,'1.0,5,\n');
fprintf(fid,'0,\n');
fprintf(fid,'*****\n'
);
fprintf(fid,'cont,                                *cont.1\n');
fprintf(fid,'0.0,0,50,50,3,%u,                    *cont.2\n',sol); %750
fprintf(fid,'0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,        *cont.3\n');
fprintf(fid,'5,0,0,0,0,0,1,1,0,0,0,1,1,0,                    *cont.6\n');
fprintf(fid,'5000.,0.0,0.0,0.0,0.0,0.0,                    *cont.7\n');
fprintf(fid,'endd\n');
fprintf(fid,'*\n');
fprintf(fid,'*end of data input\n');
fprintf(fid,'0\n');

```

%%%%%%%%%  
%%%%%%%%%

```
status = fclose(fid);
```

- % Daof
- % Daif
- % Dao
- % Dai
- % Dao
- % Daiw
- % pa-Dao
- % xp-(Dao/2)

% pa  
% 4\*Aa/Pwa  
% 4\*Ab/Pwb  
% 4\*Ac/Pwc  
% 4\*Ad/Pwd  
% 4\*Ae/Pwe

% appoc/c  
% Afa/Afs  
% Ama/Ams  
% Aca/Acs  
% SVa/SVs



## D.2 Annular 6x6

```
-----  
function annular6x6PRINTtuttoflow2(parDi,superpow,tag,pressdrop,corx,sol);  
  
% parDi=0.8;  
% superpow=1;  
% tag=1;%0  
% pressdrop=25.0826;%0  
% corx=1;  
% sol=0;  
  
parfuel=0.9;  
axialnodes=50; %79;  
%parDi=Dai/Dhs --suggested 90% (ratio between the internal diameter of the  
%annular on the hydraulic diameter of the solid)  
%parfuel=Afa/Afs ----suggested 90%  
%superpow=power upgrade besides the hot rod factor (1.4), 1 is normal  
%tag=if it is hot or average rod. Hot rod=1, average=0  
%corx chooses the correlation. 0=hench-gillis, all else, mine  
%sol=0 iterative, 1=direct, 2=recirculation  
  
%Calculation sheet for dimensions of BWR annular fuel  
%Annular - 6x6  
%Reference Solid: BWR-5 8x8  
%FINAL DESIGN / keeping the fuel volume instead  
  
%NOTE: MODIFIED to include gaps  
%Neglected the cladding of the water rods and control rods  
  
%PRINTS EXACTLY ALL VIPRE INPUT  
  
%NOTE:  
%1) The flow is uprated as the power is (we want constant quality)  
%2) One axial profile  
  
%CHECKS  
if (parDi<0.7)  
    'low pardi'  
elseif (parDi>1)  
    'pardi>1'  
end  
  
if (superpow<1)
```

```

    'superpow'
end

if ((tag~=0) & (tag~=1))
    'tag'
end

if ((pressdrop==0) & (tag~=0))
    'pressure drop'
end

%all in cm
L=13.4; % width of the assembly
t=0.085; %clad thickness

%number of rods
Ns=62; %solid --- 2 water rods
Na=34; %ann --- 2 water rod 6x6 %CORRETTO
na=6; %number of annular rods per side
ns=8; %number of solid rods per side

%solid
Ds=1.23; %solid D
Dsf=1.04; %solid fuel D
g=(Ds/2)-t-(Dsf/2); %gap in the solid fuel= gap in the annular fuel (but it has 2 of them)
p=1.62;
guide=(1.50-1.32)/2; %thickness of the guide tube in the reference design / I use the
same

Ap=p*p-((pi*Ds*Ds)/4); %flow area in a subchannel
Pw=pi*Ds; %wetted perimeter
Dh=4*Ap/Pw; %Hydraulic D /solid, RELATED TO int for annular fuel

Ams=L*L-((Ns+2)*pi*Ds*Ds/4); %area of moderator
Afs=Ns*pi*Dsf*Dsf/4; %area of fuel /RELATED

c=Afs/Ams; %RATIO, not the same for both

%annular
Dai=parDi*Dh; %internal D of ann function of hydr D of solid
Daif=Dai+(2*(t+g)); %internal D of ann fuel
tg=t+g;

%External fuel diameter calculation

Daof=sqrt(((Ns/(Na/parfuel))*Dsf*Dsf)+(Daif*Daif));

```

```

Dao=Daof+(2*(t+g));           %external diameter of annular rod

%verification
Ama=L*L-((Na)*pi*(Dao*Dao-Dai*Dai)/4)-(2*pi*(Dao*Dao-((Dao-2*guide)*(Dao-
2*guide)))/4); %CORRETTO
Afa=Na*pi*(Daof*Daof-Daif*Daif)/4;

appoc=Afa/Ama;

if ((abs(appoc/c)<0.9) | (abs(appoc/c)>1.1))
    'Vf/Vm ratio is wrong'
    appoc
    c
    appoc/c
    abs((appoc-c)/c)
else
    'right Vf/Vm'
%   appoc
%   c
%   appoc/c
%   abs((appoc-c)/c)
end

if (((L-na*Dao)/(na+1))<0.1)
    'average spacing is less than 0.1'
else
    'correct average spacing'
end

%tests

% 'Afs/Afa'
% Afs/Afa
% 'Ams/Ama'
% Ams/Ama

%end calculation

%conversion: cm/k=in
k=2.540;

%k=1; %just for calculation in cm

%measure of the distance rod-bundle (solid)

```

```

x=(L-(ns-1)*p)/2; %distance from the center of the corner rod to the bundle wall
delta=x-p;

%pitch of the annular fuel (pa)
%we impose that the ratio (p-D)/x is the same for both
delta=(p-Ds)/(x-(Ds/2));
pa=(delta*L/2-delta*Dao/2+Dao)/(1+(delta/2)*(na-1));
xp=(L-(na-1)*pa)/2; %distance from the center of the corner rod to the bundle wall

distwall=xp-(Dao/2);
if (distwall<0.1)
    'the distance from the wall is too little'
else
    'distwall OK'
end

%*****
****

%CHECKS
% 'pa-Dao'
% pa-Dao
% 'xp-(Dao/2)'
% xp-(Dao/2)
% '(pa-Dao)/(xp-(Dao/2))'
% (pa-Dao)/(xp-(Dao/2))
% 'p-Ds'
% p-Ds
% 'x-(Ds/2)'
% x-(Ds/2)
% '(p-Ds)/(x-(Ds/2))'
% (p-Ds)/(x-(Ds/2))
%
% '(L-Dao*na)/(na+1)'
% (L-Dao*na)/(na+1)
% '(L-Ds*ns)/(ns+1)'
% (L-Ds*ns)/(ns+1)

%*****
****

%Flow area Ax , x is the type (see yellow paper)
%a: corner 1/7/43/49
%b: border 2/3/4/5/6/8/14/15/21/22/28/29/35/36/42/44/45/46/47/48
%c: middle 9/10/11/12/13/16/17/20/23/27/30/33/34/37/38/39/40/41

```

%d: water 18/19/24/25/26/31/32

%e: internal 50->83

%w: water tube 84-85

$Aa = xp * xp - (\pi * Dao * Dao / 16);$

$Pwa = 2 * xp + (\pi * Dao / 4);$

$Pha = \pi * Dao / 4;$

$Ab = (pa * xp) - (\pi * Dao * Dao / 8);$

$Pwb = pa + (\pi * Dao / 2);$

$Phb = \pi * Dao / 2;$

$Ac = pa * pa - (\pi * Dao * Dao / 4);$

$Pwc = \pi * Dao;$

$Phc = Pwc;$

$Ad = pa * pa - (\pi * Dao * Dao / 4);$

$Pwd = \pi * Dao;$

$Phd = 3 * \pi * Dao / 4;$

$Ae = \pi * Dai * Dai / 4;$

$Pwe = \pi * Dai;$

$Phe = Pwe;$

%guide=(1.50-1.32)/2; %thickness of the guide tube in the reference design / I use the same

$Aw = \pi * (Dao - 2 * guide) * (Dao - 2 * guide) / 4;$

$Pww = \pi * (Dao - 2 * guide);$

$Phw = Pww;$  %VIPRE requirement

%connections

%a<->b, b<->b

conn1=xp-(Dao/2);

%b<->c, c<->c, c<->d, d<->d

conn2=pa-Dao;

%distance of centroids

%b<->b, c<->c, c<->d, d<->d

dist1=pa;

%a<->b, b<->c

dist2=(xp/2)+(pa/2);

%((pa-Dao)/(xp-(Dao/2))) %spacing ratio

%  $4 * (x * x - (\pi * Ds * Ds / 16)) / ((2 * x) + (\pi * Ds / 4))$  %corner Dh for solid

%  $4 * (x * p - (\pi * Ds * Ds / 8)) / (p + (\pi * Ds / 2))$  %border Dh for solid

```

%plots
%cladding volume
Acs=Ns*(pi/4)*(Ds*Ds-(Ds-2*t)*(Ds-2*t))+(pi/4)*(1.50*1.50-1.32*1.32);
Aca=Na*(pi/4)*((Dao*Dao-(Dao-2*t)*(Dao-2*t))+(Dai+2*t)*(Dai+2*t)-
Dai*Dai)+2*(pi/4)*(Dao*Dao-(Dao-2*guide)*(Dao-2*guide));
%heated surface on fuel volume ratio
SVs=Ns*pi*Ds/Afs;
SVa=Na*(pi*Dao+pi*Dai)/Afa;

% Na*pi*(Dao)/(Na*pi*(Dao+Dai))
%Dao/(Dao+Dai)

% Aca/Acs
% SVa/SVs

% Daof
% Daif
% Dao
% Dai
% Dao-(2*guide)

% pa
% 4*Aa/Pwa
% 4*Ab/Pwb
% 4*Ac/Pwc
% 4*Ae/Pwe
% Afa
% appoc

% Afa/Afs
% Ama/Ams
% Afa
% Afs

% pa-Dao
% xp-(Dao/2)
% appoc/c

%gap conductance calculation

%igap
hg=6000; %W/(m2K)
%from report 1: kg=hg*Ravg*ln(Ro/Ri)
kgi=hg*(((Dai/2)+t+(g/2))/100)*log((Daif/2)/((Dai/2)+t)); %converted in meters---kg->
W/mK

```

```

%outer gap
kgo=hg*(((Daof/2)+(g/2))/100)*log(((Daof/2)+g)/(Daof/2));
kth=1.73073; %divide by this to go from W/mK to Btu/hrftF

```

```

%conversion to inches
%areas ->divide by k*k

```

```
Aa=Aa/(k*k);
```

```
Ab=Ab/(k*k);
```

```
Ac=Ac/(k*k);
```

```
Ad=Ad/(k*k);
```

```
Ae=Ae/(k*k);
```

```
Aw=Aw/(k*k);
```

```
%lengths: divide by k
```

```
Pwa=Pwa/k;
```

```
Pha=Pha/k;
```

```
Pwb=Pwb/k;
```

```
Phb=Phb/k;
```

```
Pwc=Pwc/k;
```

```
Phc=Phc/k;
```

```
Pwd=Pwd/k;
```

```
Phd=Phd/k;
```

```
Pwe=Pwe/k;
```

```
Phe=Phe/k;
```

```
Pww=Pww/k;
```

```
Phw=Phw/k;
```

```
conn1=conn1/k;
```

```
conn2=conn2/k;
```

```
dist1=dist1/k;
```

```
dist2=dist2/k;
```

```
%other stuff useful for the input
```

```
pa=pa/k;
```

```
distwall=distwall/k;
```

```
Dao=Dao/k;
```

```
Dai=Dai/k;
```

```
Ama=Ama/(k*k); %area
```

```
Spessore=(Daof-Daif)/2/k;
```

```
g=g/k;
```

```
t=t/k;
```

```
guide=guide/k;
```

```
Daiw=Dao-2*(guide);
```

```
%power=179.59; %kW/rod
```

```
%changed!
```

```
power=126.77; %kW/rod
```

```
flow=36.73; %lbm/s
```

```

%'rods' construction
ii=0;

%first word: channel number
% chn=ones(50,1);
% for ii=2:50
%   chn(ii,1)=ceil(ii/2);
%   if (chn(ii,1)==chn((ii-1),1))
%       chn(ii,1)=-chn(ii,1);
%   end
% end

%Second word: rod geometry type
% rgt=ones(50,1);
% rgt(49,1)=2;
% rgt(50,1)=2;

%Third word: radial power factor
%rpf=ones(34,1);

rpf=[ 1.102, 1.085, 1.099, 1.103, 1.088, 1.102,...
      1.085, 0.377, 1.016, 1.068, 0.381, 1.087,...
      1.099, 1.016, 1.129,      1.067, 1.102,...
      1.103, 1.068,      1.129, 1.016, 1.097,...
      1.088, 0.381, 1.067, 1.016, 0.377, 1.083,...
      1.102, 1.087, 1.102, 1.097, 1.083, 1.098];

rpf=rpf';

%-----
% rpfpr=zeros(48,1);
% for ii=1:48
%   rpfpr(ii,1)=rpf(ceil(ii/2));
% end

%Fourth word: axial profiles
ax=ones(Na,1);
%definisci ax!!!!
% for ii=1:24
%   ax(ii,1)=2;
% end
% ax(7,1)=3;
% ax(9,1)=3;
% ax(16,1)=3;
% ax(18,1)=3;

```

```

% ax(1,1)=1;
% ax(5,1)=1;
% ax(20,1)=1;
% ax(24,1)=1;
%double the axial profile for internal channels
% axpp=zeros(48,1);
% for ii=1:48
%   axpp(ii,1)=ax(ceil(ii/2));
% end

%scrivo
%fid=fopen('C:\VIPRE\input','w');
fid=fopen('C:\Vipre2\input','w');

%%%%%%%%%%
%%%%%%%%%%
%%%%%%%%%%

fprintf(fid,'*****\n');
fprintf(fid,'* (flat for now) * \n');
fprintf(fid,'* 1 assembly, 6x6 annular pins, using BWR power distribution * \n');

if (tag==1)
    fprintf(fid,'* HOT ROD * \n');
else
    fprintf(fid,'* AVERAGE ROD * \n');
end
fprintf(fid,'* one axial profile and approximate radial profile * \n');
fprintf(fid,'* parDi: %2.2f * \n',parDi);
fprintf(fid,'* parfuel: %2.2f * \n',parfuel);
fprintf(fid,'* Superpower: %2.2f * \n',superpow);
if (corx==0)
    fprintf(fid,'* HENCH GILLIS correlation for CPR * \n');
else
    fprintf(fid,'* MODIFIED HG correlation for CPR * \n');
end
if (sol==0)
    fprintf(fid,'* ITERATIVE solution * \n');
elseif (sol==1)
    fprintf(fid,'* DIRECT solution * \n');
else
    fprintf(fid,'* RECIRCULATION solution * \n');
end
end

```

```

fprintf(fid,'*****\n');
*****\n');
fprintf(fid,'1,0,0,                                *vipre.1\n');
fprintf(fid,'Bwr annular fuel                      *vipre.2\n');
fprintf(fid,'*                                       \n');
fprintf(fid,'geom,85,85,%u,0,0,0,   *normal geometry input
*geom.1\n',axialnodes);
fprintf(fid,'*                                       \n');
fprintf(fid,'178.5,0.0,0.5,                        *geom.2\n');
fprintf(fid,'*                                       \n');
fprintf(fid,'1,%6.5f,%6.5f,%6.5f,2,2,%6.5f,%6.5f,8,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,d
ist2,conn1,dist2);
fprintf(fid,'2,%6.5f,%6.5f,%6.5f,2,3,%6.5f,%6.5f,9,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,d
ist1,conn2,dist2);
fprintf(fid,'3,%6.5f,%6.5f,%6.5f,2,4,%6.5f,%6.5f,10,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,
dist1,conn2,dist2);
fprintf(fid,'4,%6.5f,%6.5f,%6.5f,2,5,%6.5f,%6.5f,11,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,
dist1,conn2,dist2);
fprintf(fid,'5,%6.5f,%6.5f,%6.5f,2,6,%6.5f,%6.5f,12,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,
dist1,conn2,dist2);
fprintf(fid,'6,%6.5f,%6.5f,%6.5f,2,7,%6.5f,%6.5f,13,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,
dist2,conn2,dist2);
fprintf(fid,'7,%6.5f,%6.5f,%6.5f,1,14,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,dist2);
fprintf(fid,'8,%6.5f,%6.5f,%6.5f,2,9,%6.5f,%6.5f,15,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn2,
dist2,conn1,dist1);
fprintf(fid,'9,%6.5f,%6.5f,%6.5f,2,10,%6.5f,%6.5f,16,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn2
,dist1,conn2,dist1);
fprintf(fid,'10,%6.5f,%6.5f,%6.5f,2,11,%6.5f,%6.5f,17,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'11,%6.5f,%6.5f,%6.5f,2,12,%6.5f,%6.5f,18,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'12,%6.5f,%6.5f,%6.5f,2,13,%6.5f,%6.5f,19,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'13,%6.5f,%6.5f,%6.5f,2,14,%6.5f,%6.5f,20,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'14,%6.5f,%6.5f,%6.5f,1,21,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'15,%6.5f,%6.5f,%6.5f,2,16,%6.5f,%6.5f,22,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist1);
fprintf(fid,'16,%6.5f,%6.5f,%6.5f,2,17,%6.5f,%6.5f,23,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'17,%6.5f,%6.5f,%6.5f,2,18,%6.5f,%6.5f,24,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'18,%6.5f,%6.5f,%6.5f,2,19,%6.5f,%6.5f,25,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'19,%6.5f,%6.5f,%6.5f,2,20,%6.5f,%6.5f,26,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);

```

```

fprintf(fid,'20,%6.5f,%6.5f,%6.5f,2,21,%6.5f,%6.5f,27,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'21,%6.5f,%6.5f,%6.5f,1,28,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'22,%6.5f,%6.5f,%6.5f,2,23,%6.5f,%6.5f,29,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist1);
fprintf(fid,'23,%6.5f,%6.5f,%6.5f,2,24,%6.5f,%6.5f,30,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'24,%6.5f,%6.5f,%6.5f,2,25,%6.5f,%6.5f,31,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'25,%6.5f,%6.5f,%6.5f,2,26,%6.5f,%6.5f,32,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'26,%6.5f,%6.5f,%6.5f,2,27,%6.5f,%6.5f,33,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'27,%6.5f,%6.5f,%6.5f,2,28,%6.5f,%6.5f,34,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'28,%6.5f,%6.5f,%6.5f,1,35,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'29,%6.5f,%6.5f,%6.5f,2,30,%6.5f,%6.5f,36,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist1);
fprintf(fid,'30,%6.5f,%6.5f,%6.5f,2,31,%6.5f,%6.5f,37,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'31,%6.5f,%6.5f,%6.5f,2,32,%6.5f,%6.5f,38,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'32,%6.5f,%6.5f,%6.5f,2,33,%6.5f,%6.5f,39,%6.5f,%6.5f,\n',Ad,Pwd,Phd,con
n2,dist1,conn2,dist1);
fprintf(fid,'33,%6.5f,%6.5f,%6.5f,2,34,%6.5f,%6.5f,40,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist1);
fprintf(fid,'34,%6.5f,%6.5f,%6.5f,2,35,%6.5f,%6.5f,41,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist1);
fprintf(fid,'35,%6.5f,%6.5f,%6.5f,1,42,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'36,%6.5f,%6.5f,%6.5f,2,37,%6.5f,%6.5f,43,%6.5f,%6.5f,\n',Ab,Pwb,Phb,con
n2,dist2,conn1,dist2);
fprintf(fid,'37,%6.5f,%6.5f,%6.5f,2,38,%6.5f,%6.5f,44,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'38,%6.5f,%6.5f,%6.5f,2,39,%6.5f,%6.5f,45,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'39,%6.5f,%6.5f,%6.5f,2,40,%6.5f,%6.5f,46,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'40,%6.5f,%6.5f,%6.5f,2,41,%6.5f,%6.5f,47,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist1,conn2,dist2);
fprintf(fid,'41,%6.5f,%6.5f,%6.5f,2,42,%6.5f,%6.5f,48,%6.5f,%6.5f,\n',Ac,Pwc,Phc,conn
2,dist2,conn2,dist2);
fprintf(fid,'42,%6.5f,%6.5f,%6.5f,1,49,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist2);
fprintf(fid,'43,%6.5f,%6.5f,%6.5f,1,32,%6.5f,%6.5f,\n',Aa,Pwa,Pha,conn1,dist2);
fprintf(fid,'44,%6.5f,%6.5f,%6.5f,1,33,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'45,%6.5f,%6.5f,%6.5f,1,34,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'46,%6.5f,%6.5f,%6.5f,1,35,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);

```

```

fprintf(fid,'47,%6.5f,%6.5f,%6.5f,1,36,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist1);
fprintf(fid,'48,%6.5f,%6.5f,%6.5f,1,36,%6.5f,%6.5f,\n',Ab,Pwb,Phb,conn1,dist2);
fprintf(fid,'49,%6.5f,%6.5f,%6.5f,\n',Aa,Pwa,Pha);
fprintf(fid,'*Internal subchannels \n');
fprintf(fid,'50,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'51,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'52,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'53,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'54,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'55,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'56,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'57,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'58,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'59,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'60,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'61,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'62,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'63,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'64,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'65,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'66,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'67,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'68,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'69,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'70,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'71,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'72,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'73,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'74,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'75,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'76,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'77,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'78,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'79,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'80,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'81,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'82,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'83,%6.5f,%6.5f,%6.5f,\n',Ae,Pwe,Phe);
fprintf(fid,'84,%6.5f,%6.5f,%6.5f,\n',Aw,Pww,Phw);
fprintf(fid,'85,%6.5f,%6.5f,%6.5f,\n',Aw,Pww,Phw);
fprintf(fid,'*geom.4\n');
fprintf(fid,'prop,0,1,2,1 *internal EPRI functions *prop.1\n');
fprintf(fid,'* \n');
fprintf(fid,'rods,1,72,1,2,4,0,0,0,1,0, *three material types,one type of geo. *rods.1\n');
fprintf(fid,'144.0,13.513,0,0, *rods.2\n');
fprintf(fid,'26 *rods3\n');

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```

fprintf(fid,'*One axial profile only (rods.4)\n');
fprintf(fid,'0.,0.,?\n');
fprintf(fid,'3.,0.11769,?\n');
fprintf(fid,'9.,0.60128,?\n');
fprintf(fid,'15.,0.82226,\n');
fprintf(fid,'21.,0.9944,?\n');
fprintf(fid,'27.,1.1257,?\n');
fprintf(fid,'33.,1.20176,?\n');
fprintf(fid,'39.,1.23379,\n');
fprintf(fid,'45.,1.23859,?\n');
fprintf(fid,'51.,1.22898,?\n');
fprintf(fid,'57.,1.21297,?\n');
fprintf(fid,'63.,1.19376,\n');
fprintf(fid,'69.,1.17454,?\n');
fprintf(fid,'75.,1.15853,?\n');
fprintf(fid,'81.,1.14732,?\n');
fprintf(fid,'87.,1.14171,\n');
fprintf(fid,'93.,1.13931,?\n');
fprintf(fid,'99.,1.14171,?\n');
fprintf(fid,'105.,1.14412,?\n');
fprintf(fid,'111.,1.13211,\n');
fprintf(fid,'117.,1.08006,?\n');
fprintf(fid,'123.,0.98559,?\n');
fprintf(fid,'129.,0.83106,?\n');
fprintf(fid,'135.,0.61329,\n');
fprintf(fid,'141.,0.34508,?\n');
fprintf(fid,'144.,0.,\n');
fprintf(fid,'*\n');
fprintf(fid,'*\n');
fprintf(fid,'*****rods geomatry input                *rods.9\n');
fprintf(fid,'1,1,%1.3f,%d,1,0.25,2,0.25,8,0.25,9,0.25,\n',rpf(1,1),ax(1,1));
fprintf(fid,'-1,1,%1.3f,%d,50,1,\n',rpf(1,1),ax(1,1));
fprintf(fid,'2,1,%1.3f,%d,2,0.25,3,0.25,9,0.25,10,0.25,\n',rpf(2,1),ax(2,1));
fprintf(fid,'-2,1,%1.3f,%d,51,1,\n',rpf(2,1),ax(2,1));
fprintf(fid,'3,1,%1.3f,%d,3,0.25,4,0.25,10,0.25,11,0.25,\n',rpf(3,1),ax(3,1));
fprintf(fid,'-3,1,%1.3f,%d,52,1,\n',rpf(3,1),ax(3,1));
fprintf(fid,'4,1,%1.3f,%d,4,0.25,5,0.25,11,0.25,12,0.25,\n',rpf(4,1),ax(4,1));
fprintf(fid,'-4,1,%1.3f,%d,53,1,\n',rpf(4,1),ax(4,1));
fprintf(fid,'5,1,%1.3f,%d,5,0.25,6,0.25,12,0.25,13,0.25,\n',rpf(5,1),ax(5,1));
fprintf(fid,'-5,1,%1.3f,%d,54,1,\n',rpf(5,1),ax(5,1));
fprintf(fid,'6,1,%1.3f,%d,6,0.25,7,0.25,13,0.25,14,0.25,\n',rpf(6,1),ax(6,1));
fprintf(fid,'-6,1,%1.3f,%d,55,1,\n',rpf(6,1),ax(6,1));
fprintf(fid,'7,1,%1.3f,%d,8,0.25,9,0.25,15,0.25,16,0.25,\n',rpf(7,1),ax(7,1));
fprintf(fid,'-7,1,%1.3f,%d,56,1,\n',rpf(7,1),ax(7,1));
fprintf(fid,'8,1,%1.3f,%d,9,0.25,10,0.25,16,0.25,17,0.25,\n',rpf(8,1),ax(8,1));
fprintf(fid,'-8,1,%1.3f,%d,57,1,\n',rpf(8,1),ax(8,1));

```

```

fprintf(fid,'9,1,%1.3f,%d,10,0.25,11,0.25,17,0.25,18,0.25,\n',rpf(9,1),ax(9,1));
fprintf(fid,'-9,1,%1.3f,%d,58,1,\n',rpf(9,1),ax(9,1));
fprintf(fid,'10,1,%1.3f,%d,11,0.25,12,0.25,18,0.25,19,0.25,\n',rpf(10,1),ax(10,1));
fprintf(fid,'-10,1,%1.3f,%d,59,1,\n',rpf(10,1),ax(10,1));
fprintf(fid,'11,1,%1.3f,%d,12,0.25,13,0.25,19,0.25,20,0.25,\n',rpf(11,1),ax(11,1));
fprintf(fid,'-11,1,%1.3f,%d,60,1,\n',rpf(11,1),ax(11,1));
fprintf(fid,'12,1,%1.3f,%d,13,0.25,14,0.25,20,0.25,21,0.25,\n',rpf(12,1),ax(12,1));
fprintf(fid,'-12,1,%1.3f,%d,61,1,\n',rpf(12,1),ax(12,1));
fprintf(fid,'13,1,%1.3f,%d,15,0.25,16,0.25,22,0.25,23,0.25,\n',rpf(13,1),ax(13,1));
fprintf(fid,'-13,1,%1.3f,%d,62,1,\n',rpf(13,1),ax(13,1));
fprintf(fid,'14,1,%1.3f,%d,16,0.25,17,0.25,23,0.25,24,0.25,\n',rpf(14,1),ax(14,1));
fprintf(fid,'-14,1,%1.3f,%d,63,1,\n',rpf(14,1),ax(14,1));
fprintf(fid,'15,1,%1.3f,%d,17,0.25,18,0.25,24,0.25,25,0.25,\n',rpf(15,1),ax(15,1));
fprintf(fid,'-15,1,%1.3f,%d,64,1,\n',rpf(15,1),ax(15,1));
fprintf(fid,'16,1,%1.3f,%d,19,0.25,20,0.25,26,0.25,27,0.25,\n',rpf(16,1),ax(16,1));
fprintf(fid,'-16,1,%1.3f,%d,65,1,\n',rpf(16,1),ax(16,1));
fprintf(fid,'17,1,%1.3f,%d,20,0.25,21,0.25,27,0.25,28,0.25,\n',rpf(17,1),ax(17,1));
fprintf(fid,'-17,1,%1.3f,%d,66,1,\n',rpf(17,1),ax(17,1));
fprintf(fid,'18,1,%1.3f,%d,22,0.25,23,0.29,28,0.25,30,0.25,\n',rpf(18,1),ax(18,1));
fprintf(fid,'-18,1,%1.3f,%d,67,1,\n',rpf(18,1),ax(18,1));
fprintf(fid,'19,1,%1.3f,%d,23,0.25,24,0.25,30,0.25,31,0.25,\n',rpf(19,1),ax(19,1));
fprintf(fid,'-19,1,%1.3f,%d,68,1,\n',rpf(19,1),ax(19,1));
fprintf(fid,'20,1,%1.3f,%d,25,0.25,26,0.25,32,0.25,33,0.25,\n',rpf(20,1),ax(20,1));
fprintf(fid,'-20,1,%1.3f,%d,69,1,\n',rpf(20,1),ax(20,1));
fprintf(fid,'21,1,%1.3f,%d,26,0.25,27,0.25,33,0.25,34,0.25,\n',rpf(21,1),ax(21,1));
fprintf(fid,'-21,1,%1.3f,%d,70,1,\n',rpf(21,1),ax(21,1));
fprintf(fid,'22,1,%1.3f,%d,27,0.25,28,0.25,34,0.25,35,0.25,\n',rpf(22,1),ax(22,1));
fprintf(fid,'-22,1,%1.3f,%d,71,1,\n',rpf(22,1),ax(22,1));
fprintf(fid,'23,1,%1.3f,%d,29,0.25,30,0.25,36,0.25,37,0.25,\n',rpf(23,1),ax(23,1));
fprintf(fid,'-23,1,%1.3f,%d,72,1,\n',rpf(23,1),ax(23,1));
fprintf(fid,'24,1,%1.3f,%d,30,0.25,31,0.25,37,0.25,38,0.25,\n',rpf(24,1),ax(24,1));
fprintf(fid,'-24,1,%1.3f,%d,73,1,\n',rpf(24,1),ax(24,1));
fprintf(fid,'25,1,%1.3f,%d,31,0.25,32,0.25,38,0.25,39,0.25,\n',rpf(25,1),ax(25,1));
fprintf(fid,'-25,1,%1.3f,%d,74,1,\n',rpf(25,1),ax(25,1));
fprintf(fid,'26,1,%1.3f,%d,32,0.25,33,0.25,39,0.25,40,0.25,\n',rpf(26,1),ax(26,1));
fprintf(fid,'-26,1,%1.3f,%d,75,1,\n',rpf(26,1),ax(26,1));
fprintf(fid,'27,1,%1.3f,%d,33,0.25,34,0.25,40,0.25,41,0.25,\n',rpf(27,1),ax(27,1));
fprintf(fid,'-27,1,%1.3f,%d,76,1,\n',rpf(27,1),ax(27,1));
fprintf(fid,'28,1,%1.3f,%d,34,0.25,35,0.25,41,0.25,42,0.25,\n',rpf(28,1),ax(28,1));
fprintf(fid,'-28,1,%1.3f,%d,77,1,\n',rpf(28,1),ax(28,1));
fprintf(fid,'29,1,%1.3f,%d,36,0.25,37,0.25,43,0.25,44,0.25,\n',rpf(29,1),ax(29,1));
fprintf(fid,'-29,1,%1.3f,%d,78,1,\n',rpf(29,1),ax(29,1));
fprintf(fid,'30,1,%1.3f,%d,37,0.25,38,0.25,44,0.25,45,0.25,\n',rpf(30,1),ax(30,1));
fprintf(fid,'-30,1,%1.3f,%d,79,1,\n',rpf(30,1),ax(30,1));
fprintf(fid,'31,1,%1.3f,%d,38,0.25,39,0.25,45,0.25,46,0.25,\n',rpf(31,1),ax(31,1));
fprintf(fid,'-31,1,%1.3f,%d,80,1,\n',rpf(31,1),ax(31,1));

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fprintf(fid,'32,1,%1.3f,%d,39,0.25,40,0.25,46,0.25,47,0.25,\n',rpf(32,1),ax(32,1));
fprintf(fid,'-32,1,%1.3f,%d,81,1,\n',rpf(32,1),ax(32,1));
fprintf(fid,'33,1,%1.3f,%d,40,0.25,41,0.25,47,0.25,48,0.25,\n',rpf(33,1),ax(33,1));
fprintf(fid,'-33,1,%1.3f,%d,82,1,\n',rpf(33,1),ax(33,1));
fprintf(fid,'34,1,%1.3f,%d,41,0.25,42,0.25,48,0.25,49,0.25,\n',rpf(34,1),ax(34,1));
fprintf(fid,'-34,1,%1.3f,%d,83,1,\n',rpf(34,1),ax(34,1));
fprintf(fid,'35,2,0.0,1,18,0.25,19,0.25,25,0.25,26,0.25,           *water rod\n');
fprintf(fid,'-35,2,0.0,1,-84,1,                                   *water rod\n');
fprintf(fid,'36,2,0.0,1,24,0.25,25,0.25,31,0.25,32,0.25,       *water rod\n');
fprintf(fid,'-36,2,0.0,1,-85,1,                                   *water rod\n');
fprintf(fid,'0                                                    *rods.9\n');
fprintf(fid,'*\n');
fprintf(fid,'1,2,3,4,5,6,\n');
fprintf(fid,'7,8,9,10,11,12,\n');
fprintf(fid,'13,14,15,35,16,17,\n');
fprintf(fid,'18,19,36,20,21,22,\n');
fprintf(fid,'23,24,25,26,27,28,\n');
fprintf(fid,'29,30,31,32,33,34,\n');
fprintf(fid,'          \n');
fprintf(fid,'*blank line above necessary /rods.57 -HG CPR corr\n');
fprintf(fid,'36,%6.6f,%6.6f,%6.6f,%6.6f,           *rods.58,\n',pa,distwall,Dao,Ama);
fprintf(fid,'0                                                    *rods.59\n');
fprintf(fid,'*  \n');
fprintf(fid,'*fuel  \n');
fprintf(fid,'1,tube,%6.6f,%6.6f,5,                   *rods.68\n',Dao,Dai);
fprintf(fid,'*  \n');
fprintf(fid,'2,1,%6.6f,0.0,? *inner cladding           *rods.69\n',t);
fprintf(fid,'2,2,%6.6f,0.0,? *inner gap              *rods.69\n',g);
fprintf(fid,'8,3,%6.6f,1.0,? *fuel ring          *rods.69\n',Spessore);
fprintf(fid,'2,4,%6.6f,0.0,   *outer gap              *rods.69\n',g);
fprintf(fid,'2,1,%6.6f,0.0,   *outer cladding        *rods.69\n',t);
fprintf(fid,'*  \n');
fprintf(fid,'*water tube\n');
fprintf(fid,'2,tube,%6.6f,%6.6f,1                   *rods.68\n',Dao,Daiw);
fprintf(fid,'3,1,%6.6f,0.0,                           *rods.69\n',guide); %I put 0.0 rpf
instead of 1.0
fprintf(fid,'*  \n');
fprintf(fid,'1,18,409.0,clad,\n');
fprintf(fid,'*table for cladding                       *rods.70\n');
fprintf(fid,'0.0,0.0671,7.3304509,?\n');
fprintf(fid,'25,0.0671,7.3304509,\n');
fprintf(fid,'50,0.0671,7.33045093,?\n');
fprintf(fid,'65,0.0671,7.33045093,\n');
fprintf(fid,'80.33,0.0671,7.33045093,?\n');
fprintf(fid,'260.33,0.07212,8.11585329,\n');
fprintf(fid,'692.33,0.07904,9.80167423,?\n');

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fprintf(fid,'1502.33,0.08955,13.2923,\n');
fprintf(fid,'1507.73,0.11988,13.3211893,?\n');
fprintf(fid,'1543.73,0.14089,13.51665,\n');
fprintf(fid,'1579.73,0.14686,13.717249,?\n');
fprintf(fid,'1615.73,0.1717,13.923198,\n');
fprintf(fid,'1651.73,0.1949,14.1347101,?\n');
fprintf(fid,'1687.73,0.18388,14.351998,\n');
fprintf(fid,'1723.73,0.1478,14.5752746,?\n');
fprintf(fid,'1759.73,0.112,14.804753,\n');
fprintf(fid,'1786.73,0.085,14.9810589,?\n');
fprintf(fid,'2240.33,0.085,18.5665964,\n');
fprintf(fid,'* \n');
fprintf(fid,'*gap\n');
fprintf(fid,'2,1,0.025,igap, *rods.70\n');
fprintf(fid,'1,1.240834,0.346679, *Cp=5195J/kg-K *gap=6000 *rods.71\n');
fprintf(fid,'* \n');
fprintf(fid,'*fuel\n');
fprintf(fid,'3,22,650.617,FUO2, *rods.70\n');
fprintf(fid,'86,0.05677357,4.73275874,?\n');
fprintf(fid,'176,0.06078589,4.2991726,\n');
fprintf(fid,'266,0.06366347,3.93877428,?\n');
fprintf(fid,'356,0.06581210,3.6345405,\n');
fprintf(fid,'446,0.06747631,3.37435643,?\n');
fprintf(fid,'536,0.06880819,3.1493668,\n');
fprintf(fid,'626,0.06990545,2.95294976,?\n');
fprintf(fid,'716,0.07083283,2.78005572,\n');
fprintf(fid,'806,0.07163441,2.62676801,?\n');
fprintf(fid,'896,0.07234099,2.49000319,\n');
fprintf(fid,'986,0.07297458,2.36730189,?\n');
fprintf(fid,'1076,0.07355124,2.25667975,\n');
fprintf(fid,'1166,0.07408294,2.1565193,?\n');
fprintf(fid,'1256,0.07457886,2.06549023,\n');
fprintf(fid,'1346,0.07504628,1.98248979,?\n');
fprintf(fid,'1436,0.07549123,1.90659753,\n');
fprintf(fid,'1526,0.0759191,1.83704065,?\n');
fprintf(fid,'1616,0.07633503,1.77316713,\n');
fprintf(fid,'1706,0.0767443,1.7144247,?\n');
fprintf(fid,'1796,0.07715268,1.66034425,\n');
fprintf(fid,'1886,0.07756663,1.61052668,?\n');
fprintf(fid,'1976,0.07799351,1.5646323, *rods.71\n');
fprintf(fid,'* \n');
fprintf(fid,'*outer gap\n');
fprintf(fid,'4,1,0.025,ogap, *rods.70\n');
fprintf(fid,'1,1.240834,0.34667666, *Cp=5195J/kg-K *gap=6000
*rods.71\n');
fprintf(fid,'* \n');

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```

fprintf(fid,'*****\n');
fprintf(fid,'*P,T\n');
fprintf(fid,'oper,1,1,0,1,0,1,0,0,0          *oper.1\n');

if (tag==1)
fprintf(fid,'%6.6f,0.0,2.0,0.005,          *oper.2 *first word to be changed if you
change BC\n',pressdrop);
fprintf(fid,'0          *oper.3 *only if first w above is not 0.0\n');
else
fprintf(fid,'-1.0,0.0,2.0,0.005,          *oper.2 *first word to be changed if
you change BC\n');
fprintf(fid,'0          *oper.3 *only if first w above is not 0.0\n');
end
%oper 2 va a -1.0 !!!!!
power=power*superpow;
flow=36.73*superpow;

if (tag==1)
    power=power*1.4;
end

fprintf(fid,'1044.27,534.2,%6.6f,%6.6f,0.0,          *oper.5\n',flow,power);

fprintf(fid,'*13400 kg/s ,5%bypass and splitted evenly\n');
fprintf(fid,'*Rod power got from total power divided total number of rods\n');
fprintf(fid,'0,          *no forcing functions          *oper.12\n');
fprintf(fid,'*****\n');
fprintf(fid,'*correlations \n');
fprintf(fid,'corr,-2,2,0,          *corr.1\n');
fprintf(fid,'epri,epri,epri,none,          *corr.2 \n');
fprintf(fid,'0.2,          *corr.3 \n');
%fprintf(fid,'ditb,thsp,thsp,epri,cond,g5.7,          *correlation for boiling curve *corr.6 \n');
fprintf(fid,'ditb,chen,chen,epri,cond,g5.7,          *correlation for boiling curve *corr.6 \n');
fprintf(fid,'1,0,0.0,          *corr.16,for epri\n');

if (corx==0)
fprintf(fid,'hnch,          *corr 18 , Hench-Gillis \n');
else
fprintf(fid,'mine,          *corr 18 , Hench-Gillis \n');
end

fprintf(fid,'*****\n');

perdita1=24.28;
if (tag==1)
    perdita1=23.37;

```

end

```
fprintf(fid,'grid,0,5,                                *grid.1\n');
fprintf(fid,'%3.3f,6.63,1.50,1.46,20000,
*grid.2\n',perdita1);
fprintf(fid,'*pressure drop is 24.28 for the average rod and 23.37 for the hot rod\n');
fprintf(fid,'49,10,                                *grid.4\n');
fprintf(fid,'1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,        *grid.5\n');
fprintf(fid,'17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32, \n');
fprintf(fid,'33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48, \n');
fprintf(fid,'49,                                *grid.5\n');
fprintf(fid,'1.0,1,12.263,2,31.225,3,52.537,3,72.7,3,92.857,3,112.857,3,133.033,3,\n');
fprintf(fid,'153.203,3,175.445,4,                                *grid loc. *grid.6\n');
fprintf(fid,'34,3,\n');
fprintf(fid,'50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,\n');
fprintf(fid,'66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,\n');
fprintf(fid,'82,83,\n');
fprintf(fid,'1.0,1,12.263,2,31.225,3,\n');
fprintf(fid,'2,1,\n');
fprintf(fid,'84,85,\n');
fprintf(fid,'1.0,5,\n');
fprintf(fid,'0,\n');
fprintf(fid,'*****\n'
);
fprintf(fid,'cont,                                *cont.1\n');
fprintf(fid,'0.0,0,250,50,3,%u,                                *cont.2\n',sol); %750
fprintf(fid,'0.0,0,50,50,3,%u,                                *cont.2\n',sol); %250
fprintf(fid,'0.10,0.00001,0.001,0.05,0.01,0.9,1.5,1.0,        *cont.3\n');
fprintf(fid,'5,0,0,0,0,1,1,0,0,1,1,0,                                *cont.6\n');
fprintf(fid,'5000.,0.0,0.0,0.0,0.0,0.0,                                *cont.7\n');
fprintf(fid,'endd\n');
fprintf(fid,'*\n');
fprintf(fid,'*end of data input\n');
fprintf(fid,'0\n');
```

%%%%%%%%%%  
%%%%%%%%%

status = fclose(fid);

% Daof  
% Daif  
% Dao

% Dai  
% Dao  
% Daiw  
% pa-Dao  
% xp-(Dao/2)  
% pa  
% 4\*Aa/Pwa  
% 4\*Ab/Pwb  
% 4\*Ac/Pwc  
% 4\*Ad/Pwd  
% 4\*Ae/Pwe

% appoc/c  
% Afa/Afs  
% Ama/Ams  
% Aca/Acs  
% SVa/SVs



# Appendix E

## VIPRE CPR Correlation Modification

VIPRE calculates the CPR with the Hensch-Gillis correlation using the subroutine 'CPR1'. In addition the code allows the user to input his own correlation using the subroutine CPR3. To keep the change clear we have copied the CPR1 subroutine under CPR3 and then made the change in CPR3 so to keep the bulk of the code unchanged and have our modified Hensch-Gillis correlation as an option in the input. By choosing 'mine' in the correlation selection line of the input we use our modified correlation, while the standard option 'hneh' runs the unmodified Hensch-Gillis correlation.

The change we made is in ***underlined bold italic***

---

```
*ADDDECK CPR3
      subroutine cpr3
c
c * * * * *
c
c   cpr3 is provided for a user-coded cpr correlation
c
c   arguments - none
c
c   cpr3 is called by cprs
c   cpr3 calls bomb if a 'mine' correlation is selected but
c   has not been coded into the subroutine
c
c * * * * *
c
cstart -- start common blocks   c
      include "props"
      include "fields"
      include "fuel"
      include "mains"
      include "chfs"
c
cend -- end of common blocks
c
      common /xcpr/ xcritm,phitot
```

```

c      factrj=0.
c      delp=1.0
c
c      isboil=0
c      dxcrm=10.
c
c      determine number of fuel bundles to be
c      evaluated.....
c      for critical power
c
c      subchannel analysis - 1 bundle only
c      lumped assembly analysis - maximum of nrod bundles
c
c      ibndl=nrod
c      if(icpr .lt. 0) go to 1000
c
c      for subchannel analysis, calculate bundle-average conditions
c
c      ibndl=1
c
c      sum the channel flows and enthalpies to find
c      the bundle average enthalpy at each axial level
c
c      do 175 j=1,ndxp1
c      sumh=0.
c      sumf=0.
c      do 150 i=1,nchan1
c      do 125 l=1,icout
c      if(i .eq. iout(l)) go to 150
125    continue
c
c      sumh=sumh+f(i,j)*h(i,j)
c      sumf=sumf+f(i,j)
150    continue
c
c      hbar(j)=sumh/sumf
c      if(j .eq. 1) hinlt=hbar(j)
c
c      locate the beginning of the boiling length
c
c      xbar=(hbar(j)-hf)/hfg
c      if(xbar.lt.0.0 .or. isboil.gt.0) go to 175
c      isboil=j
175    continue
c
c      find the heated length for the bundle
c
c      do 225 j=2,ndxp1
c      jhstrt=j-1
c      do 200 n=1,nrod
c      if(radial(n) .lt. 0.10) go to 200
c      if(flux(n,j) .gt. 0.10) go to 250
200    continue
c
225    continue

```

```

c
250  continue
c
      jhs1=jhstrt+1
      do 300 j=jhs1,ndxp1
      do 275 n=1,nrod
      if(radial(n) .lt. 0.10) go to 275
      if(flux(n,j) .lt. 0.10) go to 350
275  continue
c
      jhend=j
300  continue
c
350  continue
c
      jinlt=jhstrt
      zhn(i)=x(jhend)-x(jhstrt)
c
c  do not calculate cpr if the bundle is not boiling
c
      if(isboil .le. 0) go to 2100
c
c
c  calculate the inlet subcooling
c
      dhsub=hf-hinlt
c
c  calculate the bundle average mass flux
c  and the total mass flow rate
c
      aftot=0.0
      sumf=0.
      do 400 i=1,nchan1
      do 375 l=1,icout
      if(i .eq. iout(l)) go to 400
375  continue
      sumf=sumf+f(i,l)
      aftot=aftot+an(i)
400  continue
      g=sumf/aftot*0.0036
      fdot=sumf
      sumr=0.
      phitot=0.
      do 450 nn=1,nrod
      sump=0.
      if(radial(nn) .le. 0.10) go to 450
      do 425 l=1,6
      sump=sump+phi(nn,l)
c
c
c  PXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
c  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
425  continue
c
c
c  sumr contains the total heated perimeter of the bundle
c  phitot contains the total number of heated rods in the bundle
c

```



```

c
c     jflag=2
c     go to 625
c
c 500  continue
c
c look above and below for adjacent rods
c
c     if(ir.eq.1 .or. irc(ir+1,iv).eq.0) go to 525
c
c n is a side rod (in the first or last column)
c
c     jflag=3
c     go to 625
c
c 525  continue
c
c n is a corner rod
c
c     jflag=4
c     go to 625
c
c 550  continue
c
c 600  continue
c
c 625  continue
c
c     irn=ir
c     icn=iv
c     sumi=0.
c     sumj=0.
c
c calculate the j-factor for rod n
c
c     go to (650,800,850,650), jflag
c
c n is a central or corner rod
c
c 650  continue
c
c sum the radial power factors of the adjacent i-rods
c
c     nil=irc(irn,icn+1)
c     if(nil .gt. 0) sumi=sumi+radial(nil)
c     ni2=irc(irn+1,icn)
c     if(ni2 .gt. 0) sumi=sumi+radial(ni2)
c     if(icn .eq. 1) go to 675
c     ni3=irc(irn,icn-1)
c     sumi=sumi+radial(ni3)
c
c 675  continue
c
c     if(irn .eq. 1) go to 700
c     ni4=irc(irn-1,icn)
c     sumi=sumi+radial(ni4)

```

```

700  continue
c
c  sum the radial power factors of the adjacent j-rods
c
      nj1=irc(irn+1,icn+1)
      if(nj1 .gt. 0) sumj=sumj+radial(nj1)
      if(icn .eq. 1) go to 725
      nj2=irc(irn+1,icn-1)
      if(nj2 .gt. 0) sumj=sumj+radial(nj2)
      if(irn .eq. 1) go to 750
      nj3=irc(irn-1,icn-1)
      sumj=sumj+radial(nj3)
725  continue
      if(irn .eq. 1) go to 750
      nj4=irc(irn-1,icn+1)
      sumj=sumj+radial(nj4)
750  continue
      fr=radial(n)
      if(jflag .gt. 1) go to 775
c
c  j1 for central rods
c
      fj1(n,3)=1./32.*(20.*fr+2.*sumj+sumi)
      locr=3
c
c  j3 for central rods
c
      fj3(n)=0.14/(g+0.25)-0.10
      go to 925
c
c  j1 for corner rods
c
775  continue
      fj1(n,1)=1./32.*(25.*fr+3.*sumi+sumj)
c
c  add the j1a factor for corner rods
c
      fj1(n,1)=fj1(n,1)-fj1a*(4.*fr+sumi)
      locr=1
c
c  j3 for corner rods
c
      fj3(n)=0.
      go to 925
c
c  n is a side rod (in a row)
c
c
800  continue
c
c  sum the radial power factors of the adjacent i-rods
c
      ni1=irc(irn,icn-1)
      ni2=irc(irn,icn+1)
      sumi=radial(ni1)+radial(ni2)
c

```

```

c   sum the radial power factors of the adjacent j-rods
c
      if(irn .eq. 1) go to 825
      nj1=irc(irn-1,icn-1)
      nj2=irc(irn-1,icn+1)
      sumj=radial(nj1)+radial(nj2)
      k=irc(irn-1,icn)
      fk=radial(k)
      go to 900
c
825  continue
c
      nj1=irc(irn+1,icn-1)
      nj2=irc(irn+1,icn+1)
      sumj=radial(nj1)+radial(nj2)
      k=irc(irn+1,icn)
      fk=radial(k)
      go to 900
c
c   n is a side rod (in a column)
c
850  continue
c
c   sum the radial power factors of the adjacent i-rods
c
      ni1=irc(irn+1,icn)
      ni2=irc(irn-1,icn)
      sumi=radial(ni1)+radial(ni2)
c
c   sum the radial power factors of the adjacent j-rods
c
      if(icn .gt. 1) go to 875
      nj1=irc(irn+1,icn+1)
      nj2=irc(irn-1,icn+1)
      sumj=radial(nj1)+radial(nj2)
      k=irc(irn,icn+1)
      fk=radial(k)
      go to 900
c
875  continue
c
      nj1=irc(irn+1,icn-1)
      nj2=irc(irn-1,icn-1)
      sumj=radial(nj1)+radial(nj2)
      k=irc(irn,icn-1)
      fk=radial(k)
c
900  continue
c
c   j1 for side rods
c
      fr=radial(n)
      fj1(n,2)=1./32.*(22.*fr+3.*sumi+2.*fk+sumj)
c
c   add the j1a factor for side rods
c

```

```

        fj1(n,2)=fj1(n,2)-fj1a*(2.*fr+sumi)
        locr=2
c
c   j3 for side rods
c
        fj3(n)=0.07/(g+0.25)-0.05
c
925   continue
c
        l=locr
        fctrjn=fj1(n,l)-0.19/g*(fj1(n,l)-1.)**2-fj3(n)
c
        if(fctrjn .lt. factrj) go to 950
        factrj=fctrjn
        locrm=locr
        fctrj1=fj1(n,l)
950   continue
c
c   end of calculation of bundle-average conditions
c   for subchannel cases
c
c
c
1000  continue
c
        do 2000 n=1,ibndl
        icount=1
        dxcrm=10.
c
        if(icpr .gt. 0) go to 1500
c
c   calculate correlation parameters for each active
bundle.....
c   in lumped assembly cases
c
        if(radial(n) .le. 0.10) go to 2000
c
c   find the heated length for bundle n
c
        isboil=0
        jinlt=1
        i=lr(n,1)
        do 1050 j=2,ndxp1
        jhstrt=j-1
        if(flux(n,j) .gt. 0.01) go to 1075
1050  continue
c
1075  continue
c
        jhs1=jhstrt+1
        do 1100 j=jhs1,ndxp1
        if(flux(n,j) .lt. 0.01) go to 1125
        jhend=j
1100  continue
c
1125  continue

```

```

c
    jinlt=jhstrt
    zhn(n)=x(jhend)-x(jhstrt)
    if(icout .le. 0) go to 1175
    do 1150 l=1,icout
    if(iout(l) .eq. i) go to 2000
1150 continue
c
1175 continue
c
c find beginning of boiling length
c for bundle n
c
    hinlt=h(i,jinlt)
c
    do 1200 j=1,ndxp1
    hbar(j)=h(i,j)
c
c include the water tube flow in the bundle average enthalpy
c calculation if the tubes are modeled
c
    if(j .gt. jbwat(i) .and. j .lt. jewt(i)) hbar(j)=(h(i,j)*f(i,j)
    1 +hw(i,j)*fw(i,j))/(f(i,j)+fw(i,j))
    xbar=(hbar(j)-hf)/hfg
    if(xbar.le.0.0 .or. isboil.gt.0) go to 1200
    isboil=j
1200 continue
c
    if(isboil .eq. 0) go to 2100
c
c find the total heated perimeter of bundle n
c
    it=idfuel(n)
    sumr=heatp(it)*phi(n,1)
c find the inlet subcooling of bundle n
c
    dhsub=hf-hinlt
c
c beginning of iteration loop for critical bundle power
c
1500 continue
c
    delxcm=1.0
c
    if(icount .gt. 99) go to 2200
    if(icount .eq. 1) go to 1600
c
c adjust hbar for new power level and recompute
c location of begining of boiling
c
    isboil=0
    jin2=jinlt+1
    do 1550 j=jin2,jhend
    hbar(j)=delp*(hbar(j)-hinlt)+hinlt
    xbar=(hbar(j)-hf)/hfg
    if(xbar.le.0.0 .or. isboil.gt.0) go to 1550

```

```

        isboil=j
1550 continue
c
        if(isboil .eq. 0) go to 2100
c
1600 continue
c
c   evaluate the critical quality at each axial
c   level along the boiling length
c
        isbp=isboil+1
        jx=isbp
c
c   calculate g and fdot in the bundle
c
        if(icpr .lt. 0) go to 1700
c
c   subchannel case
c
        sumf=0.
        aftot=0.
        do 1650 i=1,nchanl
        do 1625 l=1,icout
        if(i .eq. iout(l)) go to 1650
1625 continue
        sumf=sumf+f(i,jx)
        aftot=aftot+a(i,jx)
1650 continue
        gold=g
        g=sumf/aftot*0.0036
        fdot=sumf
        if(abs(g-gold) .lt. 0.001) go to 1750
c
c   recompute j-factor if g has changed
c
        fctrj3=0.
        if(locrm .eq. 1) fctrj3=0.14/(g+0.25)-0.10
        if(locrm .eq. 2) fctrj3=0.07/(g+0.25)-0.05
c
        factrj=fctrj1-0.19/g*(fctrj1-1.)**2-fctrj3
c
        go to 1750
c
1700 continue
c
c   lumped channel
case.....
c
c
        aftot=a(i,jx)
        fdot=f(i,jx)
        if(ntube .gt. 0) fdot=f(i,jx)+fw(i,jx)
        g=fdot/aftot*0.0036
c
c   recompute j-factor with new g
c

```

```

c maximum j-factor for corner rods
c
c   fjcrrn=fj1(n,1)-0.19/g*(fj1(n,1)-1.0)**2
c
c maximum j-factor for side rods
c
c   fjside=fj1(n,2)-0.19/g*(fj1(n,2)-1.0)**2-(0.07/(g+0.25)-0.05)
c
c maximum j-factor for interior rods
c
c   fjint=fj1(n,3)-0.19/g*(fj1(n,3)-1.0)**2-(0.14/(g+0.25)-0.1)
c
c   factrj=amax1(fjcrrn,fjside,fjint)
c
1750 continue
c
c pressure correction factor
c
c   ffp=0.006-0.0157*(pref-800.)/1000.0-0.0714*((pref-800.)/1000.0)**2
c
c   do 1800 j=isbp,jhend
c
c calculate boiling length and dimensionless boiling length ratio
c
c   bl=x(j)-x(isboil)
c   blr=sumr*bl/aftot
c
c
c critical quality
c
c   xcrit=ffp+0.50*g**(-0.43)*blr*(2.-factrj)/(165.+
1   115.*g**2.3+blr)
c
c   xloc=(hbar(j)-hf)/hfg
c
c   xcrit=amin1(xcrit,1.0)
c   xloc=amin1(xloc,1.0)
c   dxcrm=(xcrit+dhsub/hfg)/(xloc+dhsub/hfg)
c
c find the minimum thermal margin in the bundle
c
c   delxc=abs(xcrit-xloc)
c   if(delxc .gt. delxcm) go to 1800
c   delxcm=delxc
c   xcritm=xcrit
c   dxcrm=dxcrm
c   dhcpr=hbar(jhend)-hbar(jinlt)
c   fdotm=fdot
c   jcrit(n)=j
c   xlocm=xloc
c
1800 continue
c
c check the new minimum margin. has it converged to 1.0 + or -
c dnbrc yet?
c

```

```

c
  pfactr=(xcritm+dhsb/hfg)/(xlocm+dhsb/hfg)
  delpwr=1.0-pfactr
  if(abs(delpwr) .lt. dnbrc) go to 1900
c
c  not converged -- do another iteration
c
  delp=pfactr
  icount=icount+1
  go to 1500
c
1900 continue
c
c  converged -- calculate critical bundle power
c          from the adjusted enthalpy rise
c
c
c          pcrit(n)=dhcpr*fdotm
c
c  write critical power summary to tape 7 -- case no., rod(bundle)
c  index, critical quality, critical boiling length (in.) and
c  boiling length ratio, critical power, bundle mass flux, inlet
c  enthalpy, actual power and cpr
c
  if(icpr .lt. 0) prout=aflux*radial(n)*phi(n,1)*zhn(n)
  if(icpr .gt. 0) prout=aflux*phitot*zhn(1)
  prout=prout*1.0548
  pcout=pcrit(n)*1.0548
  cpr=pcout/prout
  blout=bl*12.
  write(7,10180) kase,n,xcritm,blout,blr,pcout,g,hinlt,prout,cpr
10180 format(5x,2i5,2x,f5.3,2(2x,f8.3),1x,f8.2,2x,'*',2x,
1      f5.3,3x,f6.2,2x,f7.2,2x,f6.3)
2000 continue
c
  return
c
2100 continue
c
  write(i3,10190)
10190 format(10x,'**** error in cpr calculation with hench-gillis ',
1      'correlation ****',/20x,
2      ' cannot find location of beginning of saturated boiling')
  return
c
2200 continue
c
  write(i3,10200) icount
10200 format(10x,'**** error in cpr calculation with hench-gillis',
1      ' correlation ****',/20x,
2      ' not converged on critical power after',i5,' iterations')
  return
  end

```

---