OPTIMIZATION OF THORIUM-BASED SEED-BLANKET FUEL CYCLES FOR NUCLEAR POWER PLANTS

by

Martin Busse

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Signature of Author ....
System Design and Management Program
May 5, 2000

Certified by ....
Mujid S. Kazimi
TEPCO Professor of Nuclear Engineering
Thesis Supervisor

Accepted by ....
Thomas A. Kochan
George M. Bunker Professor of Management
LFM/SDM Co-Director

Accepted by ....
Paul A. Lagace
Professor of Aeronautics & Astronautics and Engineering Systems
LFM/SDM Co-Director

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ABSTRACT

From the inception of nuclear power, thorium-based fuels have been of interest due to the abundance of thorium ore and to potential neutronic advantages in the efficiency of creating new fissile materials in the core. Early reviews of nuclear fuel cycles tended to conclude that the uranium cycle, currently used in nuclear power plants, was more preferable than the thorium cycle, partly because of its simpler reprocessing and fabrication. The conditions of the nuclear industry have changed, focusing on high burnup once-through fuel cycles (no reprocessing). This creates incentives for further analysis of the thorium-based cycle to assess improved economic performance and safety margins in addition to the expected reduced waste production and enhanced proliferation resistance.

This thesis analyzes alternative thorium-based fuel approaches from a thermal-hydraulics point of view. The proposed cycle's performance is optimized given constraints that will facilitate the implementation of the concept in typical commercial power plants. The new designs are based on a seed and blanket configuration, where the seed region is rich in uranium fuel (U-235), thus is the supplier of neutrons, and the blanket region is a net neutron absorber to generate new fuel (U-233) from thorium.

Two different designs are analyzed: the Seed and Blanket assembly as one Unit (SBU) and the Whole assembly as a Seed or Blanket (WSB). These designs are optimized from a thermal-hydraulic perspective and their economic performance is compared to the current fuel cycle. The optimization involves extracting the maximum energy without violating the limits on heat flux from fuel rods to the coolant.

The proposed best approach for improving fuel thermal-hydraulics performance is based on the use of grids that allow differential loss coefficients between the seed and the blanket regions. This preferred approach to optimization was found to be more effective in the case of the WSB design because of its power distribution and the larger spatial separation between regions.

A very important factor in the economics of these designs is the achievable cycle length, which is a function of the neutronic design. An eighteen-month cycle is required in order to be economically comparable to the current fuel cycle. With comparable length, the fuel cost per unit energy is found comparable to the current cycle, with slight benefits achieved for all urania or thoria-based fuel depending on the cost of enrichment. However, waste performance and non-proliferation advantages may play an important role in fuel attractiveness to nuclear power plants and to the government and these were not factored in the economic analysis.

Thesis Supervisor: Dr. Mujid S. Kazimi

Title: TEPCO Professor of Nuclear Engineering

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This thesis is dedicated to my parents for all their continual support and sacrifices during my graduate studies, and specially to my wife Mery. Without her love and encouragement these two years at MIT would not have been possible. I cannot truly express my appreciation for her patience and sacrifice in supporting me through the SDM program.

Chapter 1

THORIUM-BASED FUELS FOR PWRS

1.1 Introduction

Thorium-based fuels had been of interest to the nuclear industry due to the abundance of thorium ore and also because of some important neutronic advantages. Thorium cycles differ from the conventional uranium cycle in that thorium-232 (Th^{232}) produces uranium-233 (U^{233}), which generates neutrons by fission in the thermal and epithermal neutron fluxes. The different processes are shown below:

$$U^{238} + n \rightarrow Pu^{239}$$
$$Th^{232} + n \rightarrow U^{233}$$

This thermal absorption cross section to convert the fertile atom into a fissile one is higher for Th^{232} than for uranium-238 (U^{238}). Thus the in-core fissile generation capability of thorium-based fuels can be higher, reducing the need of fuel ore and/or the enrichment per unit of energy generation. The enhanced proliferation resistant features of the spent fuel complement these potential economic benefits. This includes the reduced production of plutonium and the mix of its isotopes that would be less useful in weapons.

The main drawback of the thorium cycle is the lack of U^{233} in nature. This translates in the need for a fissile material such as uranium-235 (U^{235}) or plutonium-239 (Pu^{239}) as a source of neutrons in the early stages of the cycle. Thus, thorium is used as a part of a thorium-uranium (or thorium-plutonium) fuel mixture. Although the use of two materials seems as a disadvantage, it is offset by the significant reduction in plutonium content of the fuel cycle [Ref. 1].

Early reviews of nuclear fuel cycles tended to conclude that the uranium cycle was more preferable than the thorium cycle because of the high cost of the initial investment in U^{235} and the relative reprocessing disadvantages of the thorium fuel. The conditions of the nuclear industry have changed, focusing on once-through fuel cycles (no reprocessing). The incentives for further analysis of fuel alternatives such as the thorium-based cycle given this situation are clear: economic performance, safety, reduced waste production and enhanced proliferation resistance.

1.2 Historical Review of the use of Thorium in nuclear reactors

The first core experiments in the use of thorium-uranium oxide fuels date from the 1960s and 1970s. Two types of designs were analyzed at that time, a uniform lattice with mixed thorium oxide with highly enriched uranium oxide and an heterogeneous arrangement of seed and blanket regions, where the blanket is responsible of producing in-core fissile material while the seed is the source of neutrons, especially in the early stages of the cycle.

These early approaches to thorium based fuels were done at a time when reprocessing of the spent fuel for recycling fissile material was the prevailing expectation and the proscription of a 20% uranium enrichment limit against proliferation was not an issue. The high gamma energy associated with U-232 in the thorium cycle increases the radiological protection needs during reprocessing making the use of thorium less appealing.

The Light Water Breeder Reactor (LWBR) program at Shippingport was the first to demonstrate the seed-blanket concept for commercial power generation in the late 1970s. Some shortcomings from the LWBR were the lower power density of the core compared to modern PWRs, and the more complicated recycling process for two types of fuels containing U and Th compared to recycling one type of fuel in the U and Pu cycle, especially because of the need of extra shielding in the fabrication process.

Later, in mid 1970s EPRI commissioned a study of the use of thorium in modern Light Water Reactors (LWRs). The conclusions were that the use of thorium with recycle can increase the energy output per mined ton of uranium but with no economic attractiveness (savings occurring later in the cycle). Additionally the study concluded that thorium fueling was feasible, and no modifications to a PWR design were needed [Ref. 2].

Reactor types other than LWRs have experimented with the use of thorium, but no design proved successful enough to justify further investigations [Ref. 3].

Recently, some new characteristics of the thorium cycle attracted the attention of the nuclear community. The increased cost of management of spent fuel and the proliferation resistance attributes of spent fuel from US reactors are among the key reasons for new research initiatives [Ref. 4].

An improved seed-blanket concept was recently proposed by Alvin Radkowsky based on the ideas of the LWBR program. This once-through light water thorium technology, known as RTF (Radkowsky thorium fuel), is nonproliferative, provides reduction in fuel waste and is expected to reduce fuel costs. A key feature is that an RTF design can be implemented in current PWRs cores [Ref. 5][Ref. 6].

1.3 Alternative designs analyzed

In the present study, heterogeneous seed-blanket designs are analyzed. Keeping in mind the goals of the new fuel, some design constraints were applied in order to take into account the context where the fuel is going to be used. These constraints will facilitate the commercial implementation of the concept by allowing the use of the new fuel in typical commercial PWRs.

The most relevant constraints are:

- Compatibility with existing PWR's
- Comparable Environmental, Safety and Health characteristics
- Economic Competitiveness

Two designs are analyzed: the Seed Blanket Unit (SBU) and the Whole Seed and Blanket array (WSB). Both approaches are based on the seed and blanket regions concept. However, while the SBU implements these regions within a fuel assembly, the WSB has whole assemblies as seeds or blankets. Figure 1 compares a conventional PWR uranium based assembly with the SBU design approach. The seed region is fissile rich, while the blanket region has low initial fissile content.

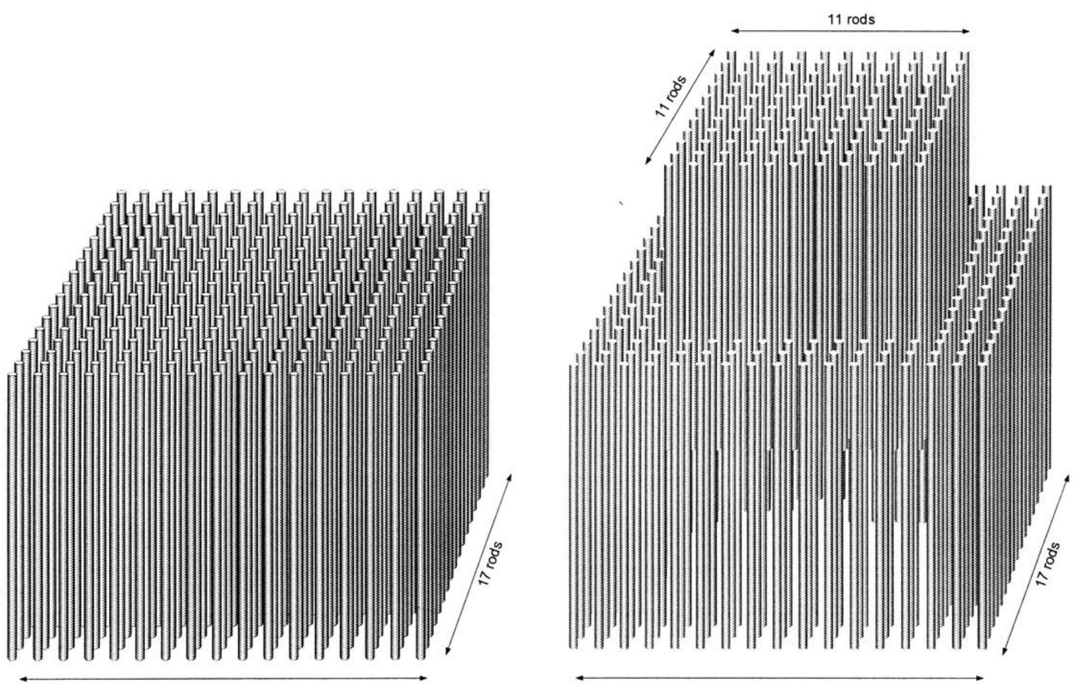


Figure 1 Conventional PWR fuel assembly vs. SBU assembly.

The SBU is designed to be used in current PWRs, whose core layout is depicted in Figure 2. Each assembly has two regions; the center is composed of seed rods while the blanket is surrounding it. These regions should be stand alone elements as their fuel type and management are very different (this will be discussed in detailed in the next chapter). Because of its higher power density, the seed region requires smaller fuel pin diameters and/or fuel material with higher conductivity than the blanket region. In Chapter 3 a detailed analysis of the SBU will be given.

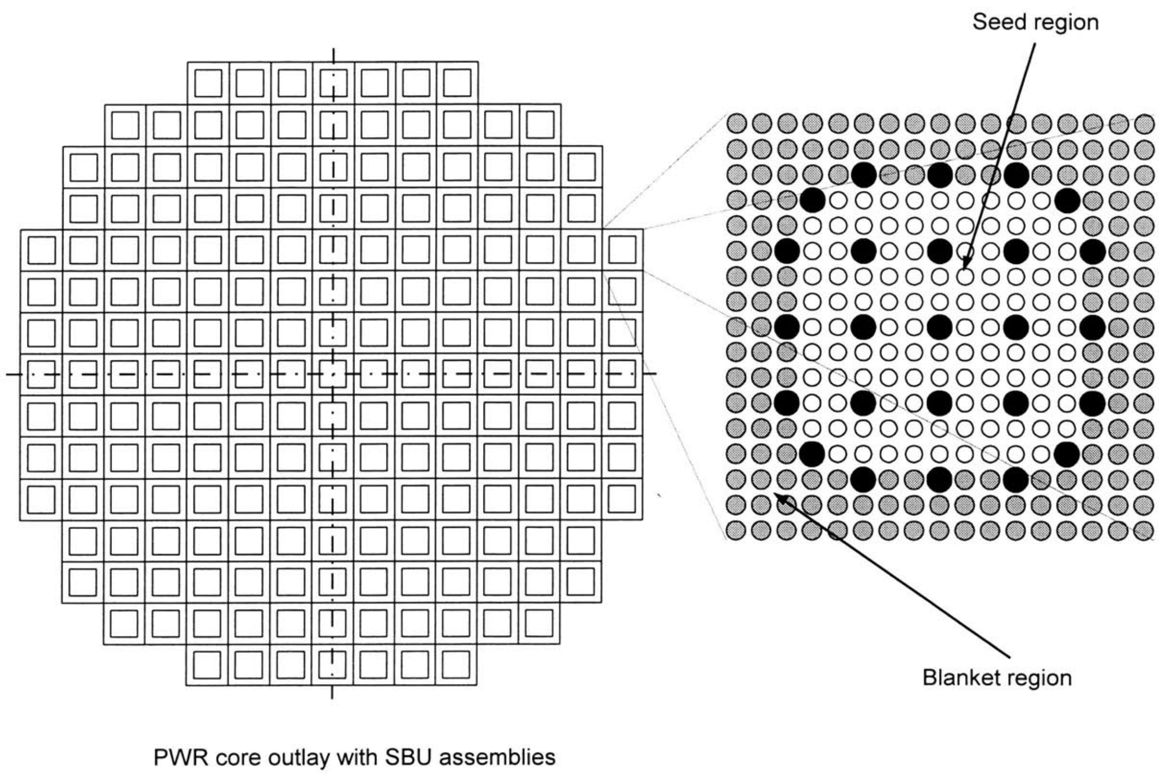


Figure 2 SBU assembly as part of a PWR core

The WSB approach uses a whole assembly as a seed or a blanket. The resulting core looks like a checkerboard with seed assemblies surrounded by blankets. In this case each assembly follows different fuel management policies.

The checkerboard approach is very appealing given that the refueling units are the same as those used in current PWRs. A more detailed analysis of this design will be given in Chapter 4.

The basic layout of the checkerboard array is shown in Figure 3.

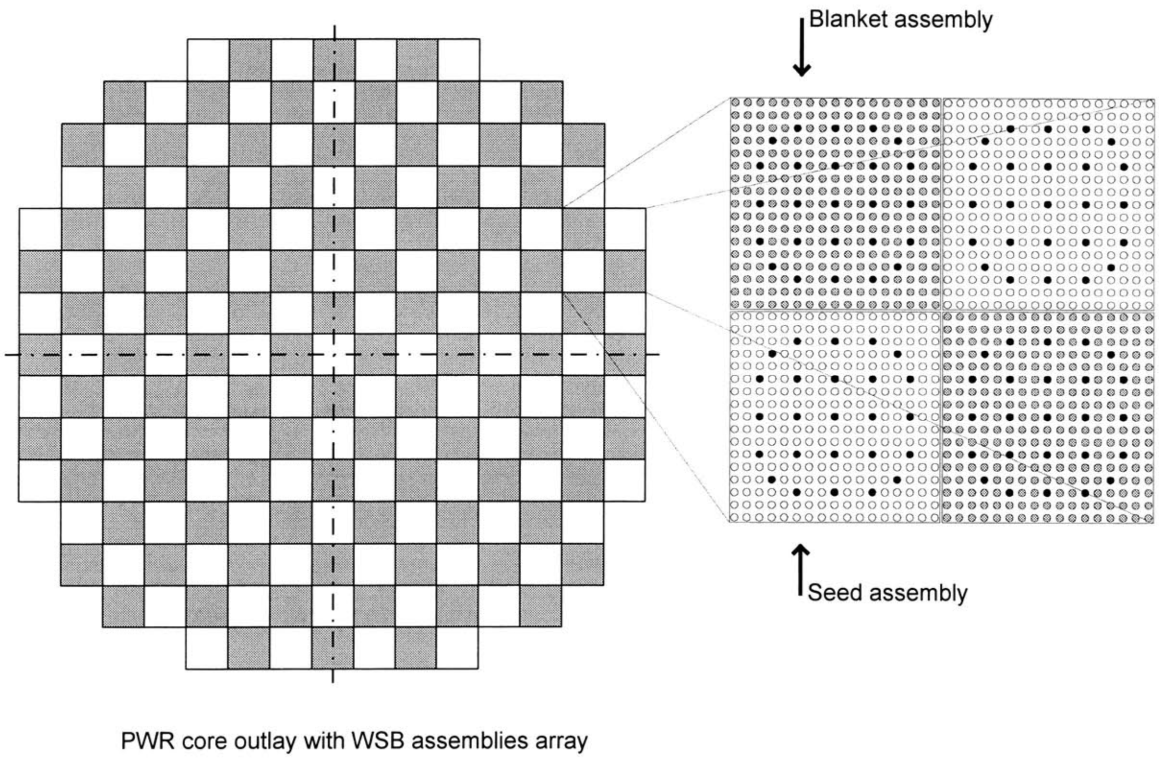


Figure 3 WSB assembly array in a PWR core.

Chapter 2

THERMAL-HYDRAULIC ANALYSIS

2.1 Introduction

The thermal-hydraulic analysis is part of the New Fuel Design Process. This process can be divided in reactor physics, thermal-hydraulics, materials, waste-management and overall performance. The relationship between these design groups is shown in Figure 4.

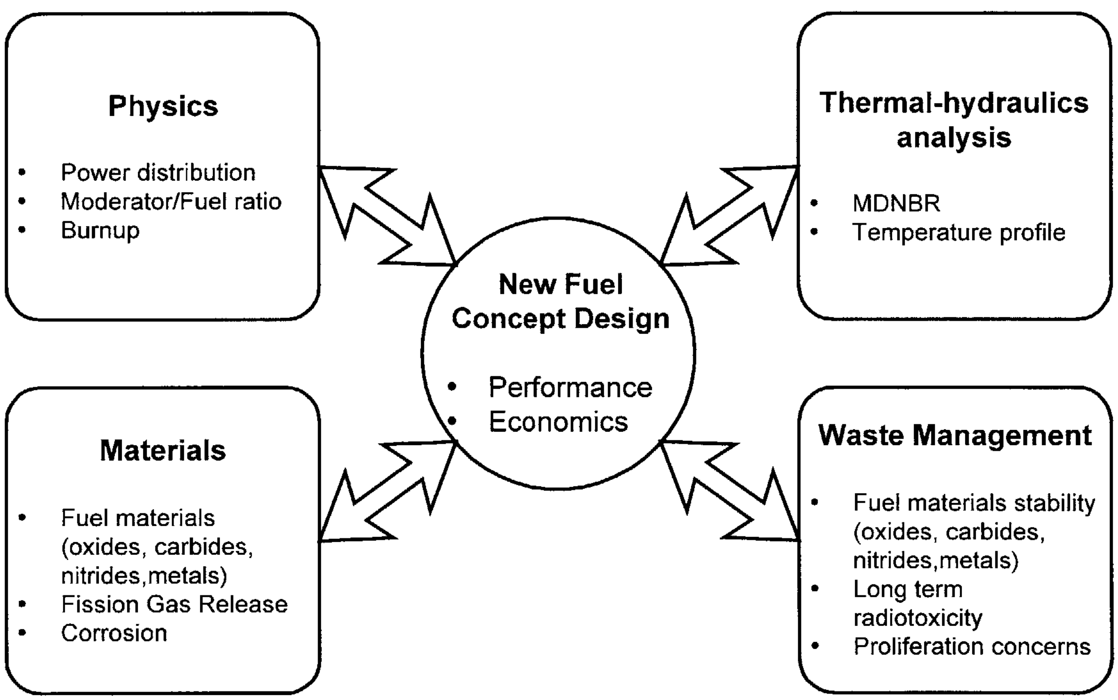


Figure 4 Different groups involved in the new product design process

The fuel design is a feedback process among all these groups as the inputs for one of them are the outputs from another. For example, the type of material selected will directly affect the fissile material density in the fuel, constraining some neutronic design parameters. On the other hand, neutronic parameters will determine the power generation distribution, which drives the fuel thermal-hydraulics performance. As a result of the thermal analysis, the materials group should assess the cladding and fuel temperatures, ending in this way one of the several feedback loops in the product design process (PDP).

The thermal-hydraulic performance of the different designs was assessed by the use of a Thermal-Hydraulic Code for Reactor Cores –VIPRE-01-. The selection of a nuclear reactor modeling code was based on the feasibility to model heterogeneous assemblies and the verification and prior use for safety licensing submittals.

Additionally, this code helps to evaluate nuclear reactor core safety limits including minimum departure from nucleate boiling ratio (MDNBR), critical power ratio (CPR), fuel and clad temperatures, and coolant properties in normal operation and assumed accident conditions. Typical coolant, fuel and cladding physical properties are also included in the code, all of them being largely previously benchmarked [Ref. 7].

2.2 VIPRE code

VIPRE (Versatile Internals and Component Program for Reactors; EPRI [Ref. 7]) was developed for nuclear power utility thermal-hydraulic analysis applications.

The code was developed by EPRI in response to the utility industry's need for a publicly available code for boiling water reactors (BWR) and PWR core analysis. It predicts the three-dimensional velocity, pressure, and thermal energy fields and fuel rod temperatures for single- and two-phase flow in PWR and BWR cores. The code solves the set of finite-difference conservation equations for mass, energy and momentum of the coolant in interconnected subchannels, assuming incompressible thermally expandable homogeneous flow. Although the formulation is based on homogeneous coolant for each finite volume, nonmechanistic models are included for subcooled boiling and vapor/liquid slip in two-phase flow.

2.2.1 *VIPRE model capability*

VIPRE modeling structure is based on subchannel analysis. The core, fuel bundle or any other section of symmetry is defined as an array of parallel flow channels with lateral connections between adjacent channels. A channel may represent a small area between fuel rods or a larger area representing several rod bundles. The shape and size of these subchannels is arbitrary, depending on the expected level of detail in the analysis. In areas where the fuel design is expected to be critical, the fuel is analyzed in detail, while in the rest of the core average values are good enough.

The code is tailored to the utilities' analytical requirements in fuel reload analysis, allowing for example the use of several Critical Heat Flux (CHF) correlations, capability to iterate operating conditions to a given MDNBR (safety requirement), and thermal transport within fuel rods with gap conductance model.

2.2.2 *Inputs to the code*

Input to the VIPRE code is organized into several groups. These groups can be divided in geometry of the problem, physical properties of the coolant, boundary conditions, models to be used for the flow and heat transfer solutions, and the numerical method to be used.

In order to understand the model used in this study, an example of the geometry input will be given. The main parts of the geometry are described by the subchannels, the gaps connecting them, and the rods.

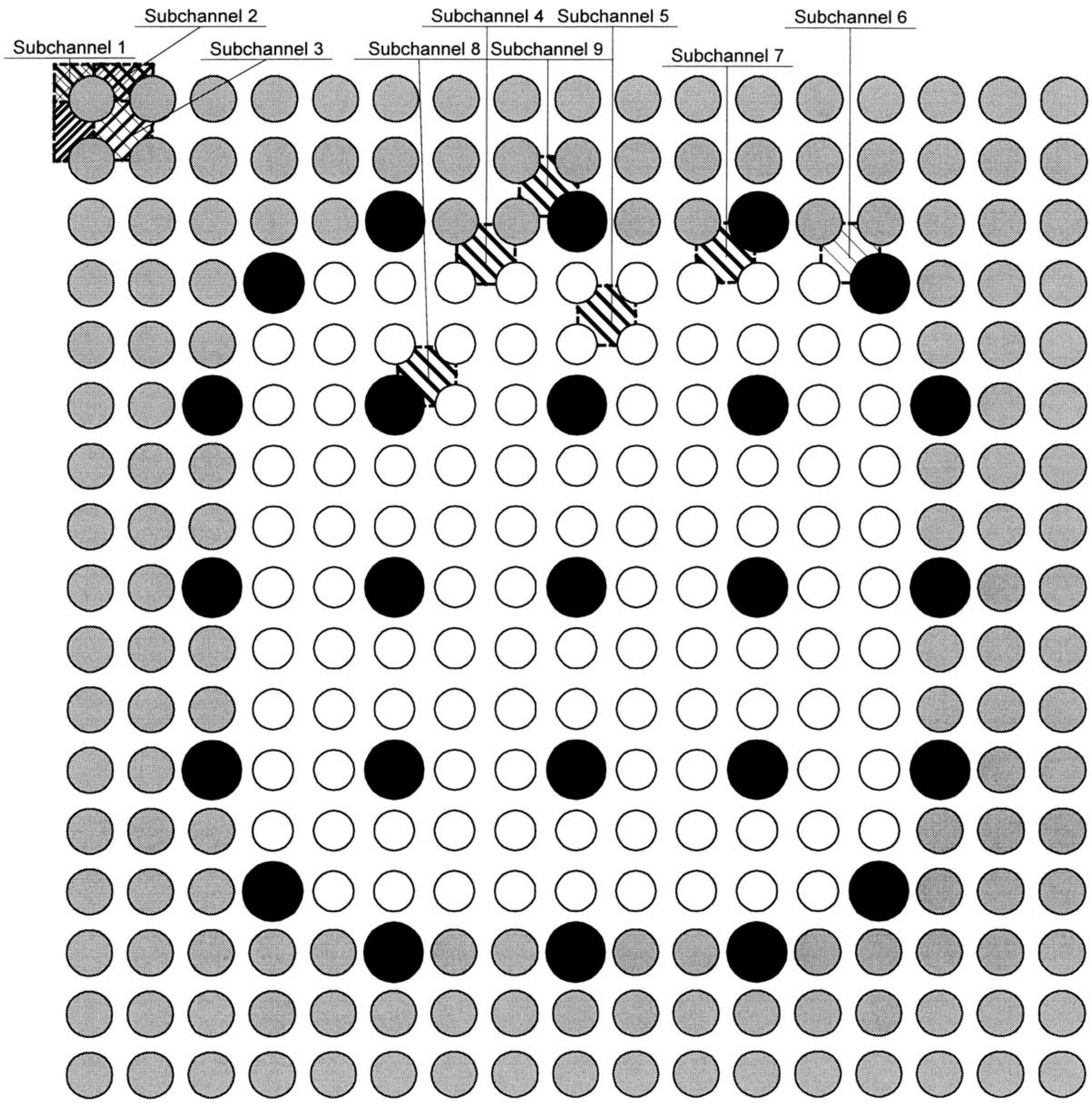


Figure 5 Subchannel analysis of a SBU bundle

Figure 5 shows a typical SBU bundle, with the different kinds of subchannels that were defined for the analysis. In this case nine different subchannels were identified. Each subchannel has a characteristic flow area, wetted perimeter and heated perimeter All of the subchannels in the model belong to one of the types shown in Figure 5. Once this information is supplied to the code, some additional geometry relationships are needed as gap types (dimensions), wetted and heated perimeters and distance between centroids of channels.

This information for a specific subchannel is shown in Figure 6.

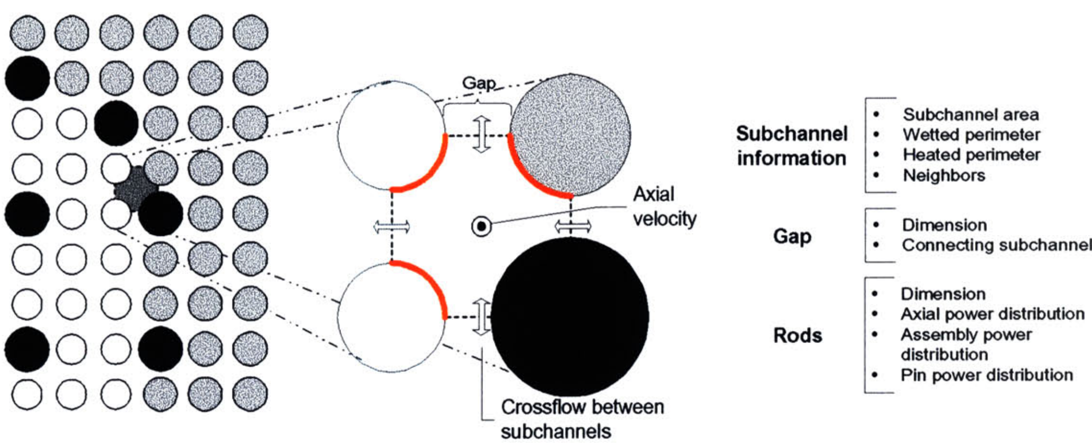


Figure 6 Subchannel, gap and rod information input

The wetted perimeter is given by the proportional perimeter of the surrounding rods facing each subchannel, while the heated perimeter is constrained to heat generating rods (exclusion of control and structural rods).

In the following chapters more detailed inputs for each case will be given, but all of them are based on the same kind of model: a subchannel analysis of a fuel bundle. This analysis can be applied to the hot assembly in the core (in order to analyze safety requirements as MDNBR) and to the average assembly (to for example analyze exit temperature profiles between the seed and the blanket region).

2.3 Thermal Performance Assessment

In the thermal design analysis, fuel integrity will define the maximum allowable power level in a nuclear reactor. The most important factors are:

- Fuel temperature safely below the melting point or phase transition points
- Heat flux to coolant below a maximum value allowable by coolant conditions (under expected operating conditions and under postulated accidents)
- Burnup and fission-gas release inside the rod limited to avoid excessive internal pressure
- Suitable power density for a convenient refueling time and reasonable fabrication cost
- Rate of power change limited to prevent excessive local stresses

The first two factors are analyzed in the current study, while the materials and physics properties for the SBU and WSB were addressed by others at MIT [Ref. 8] [Ref. 9].

The major limitation on the thermal design of a PWR is the necessity to maintain an adequate safety margin between operating heat generation conditions and the critical heat flux or critical power. The fuel design criterion in PWR is usually stated in terms of a departure from nucleate boiling ratio (DNBR), that is defined as:

$$DNBR = \frac{DNB\,heat\;flux\;predicted\;by\;applicable\;correlation}{local\;heat\;flux\;from\;fuel\;cladding\;to\;coolant}$$

It can be seen that the DNBR is a function of the coolant conditions at a certain location (numerator) and of the power distribution in the fuel (denominator). It is the minimum DNBR (MDNBR) in the hottest channel that drives the design process.

A typical PWR criterion is that the MDNBR $\geq$ 1.30 at maximum overpower conditions with high level of confidence. The probability of a PWR reaching this condition is very small and even then the number of rods in the fuel with DNBRs close to 1.3 is also small.

It should be noted that the departure from nucleate boiling does not necessarily lead to fuel damage. Some development tests and reactor tests have shown that operation at or beyond DNB can proceed for limited periods of time without adverse effects [Ref. 10]. But the lack of sufficient data to describe the fuel damage leads to the licensing assumption that fuel damage will occur whenever the heat flux exceeds the DNB value.

For light water reactors the key thermal-hydraulic design criterion to be satisfied is [Ref. 11]: "For departure from nucleate boiling ratio (DNBR) or critical heat flux ratio (CHFR) correlations, there should be a 95% probability, at the 95% confidence level, that no fuel rod in the core experiences a departure from nucleate boiling condition during normal operation or transients that are anticipated to occur with moderate frequency".

In order to satisfy the above licensing criterion, the following is necessary [Ref. 12]:

- To have a correlation to calculate DNB heat flux
- To be able to calculate the parameters that are needed to predict the DNB

- To express the DNB thermal design criterion in terms of the MDNBR
- To make allowance for the uncertainties in evaluating the minimum DNBR
- To establish which of the anticipated transients is the most limiting for DNB

Regarding correlations for DNB, a number of different correlations have been developed. Among them, the most well known and publicly available are the Westinghouse W-3 CHF correlation, Babcock & Wilcox BAW-2 CHF correlation, the EPRI correlation, and the Combustion Engineering CHF correlation CE-1. These correlations were developed for 15 x 15 fuel bundles, but when they were used for 17 x 17 bundles it was observed that they do not predict the fuel behavior with sufficient accuracy. New correlations were fitted for this case but because of the proprietary nature of them, the approach used in this study is constrained to the previous set of correlations. Although these calculations may not be highly accurate, the results obtained are expected to be relevant in order to compare different designs since all have the same boundary conditions and very similar geometry configurations.

The selected correlation for this study is the Westinghouse W-3L that takes into account the effects of grids and rod bundle effects on the DNB (L factor). This correlation is included in the VIPRE code. The W-3 correlation was developed using Westinghouse' THINC subchannel code. Since VIPRE and THINC have similar two-phase flow correlations and the benchmarks of VIPRE against THINC performed by Westinghouse showed good agreement between them, the use of the W-3 correlation with VIPRE was considered suitable for the purpose of the present study.

A MDNBR limit must be specified in order to satisfy the 95% probability of not having any rod experiencing departure from nucleate boiling with 95% of confidence level. This limit definition depends on the data population used to construct the CHF correlation, the larger the amount of data the more reliable the correlation. As the estimations are more reliable, the DNBR required limit is smaller. The limit is also affected by the slope of the correlation in the CHF-quality plane [Ref. 13]. As an example of these effects, the W-3 correlation has a limit for MDNBR of 1.30 while the CE-1 correlations has a limit of 1.13. All the correlations satisfy the 95% probability at 95% confidence level criterion. All thermal analysis in this study will use the MDNBR of 1.3 applicable to the W-3L CHF correlation.

The general design criteria require the consideration of normal operating conditions and frequent transients. In order to take into account these situations, a shortcut was used in the design process. DNBR calculations are taken at 118% rated power, and the MDNBR is required to be above its limit [Ref. 12]. Additional analysis of transients, such as excessive load increase transient, uncontrolled control rod assembly withdrawal at power and complete loss of reactor coolant flow, should be considered for further studies.

2.4 Reference PWR core description

The selected PWR design for analysis of the different fuel arrangements was a Westinghouse 3400 MWth four loop plant. This core design will constrain fuel assembly configurations in order to make them compatible and ready to use in current reactors. The most important boundary conditions for this type of plant are summarized in Table 1.

The fuel assemblies analyzed were a 17 x 17 array of fuel rods with 24 guide thimbles for control rods and one guide tube for instrumentation. A photograph of an assembly is shown in Figure 7 while the most important fuel dimensions are given in Figure 8. The core is of the open type, this means that the assemblies are not contained in individual channels. Eight spacer grids were considered equally spaced in the fuel length and the L-grid with mixing vanes correlation was selected to take them into account in the DNB correlation (W-3L).

Table 1 Operating parameters of a typical Westinghouse 4-loop PWR

Parameter	Value
Reactor Core Heat Output [MWth]	3,400
System Pressure, nominal [MPa]	15.5
Total Flow Rate [Mg/s]	18.63
Effective Flow Rate for heat removal [Mg/s]	17.70
Active Fuel Height [cm]	366
Number of Assemblies	193
Inlet Coolant Temperature [°C]	289

Figure 7 Westinghouse PWR fuel assemblies [Ref. 14]

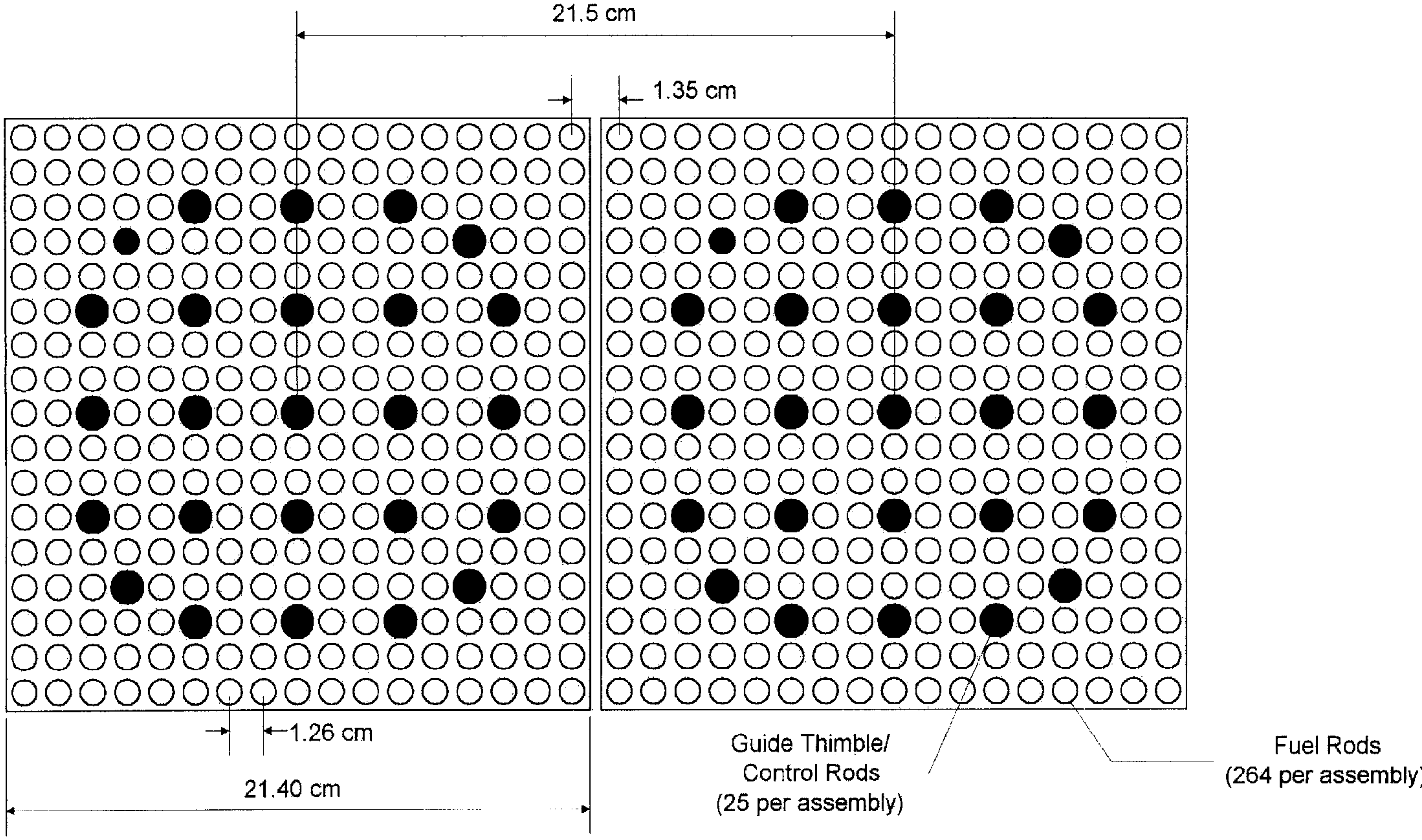


Figure 8 PWR Fuel assembly with dimensions

Chapter 3

SEED BLANKET UNIT (SBU) DESIGN

In the proceedings for the International Conference On Future Nuclear Systems, Global 99, Galperin et. al. presented a thorium-based fuel design approach compatible with existing PWRs [Ref. 15]. The objectives of this design were to enhance the proliferation-resistance, reduce waste storage and disposal requirements and produce fuel cycle cost savings, while keeping comparable environmental and safety characteristics of current nuclear fuels.

In a conventional PWR fuel assembly, the type of fuel -UO_2- and rods are homogenous but within the SBU assembly two different fuel types in two regions are defined as shown in Figure 9. The central part is called the seed region because it is the supplier of neutrons for the assembly (supercritical) while the surrounding area is the blanket which is a subcritical energy and fissile material generator.

The SBU allows a spatial separation of the seed and the blanket within the fuel assembly with the possibility of having different core management cycles for each of them. The seed region (central rods in Figure 9) has a metallic fuel alloy composed of approximately 45% U (20% enriched) and 55% Zr by weight. This enrichment is accepted to be nonproliferative and the U^{235} presence in the seed fuel is enough to supply neutrons to the blanket in an efficient way. The use of metallic fuel in the seed region is driven by its better heat conductance characteristics (hot region with high heat rate generation) and potential production cost reduction. On the other hand, the blanket fuel consists of oxides of thorium plus a small amount (~10% in weight) of uranium oxide enriched to less than 20%.

The seed is where most of the power is generated in the early parts of the cycle. Thus, its power density is higher than in a conventional PWR assembly with a relative peak power in fuel pins of 1.69.

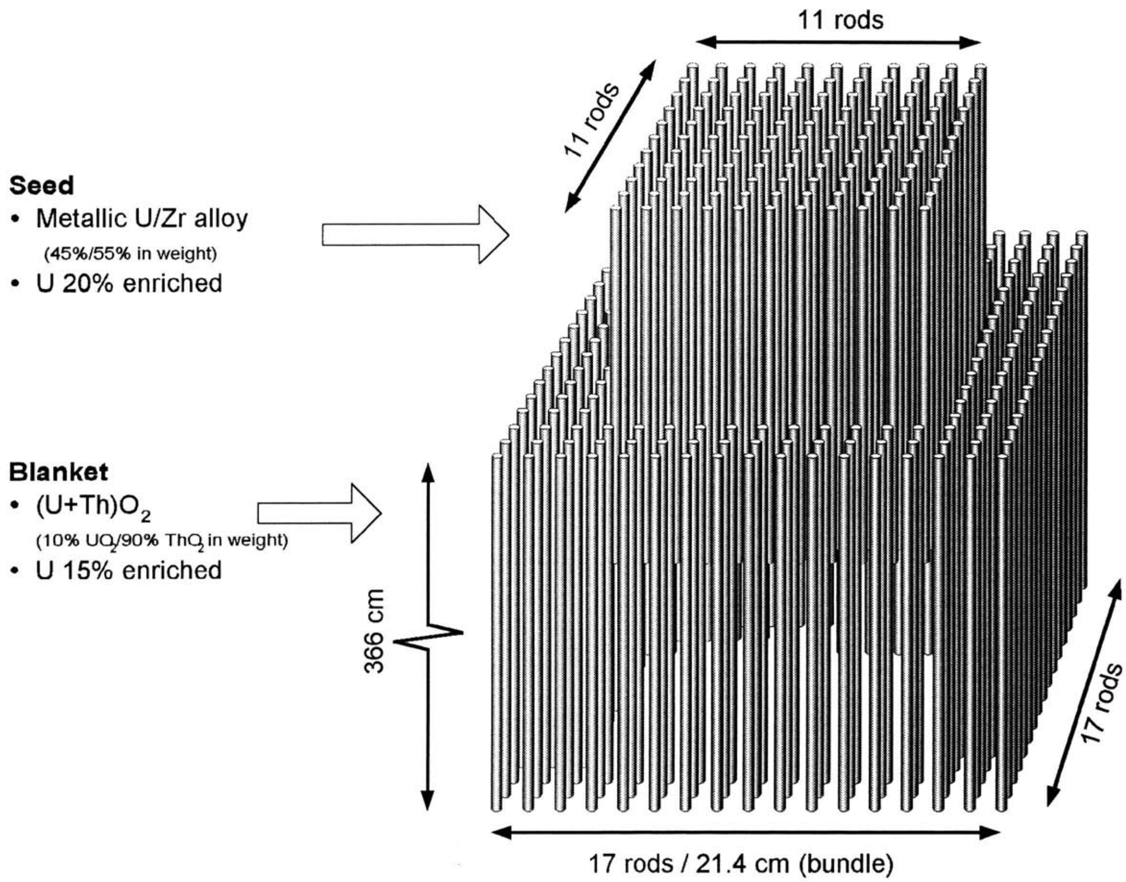


Figure 9 SBU seed and blanket regions

The extra uranium in the blanket is added for two reasons:

- Natural thorium has no fissile content, so enriched uranium is required to provide power during the initial period of uranium-233 build up (product of burning the thorium in the blanket).

- The uranium-238 and other nonfissile uranium isotopes denature the discharged blanket residual U-233 so that it is also nonproliferative; i.e. its percentage in total uranium is always below 12%.

3.1 Design parameters

Table 2 shows the SBU design parameters. Notice that seed rods have smaller diameter than those in the blanket area, increasing the coolant flow in the central region (taking into account a boundary condition of constant pressure drop).

Table 2 SBU Fuel Assembly Parameters 15.

Parameter	Seed	Blanket
Fuel Assembly Size [cm]	21.4 x 21.4	
Side Dimensions [cm]	13.83	21.4
Fuel Material Composition	U/Zr metal alloy (45%/55% in weight) U 20% enriched	$(U+Th)O_2$ (10% UO_2/90% ThO_2 in weight) U 15% enriched
Number of Fuel Rods	108	156
Fuel Pellet Radius [cm] inner-outer	0.20 - 0.38	0.0 - 0.4095
Fuel-Clad Gap [cm]	No	0.0085
Cladding material thickness [cm]	0.04	0.057
Fuel Cell Pitch [cm]	1.26	1.26
Moderator/Fuel Volume Ratio	3.3	1.7
Volume Fraction [%]	41	59

Although some previous similar designs considered a separating wall between the seed region and the blanket, the one analyzed in this study has no walls of this type.

3.2 In-core fuel management

The seed and blanket have different in-core fuel management schemes. The residence time of the SBU's seeds in the core is about 3 years, leading to a high burnup (over 75 MWd/kg HM). The residence time for the blankets is quite long, about 9 years, which achieves a large burnup (above 100 MWd/kg HM).

The seeds follow a multi-batch replacement strategy, similar to the standard PWR fuels cycle. Approximately one third of the seeds are replaced periodically (12 to 18 months) by fresh ones, leaving an inventory of fresh, once burned and twice burned seed assemblies. All seeds are reshuffled with the partially burned blankets to the required configuration for the next cycle. The reload period for the seed is planned to be 1 year.

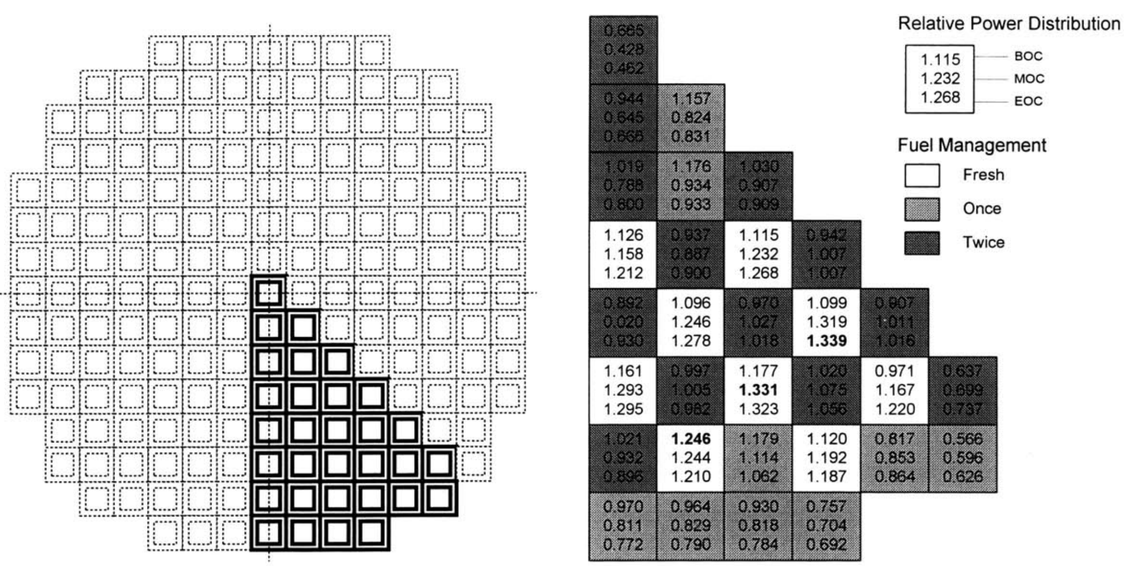


Figure 10 SBU radial core power map (cycle 5)

A summary of the core relative power map is given in Figure 10. These results, given in the Global 99 report [Ref. 15], correspond to the beginning of cycle (BOC), middle of cycle (MOC) and end of cycle (EOC) of the 5^{th} cycle (mid life of the blanket).

The assembly power distribution given in Figure 10 was used in this study to identify the hot channel in the core and analyze its thermal-hydraulics performance, since it will be the one to constrain the power level of the reactor.

Within each assembly, the relative pin power distribution was taken from the same source (see Figure 11). This distribution (assumed equal for every assembly) represents the seed to blanket relative power generation and will identify the hottest subchannel in the assembly.

Pin # \ Pin #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.600	0.600	0.600	0.668	0.676	0.682	0.678	0.669	0.664	0.669	0.678	0.682	0.676	0.668	0.620	0.620	0.620
2	0.600	0.581	0.581	0.648	0.665	0.685	0.666	0.640	0.622	0.640	0.666	0.685	0.665	0.648	0.601	0.601	0.620
3	0.600	0.581	0.572	0.636	0.666	0.000	0.668	0.620	0.000	0.620	0.668	0.000	0.666	0.636	0.591	0.601	0.620
4	0.655	0.636	0.624	0.000	1.637	1.695	1.656	1.590	1.546	1.590	1.656	1.695	1.637	0.000	0.647	0.659	0.679
5	0.663	0.653	0.654	1.637	1.508	1.473	1.484	1.470	1.441	1.470	1.484	1.473	1.508	1.637	0.678	0.677	0.687
6	0.669	0.672	0.000	1.695	1.473	0.000	1.421	1.424	0.000	1.424	1.421	0.000	1.473	1.695	0.000	0.697	0.693
7	0.666	0.654	0.656	1.656	1.484	1.421	1.446	1.467	1.456	1.467	1.446	1.421	1.484	1.656	0.680	0.677	0.690
8	0.657	0.628	0.608	1.590	1.470	1.424	1.467	1.543	1.612	1.543	1.467	1.424	1.470	1.590	0.631	0.651	0.681
9	0.652	0.610	0.000	1.546	1.441	0.000	1.456	1.612	0.000	1.612	1.456	0.000	1.441	1.546	0.000	0.633	0.675
10	0.657	0.628	0.608	1.590	1.470	1.424	1.467	1.543	1.612	1.543	1.467	1.424	1.470	1.590	0.631	0.651	0.681
11	0.666	0.654	0.656	1.656	1.484	1.421	1.446	1.467	1.456	1.467	1.446	1.421	1.484	1.656	0.680	0.677	0.690
12	0.669	0.672	0.000	1.695	1.473	0.000	1.421	1.424	0.000	1.424	1.421	0.000	1.473	1.695	0.000	0.697	0.693
13	0.663	0.653	0.654	1.637	1.508	1.473	1.484	1.470	1.441	1.470	1.484	1.473	1.508	1.637	0.678	0.677	0.687
14	0.655	0.636	0.624	0.000	1.637	1.695	1.656	1.590	1.546	1.590	1.656	1.695	1.637	0.000	0.647	0.659	0.679
15	0.588	0.569	0.560	0.618	0.648	0.000	0.650	0.602	0.000	0.602	0.650	0.000	0.648	0.618	0.573	0.583	0.602
16	0.588	0.569	0.569	0.630	0.646	0.666	0.647	0.622	0.604	0.622	0.647	0.666	0.646	0.630	0.583	0.583	0.602
17	0.587	0.588	0.588	0.649	0.657	0.662	0.659	0.650	0.645	0.650	0.659	0.662	0.657	0.649	0.602	0.602	0.601

Figure 11 SBU relative pin power distribution

Finally the axial power distribution for the three stages of the cycle was also considered in the thermal-hydraulics calculations. This distribution is very important to identify the location of the MDNBR within the fuel length. As the peak location is shifted to the outlet of the reactor, the CHF at this peak is reduced as a result of a higher average temperature in the coolant.

Figure 12 shows the shape of the axial power distribution for the beginning, middle and end of cycle.

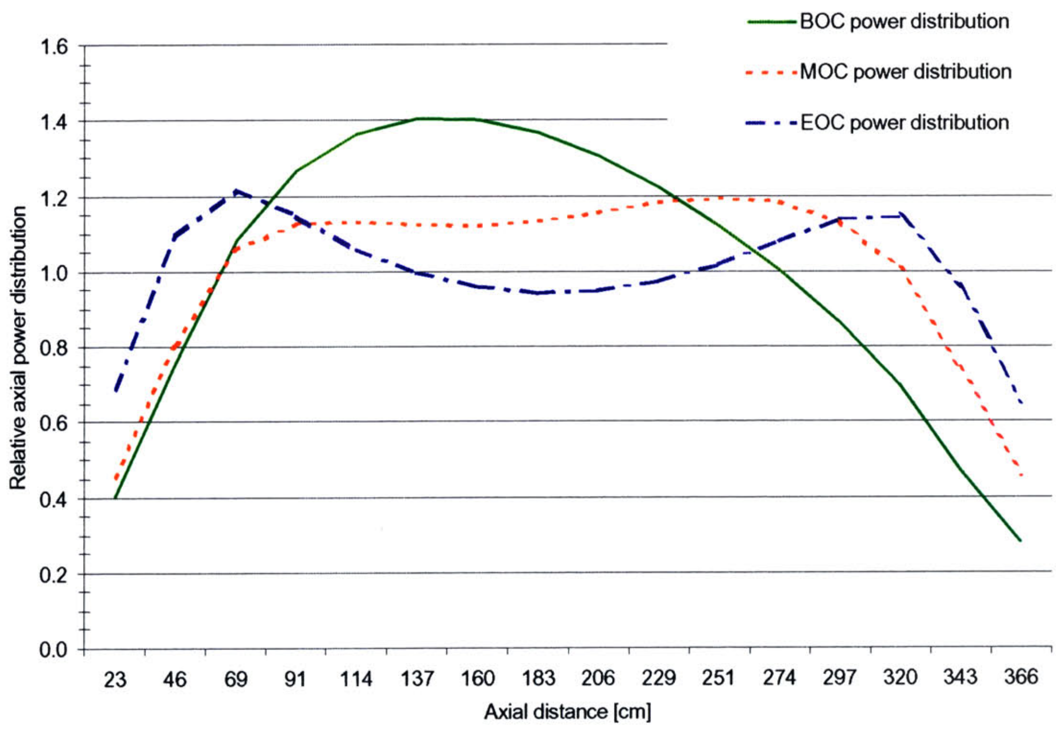


Figure 12 SBU axial power distribution

The SBU assembly modeling process is discussed in the following section, where all the power distribution information will be used with the design characteristics of the fuel as an input to the VIPRE code to predict the thermal-hydraulics performance.

3.3 Inputs to the VIPRE code

In this section the modeling within the VIPRE code is discussed. As was mentioned earlier in Chapter 2, VIPRE requires the user to define subchannels within the model, with their physical characteristics (i.e. flow cross-sectional area, wetted perimeter, heated perimeter, neighbors). Additional information is needed for the gaps connecting the subchannels and the rods.

For this study one whole assembly will be modeled assuming that the boundaries with adjacent assemblies are symmetric. This means that no heat or mass fluxes between assemblies are considered.

The selected subchannel definition for the SBU assembly is shown in Figure 5. Nine different types of subchannels were used for modeling the SBU assembly. A total of 324 subchannels were defined, each subchannel being the flow area between fuel rods in a regular rectangular array. This kind of channel grouping by equal flow area is very useful in order to input the required data into VIPRE. Subchannels, rods and gaps modeled are shown in Figure 13.

Identification of all subchannels, rods and gaps used in the model are given in Figure 14, Figure 15, and Figure 16 respectively. An example of a VIPRE input file can be found in Appendix C.

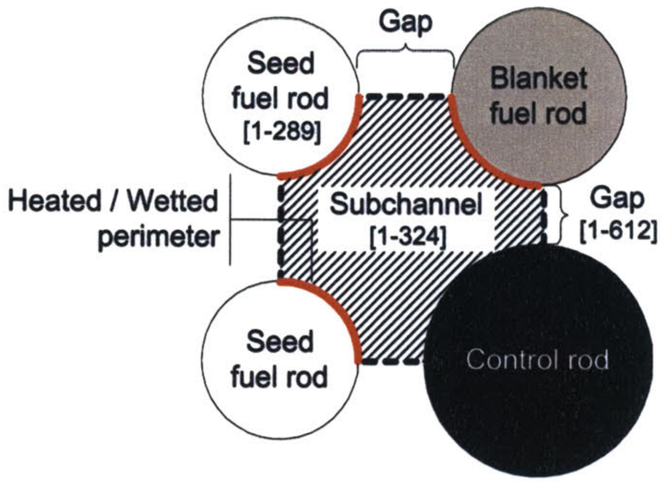


Figure 13 Subchannel, rod and gap definition for the SBU assembly.

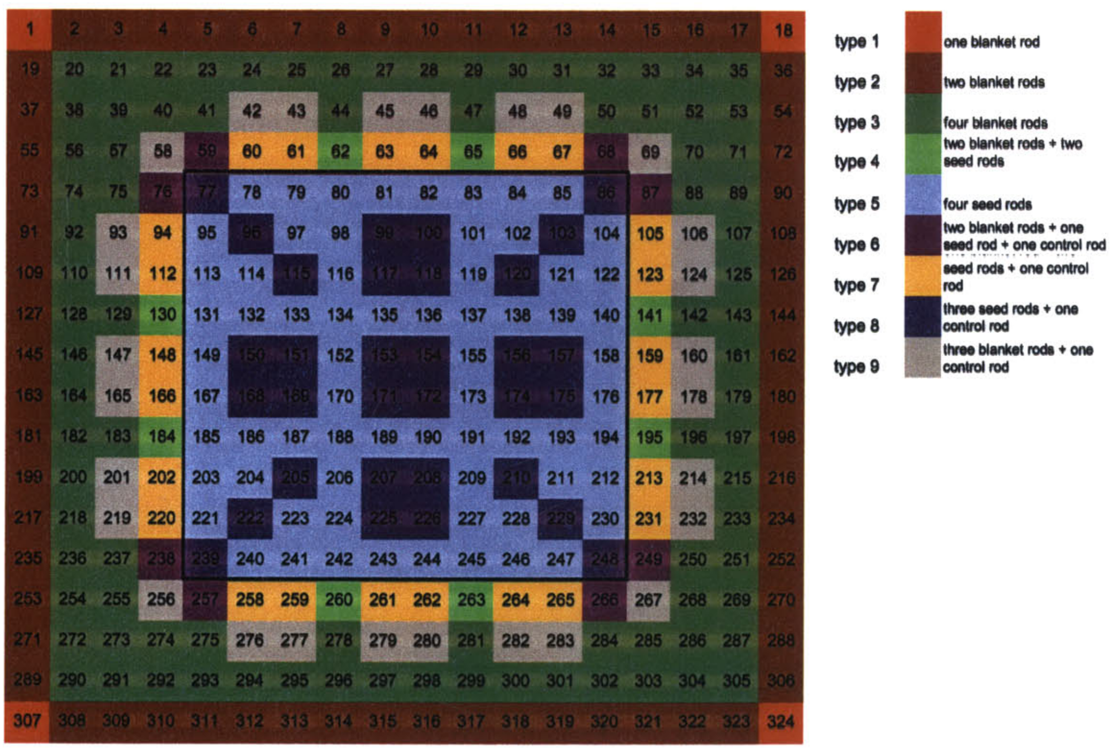


Figure 14 SBU subchannel identification

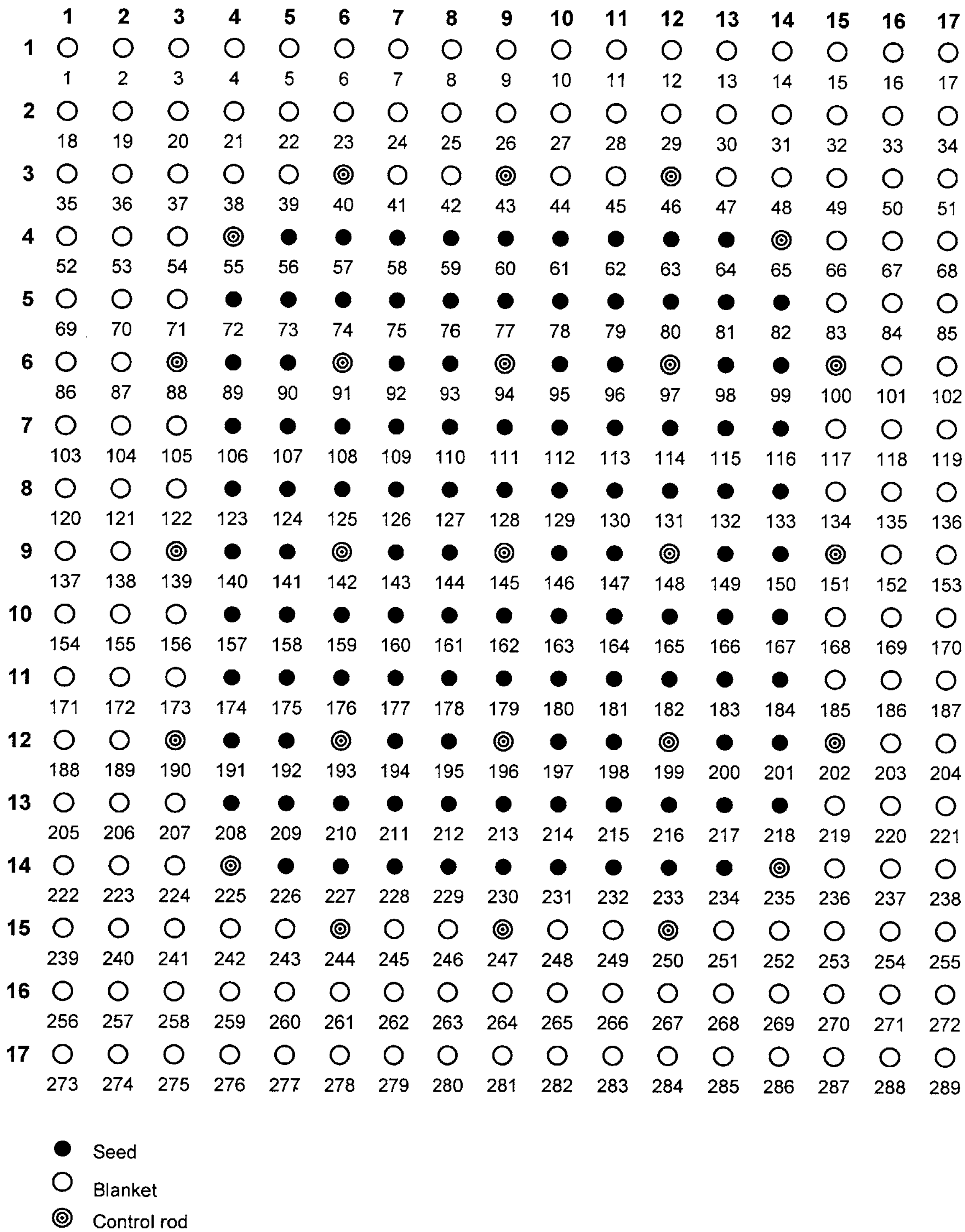


Figure 15 SBU rod identification

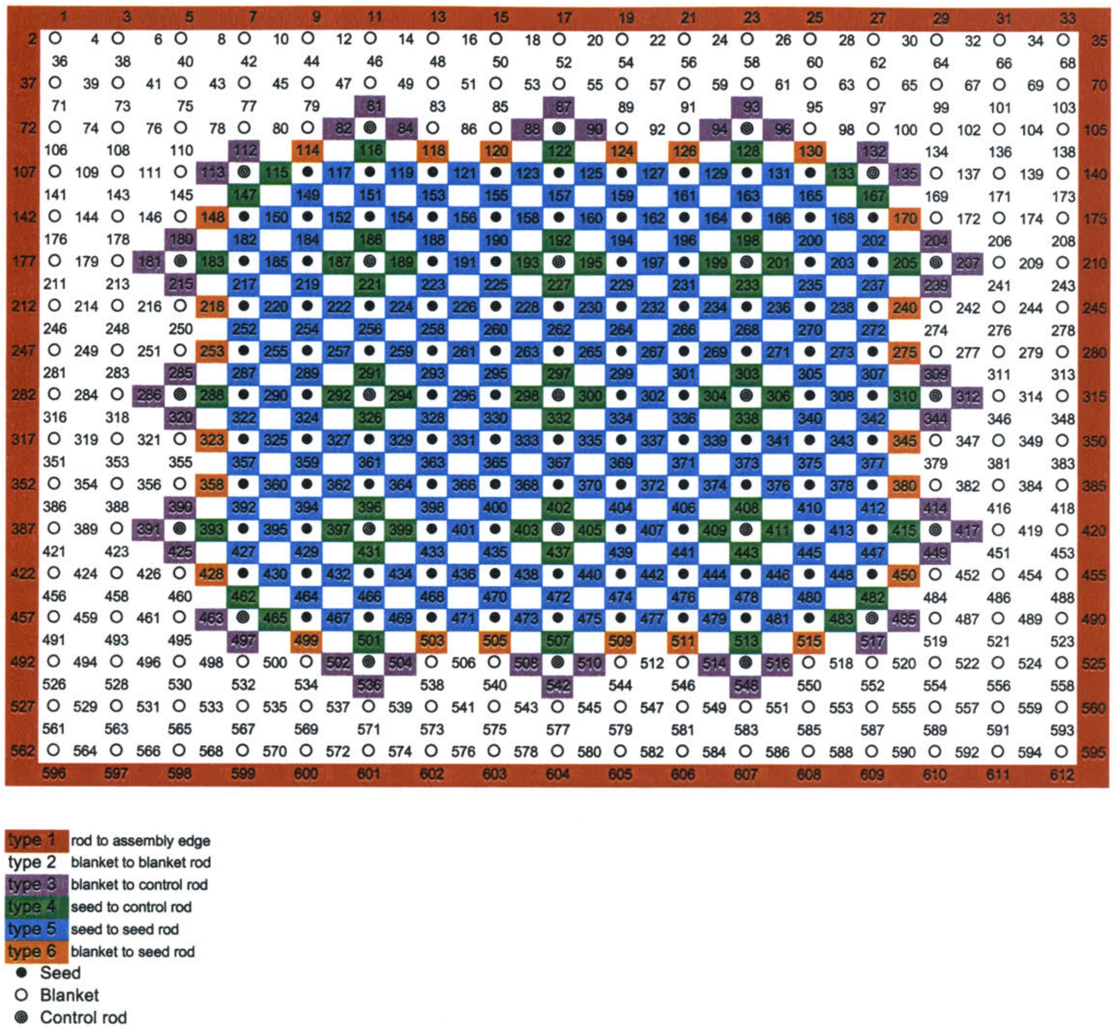


Figure 16 SBU gap identification

3.4 SBU Thermal-hydraulics

In this section, the VIPRE thermal-hydraulics results for the base design given in the Global 99 report [Ref. 15] are studied for the different stages of a cycle. Following these results, the highest power level achievable with this fuel will be calculated based on a more detailed analysis of the most restrictive operating condition, including temperature profiles and DNB analysis.

3.4.1 *BOC, MOC and EOC thermal-hydraulic fuel assembly performance*

The different power distributions of the SBU fuel during a typical cycle (5^{th} cycle) directly impact the fuel performance (see Figure 10 and Figure 12). The most restrictive condition will constrain the reactor power level, since no boundary conditions or physical arrangements can be changed during one cycle.

The core radial power distribution shown in Figure 10 was used to identify the hottest channel in the reactor. Its power level given the boundary conditions of a W-PWR (3400 MWth, see Table 1) and the radial peaking factor was used to analyze the fuel performance at each stage of the cycle.

Figure 17 shows the average coolant temperature in the SBU analyzed channel (hot channel). The higher peak factors for the MOC and EOC result in higher average exit temperatures for these parts of the cycle. The plotted temperature is the average across the whole bundle, but as significant different power levels can be found in the seed compared to the blanket, the problem must be analyzed at the hottest spot in the fuel. In this case, the hottest subchannel shows the higher temperature found in the fuel. The temperature profile for this critical location is shown in Figure 18. The coolant temperature reaches the boiling temperature in the region close to the exit, meaning that saturated boiling is taking place. It should be noted that this situation is found only in a specific location in some of the hot-channels in the reactor core. The appearance of positive coolant flow quality [i] is shown in Figure 19 for the MOC power distribution (it should be noted that flow quality is differently defined compared to the thermal equilibrium quality. The flow quality accounts for vapor present under subcooled bulk coolant conditions, while thermal equilibrium quality does not. This is the reason why its value decreases close to the exit

---

[i] The EPRI correlation developed by Lellouche and Zolotar was used for calculating the flow quality.

where heat flux from the fuel is low. For detailed information about the boiling models used and correlations see VIPRE-01 Mathematical Modeling [Ref. 16]).

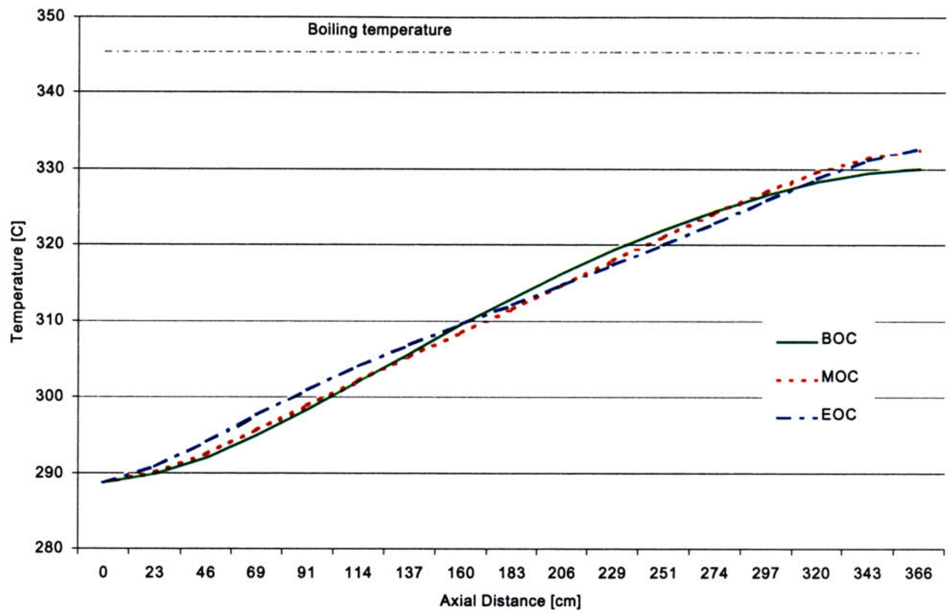


Figure 17 Hot channel avergage axial temperature profile

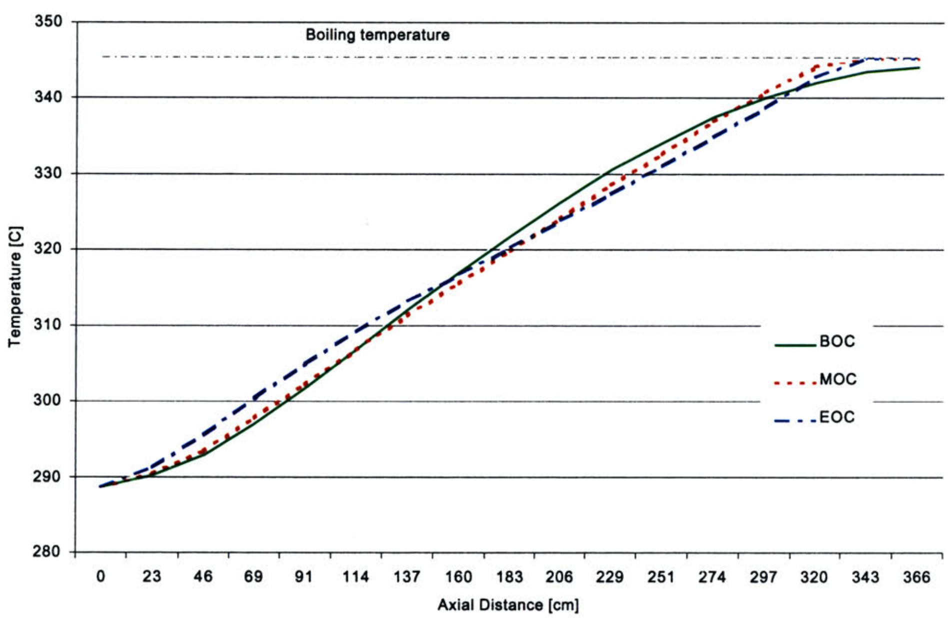


Figure 18 Hot channel – hottest subchannel axial temperature profile

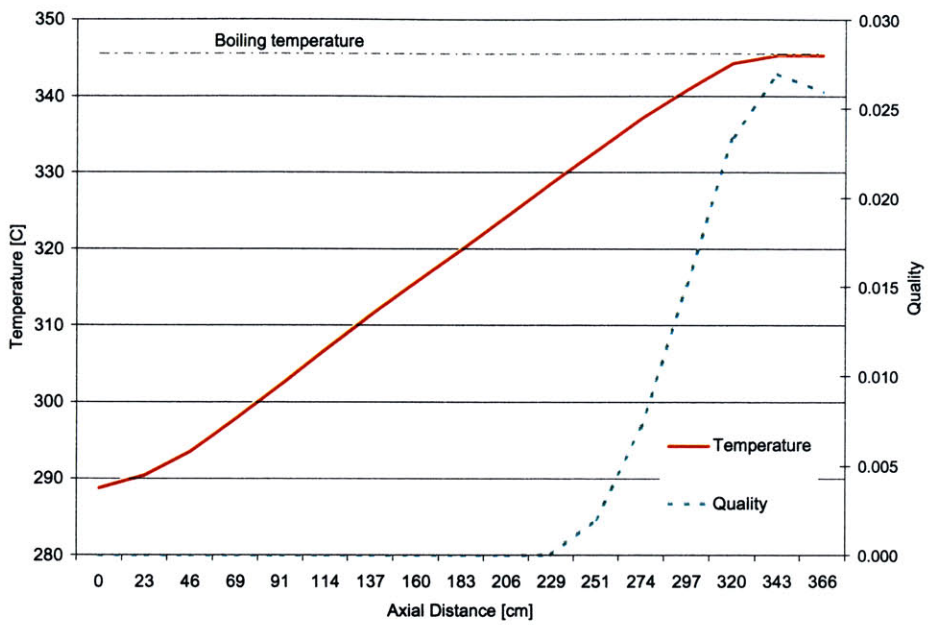


Figure 19 Hottest channel MOC axial temperature and quality profile

An analysis of the DNBR for the hottest subchannel in the fuel can easily show that some parts of the cycle are more critical than others. Figure 20 shows the DNBR along the length of the fuel for the three parts of the cycle. The minimum DNBR found is very similar for the MOC and EOC, because their peaks are shifted to the exit of the channel, where the coolant temperature is higher and consequently the DNB is lower.

Since the MOC distribution usually describes a larger period of time of the fuel in the core, it was selected as the best one to use for fuel performance evaluation.

The MOC exit temperature profile gives a very good sense of the impact of different power levels between the seed and the blanket, and also shows the hot locations within the fuel (see Figure 21 and Figure 22).

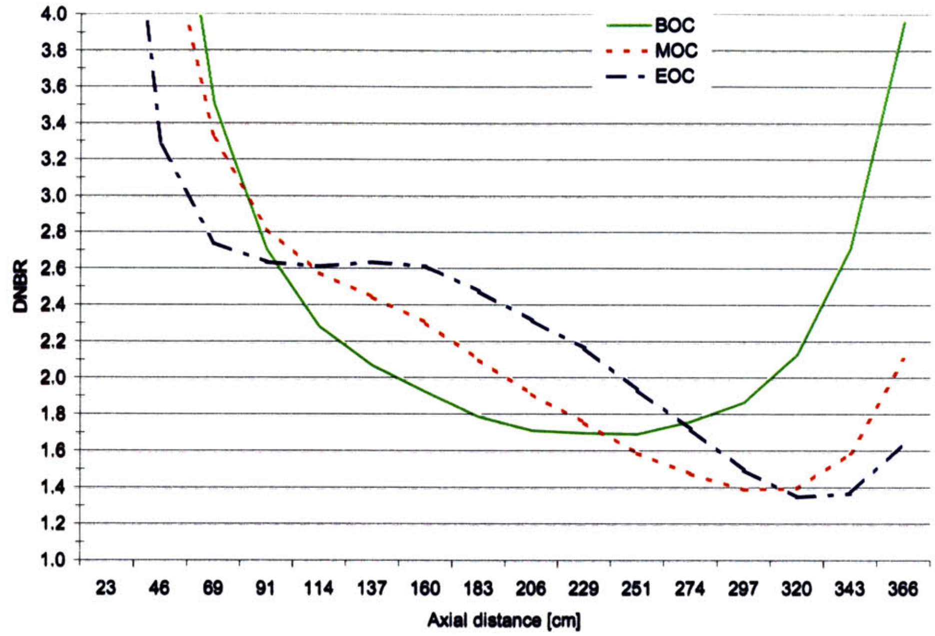


Figure 20 SBU DNBR analysis for the BOC, MOC and EOC

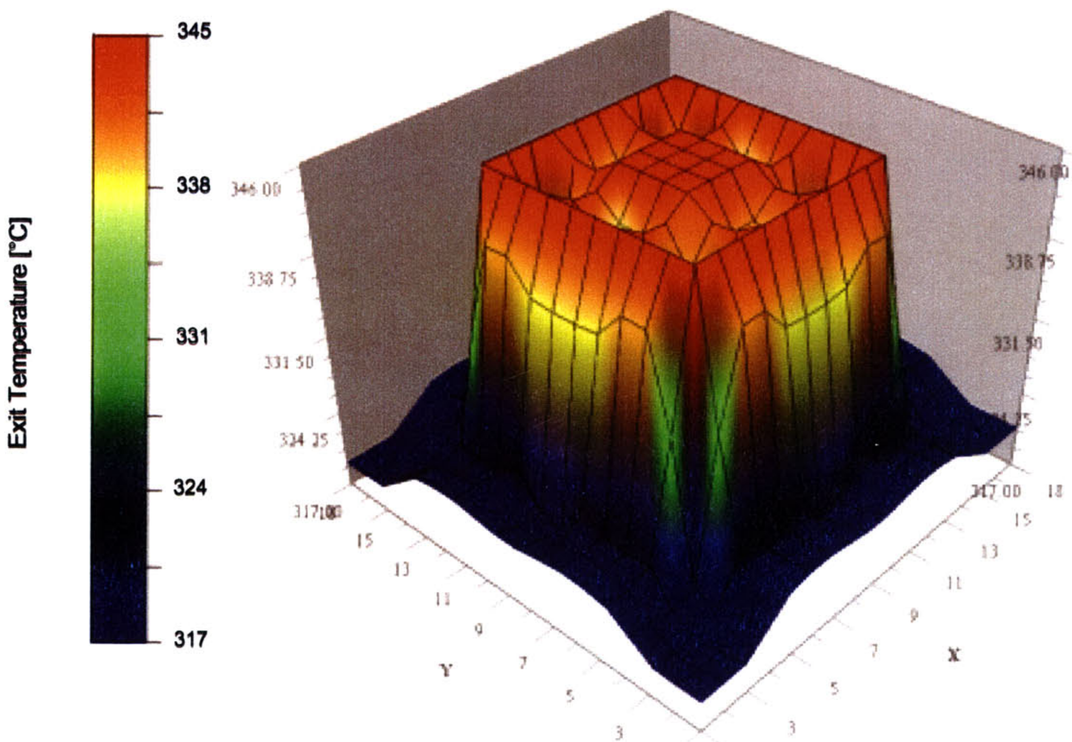


Figure 21 SBU MOC exit temperature profile

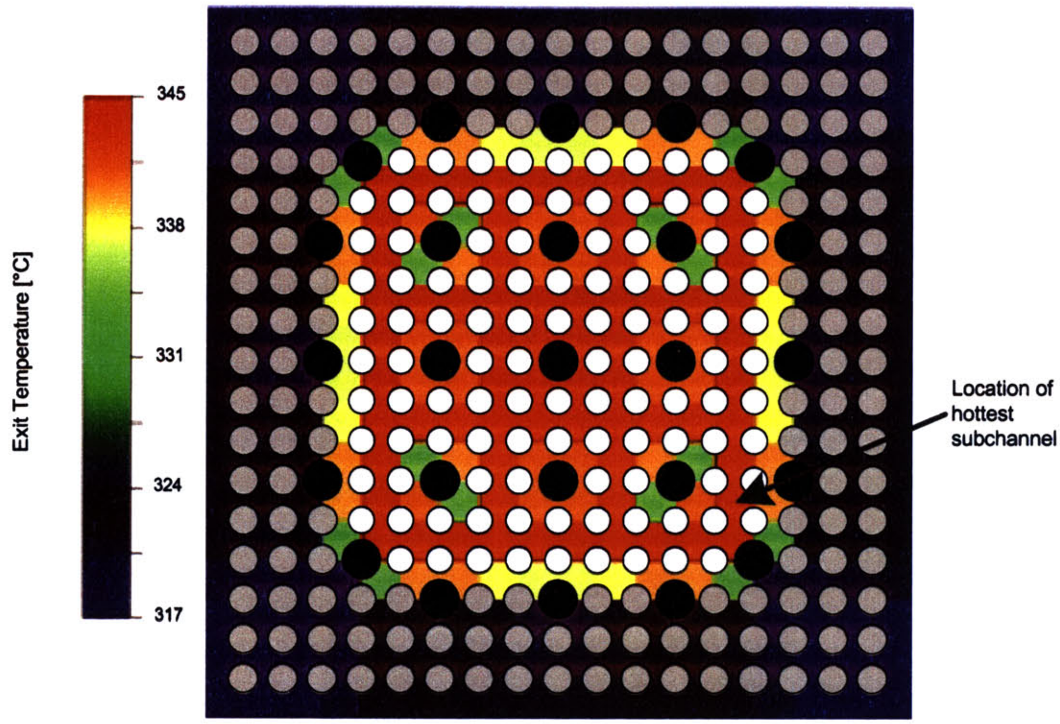


Figure 22 SBU hottest subchannel location

Other results from the simulation can give some additional insights of the fuel thermal-hydraulics performance. The void fraction found at the exit of the modeled channel (SBU hot channel) clearly shows the location of the most compromising areas, where two phase flow is taking place, see Figure 23. As one can expect, these regions are the locations where the coolant temperature is higher.

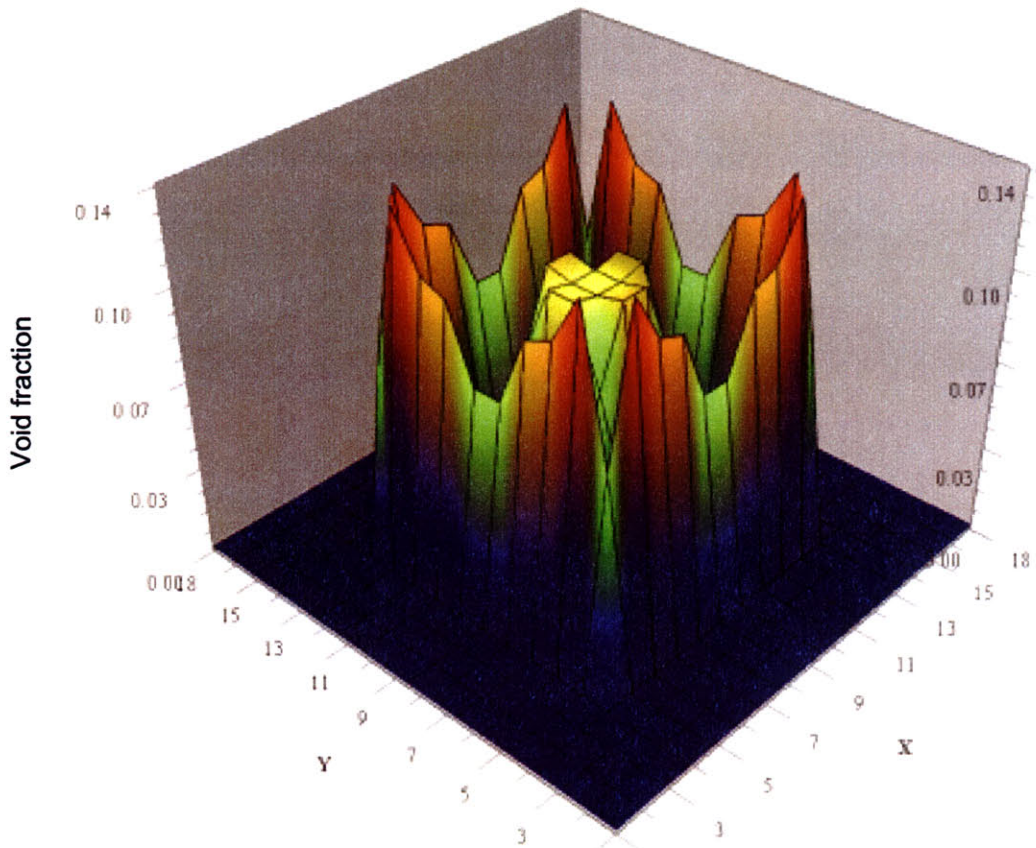


Figure 23 SBU MOC exit void fraction

3.4.1.1 Impact of the fuel's thermal-hydraulics performance on materials temperatures

The temperature condition within seed and blanket rods was analyzed by using a conduction model for each part of the fuel. The conduction heat transfer model applied was based on a control volume formulation of the conduction equation, and was supported by the VIPRE code.

For the class of problems addressed in this study, axial and circumferential conduction in rods were relatively unimportant, and only radial conduction was considered. In order to solve the conduction equation, radial nodes are positioned within the conductor material (fuel and gap) and local radial power distributions are assigned.

Fuel materials properties for the seed rods were taken from the MATPRO library of thermal conductivity for metallic uranium nuclear fuels [Ref. 17]. The model does not take into account burnup, fission product appearance or irradiation and is based on a second order polynomial curve derived from experimental data:

$$K = 20.457 + 1.204710^{-2} \cdot T - 5.736810^{-6} \cdot T^{2}$$

Equation 1

where :
$K[W/(m\ ^{o}K)]\, and\, T[^{o}K]$

For the seed's Zr a constant conductivity of 22.7 W/(m °K).

For the blanket's thermal conductivity, the Belle and Berman correlation was used [Ref. 17]. This correlation calculates the thermal conductivity of thoria-urania mixtures as a function of temperature:

$$K = \frac{1}{A + B \cdot T},$$
$$A = \frac{1}{A_0 + A_1 \cdot M},$$
$$B = B_0 + B_1 \cdot M + B_2 \cdot M^2,$$

Equation 2

where :
$A_0 = 46.958,\ B_0 = 1.59710^{-4},\ A_1 = -112.072,\ B_1 = 6.73610^{-4},\ B_2 = -2.15610^{-3}$
$K[W/(m\ ^{o}K)], T[^{o}K]\, and\, M[mole\ fraction\ of\ UO_2]$

A uniform radial power profile for the fuel rod was assumed in order to calculate the internal temperature distribution.

The temperature profile for the hottest seed rod (rod 201, Figure 15) is given in Figure 24 for an operating condition satisfying the required MDNBR=1.3 (25.09 kW/m average linear power for the hot channel).

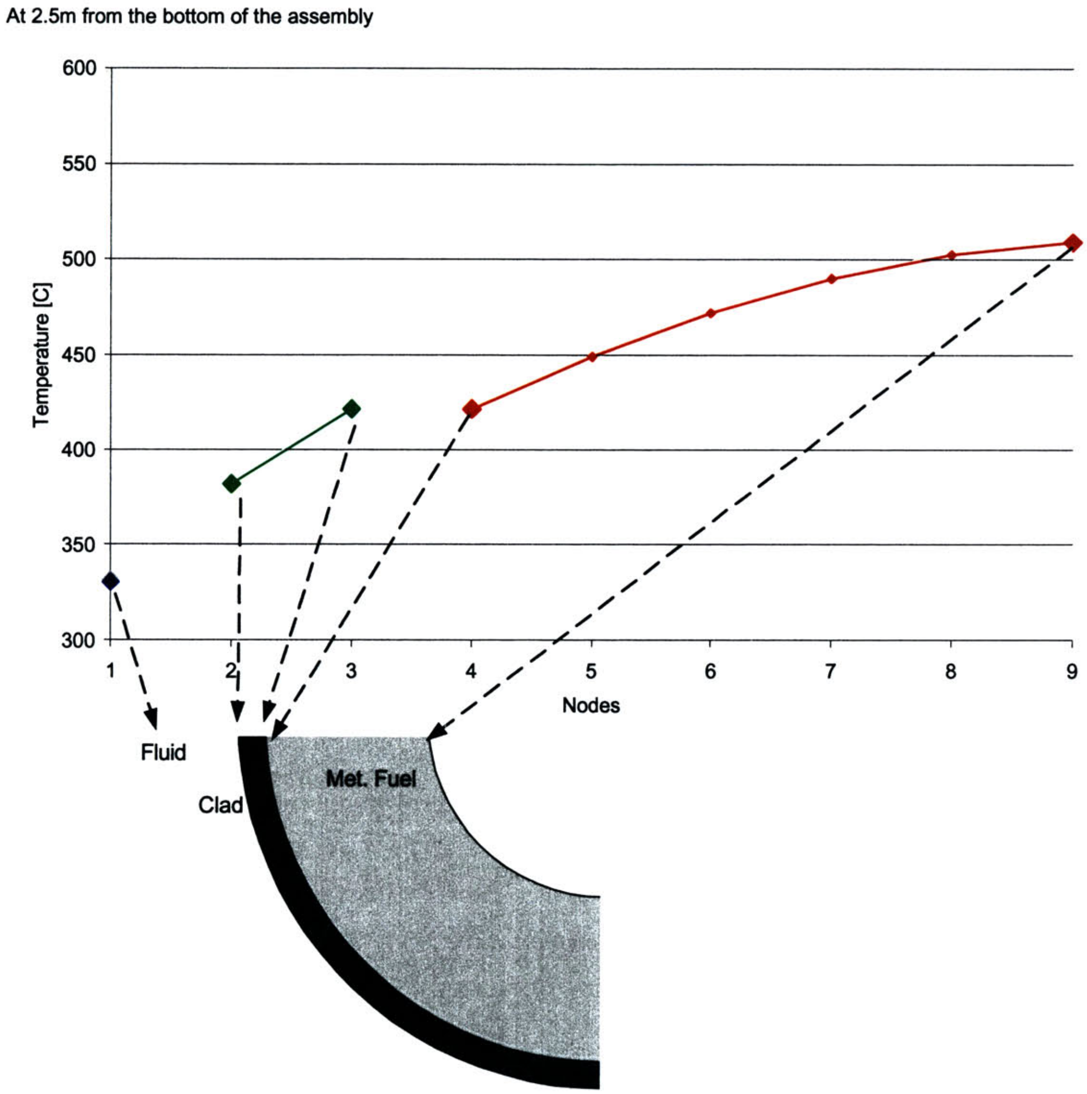


Figure 24 MOC radial temperature profile in the hottest seed rod at an assembly average q'=25 kW/m

In the case of the hottest blanket rod (rod 117, Figure 15), the same operating condition was taken, but additionally the fuel-clad gap conductance was taken into account.

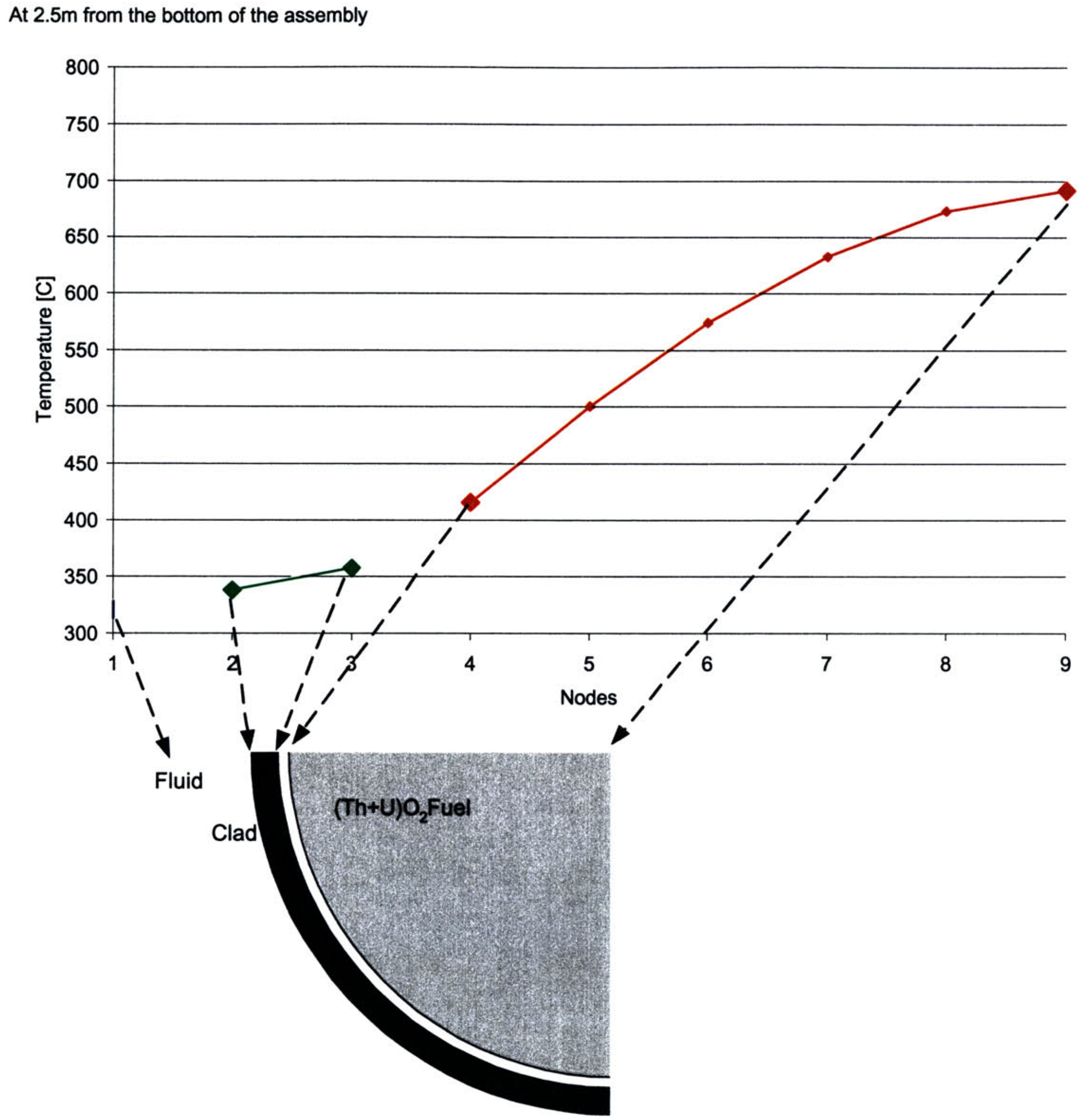


Figure 25 MOC radial temperature profile in the hottest blanket rod at an assembly average q'=25 kW/m

3.5 SBU design optimization

In order to optimize the SBU thermal-hydraulics, a MDNBR criteria was used as a metric for fuel performance. For all cases, the boundary conditions were kept constant (inlet flow, inlet temperature, power distribution) in order to compare different designs.

Three design alternatives were analyzed to gain insight into the safety margin of this assembly. The analysis involved:

- Changing the seed rod diameter
- Changing the blanket rod diameter
- Introduction of differential seed-blanket grid resistance

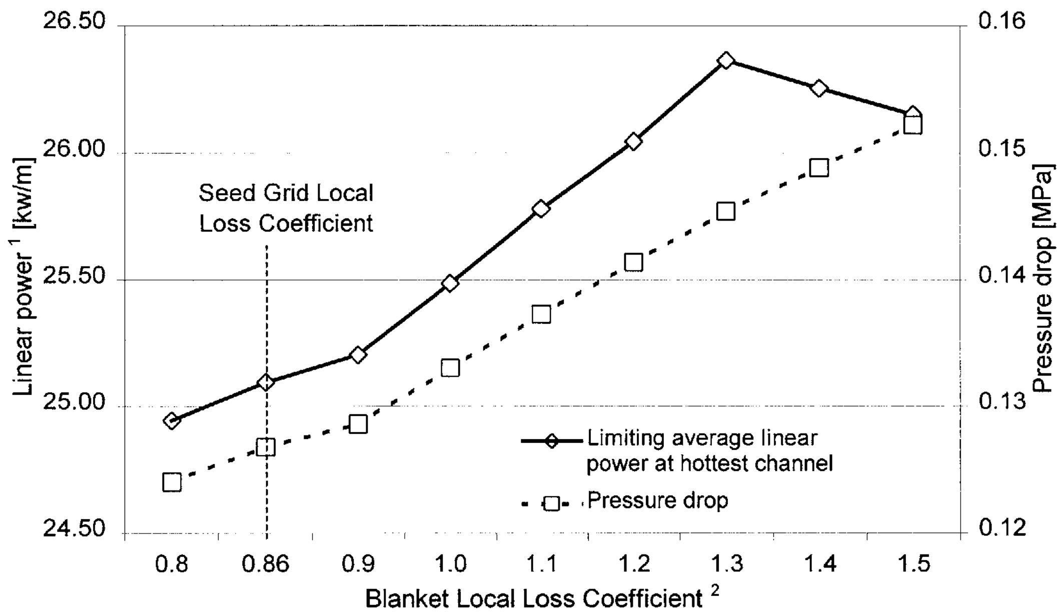
A sensitivity analysis for the first two alternatives is shown in Table 3. For this calculation the limiting linear power level for the average pin in the hot assembly was adjusted in order to meet the MDNBR. From Table 3 it is clear that no significant improvement can be gained by rod diameter changes without changing the reactor physics (moderator/fuel ratio).

Table 3 SBU rod diameter sensitivity analysis

	Rod diameter [cm]				Moderator/Fuel		Limiting power level for MDNBR (=1.3) (1)					
Design	Seed			Blanket	Volume ratio		W-3L Correlation			BAW 2 Correlation		
	Clad	Fuel out	Fuel in	Clad	Seed	Blanket	[kw/m]	[MWth] (2)		[kw/m]	[MWth] (2)	
Global 99	0.840	0.760	0.400	0.950	3.3	1.6	25.09	2,978	base	26.72	3,171	base
Seed +5% (3)	0.882	0.802	0.496	0.950	3.3	1.6	25.57	3,034	1.9%	26.70	3,168	-0.1%
Seed -5% (3)	0.798	0.718	0.275	0.950	3.3	1.6	24.28	2,881	-3.2%	26.38	3,130	-1.3%
Blanket +5% (3)	0.840	0.760	0.400	0.997	3.3	1.4	26.46	3,139	5.4%	28.03	3,326	4.9%
Blanket -5% (3)	0.840	0.760	0.400	0.902	3.3	2.0	23.95	2,842	-4.6%	25.59	3,036	-4.2%

(1) Limit on the hottest rod of the hot channel. Power distribution of MOC.
(2) 18% overpower for transients considered.
(3) Boundary condition: constant inlet effective mass flow of 17.7 Mg/sec

The differential grid resistance option was analyzed by modeling different grid local loss coefficients for each assembly area (8 grids equally spaced in the assembly). Figure 26 shows the effect on pressure drop and the limiting pin average linear power of the hot channel for different blanket grid loss coefficients. The limiting rod moves from the seed to the blanket when the blanket local loss coefficient is increased above 1.2 (compared to the base 0.86 loss coefficient) as shown in Figure 27. In this case the linear power level is approximately 5% above the reference design [Ref. 15]. The same linear power and pressure drop could be obtained by a 5% increase in blanket diameter, which would impact the reactor physics.



[1] Limiting linear power in the hot channel constrained by MDNBR=1.3 and MOC power distribution

[2] 8 grids equally spaced in the assembly

Figure 26 Effect of different blanket local loss coefficient on limiting linear power and pressure drop for the SBU assembly

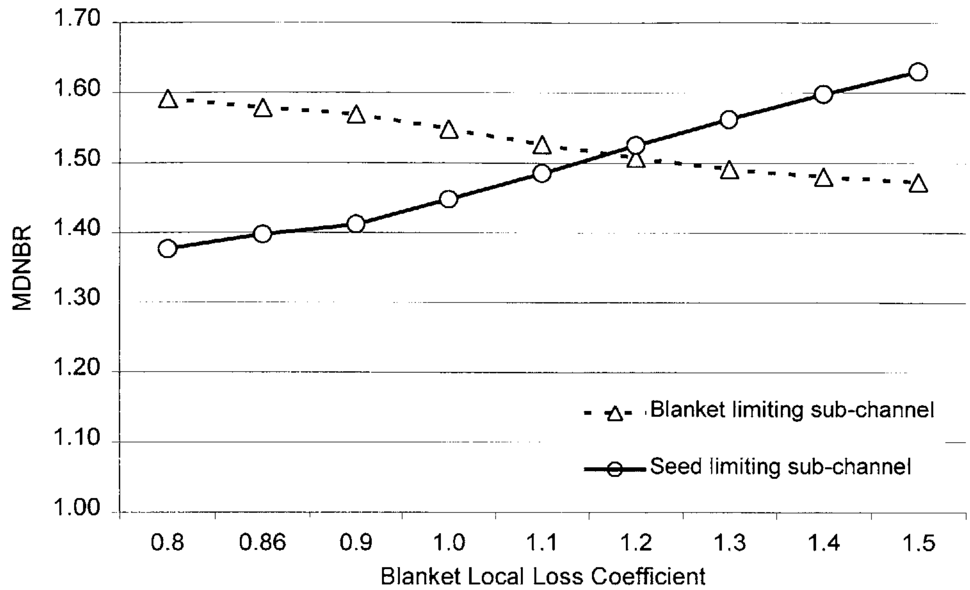


Figure 27 Effect of different blanket local loss coefficient on MDNBR for the SBU assembly

From the three different thermal-hydraulics design optimization alternatives that were analyzed for the SBU fuel design, the differential local loss coefficient for the blanket region was found to be the best design improvement approach. It provided the higher allowable level of linear power with minimal impact on the reactor physics characteristics. The differential-grid optimized design is compared to the base one in Figure 28 and Figure 29, where the temperature distribution in the two types of fuel rods (hottest rods of each kind shown) is shown.

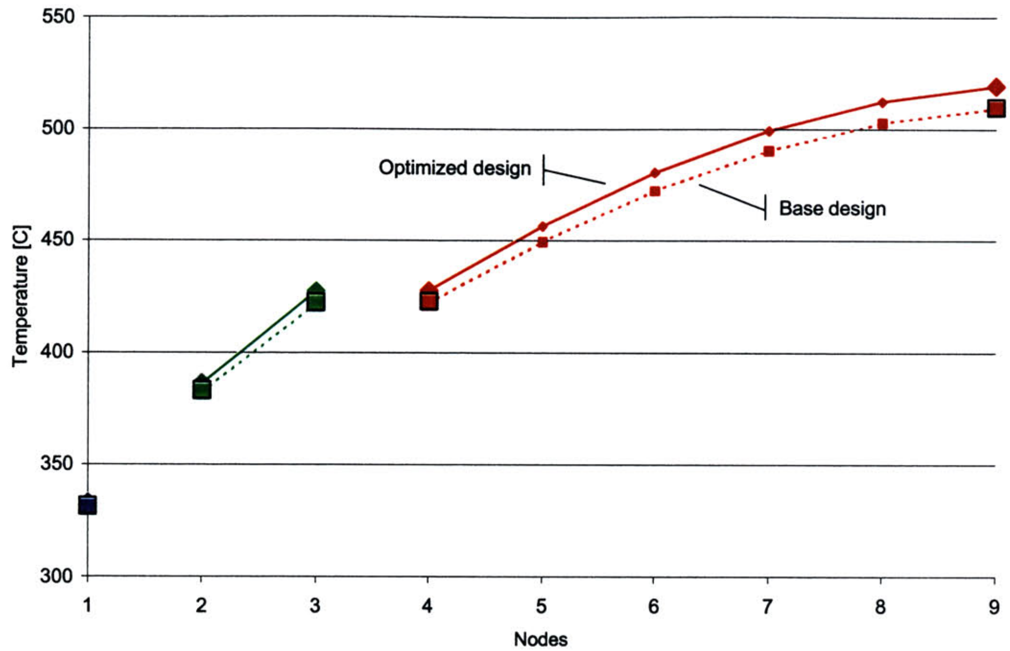


Figure 28 Optimized vs. base design temperature profile for the hottest seed rod

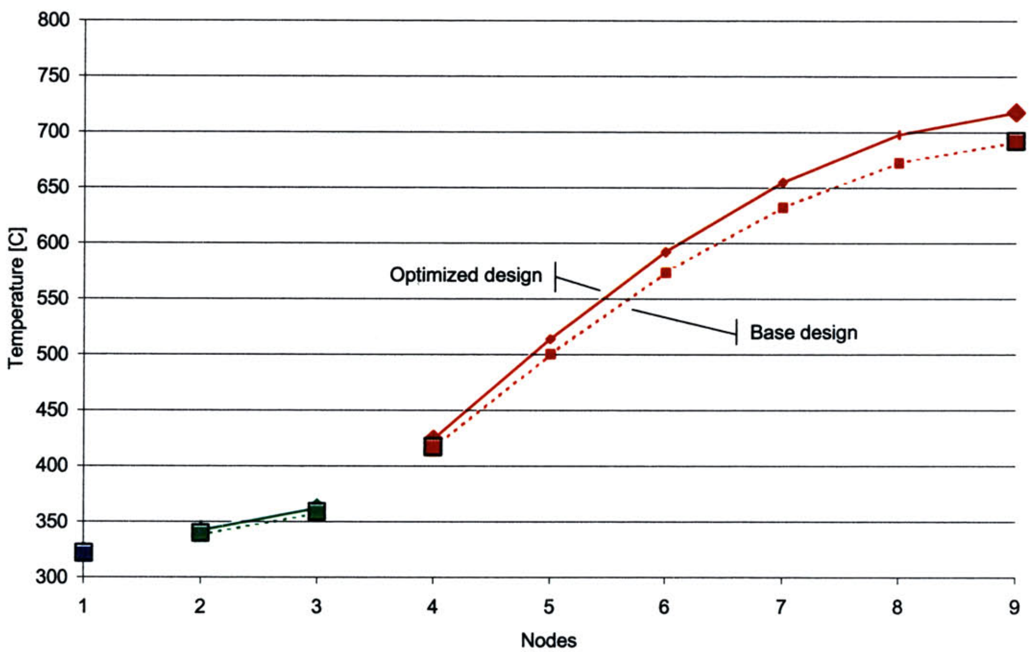


Figure 29 Optimized vs. base design temperature profile for the hottest blanket rod

In both kinds of rods the temperature could be raised because the coolant flow was optimally distributed between the two regions: increased in the seed and lowered in the blanket. It can be seen from the plots that the optimization allowed a slight increase in the coolant local temperature (aprox. 2°C), but most importantly an increase in the heat flux that results in higher internal temperatures in the fuel (10°C in the seed and 27°C in the blanket).

The maximum power achievable by this design, at an assembly level, comes from the relative power between the seed and blanket region, and from the pin power distribution within the same region. The first problem can be solved by the proposed differential grid loss factor. This optimization allows a 5% increase in the allowable power level. At this point the design is constrained by the relative power distribution within the region (seed and blanket) and the location of the hottest rod in that region.

Chapter 4

WHOLE ASSEMBLY SEED AND BLANKET (WSB) DESIGN

The Seed and Blanket core designs based on the use of thorium fuel, have attracted the attention of the nuclear community mostly because of the improved anti-proliferation characteristics of the spent fuel (reduced plutonium content and worse isotopic content of Pu from a weapon-use point of view). The SBU design [Ref. 15] is one of this approaches that incorporates these characteristics to current PWRs. An alternative design has been studied at MIT addressing the possibility to have a Seed and Blanket approach where each type of fuel occupies one full-size assembly [Ref. 8]. These two types of assemblies are arranged in a checkerboard distribution.

This design is also constrained by the requirement of retrofitability into current PWRs as was discussed for the SBU. The main advantages of this new design are simpler fabrication, easier in-core management and potentially easier optimization of the thermal-hydraulic performance. On the other hand, having the same amount of seed and blanket assemblies becomes a challenge from the physics point of view, where based on the SBU design a 40%/60% seed-to-blanket volume ratio is optimal for fuel performance.

4.1 Design parameters

The seed and blanket regions in this design are made up of whole assemblies. The checkerboard array distribution in a PWR core is shown in Figure 30 with a detail of a seed and blanket cluster.

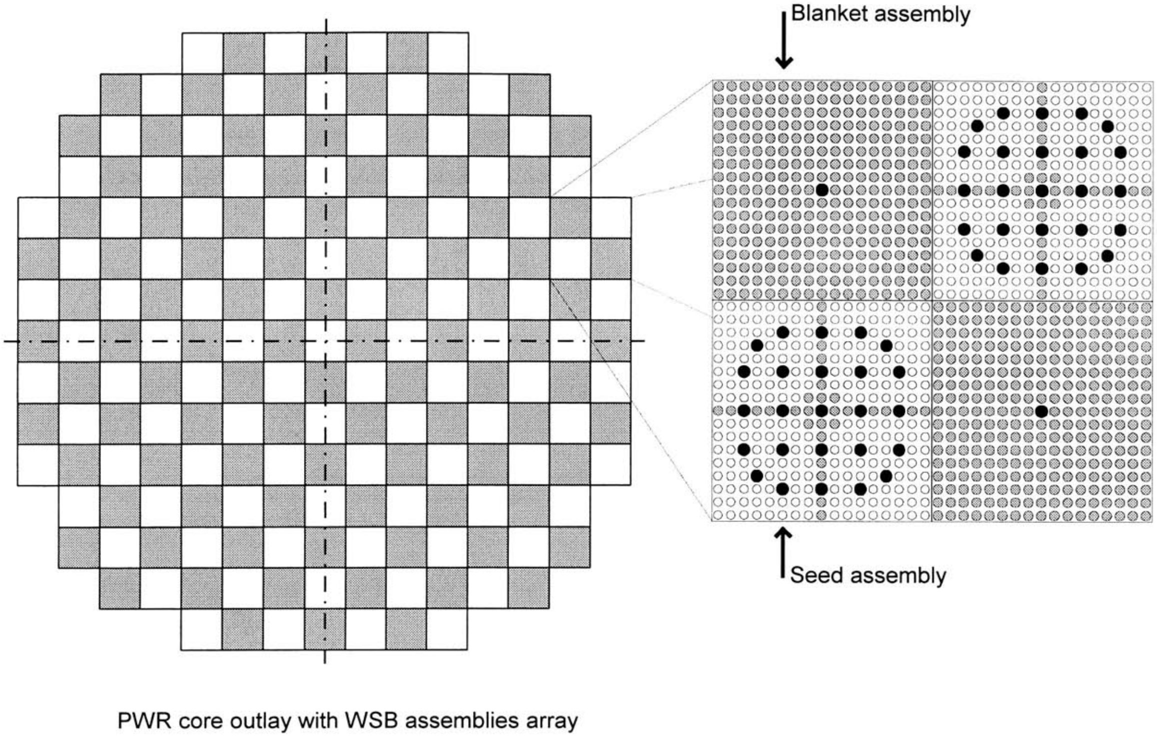


Figure 30 WSB design

The fuel pins of each type can be identical to those specified in the SBU design but arranged in a 17x17 Westinghouse PWR fuel assembly (Design WSB-A) or the seed pins can be made of UO_2 annular pellets (Design WSB-B).

The blanket fuel pins are assembled into a bundle with just one guide tube at the center. Given the lower power generation and because it is mainly an area where neutrons are absorbed, no control rods are considered in this type of assembly. This design decision should be further assessed from a mechanical point of view, to see whether guide tubes are needed for structural strength and grid spacers positioning.

In the case of the seed assemblies, seed fuel pins are bundled together with adjusted fuel pins (blanket pins located in seed assemblies) and control and instrumentation rods. These adjusted pins optimize the seed/blanket ratio in the design and also help to reduce the seed's power peak. This is the reason why they are concentrated in the center of the seed bundle. Although these pins play the role of the blanket in the design, they are expected to be an integral part of the seed assembly, thus following the same refueling cycle.

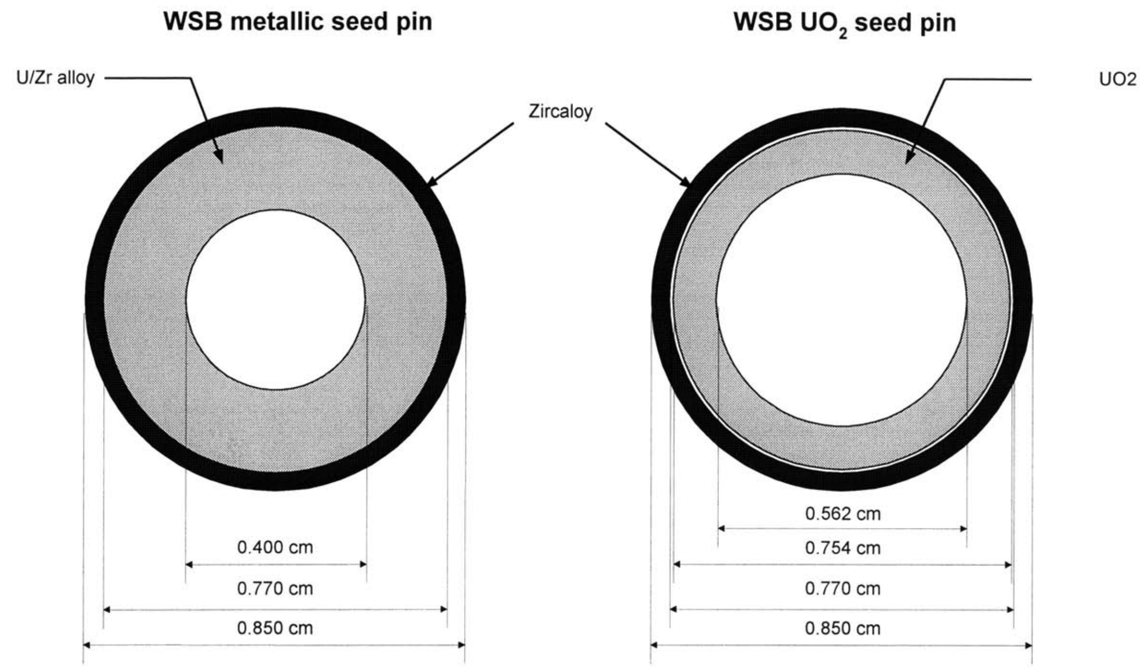


Figure 31 WSB alternative seed rod designs

Two alternative designs were analyzed for the WSB approach. The only difference between them is the fuel material in the seed region. The first option has a metallic alloy (U+Zr) that is co-extruded with the cladding Zircaloy in order to produce seed rods. These seed rods follow the same approach of the Galperin's SBU assembly. The second option has uranium dioxide pellets as fuel material in the seed. These WSB options are shown in Figure 31.

4.1.1 *WSB metallic seed design*

This design (called WSB-A), has the same type of seed pins like the SBU but is based on a whole assembly arrangement.

The most relevant design parameters are given in Table 4.

Table 4 WSB-A assemblies design parameters.

Parameter	Seed assembly	Blanket assembly
Fuel Assembly Size [cm]	21.4 x 21.4	21.4 x 21.4
Fuel Material Composition	U/Zr metal alloy (45.3% U, 54.7% Zr) U 20% enriched (1)	$(U+Th)O_2$ (10% UO_2/90% ThO_2 in weight) U 15% enriched
Number of Rods	236 seed rods (1) 28 adjusted rods (2) 25 control/guide rods	288 blanket rods 1 guide tube
Fuel Pellet Radius [cm] inner-outer	0.20 - 0.38	0.0 - 0.4095
Fuel-Clad Gap [cm]	No	0.0085
Cladding material thickness [cm]	0.04	0.057
Fuel Cell Pitch [cm]	1.26	1.26

(1) metallic fuel
(2) $(U+Th)O_2$ fuel –similar to blanket material-

4.1.2 *WSB uranium dioxide seed pellet design*

In this design (called WSB-B), the seed rods are filled with uranium dioxide pellets. The advantage of this option is its proven design and better performance under some accident scenarios. Additionally, licensing problems can be minimized as UO_2 pellets are currently used in most commercial PWRs.

The most relevant design parameters are given in Table 5. The design preserves the same amount of U^{235} and U^{238} in the seed and blanket pins.

Table 5 WSB-B assemblies design parameters.

Parameter	Seed assembly	Blanket assembly
Fuel Assembly Size [cm]	21.4 x 21.4	21.4 x 21.4
Fuel Material Composition	UO_2 U 20% enriched	$(U+Th)O_2$ (10% UO_2/90% ThO_2 in weight) U 15% enriched
Number of Rods	264 seed rods 25 control/guide rods	288 blanket rods 1 guide tube
Fuel Pellet Radius [cm] inner-outer	0.281 - 0.377	0.0 - 0.4095
Fuel-Clad Gap [cm]	0.0085	0.0085
Cladding material thickness [cm]	0.04	0.057
Fuel Cell Pitch [cm]	1.26	1.26

4.2 In-core fuel management

The fuel management policies are very similar to a typical PWR with the difference that blanket assemblies have a residence period close to 10 years. At the present, seed refueling cycle length is one year for the WSB-A alternative, while a 18 month cycle is achievable with the WSB-B. Both can be expected to meet the 18 month cycle requirement with careful design.

The refueling process will clearly be simplified for the facilities by the use of any of these seed and blanket designs because the load units remain the same as today and no specific training is expected to be required to handle the new fuel. However, for a 50%-50% seed-blanket division, the number of assemblies involved in any reload will be cut by 1/3.

Physics calculations for the WSB design at the time of this study were available at an assembly level. Whole core calculations are underway but in order to analyze and compare the different alternative designs, the core radial and axial power distribution were taken from the SBU MOC results (please refer to Figure 10 and Figure 12). The relative pin power distribution for the WSB-A seed and blanket cluster is given in Figure 32. The same distribution but in this case for the WSB-B option is shown in Figure 33.

4.3 Inputs to the VIPRE code

The thermal-hydraulics modeling of the WSB design using the VIPRE code was done in a similar way as for the SBU and will be discuss briefly in this section. Only the differentiating variables are shown as in this case two different types of assemblies are modeled in the same problem.

In this case, the selected modeling region was taken as the symmetric volume composed of one quarter each of two seed assemblies and one quarter each of two blanket assemblies, as shown in Figure 34.

The rods located at the perimeter of the modeled region were analyzed as shared at halves (in area and power generation) with the surrounding channels.

Subchannels, rods and gaps were also defined in a similar way as was done for the SBU. The identification used for them (the same in WSB-A/B) is shown in Figure 35, Figure 37 and Figure 39.

	¼ seed assembly									¼ blanket assembly								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	0.000	1.217	1.145	0.000	1.091	1.081	0.000	1.063	1.058	0.534	0.540	0.559	0.553	0.559	0.580	0.586	0.627	0.000
2	1.217	1.108	1.664	1.640	1.578	1.566	1.593	1.557	1.618	0.532	0.542	0.553	0.558	0.564	0.572	0.583	0.604	0.627
3	1.145	1.664	1.570	1.572	1.511	1.503	1.540	1.502	1.575	0.527	0.540	0.551	0.558	0.563	0.568	0.575	0.583	0.586
4	0.000	1.640	1.572	0.000	1.537	1.534	0.000	1.524	1.561	0.524	0.538	0.549	0.556	0.561	0.564	0.568	0.572	0.580
5	1.091	1.578	1.511	1.537	1.512	1.546	1.532	1.471	1.546	0.521	0.536	0.547	0.554	0.558	0.561	0.563	0.564	0.559
6	1.081	1.566	1.503	1.534	1.546	0.000	1.498	1.438	1.533	0.519	0.533	0.544	0.550	0.554	0.556	0.558	0.558	0.553
7	0.000	1.593	1.540	0.000	1.532	1.498	1.436	1.421	1.524	0.516	0.529	0.539	0.544	0.547	0.549	0.551	0.553	0.559
8	1.063	1.557	1.502	1.524	1.471	1.438	1.421	1.429	1.529	0.512	0.521	0.529	0.533	0.536	0.538	0.540	0.542	0.540
9	1.058	1.618	1.575	1.561	1.546	1.533	1.524	1.529	1.598	0.513	0.512	0.516	0.519	0.521	0.524	0.527	0.532	0.534
10	0.534	0.532	0.527	0.524	0.521	0.519	0.516	0.512	0.513	1.598	1.529	1.524	1.533	1.546	1.561	1.575	1.618	1.058
11	0.540	0.542	0.540	0.538	0.536	0.533	0.529	0.521	0.512	1.529	1.429	1.421	1.438	1.471	1.524	1.502	1.557	1.063
12	0.559	0.553	0.551	0.549	0.547	0.544	0.539	0.529	0.516	1.524	1.421	1.436	1.498	1.532	0.000	1.540	1.593	0.000
13	0.553	0.558	0.558	0.556	0.554	0.550	0.544	0.533	0.519	1.533	1.438	1.498	0.000	1.546	1.534	1.503	1.566	1.081
14	0.559	0.564	0.563	0.561	0.558	0.554	0.547	0.536	0.521	1.546	1.471	1.532	1.546	1.512	1.537	1.511	1.578	1.091
15	0.580	0.572	0.568	0.564	0.561	0.556	0.549	0.538	0.524	1.561	1.524	0.000	1.534	1.537	0.000	1.572	1.640	0.000
16	0.586	0.583	0.575	0.568	0.563	0.558	0.551	0.540	0.527	1.575	1.502	1.540	1.503	1.511	1.572	1.570	1.664	1.145
17	0.627	0.604	0.583	0.572	0.564	0.558	0.553	0.542	0.532	1.618	1.557	1.593	1.566	1.578	1.640	1.664	1.108	1.217
18	0.000	0.627	0.586	0.580	0.559	0.553	0.559	0.540	0.534	1.058	1.063	0.000	1.081	1.091	0.000	1.145	1.217	0.000

Figure 32 WSB-A relative pin power distribution

	¼ seed assembly									¼ blanket assembly								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	0.000	1.542	1.538	0.000	1.527	1.520	0.000	1.535	1.612	0.497	0.510	0.518	0.522	0.523	0.524	0.530	0.550	0.000
2	1.542	1.494	1.490	1.533	1.480	1.474	1.520	1.491	1.609	0.497	0.510	0.519	0.522	0.523	0.524	0.528	0.537	0.550
3	1.538	1.490	1.488	1.532	1.481	1.476	1.521	1.490	1.609	0.497	0.510	0.519	0.522	0.523	0.523	0.525	0.528	0.530
4	0.000	1.533	1.532	0.000	1.536	1.536	0.000	1.536	1.610	0.497	0.511	0.519	0.523	0.523	0.523	0.523	0.524	0.524
5	1.527	1.480	1.481	1.536	1.516	1.556	1.543	1.485	1.602	0.497	0.510	0.520	0.523	0.524	0.523	0.523	0.523	0.523
6	1.520	1.474	1.476	1.536	1.556	0.000	1.509	1.452	1.592	0.495	0.510	0.519	0.522	0.523	0.523	0.522	0.522	0.522
7	0.000	1.520	1.521	0.000	1.543	1.509	1.444	1.439	1.588	0.494	0.507	0.515	0.519	0.520	0.519	0.519	0.519	0.518
8	1.535	1.491	1.490	1.536	1.485	1.452	1.439	1.459	1.604	0.492	0.500	0.507	0.510	0.510	0.511	0.510	0.510	0.510
9	1.612	1.609	1.609	1.610	1.602	1.592	1.588	1.604	1.710	0.495	0.492	0.494	0.495	0.497	0.497	0.497	0.497	0.497
10	0.497	0.497	0.497	0.497	0.497	0.495	0.494	0.492	0.495	1.710	1.604	1.588	1.592	1.602	1.610	1.609	1.609	1.612
11	0.510	0.510	0.510	0.511	0.510	0.510	0.507	0.500	0.492	1.604	1.459	1.439	1.452	1.485	1.536	1.490	1.491	1.535
12	0.518	0.519	0.519	0.519	0.520	0.519	0.515	0.507	0.494	1.588	1.439	1.444	1.509	1.543	0.000	1.521	1.520	0.000
13	0.522	0.522	0.522	0.523	0.523	0.522	0.519	0.510	0.495	1.592	1.452	1.509	0.000	1.556	1.536	1.476	1.474	1.520
14	0.523	0.523	0.523	0.523	0.524	0.523	0.520	0.510	0.497	1.602	1.485	1.543	1.556	1.516	1.536	1.481	1.480	1.527
15	0.524	0.524	0.523	0.523	0.523	0.523	0.519	0.511	0.497	1.610	1.536	0.000	1.536	1.536	0.000	1.532	1.533	0.000
16	0.530	0.528	0.525	0.523	0.523	0.522	0.519	0.510	0.497	1.609	1.490	1.521	1.476	1.481	1.532	1.488	1.490	1.538
17	0.550	0.537	0.528	0.524	0.523	0.522	0.519	0.510	0.497	1.609	1.491	1.520	1.474	1.480	1.533	1.490	1.494	1.542
18	0.000	0.550	0.530	0.524	0.523	0.522	0.518	0.510	0.497	1.612	1.535	0.000	1.520	1.527	0.000	1.538	1.542	0.000

Figure 33 WSB-B realtive pin power distribution

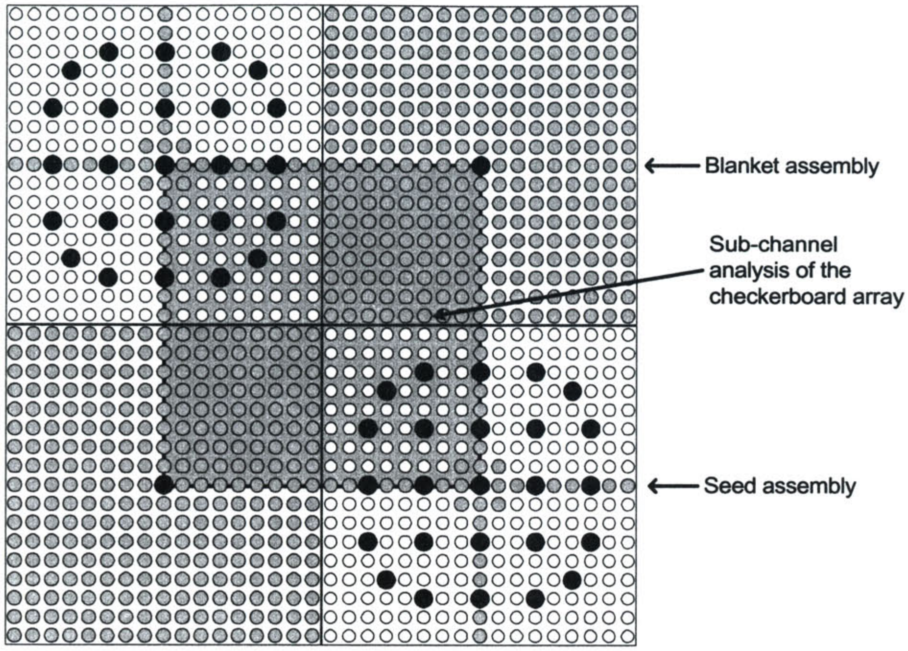


Figure 34 Sub-channel analysis of the WSB array design

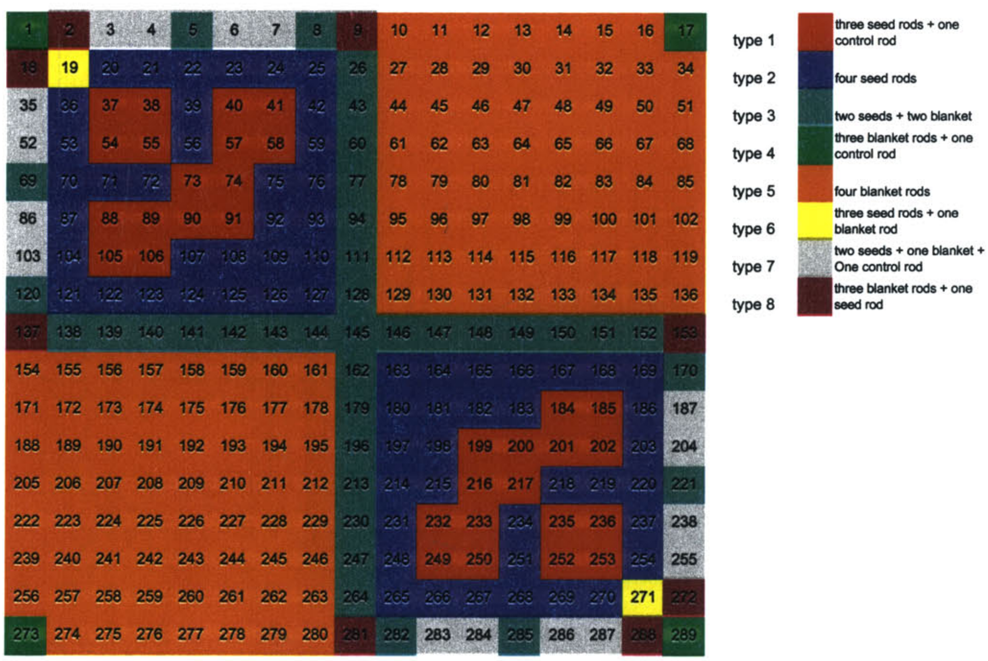


Figure 35 WSB-A subchannel identification

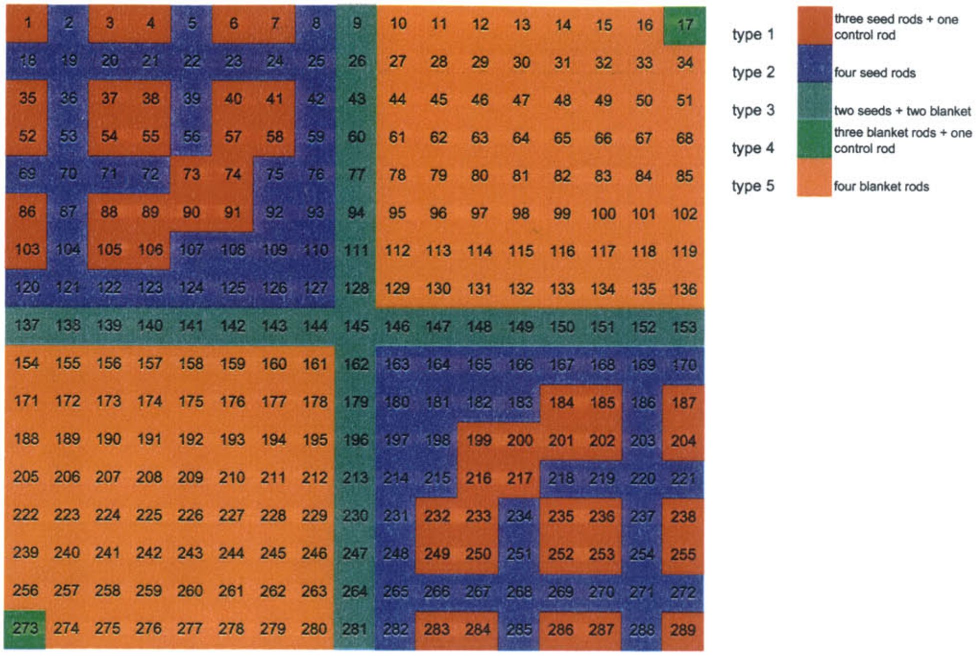


Figure 36 WSB-B subchannel identification

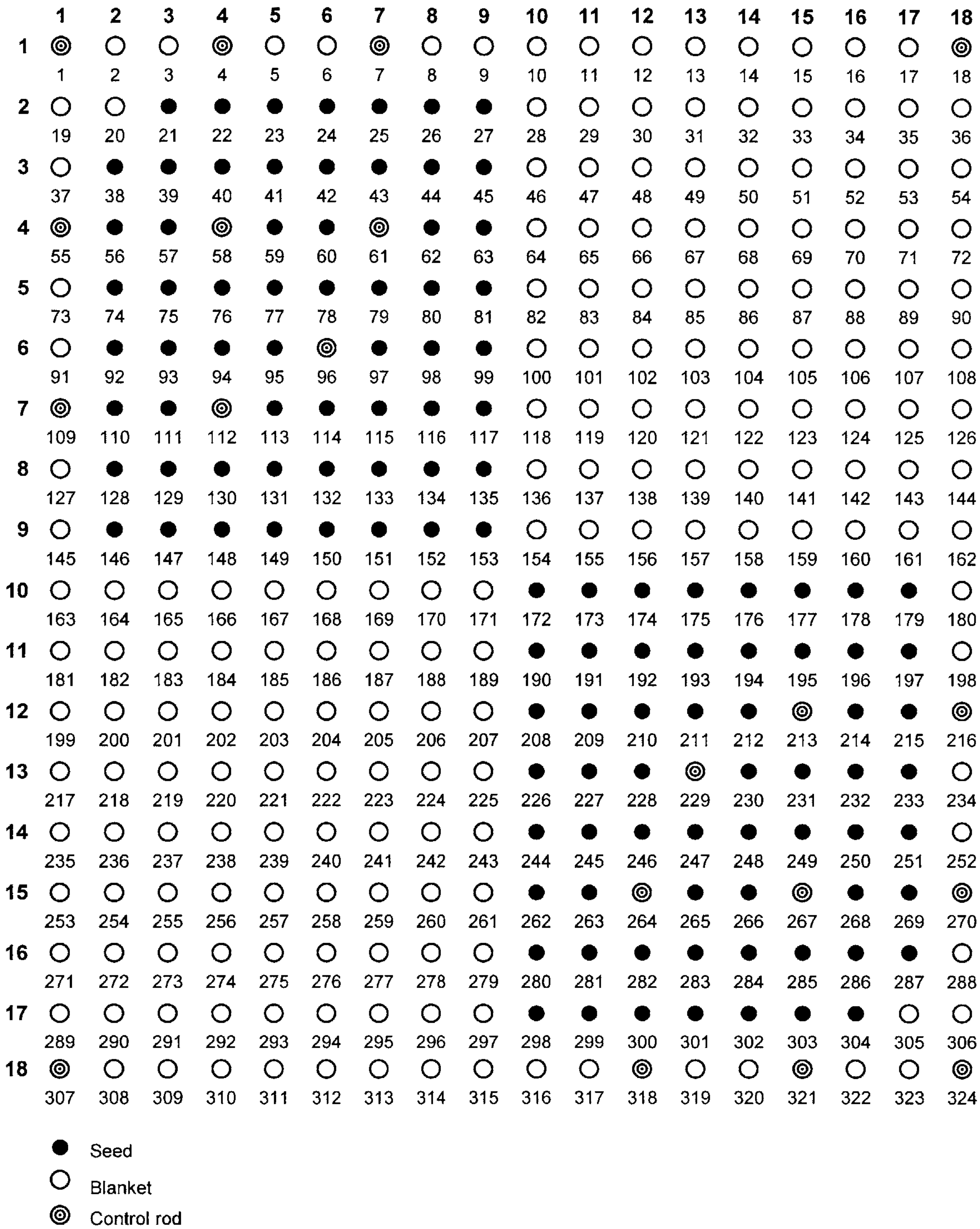


Figure 37 WSB-A rod identification

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	◎ 1	● 2	● 3	◎ 4	● 5	● 6	◎ 7	● 8	● 9	○ 10	○ 11	○ 12	○ 13	○ 14	○ 15	○ 16	○ 17	◎ 18
2	● 19	● 20	● 21	● 22	● 23	● 24	● 25	● 26	● 27	○ 28	○ 29	○ 30	○ 31	○ 32	○ 33	○ 34	○ 35	○ 36
3	● 37	● 38	● 39	● 40	● 41	● 42	● 43	● 44	● 45	○ 46	○ 47	○ 48	○ 49	○ 50	○ 51	○ 52	○ 53	○ 54
4	◎ 55	● 56	● 57	◎ 58	● 59	● 60	◎ 61	● 62	● 63	○ 64	○ 65	○ 66	○ 67	○ 68	○ 69	○ 70	○ 71	○ 72
5	● 73	● 74	● 75	● 76	● 77	● 78	● 79	● 80	● 81	○ 82	○ 83	○ 84	○ 85	○ 86	○ 87	○ 88	○ 89	○ 90
6	● 91	● 92	● 93	● 94	● 95	◎ 96	● 97	● 98	● 99	○ 100	○ 101	○ 102	○ 103	○ 104	○ 105	○ 106	○ 107	○ 108
7	◎ 109	● 110	● 111	◎ 112	● 113	● 114	● 115	● 116	● 117	○ 118	○ 119	○ 120	○ 121	○ 122	○ 123	○ 124	○ 125	○ 126
8	● 127	● 128	● 129	● 130	● 131	● 132	● 133	● 134	● 135	○ 136	○ 137	○ 138	○ 139	○ 140	○ 141	○ 142	○ 143	○ 144
9	● 145	● 146	● 147	● 148	● 149	● 150	● 151	● 152	● 153	○ 154	○ 155	○ 156	○ 157	○ 158	○ 159	○ 160	○ 161	○ 162
10	○ 163	○ 164	○ 165	○ 166	○ 167	○ 168	○ 169	○ 170	○ 171	● 172	● 173	● 174	● 175	● 176	● 177	● 178	● 179	● 180
11	○ 181	○ 182	○ 183	○ 184	○ 185	○ 186	○ 187	○ 188	○ 189	● 190	● 191	● 192	● 193	● 194	● 195	● 196	● 197	● 198
12	○ 199	○ 200	○ 201	○ 202	○ 203	○ 204	○ 205	○ 206	○ 207	● 208	● 209	● 210	● 211	● 212	◎ 213	● 214	● 215	◎ 216
13	○ 217	○ 218	○ 219	○ 220	○ 221	○ 222	○ 223	○ 224	○ 225	● 226	● 227	● 228	◎ 229	● 230	● 231	● 232	● 233	● 234
14	○ 235	○ 236	○ 237	○ 238	○ 239	○ 240	○ 241	○ 242	○ 243	● 244	● 245	● 246	● 247	● 248	● 249	● 250	● 251	● 252
15	○ 253	○ 254	○ 255	○ 256	○ 257	○ 258	○ 259	○ 260	○ 261	● 262	● 263	◎ 264	● 265	● 266	◎ 267	● 268	● 269	◎ 270
16	○ 271	○ 272	○ 273	○ 274	○ 275	○ 276	○ 277	○ 278	○ 279	● 280	● 281	● 282	● 283	● 284	● 285	● 286	● 287	● 288
17	○ 289	○ 290	○ 291	○ 292	○ 293	○ 294	○ 295	○ 296	○ 297	● 298	● 299	● 300	● 301	● 302	● 303	● 304	● 305	● 306
18	◎ 307	○ 308	○ 309	○ 310	○ 311	○ 312	○ 313	○ 314	○ 315	● 316	● 317	◎ 318	● 319	● 320	◎ 321	● 322	● 323	◎ 324

● Seed
○ Blanket
◎ Control rod

Figure 38 WSB-B rod identification

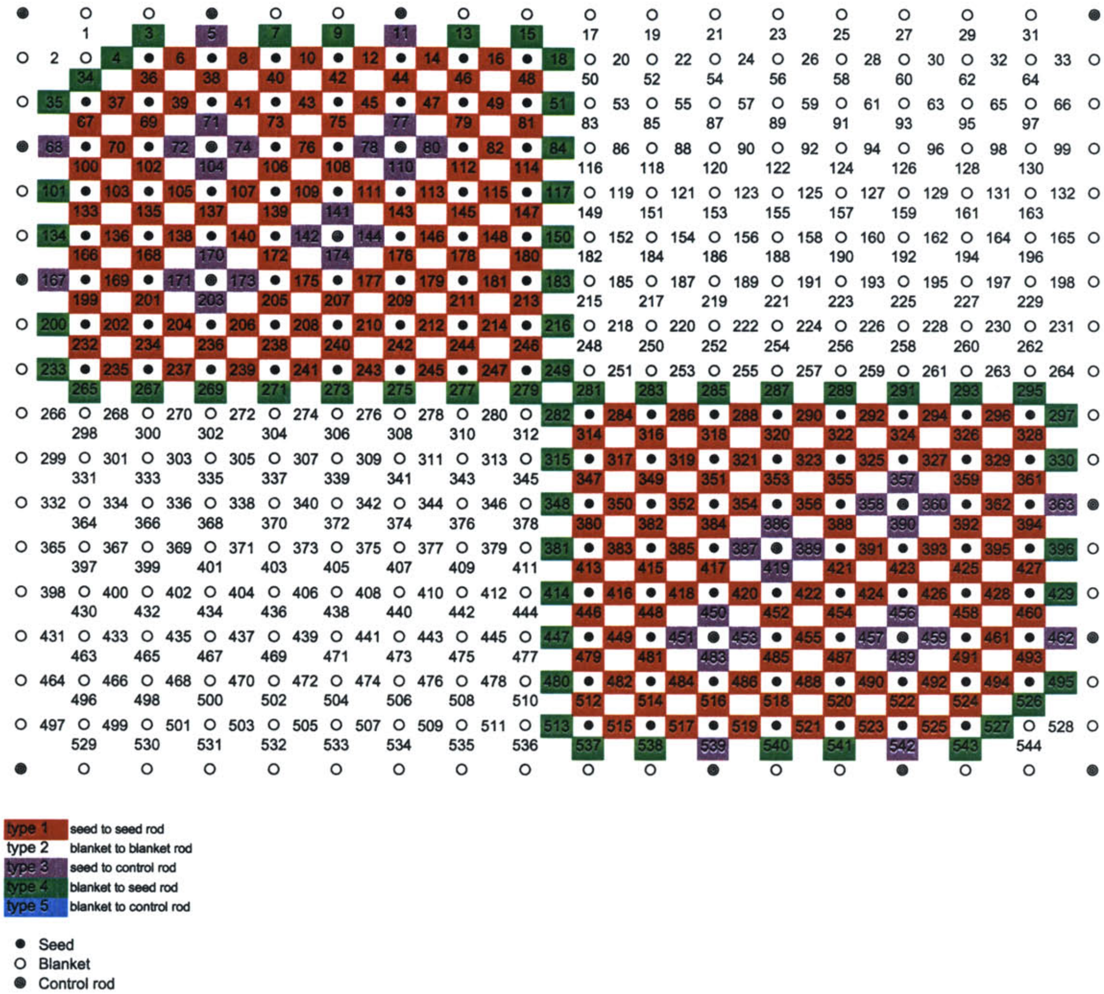


Figure 39WSB-A gap identification

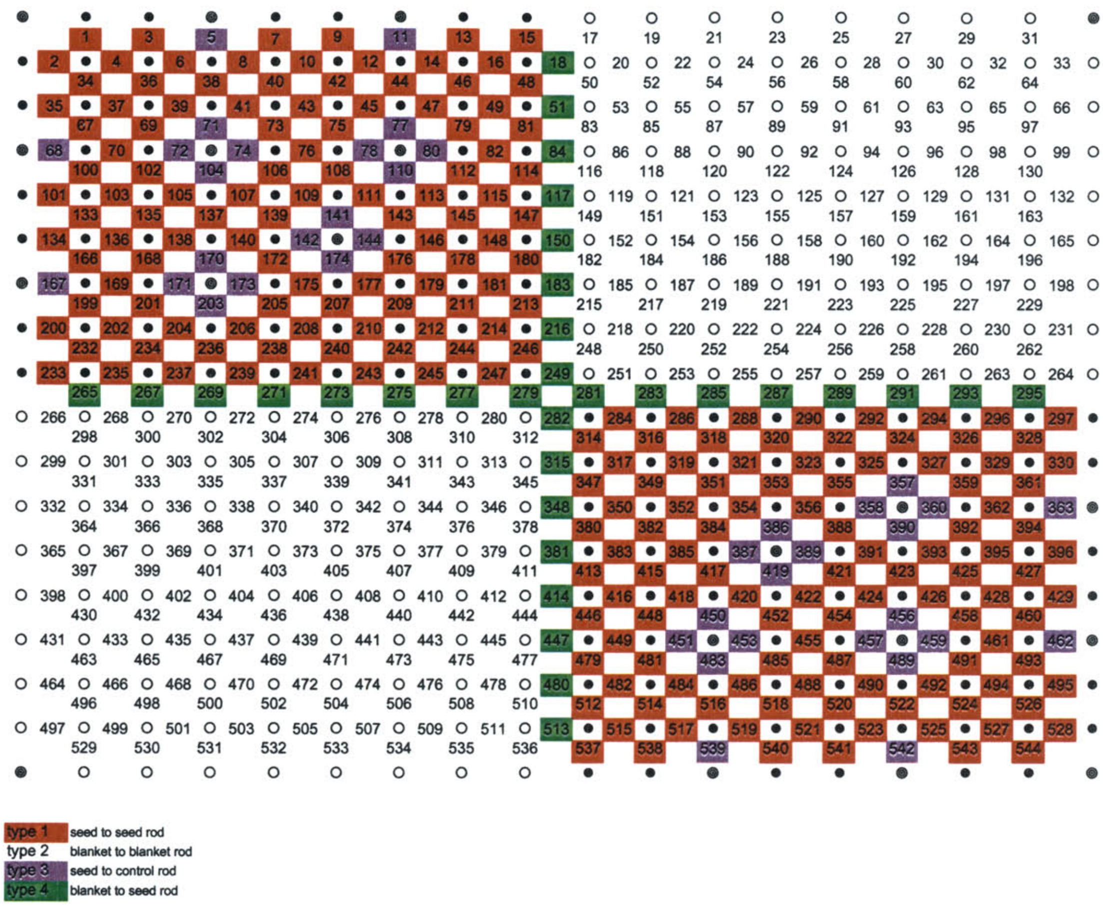


Figure 40 WSB-B gap identification

A VIPRE input file for the WSB design can be found in Appendix D.

4.4 WSB Thermal-hydraulics modeling results

The thermal-hydraulics performance of the WSB designs was evaluated based on the typical boundary conditions found in a Westinghouse PWR plant. Additionally, the radial hot channel power peak factor and the axial power distribution was taken from the SBU's MOC calculations as no detailed core neutronic results were available at the time of this study.

Average coolant temperature in the WSB-A cluster is compared to the hottest spot in it in Figure 41. While the WSB-A has the same average temperature profile as the SBU, the hottest subchannel peak temperature is reduced in the WSB design (compare Figure 41 with Figure 18). This lower temperature in the most constrained region of the fuel leads to a higher MDNBR in both WSB designs compared to the SBU as shown in Figure 42.

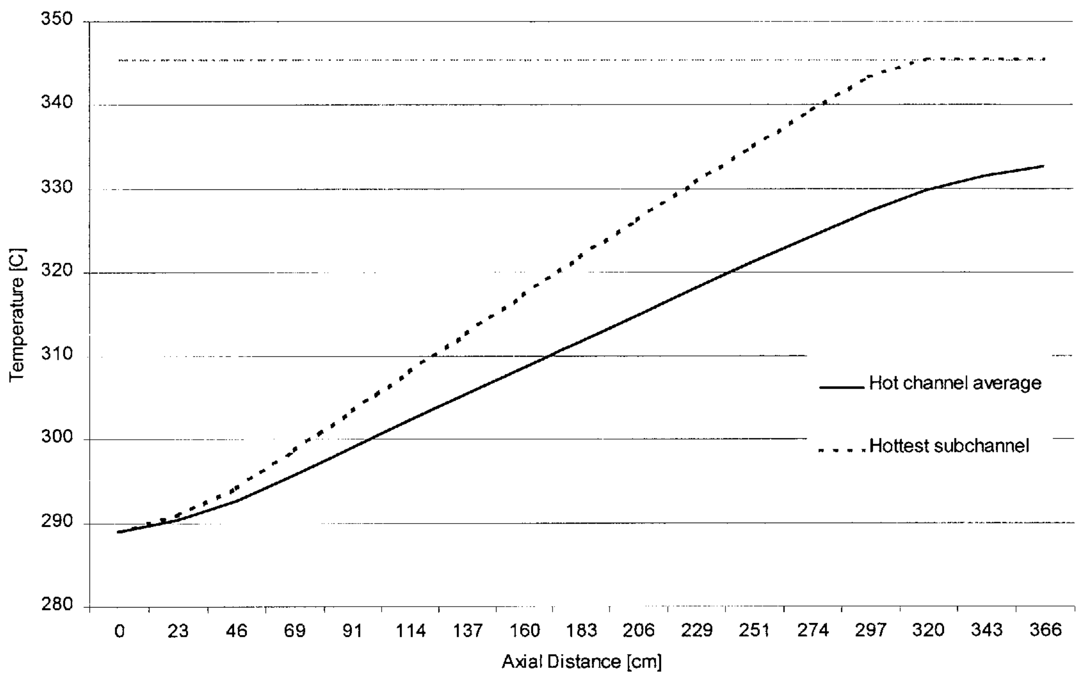


Figure 41 WSB axial temperature profile

Figure 43 shows the coolant temperature distribution at the exit of a WSB-A cluster of two seed and two blanket assemblies. The same result for WSB-B is shown in Figure 45. Notice the impact of the adjusted pins (blanket-type pins in the seed assembly) in flattening the distribution at the center of the seed assemblies in alternative WSB-A.

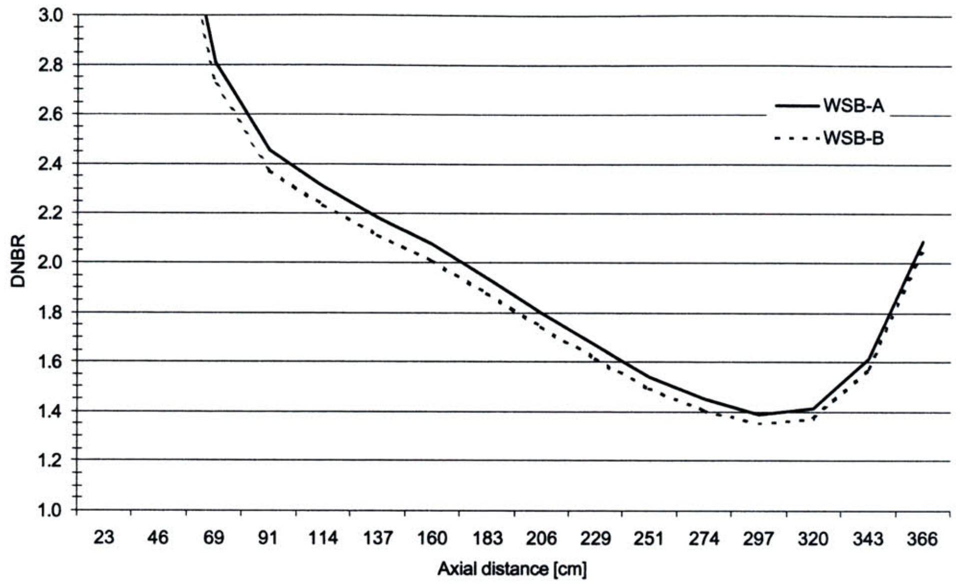


Figure 42 WSB-A/B DNBR analysis for MOC of the hot seed assembly

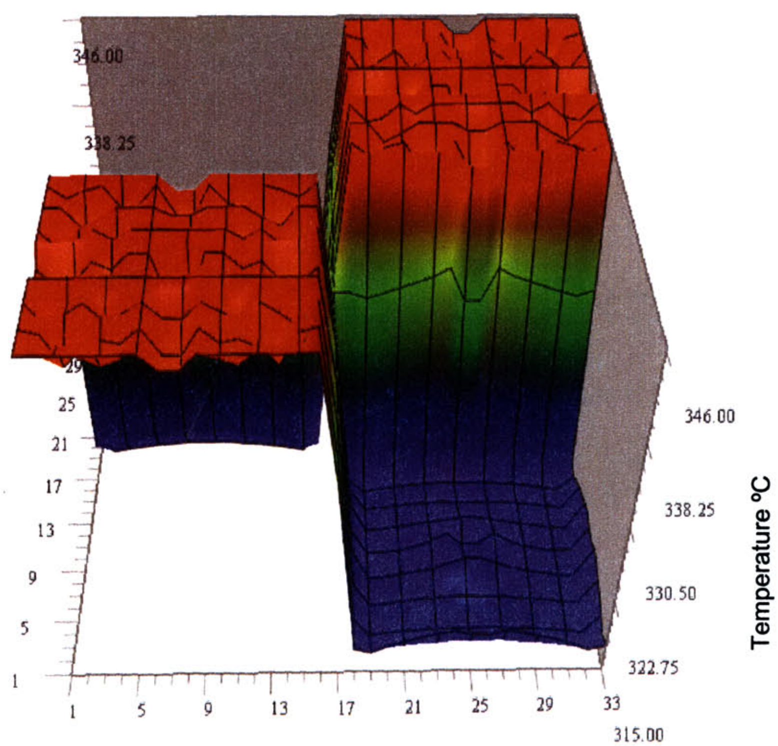


Figure 43 WSB-A four assemblies coolant exit temperature profile

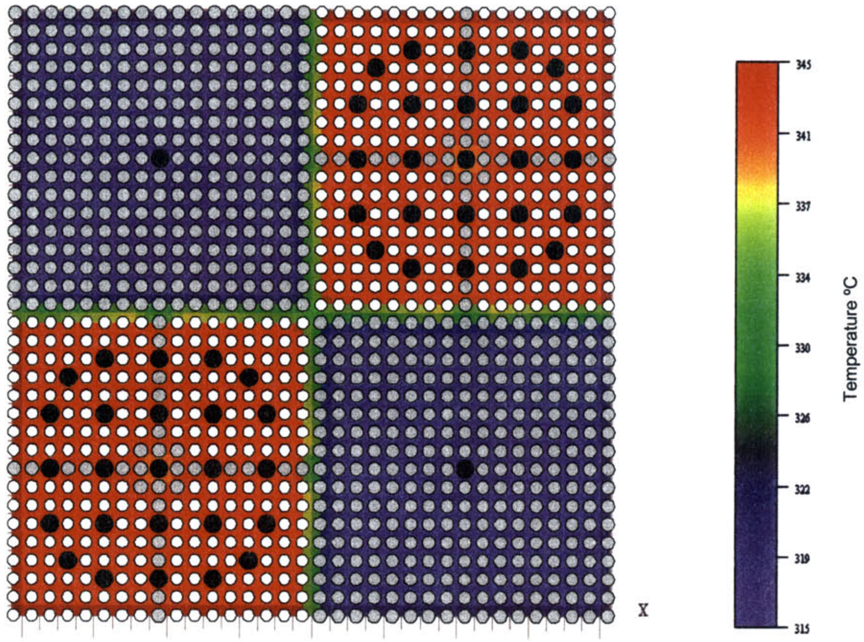


Figure 44 WSB-A coolant exit temperature distribution

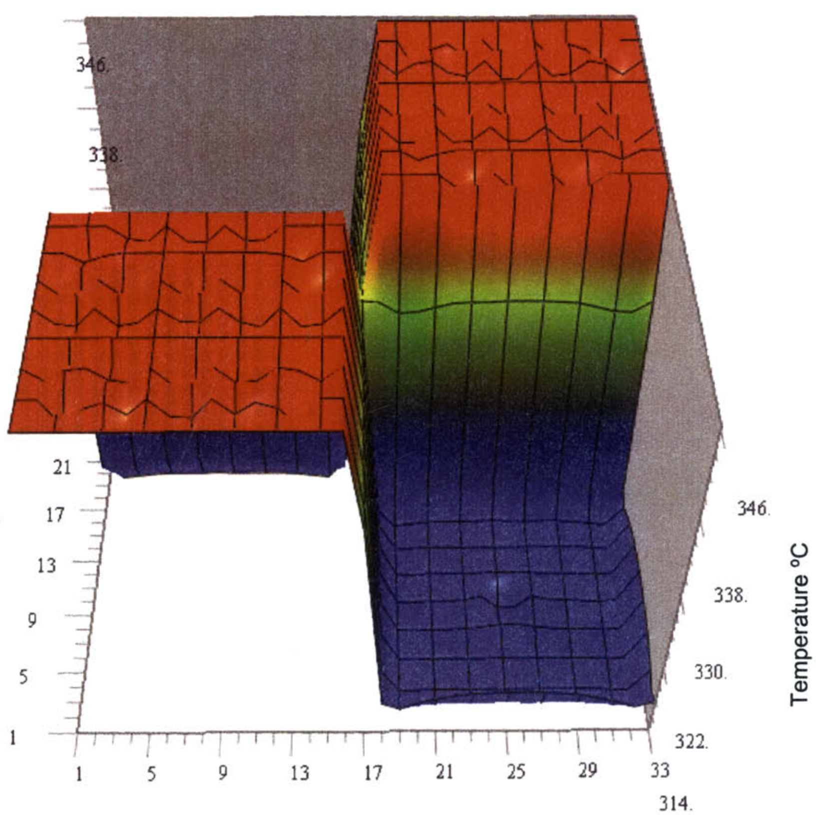


Figure 45 WSB-B four assemblies coolant exit temperature profile

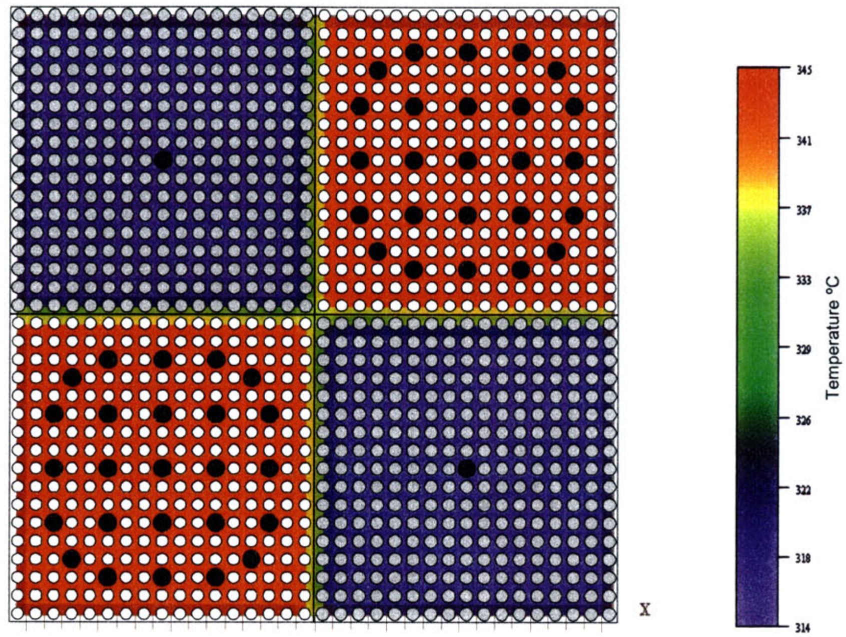


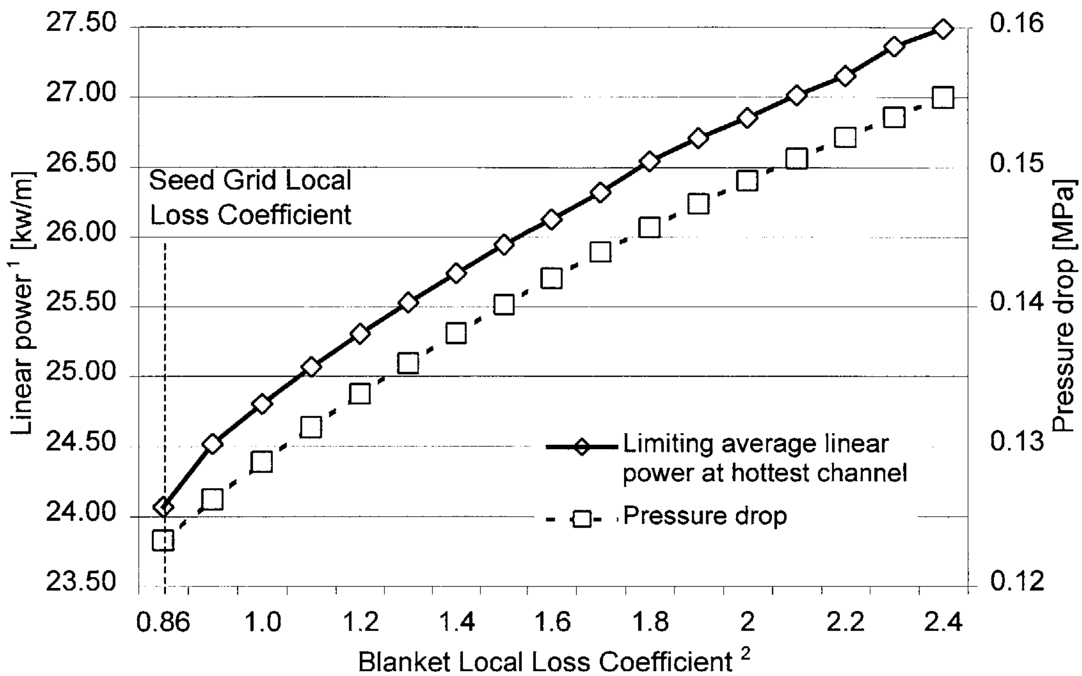
Figure 46 WSB-B coolant exit temperature distribution

4.5 WSB design optimization

The optimization approach for the WSB designs was done in a similar way to that of the SBU. Differential loss-coefficients for the two kinds of assemblies were analyzed because of the possibility to redirect coolant flow into the hot areas and the minimal impact on the fuel physics.

Coolant temperature and flow boundary conditions were kept constant in all cases, and the difference in pressure drop in the reactor core was assumed to be compensated by the reactor's pumps.

As in this design each seed or blanket area is composed of an entire assembly, the flow distribution was achieved by not only having different loss factors in 8 equally spaced grids but also by having different inlet orifice losses (inlet losses were modeled as a local loss at the beginning of the fuel). The effect of increasing the loss coefficient of the grids and at channel inlet in the blanket assemblies while keeping them constant in the seed for the WSB-A alternative is shown in Figure 47.



[1] Limiting average linear power constrained by MDNBR=1.3 and MOC power distribution

[2] 8 grids equally spaced in the assembly + inlet orifice

Figure 47Effect of different blanket local loss coefficient on limiting linear power and pressure drop for the WSB-A assembly

A similar result is found for the WSB-B version with higher loss-coefficient differences as the power distribution is more limiting in this case (see Figure 33 and Figure 42), and the hottest rod located in the seed region is closer to the blanket boundary.

In the WSB-A design the hottest rod in the seed assembly is located close to the center (see Figure 32 and Figure 43). The optimization provided by the incremental flow in the seed assembly, and consequently decrease in the blanket, has a direct impact on the achievable average linear power for the

WSB cluster and also on the pressure drop. For the range of loss coefficient studied, the most constrained rod (where the MDNBR was found for the cluster) was always located in the seed assembly. This result, as opposed to the SBU where for higher local losses in the blanket the critical rod changed from the seed to the blanket region, is not surprising because the distance between the seed and blanket hot rods in the WSB is nearly four times that in the SBU. This difference allows for higher coolant flow in the seed region without significant mix with the adjacent blanket.

The same type of flow redistribution optimization can be achieved by reducing the grids' loss factor in the seed region, with the further benefit of reduced pressure drop across the core. New grid designs can reach loss factors of approximately 0.6 [Ref. 18] (compared to the base design of 0.86). The use of this improved grid design in the seed region was also analyzed. In Table 6 the optimal values for each region loss coefficient for meeting the required power level (3400 MWth, with a 18% of overpower buffer and 1.3 MDNBR) is given for the two possible configurations.

From the results in Table 6 it is also clear to see that the WSB-B has a more demanding design from the thermal-hydraulics perspective, as the required differences in loss coefficient are higher than in the WSB-A case. This is the result of a higher power peak in the seed and a closer location of this hot rod to the blanket area.

Table 6 WSB differential loss coefficient optimization results

Design	Loss coefficient Grids Seed	Loss coefficient Grids Blanket	Loss coefficient Blanket Inlet	Pressure drop (3) [MPa]	Active rods per modeled assembly	Limiting power level for MDNBR (=1.3) (1) W-3L Correlation [kW/m]	Limiting power level for MDNBR (=1.3) (1) W-3L Correlation [MWth] (2)
WSB A	0.86	0.86	-	0.123	276	24.07	2,986
WSB-A optimized 1	0.86	2.35	2.35	0.154	276	27.43	3,403
WSB-A optimized 2	0.60	1.80	1.80	0.129	276	27.42	3,402
WSB-B	0.86	0.86	-	0.122	276	23.66	2,935
WSB-B optimized 1	0.86	3.35	3.35	0.167	276	27.44	3,404
WSB-B optimized 2	0.60	2.55	2.55	0.139	276	27.41	3,401

(1) Limit of average linear power on the hottest rod of the hot channel. Power distribution of MOC.

(2) 18% overpower for transients considered.

(3) Boundary condition: constant inlet effective mass flow of 17.7 Mg/sec

An important constraint for the WSB-B design can be the fuel temperature at the seed rods given their high power generation level and also because the type of fuel used. This last design variable is the main difference between the WSB A and B options. Its importance is given because the following reasons:

- UO_2 fuels have lower conductivity than metallic fuels (i.e. conductivity in the metallic seed rods was approximately 7 times the one in UO_2 rods)
- Metallic fuels can be co-extruded with the cladding, avoiding any gap between them. UO_2 is used in the form of pellets that are inserted in Zircaloy rods. The existing gap between the pellet and the cladding generates a significant increase in temperature in the fuel centerline.

The physical properties of UO_2 are nearly design independent. On the other hand, pellet design can be optimized in order to avoid high temperatures in the UO_2. In the WSB-B design this was done by leaving an empty hole in the pellet (to be filled by ZrO_2). This design allows the maximum contact area between fuel and gap/cladding and also avoids high temperatures by limiting the fuel radial depth.

A detail analysis for this design was done in order to assess its viability. The WSB-B optimized 2 was selected at the operating condition corresponding to a MDNBR=1.30. The temperature profiles for the hottest rods in the seed and in the blanket are shown in Figure 48 and Figure 49.

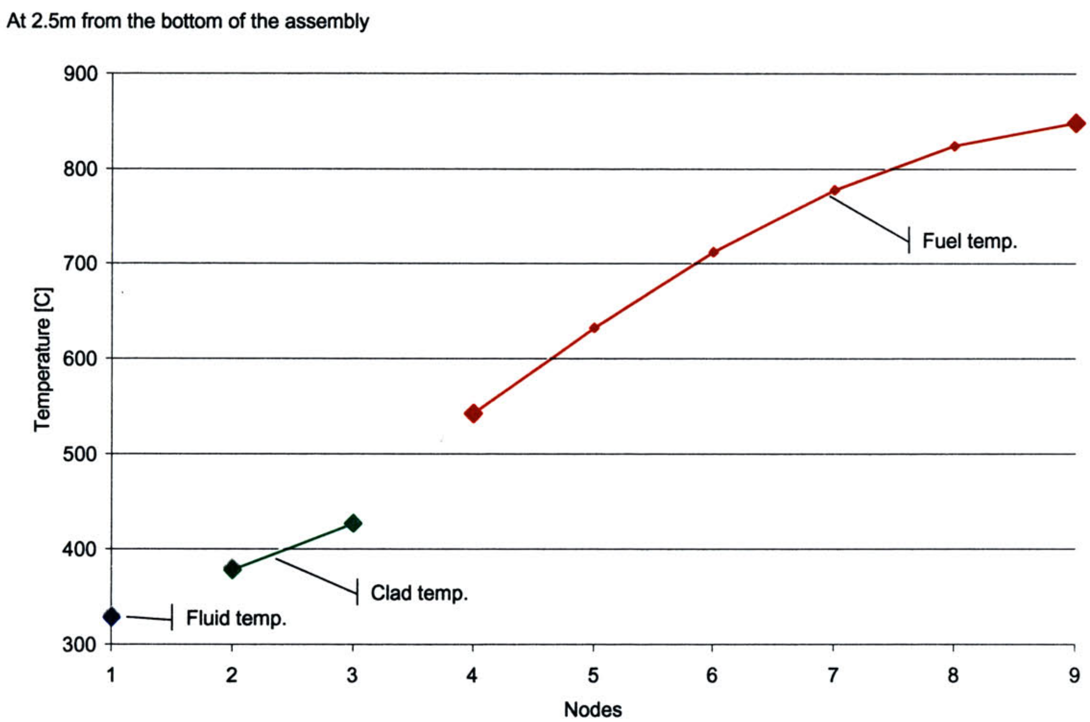


Figure 48 WSB-B temperature distribution at the hottest seed rod at an assembly average q'=27 kW/m

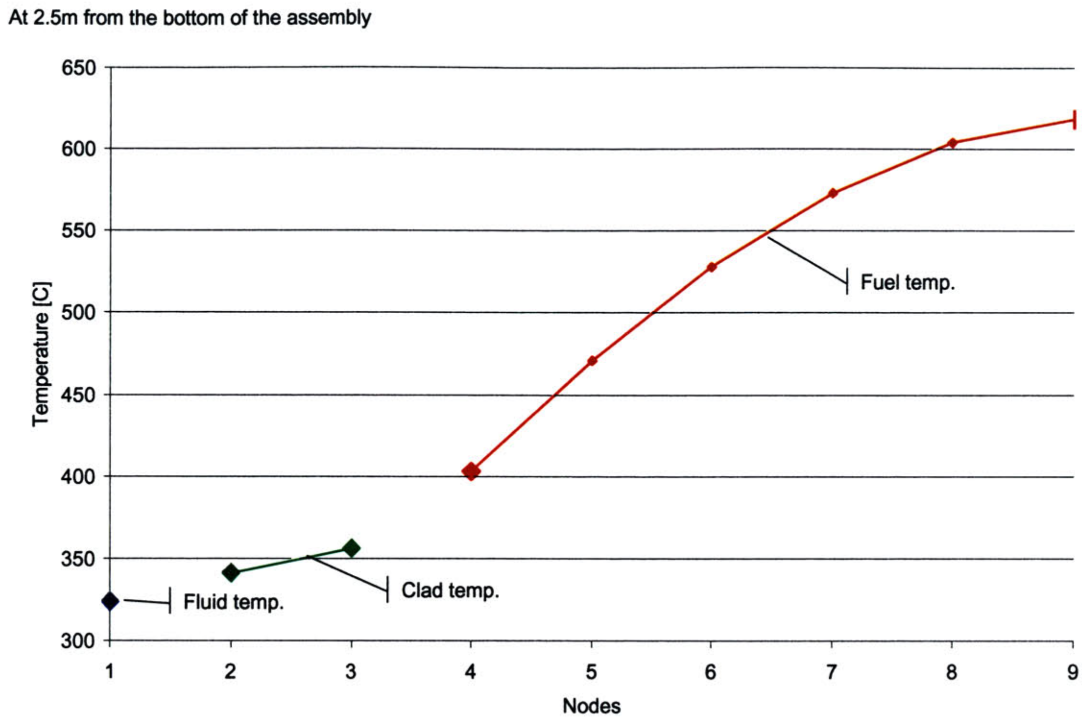


Figure 49 WSB-B temperature profile at the hottest blanket rod at an assembly average q'=27 kW/m

The nodes were located in fuel subregions of equal radial thickness, from the central void to the outside diameter.

The hottest point in the seed region (approximately at 850 °C) is safely below the UO_2 melting point (2,800 °C), leaving enough buffer to consider transients and possible flux inhomogeneities. These temperature profiles can be compared to a typical PWR UO_2 based fuel shown in Figure 64, Appendix B.

Exit temperatures for the original and optimized 2 WSB-B designs are compared in Figure 50 and Figure 51.

It is clear to see that the optimized coolant flow is increased in the seed region, allowing the required MDNBR, while the decrease in the coolant flow in the blanket region increases the exit temperature in those channels.

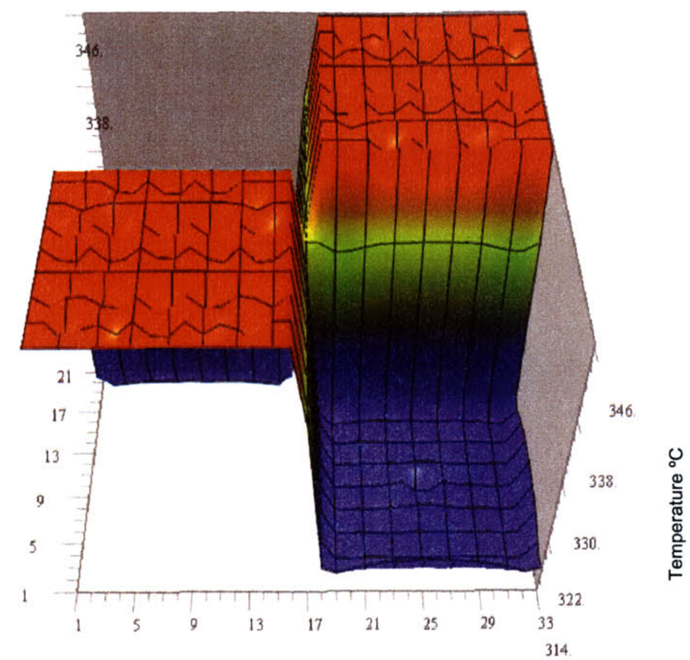


Figure 50 WSB-B base design exit temperature profile

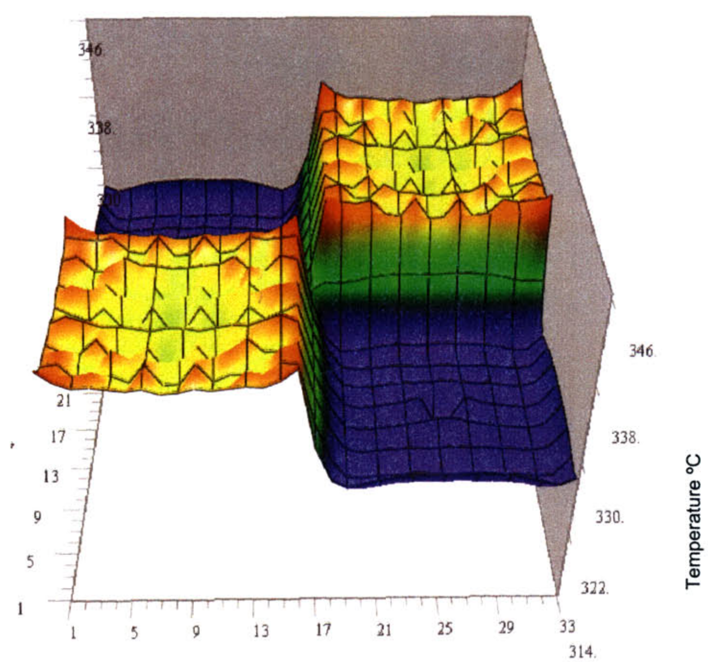


Figure 51 WSB-B optimized design exit temperature

Chapter 5

THORIUM-BASED FUEL THERMAL-HYDRAULICS : COMPARISON OF OPTIONS

The thermal-hydraulic analysis for both SBU and WSB fuel designs concluded in the recommendation of improving the performance by using different types of grids in the two regions of the fuel.

This optimization is to be implemented in the SBU design by using higher blanket loss coefficient grids along the whole assembly (8 equally spaced grids were considered in this study). As the fuel grids are responsible of the structural strength of the rods, the design of this new type of grids will be a challenging task mostly because of the need for detachable seed and blanket regions.

In the WSB approach, the advantage of having a whole assembly as a seed or blanket comes not only from a design perspective but also from an operational point of view. The design optimization relies on higher loss factor grids in the blanket (relative to the seeds') and in differential inlet loss coefficients also. As a result the total localized losses in the channel are at the inlet and in 8 grid equally spaced grid positions. The operational advantage of the WSB compared to the SBU will be discussed in Chapter 6 where the economics involved are assessed.

The thermal-hydraulics performance of the SBU and WSB base and optimized designs are compared in Table 7. In all calculations a MDNBR of 1.3 was taken for an 18% overpower condition.

Table 7 Thorium-Based Seed-Blanket fuel design comparison

Design	Loss coefficient			Pressure drop (3)	Active rods per modeled assembly	Limiting power level for MDNBR (=1.3) (1) W-3L Correlation		
	Grids		Blanket					
	Seed	Blanket	Inlet	[MPa]		[kW/m]	[MWth] (2)	
SBU (Global 99)	0.86	0.86	-	0.127	264	25.09	2,978	base
SBU optimized	0.86	1.30	-	0.145	264	26.36	3,128	5.1%
WSB A	0.86	0.86	-	0.123	276	24.07	2,986	0.3%
WSB-A optimized 1	0.86	2.35	2.35	0.154	276	27.43	3,403	14.3%
WSB-A optimized 2	0.60	1.80	1.80	0.129	276	27.42	3,402	14.3%
WSB-B	0.86	0.86	-	0.122	276	23.66	2,935	-1.4%
WSB-B optimized 1	0.86	3.35	3.35	0.167	276	27.44	3,404	14.3%
WSB-B optimized 2	0.60	2.55	2.55	0.139	276	27.41	3,401	14.2%

(1) Limit of average linear power on the hottest rod of the hot channel. Power distribution of MOC.
(2) 18% overpower for transients considered.
(3) Boundary condition: constant inlet effective mass flow of 17.7 Mg/sec

Chapter 6

ECONOMIC ANALYSIS

In this chapter, the analyzed thorium-based fuel designs are evaluated from an economic perspective. The economic competitiveness of thorium-based fuels is a key goal if this type of fuel is to be used in commercial reactors.

The methodology for the economic assessment of the new designs will be explained with their assumptions. The final comparison between the base U fuel cycle and the thorium-based cycles will show the cost drivers and possible advantages of these fuels under different market scenarios.

6.1 Analysis methodology and assumptions

The fuel cycle cost was divided into three groups: front end costs, operating costs and disposal costs.

6.1.1 Front end costs

In this part of the cycle four steps were considered: mining, conversion, enrichment and fabrication. Some of these steps are easily quantifiable as pricing information is available for current types of fuels. On the other hand, some estimates were used when new materials or fabrication processes are used.

A flow chart showing the different material flows for uranium in a PWR is given in Figure 52. For other materials or types of fuels a similar model was used based on mass and isotope flow conservation.

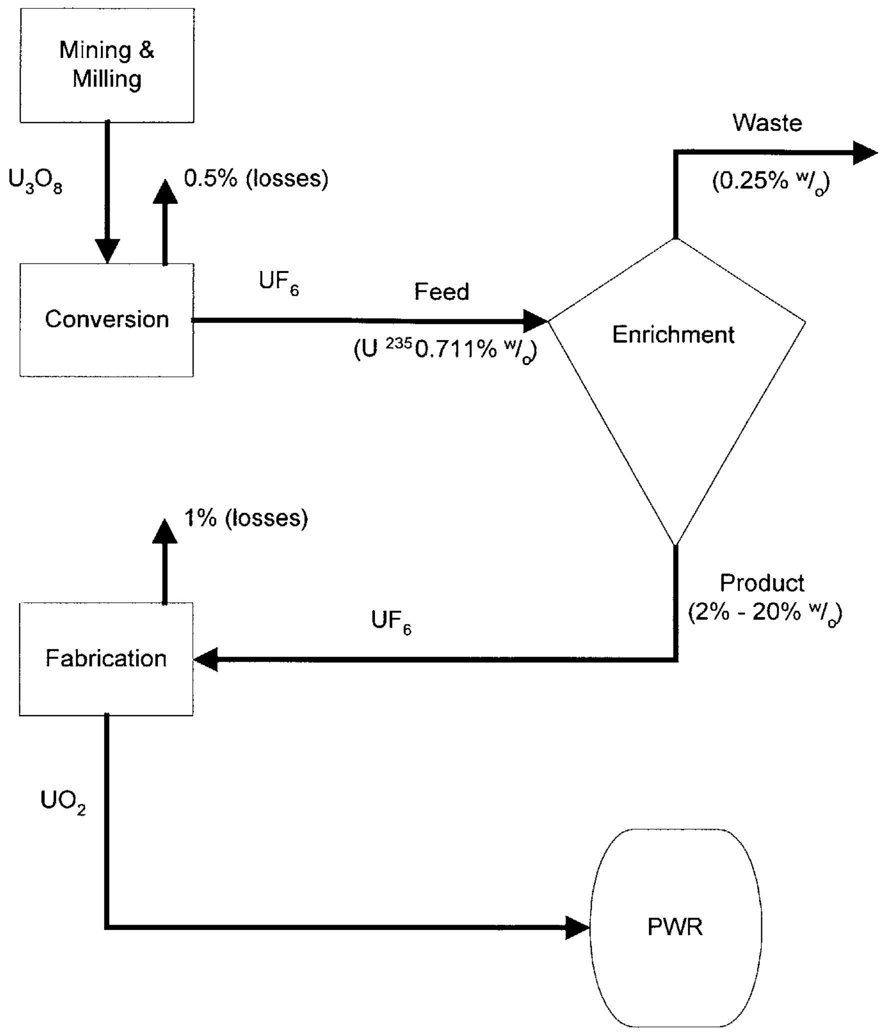


Figure 52 Front end fuel cycle fowchart

6.1.1.1 Mining

Uranium at natural isotopic concentration (0.711 % $^w/_o$) is the first cost to be incurred in the production process. U_3O_8 or "yellow cake" is delivered to the conversion (to UF_6) plant in sufficient amount to account for the required enriched final fuel $U0_2$ and all losses.

The cost was assumed to be proportional to the amount of natural uranium needed and equal to $50/kg [Ref. 19].

The cost for thorium was estimated to be $85/kg [Ref. 20], while for zirconium the estimated purchase price was $30/kg [Ref. 21].

6.1.1.2 Conversion

In the case of uranium, the conversion process ($U_3O_8 \rightarrow UF_6$) is needed in order to prepare for enrichment. The estimated price for conversion was $8/kg HM [Ref. 19].

For the other materials (Th and Zr) all preparatory costs are assumed to be included in the cost of fabrication.

6.1.1.3 Enrichment

This step is only associated with the uranium content of the fuel. The calculation is based on the Separative Work Units (SWU) required to enrich the uranium from the natural enrichment to the desired enrichment in the fuel at a specified enrichment in the waste or tails.

The tails' enrichment can also be optimized depending on the price of a SWU and the price of the raw material for the process (UF_6). The higher the price of the SWU compared to the raw material, the more preferable it is to increase the enrichment of the tails in order to minimize the total cost. The optimal value for tails enrichment for an enrichment cost of $110/SWU and a natural uranium plus conversion cost of $58/kg is approximately 0.28% $^{w}/_{o}$ (optimization of the whole cycle cost as a function of tails' enrichment).

If future prices of SWU decrease from the assumed $110/SWU, a decrease in the optimum tails enrichment would be appropriate.

It should be noted that transportation costs are assumed to be included in the cited prices for each process step. Transportation is licensed for current enrichment levels and may require special safety and licensing measures to be considered in the case of higher concentrations. A similar situation applies to the fabrication step, and shipment and storage at the reactor site.

6.1.1.4 Fabrication

Although this step is not the most expensive in the front end fuel costs it is the principal differentiator between all designs.

The production costs were divided into three categories:

1. Hardware costs: Including top/bottom nozzles and grids (measured in $/assembly).

2. Process cost: Fuel rod fabrication including Zircaloy, burnable poisons, pellet fabrication, final assembly and welding (measured in $/kg Heavy Metal).

3. QA, safety and administrative: Quality assurance, safety and administrative costs (measured in $/assembly).

Given the typical cost of current UO_2 fueled PWR assemblies (457 kg HM/assy. X 275 $/kg HM=$125,675), this cost was subdivided into a 20% for hardware (1), 70% for processing (2) and 10% for QA (3) [Ref. 22].

With these results, the final unit values are:

1. Hardware costs: $25,135 per assembly.

2. Process cost: $192.5 per kg HM.

3. QA, safety and administrative: $12,568 per assembly.

In the case of hardware costs, a 10% increase in price was taken for the SBU design ($27,649 per assembly) taking into consideration the additional cost of manufacturing two different, stand alone, regions for each fuel. This requirement comes from the fact that the blanket area is designed to be separated from their original seed in order to have an average residence time in the reactor of 10 years (compared to 3 years for a seed).

The processing cost was reduced to 80% of a typical UO_2 assembly for the seeds' metallic rods. This assumption is based on estimates that the process of co-extrusion of the uranium-zirconium fuel meat with the Zircaloy cladding will result in process savings 15.

For QA, safety and administrative cost, an additional 10% was considered for the SBU design based on the same reasons discussed for the hardware costs.

6.1.1.5 *Front end final product cost calculation*

All the front end cost were calculated based on the present value of all the expenses. Each step was discounted forward, in order to estimate the total fuel cost at the time of its use in the reactor.

For each step this in-service cost was evaluated as follow,

$$FC = C \cdot (1 + r_y)^{t_y}$$

where the future cost *FC* at the time of use of the fuel in the reactor, is the actual cost *C*, discounted forward at an annual discount rate r_y for a period of t_y years (time between actual expense and use of the fuel in the reactor). A graphical representation for this fuel front end cost calculation is shown in Figure 53.

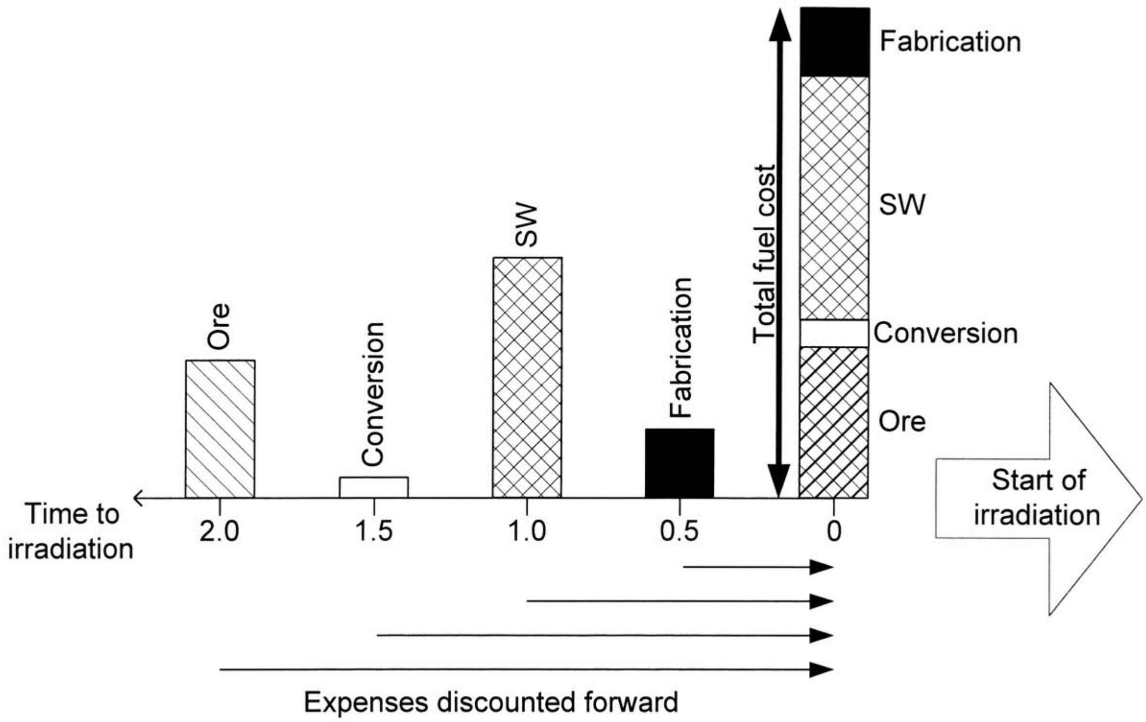


Figure 53 Fuel front–end cost calculation

This future cost was later annualized based on the residence time in the reactor. The annual cost was calculated based on:

$$A = FC \cdot \frac{r_y \cdot (1+r_y)^{t_{residence}}}{(1+r_y)^{t_{residence}} - 1}$$

where the annualized cost *A*, is calculated on the basis of the future cost *FC*, and an annual discount rate r_y, during a period of $t_{residence}$ years (time of residence of the fuel in the reactor core). This approach was chosen in order to simplify the calculations of different residence times as is the case of seed and blanket areas.

6.1.2 *Operational costs*

These costs were calculated based on an estimated cost per reactor refueling outage of $20M for the material and manpower used [Ref.19]. This cost was converted into an annualized cost using the following relation:

$$A = ROC \cdot \frac{r_y \cdot (1+r_y)^{t_{cycle}}}{(1+r_y)^{t_{cycle}} - 1}$$

where the annualized cost *A*, is calculated on the basis of the actual refueling outage cost *ROC*, an annual discount rate r_y, during a period of t_{cycle} years. As the economic analysis considered an assembly as the unit for comparison, this refueling cost was divided by the average number of fuel assemblies changed in each outage (196 assemblies/3 batchs). The t_{cycle} was taken as the in-core residence time for the fuel (typically 4.5 years for a 18 month cycle). Additionally, only seed regions were assumed responsible for paying the refueling cost, as their shorter residence time is constraining the cycle length.

The annual cost calculation for front end and operational costs is shown in Figure 54.

Additionally, the refueling downtime was taken into account in order to calculate the total amount of energy produced by the reactor during one year:

$$EE = P \cdot 24 \, {}^{hs}\!/_{day} \cdot 365 \, {}^{day}\!/_{year} \cdot Plant\,efficiency \cdot Availability \cdot \left(1 - \frac{ref.length}{Cycle\,length}\right)$$

where P is the nominal thermal power of the facility (different for each design and a function of the safety requirements discussed in Chapter 3, Chapter 4, and results of Chapter 5); plant efficiency is the thermodynamic efficiency of transforming thermal into electrical power (taken equal to 1150 MWe/3411 MWth=33.71%). Forced outages were taken into account in the availability

(100%-Forced outages rate=95%). The impact of refueling outages was calculated by subtracting its relative contribution from the total cycle length.

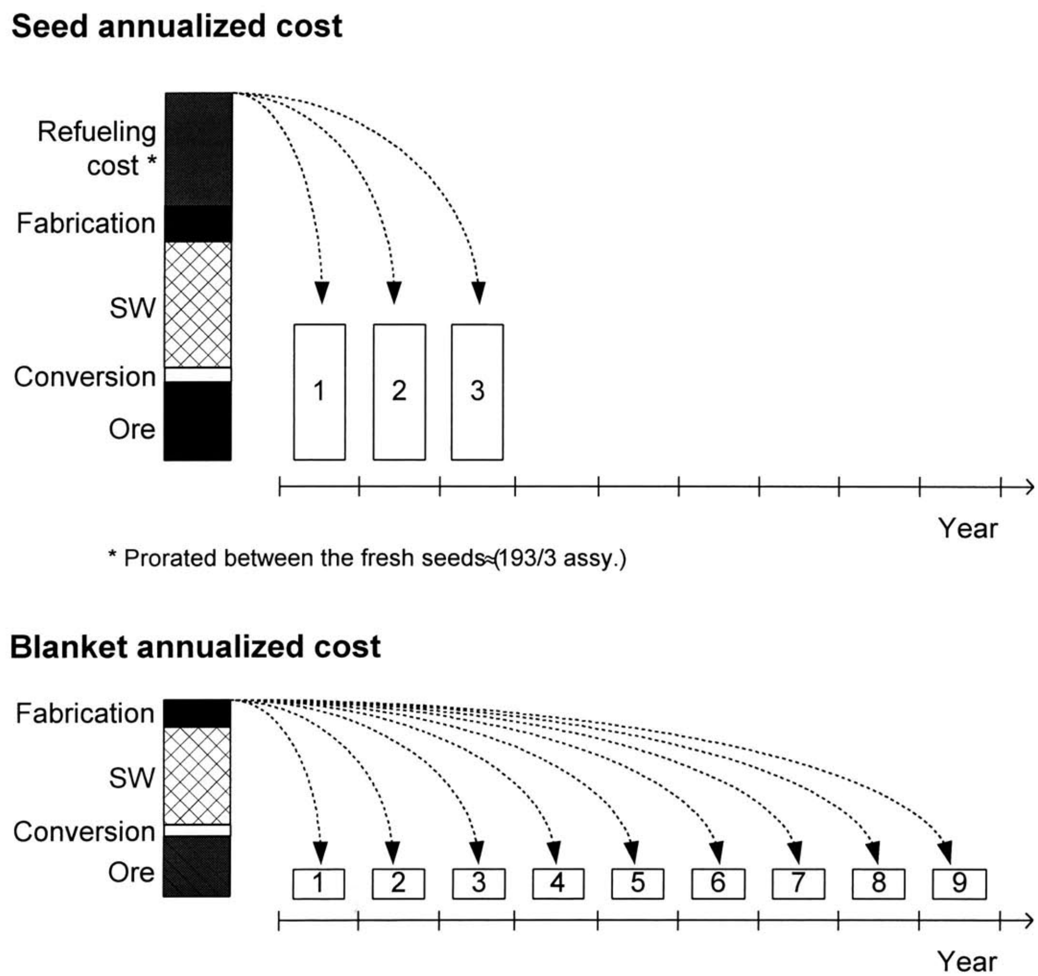


Figure 54 Annualized cost calculation for one cycle

6.1.3 Fuel disposal costs

One of the objectives of thorium-based fuels is the reduction of waste storage and disposal requirements [Ref. 15]. Current research efforts are focused on analyzing fuel material stability, long term radiotoxicity and potential proliferation reduction.

Although this advantage can be a very important factor in the decision to change to thorium-based fuels, it was not taken into account in the economic analysis. This conservative approach was chosen as no conclusive results and/or disposal policies are available at the time of the study.

The fuel disposal cost was assumed covered by the Federal waste disposal fee, equivalent to 1 Mills/kwhre. The same value was used for all fuel types, thus no economic advantage was taken into account for thorium-based fuels for the back end costs. On the other hand, the cost to utilities of storing the fuel onsite may in fact be reduced when spent fuel/kWhr is reduced at the high burnups reached with the aid of thorium

6.2 Economic design comparison

In Table 8 the economic comparison for each design is shown. For all alternatives an assembly is taken as the unit of analysis:

- All U: A 17x17 assembly based on UO_2 pellets

- SBU: A 17x17 assembly where hardware and QA costs were divided between seed and blanket proportionally to the number of rods (11 x 11 seed).

- WSB: A cluster of two quarters of a seed assembly and two quarters of a blanket assembly, as shown in Figure 34. In this case hardware and QA cost per assembly were evenly divided between seed and blanket.

Thorium-based fuels economic compariso

Fuel	Ore					Conversion				
	Enrich.	kg/assy.	Unit Cost $/kg	Total Cost $/assy.	LTI years	kg/assy. (feed)	kg/assy. (product	Unit Cost $/kg	Total Cost $/assy.	LTI years
All U										
U	0.71%	4,287	50	$214,356	2	4,287	4,266	8	$34,126	1.5
SBU										
Seed										
U	0.71%	2,422	50	$121,125	2	2,422	2,410	8	$19,283	1.5
Zr	1	68	30	$ 2,048	2	68	68	0	$ -	1.5
Blanket										
U	0.71%	895	50	$ 44,747	2	895	890	8	$ 7,124	1.5
Th	1	229	85	$ 19,492	2	229	228	0	$ -	1.5
		3,615		$187,412		3,615	3,597		$26,407	
WSB A										
Seed										
U	0.71%	2,961	50	$148,041	2	2,961	2,946	8	$23,568	1.5
Zr	1	83	30	$ 2,504	2	83	83	0	$ -	1.5
Blanket										
U	0.71%	826	50	$ 41,304	2	826	822	8	$ 6,576	1.5
Th	1	212	85	$ 17,993	2	212	211	0	$ -	1.5
		4,082		$209,841		4,082	4,062		$30,144	
WSB B										
Seed										
U	0.71%	3,771	50	$188,526	2	3,771	3,752	8	$30,013	1.5
Blanket										
U	0.71%	826	50	$ 41,304	2	826	822	8	$ 6,576	1.5
Th	1	212	85	$ 17,993	2	212	211	0	$ -	1.5
		4,808		$247,823		4,808	4,784		$36,589	

LTI: lead time to irradiation

Table 8 Thorium-based fuels economic comparison

Thorium-based fuels economic comparison

Fuel	Separative Work					Fabrication						
	Enrich.	SWU/assy	Unit Cos $/SWU	Total Cost $/assy.	LTI years	kg/assy. (feed)	kg/assy. (product)	Hardware Cost $/assy.	Process Cost $/kg	QA + safet $/assy.	Total Cost $/assy.	LTI years
All U												
U	4.51%	3181	110	$349,962	1	462	457	25,135	192.5	12,568	$125,675	0.5
SBU												
Seed												
U	20.00%	2339	110	$257,308	1	56	56		154.0		$ 8,578	0.5
Zr	1	0		$ -	1	68	67	11,576	154.0	5,788	$ 27,722	0.5
Blanket												
U	15.00%	839	110	$ 92,254	1	28	28		192.5		$ 5,304	0.5
Th	1	0		$ -	1	228	226	16,072	192.5	8,036	$ 67,593	0.5
				$349,563		380	376	27,649		13,824	$109,196	
WSB A												
Seed												
U	20.00%	2859	110	$314,487	1	69	68		154.0		$ 10,484	0.5
Zr	1	0		$ -	1	83	82	12,568	154.0	6,284	$ 31,511	0.5
Blanket												
U	15.00%	774	110	$ 85,156	1	26	25		192.5		$ 4,896	0.5
Th	1	0		$ -	1	211	209	12,568	192.5	6,284	$ 58,990	0.5
				$399,643		388	384	25,135		12,568	$105,881	
WSB B												
Seed												
U	20.00%	3641	110	$400,491	1	88	87	12,568	192.5	6,284	$ 35,540	0.5
Blanket												
U	15.00%	774	110	$ 85,156	1	26	25		192.5		$ 4,896	0.5
Th	1	0		$ -	1	211	209	12,568	192.5	6,284	$ 58,990	0.5
				$485,647		324	321	25,135		12,568	$ 99,426	

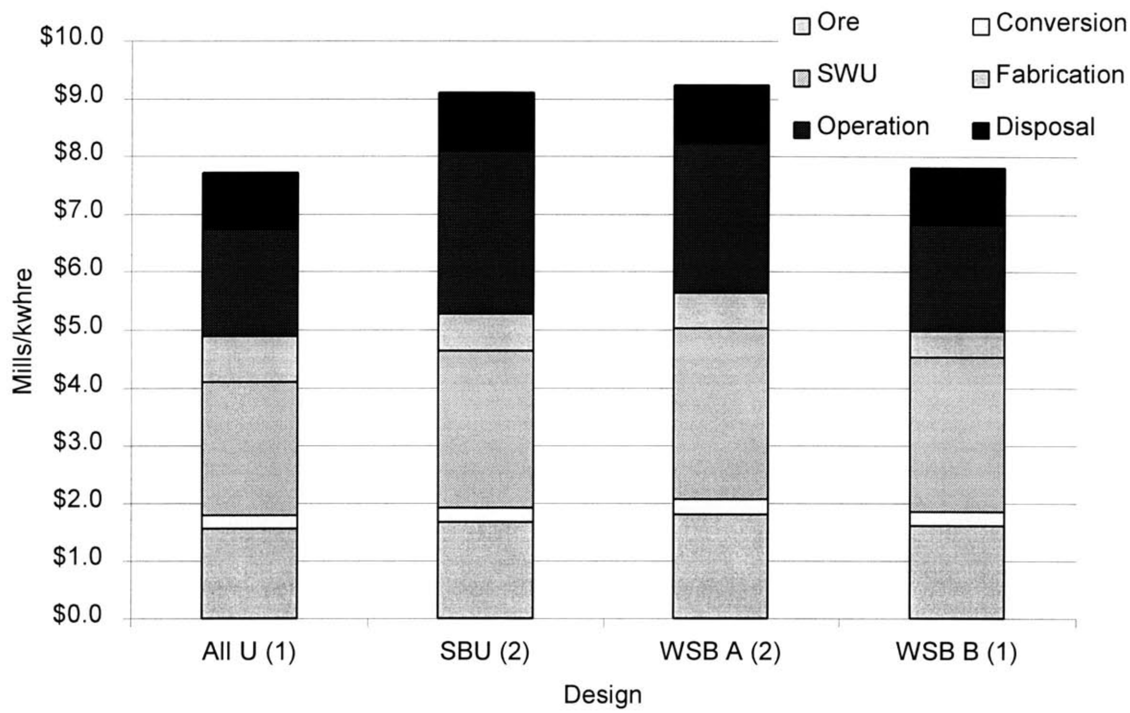
LTI: lead time to irradiation

Thorium-based fuels economic comparison

Fuel	Total cost per assembly	Max. Power MWth	**Total fuel cost Mills/kWhre**	Refueling Cost Millons	Refueling Length months	Cycle time years	Annual Cost	Oper. cost Mills/kWhre	Disposal fee Mills/kwhre	**Total cycle cost Mills/kWhre**
						Final Product				
All U										
U	$ 819,921	3400	**4.89**	$ 20 M	1.50	4.5	$322,859	6.72	1.00	**7.72**
SBU										
Seed										
U	$ 436,534	3128		$ 20 M	1.50	3	$311,355			
Zr	$ 31,637									
Blanket										
U	$ 160,709					10	$ 41,588			
Th	$ 94,831									
	$ 723,711		**4.98**				$352,943	8.10	1.00	**9.10**
WSB A										
Seed										
U	$ 533,539	3400		$ 20 M	1.50	3	$352,187			
Zr	$ 36,175									
Blanket										
U	$ 148,343					10	$ 37,806			
Th	$ 83,960									
	$ 802,017		**5.33**				$389,993	8.23	1.00	**9.23**
WSB B										
Seed										
U	$ 702,770	3400		$ 20 M	1.50	4.5	$289,270			
Blanket										
U	$ 148,343					10	$ 37,806			
Th	$ 83,960									
	$ 935,074		**4.98**				$327,076	6.81	1.00	**7.81**

LTI: lead time to irradiation

The contribution of each step of the fuel cycle for all alternative designs is shown in Figure 55. The most important components come from the enrichment process, ore and mining and operation. The last one is largely affected by the reduction of cycle length. Both designs based on a 12 month cycle suffer this disadvantage.



(1) 18 month cycle
(2) 12 month cycle

Figure 55 Contribution of each step of the fuel cycle to total cycle cost

6.3 Sensitivity analysis

The sensitivity of the total cycle cost to the change in some of the parameters was analyzed. The most important ones are the SWU price, the total fabrication price and the refueling outage length.

Prices of SWU are expected to fall in the long term; changes can reduce the case-to-case cost differentials. The total cost sensitivity to the SWU price is shown in Figure 56.

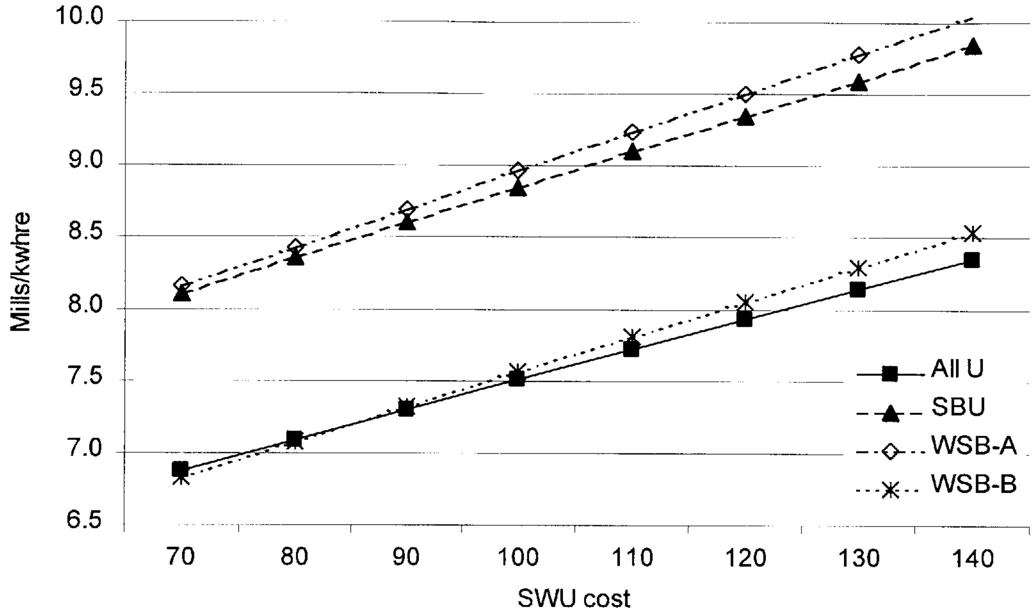


Figure 56 Total cycle cost sensitivity to SWU cost

The impact of fuel fabrication cost on the total cycle cost was also analyzed because a decline in its value has been observed during the past. The sensitivity analysis for this factor is shown in Figure 57. In this case the equivalent cost per kilogram of U HM was modified and all related production cost were changed proportionally.

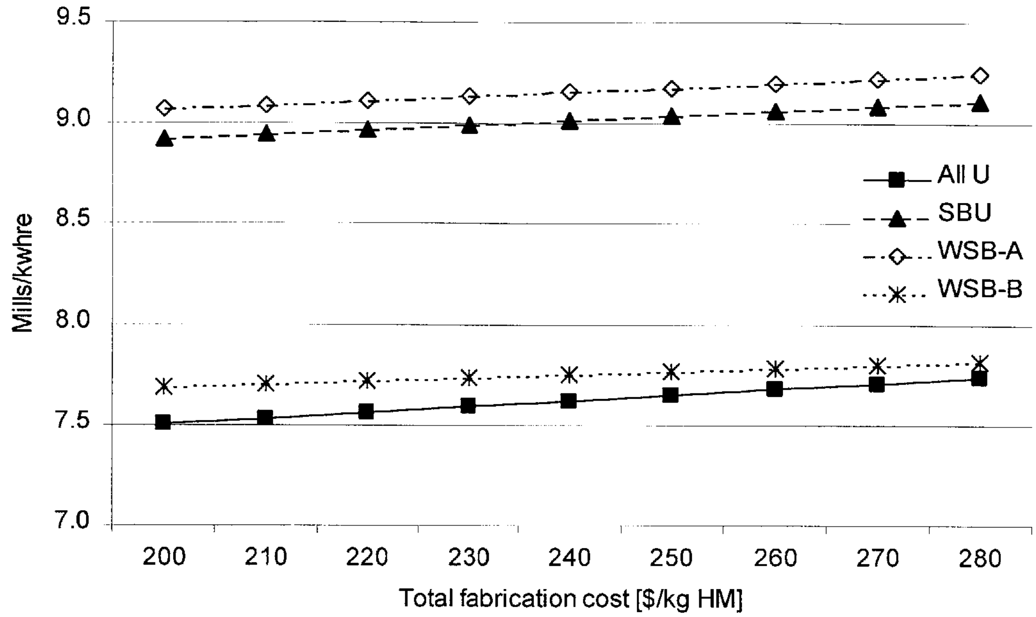


Figure 57 Total cycle cost sensitivity to total fabrication cost

The final variable analyzed was the refueling outage length. Although nowadays core refueling is not in the critical path of a refueling outage, some improvements in new designs may enable some reductions in the time involved in refueling. The impact of this period where the plant is not generating energy in the total cycle cost is shown in Figure 58.

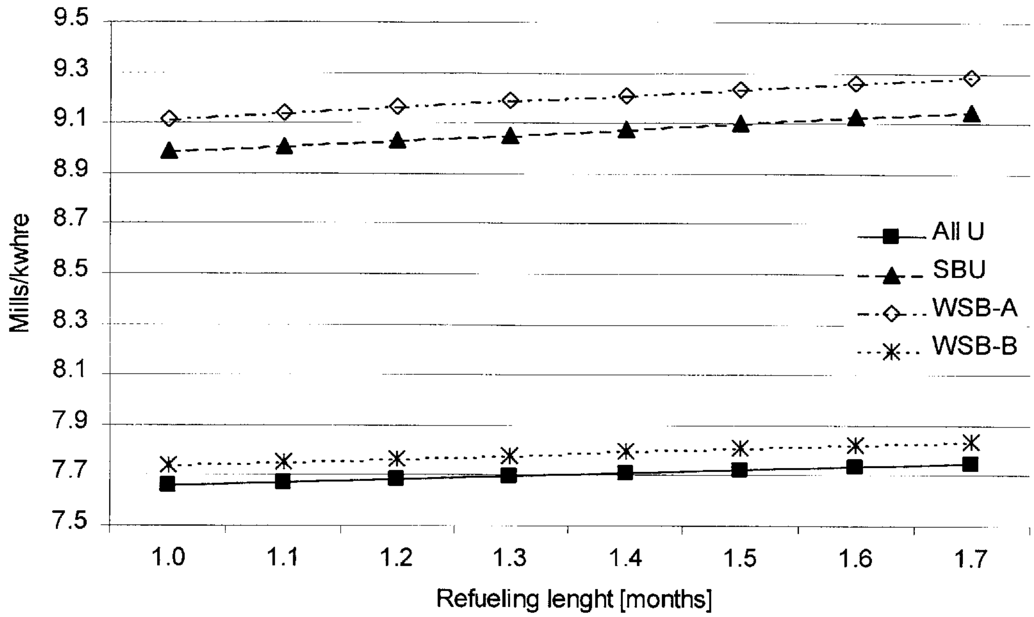


Figure 58 Total cycle cost sensitivity to refueling outage length

Chapter 7

CONCLUSION

As a result of this study several different thorium-based fuels were analyzed from their thermal-hydraulics and their economic performance. The main contribution is to clarify the best path to follow in future research on this type of fuel elements and to identify the key parameters that will enable future commercial use of these nuclear fuels.

7.1 Thermal-hydraulics results

The most important challenge for all of the analyzed designs was to deal with the difference in power generation between the seed and the blanket. The best solution to attack this problem was to use different grids' local loss coefficient in order to improve coolant flow in the seed region.

After this optimization, there is a limit on the allowable power generated in the assembly given by the pin peak location in each region. As the seed's and blanket's peaks are set further apart from each other the better this solution is. An example can be found in that the SBU design has a limiting average linear power in the hot assembly of 26.36 kW/m while the same metric in the WSB-B design can be increased to 27.41 kW/m.

The WSB approach is the most promising design because it separates the two regions enough to allow differential flow and heat transfer in different locations of the assembly.

It should be noted that this optimization comes at the expense of a higher pressure drop in the core. Thus, its feasibility should be assessed in case of implementation in PWRs.

Another important result from the thermal analysis is that there is no specific need for the use of metallic fuel in the seed region (other than potential economic savings). The annular pellet solution shows a good performance, with the additional advantage of being a very well known and benchmarked fabrication process, and that the fuel licensing is expected to be much shorter and simpler.

All results are based on SBU core power distribution [Ref. 15]. Peaking factors for other designs should be analyzed in detail in order to validate this assumption.

7.2 Economic results

As a result of an analysis of the fuel cycle cost, the most important drivers for fuel deployment form an economic perspective were identified.

Cycle length (12 vs. 18 months) is by far the most important objective to take into account for a design. The operational costs involved in each refueling outages are responsible for a very important part of the whole cycle cost.

A scenario where SWUs prices decline will enhance the SBU and WSB attractiveness compared to current fuels cycles. This is due to the fact that they both depend on 20% U enrichment which becomes less costly as the SWU become less expensive.

Important savings in metallic pin production can potentially improve seed blanket fuels but a trade-off between the use of this technology and safety and licensing problems should be assessed in detail.

Disposal and non-proliferation incentives were not taken into account in the economics. Potential benefits for the facilities from this point of view can become important factors the acceptance of the seed and blanket approach.

7.3 Future research

Future research in this area should be focused on having a detailed analysis of a whole core for the different designs. Axial and radial peaking factors are very important in order to assess fuel operating limitations under the safety requirements.

Detailed analysis of the boundary between the seed and blanket regions is also an area where some further investigation is needed. Mixed coefficients and fluid dynamics in these regions of high temperature and velocity gradients can bring some insights about fuel performance from a thermal perspective and also from a structural one.

The utilization of just one guide tube in blankets assemblies (WSB designs) should also be assessed from a structural point of view. Grid and spacers attachment to the fuel can be a constraint for it.

The utilization of new developed types of grids (with loss coefficients as low as 0.6) should be analyzed and tested in these types of designs.

Pump power and flow distribution within the core should also be assessed in the case of higher pressure drops.

Appendix A : ANNUALIZED COST CALCULATION

The annualized cost for front end and operational cost was calculated based on an annuity formula:

$$A = FC \cdot \frac{r_y \cdot (1+r_y)^{t_{residence}}}{(1+r_y)^{t_{residence}} - 1}$$

The residence time depends on the part of the fuel considered as seeds are more often replaced. A graphical representation of how annualized costs were calculated can be seen in Figure 54.

This type of calculation also applies to an entire cycle for a blanket assembly. The comparison is shown in Figure 59.

The *equal length analysis* assumes a total cycle length equal to the blanket residence time (*3L*). In this case the annualized cost for the three seeds (*S)* can be calculated as follows,

$$A_S = \left[S \cdot \left(1 + \frac{1}{(1+r_y)^L} + \frac{1}{(1+r_y)^{2L}} \right) \right] \cdot \frac{r_y \cdot (1+r_y)^{3L}}{(1+r_y)^{3L} - 1}$$

On the *year based analysis* used in the present study, just one period *L* is used to calculate the annual cost. The annual cost calculated by this approach is:

$$A_S = S \cdot \frac{r_y \cdot (1+r_y)^L}{(1+r_y)^L - 1}$$

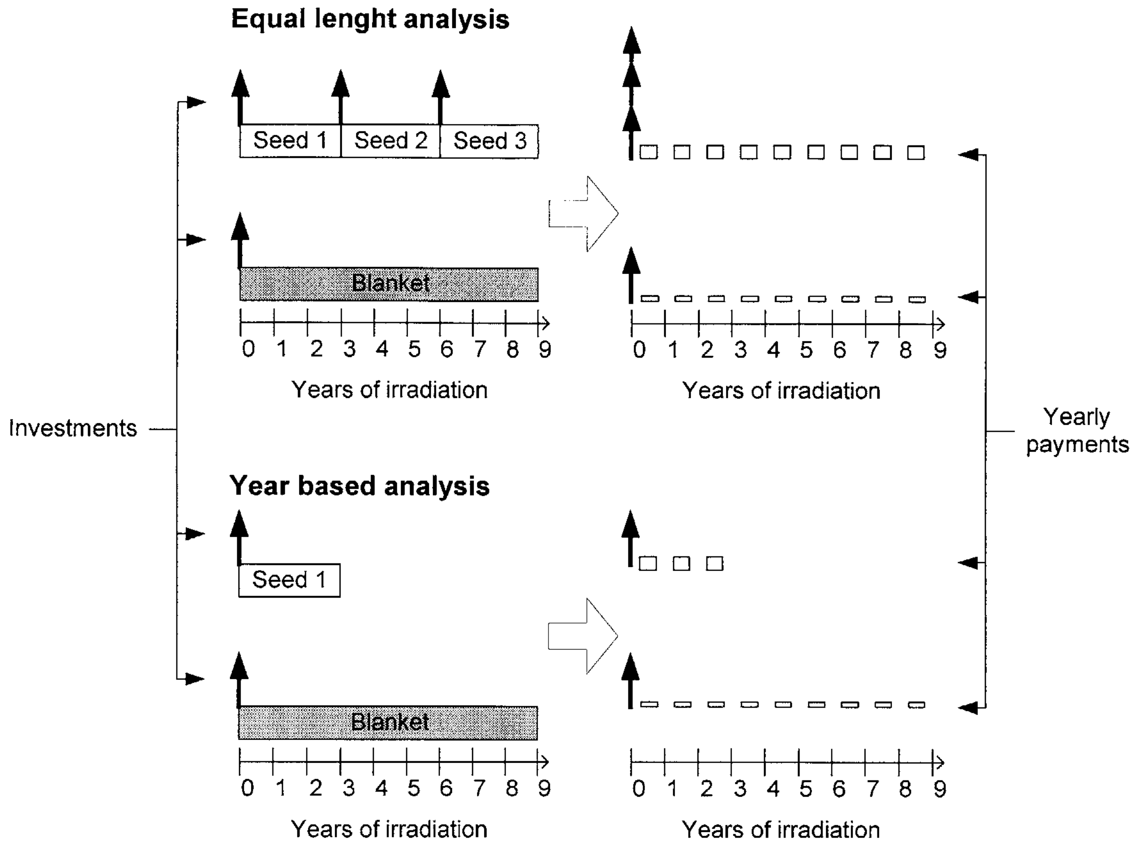


Figure 59 Different economic analysis approaches

Mathematical transformations of the above expressions shows that the two approaches are totally equivalent.

All the calculations are based on real values, and all results should be understood as evaluated at current prices. Additionally no credit is taken for possible price decrease due to improve technology, such as isotope separation methods or machines.

Appendix B : PWR BASE DESIGN ANALYSIS

A typical UO2 PWR fuel assembly was also modeled in VIPRE in order to compare all new designs characteristics with this type of fuel.

A 17 x 17 assembly (shown in Figure 8) was modeled based on subchannel analysis in a very similar way done for the other designs. Subchannel, rod and gaps identification assignments are shown in Figure 60, Figure 61 and Figure 62.

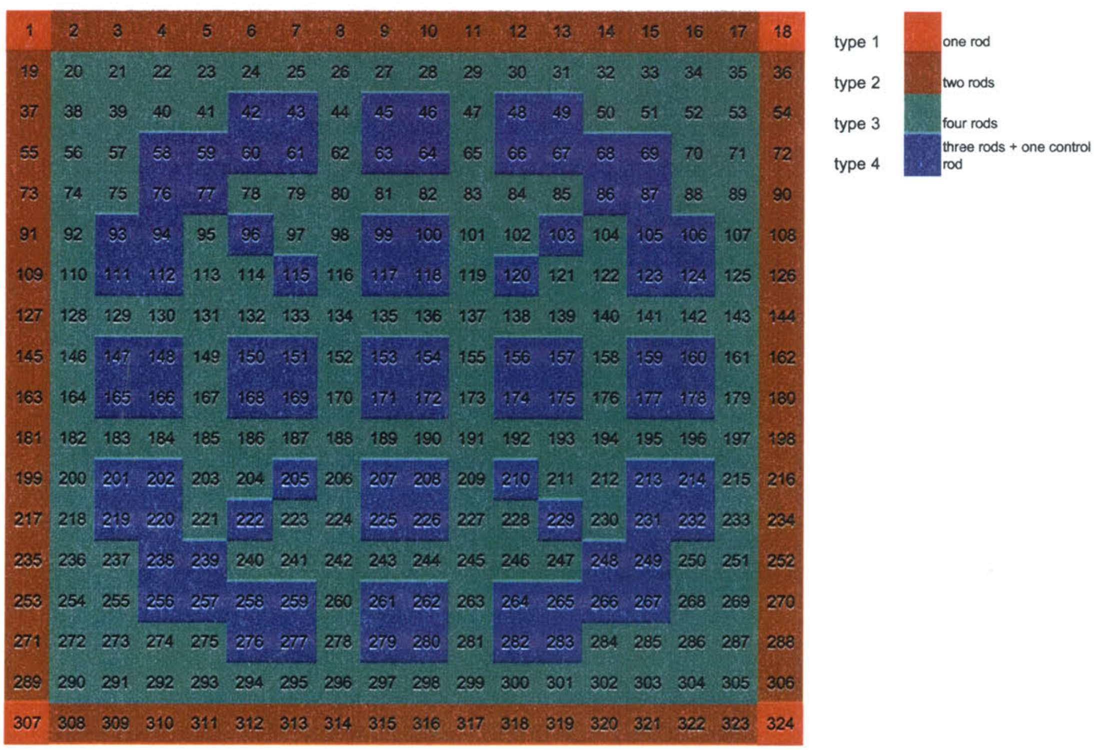


Figure 60 PWR assembly subchannel identification

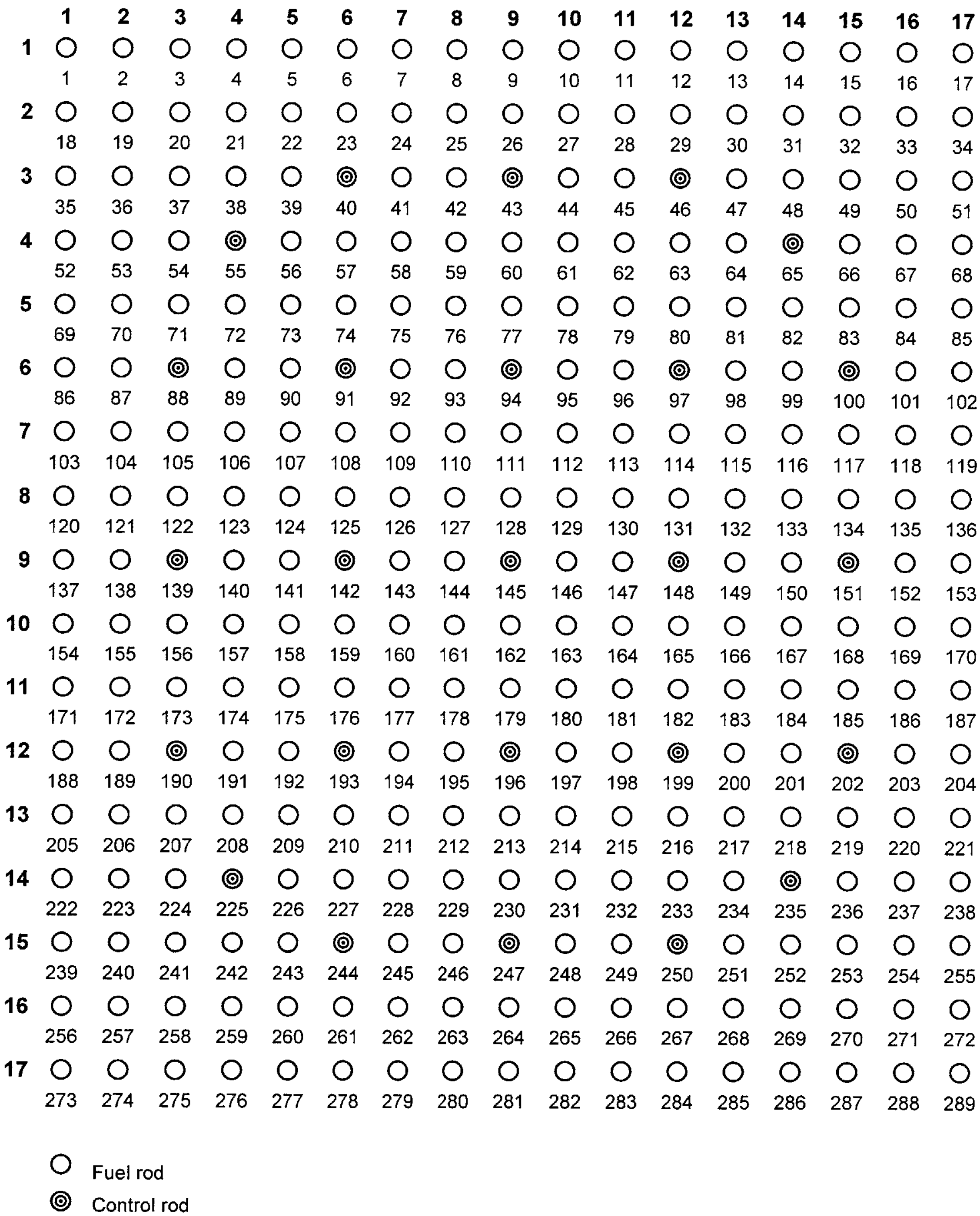


Figure 61 PWR assembly rod identification

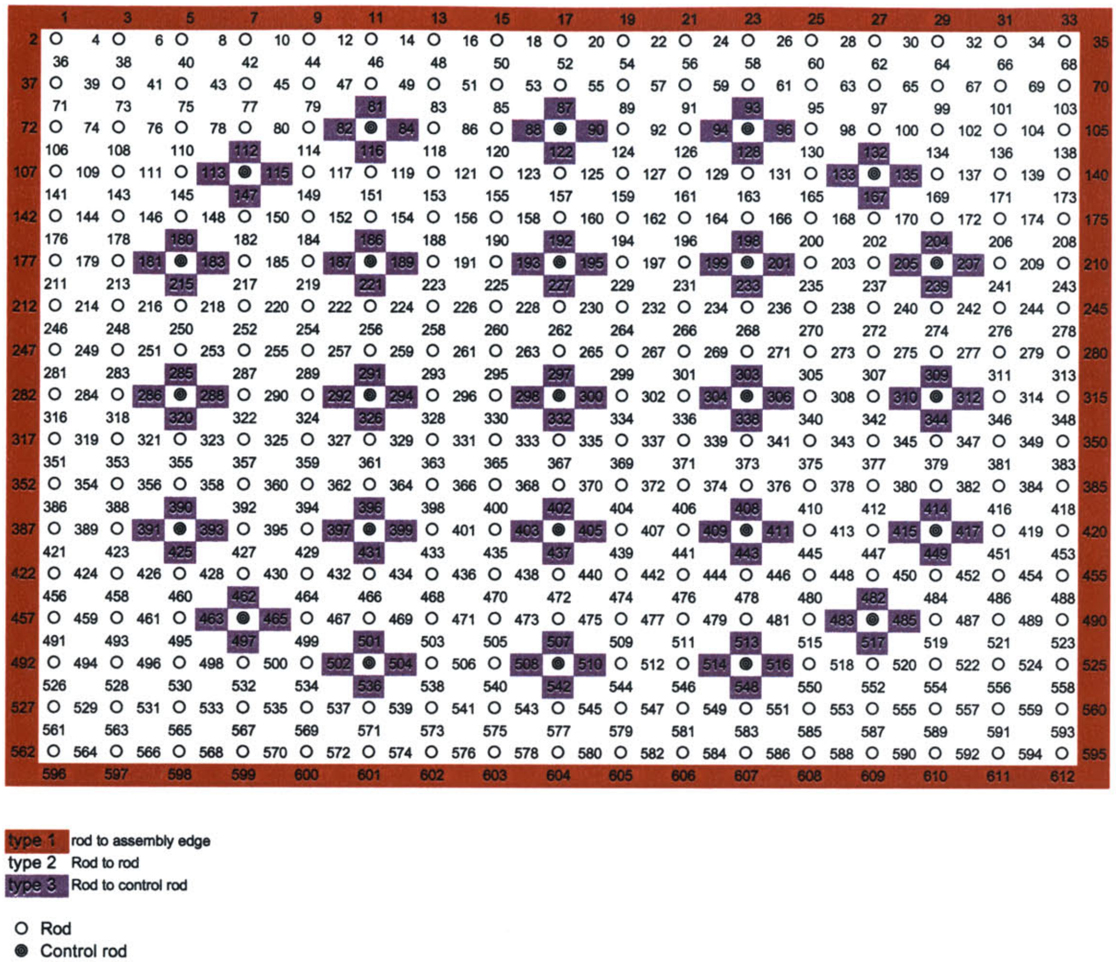


Figure 62 PWR assembly gap identification

Operating conditions for this assembly were taken also from Table 1. Additionally a 1.55 peak to average chopped-cosine axial power distribution was assumed [Ref. 23]. The peak to average radial assembly ratio was assumed equal to 1.587 [Ref. 23].

Figure 63 shows the relative pin power distribution used for this assembly.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.000	0.967	0.965	0.973	0.983	0.991	0.991	0.992	0.994	0.992	0.991	0.991	0.983	0.973	0.965	0.967	1.000
2	0.967	0.934	0.940	0.956	0.978	1.010	0.983	0.983	1.009	0.983	0.983	1.010	0.978	0.956	0.940	0.934	0.967
3	0.965	0.940	0.964	1.012	1.035	0.000	1.021	1.020	0.000	1.020	1.021	0.000	1.035	1.012	0.964	0.940	0.965
4	0.973	0.956	1.012	0.000	1.051	1.038	0.999	0.996	1.024	0.996	0.999	1.038	1.051	0.000	1.012	0.956	0.973
5	0.983	0.978	1.035	1.051	1.027	1.039	1.002	0.999	1.027	0.999	1.002	1.039	1.027	1.051	1.035	0.978	0.983
6	0.991	1.010	0.000	1.038	1.038	0.000	1.030	1.029	0.000	1.029	1.030	0.000	1.038	1.038	0.000	1.010	0.991
7	0.991	0.983	1.021	0.999	1.001	1.030	1.000	1.000	1.028	1.000	1.000	1.030	1.001	0.999	1.021	0.983	0.991
8	0.991	0.983	1.019	0.996	0.999	1.029	1.000	1.000	1.029	1.000	1.000	1.029	0.999	0.996	1.019	0.983	0.991
9	0.994	1.009	0.000	1.024	1.027	0.000	1.028	1.029	0.000	1.029	1.028	0.000	1.027	1.024	0.000	1.009	0.994
10	0.991	0.983	1.019	0.996	0.999	1.029	1.000	1.000	1.029	1.000	1.000	1.029	0.999	0.996	1.019	0.983	0.991
11	0.991	0.983	1.021	0.999	1.001	1.030	1.000	1.000	1.028	1.000	1.000	1.030	1.001	0.999	1.021	0.983	0.991
12	0.991	1.010	0.000	1.038	1.038	0.000	1.030	1.029	0.000	1.029	1.030	0.000	1.038	1.038	0.000	1.010	0.991
13	0.983	0.978	1.035	1.051	1.027	1.039	1.002	0.999	1.027	0.999	1.002	1.039	1.027	1.051	1.035	0.978	0.983
14	0.973	0.956	1.012	0.000	1.051	1.038	0.999	0.996	1.024	0.996	0.999	1.038	1.051	0.000	1.012	0.956	0.973
15	0.965	0.940	0.964	1.012	1.035	0.000	1.021	1.020	0.000	1.020	1.021	0.000	1.035	1.012	0.964	0.940	0.965
16	0.967	0.934	0.940	0.956	0.978	1.010	0.983	0.983	1.009	0.983	0.983	1.010	0.978	0.956	0.940	0.934	0.967
17	1.000	0.967	0.965	0.973	0.983	0.991	0.991	0.992	0.994	0.992	0.991	0.991	0.983	0.973	0.965	0.967	1.000

Figure 63 PWR assembly relative pin power distribution

The temperature profile for the hottest rod in the assembly, calculated based on a conduction model is shown in Figure 64. This profile can be taken as a base point in order to compare new UO_2 based fuel performance.

At 2.1m from the bottom of the assembly

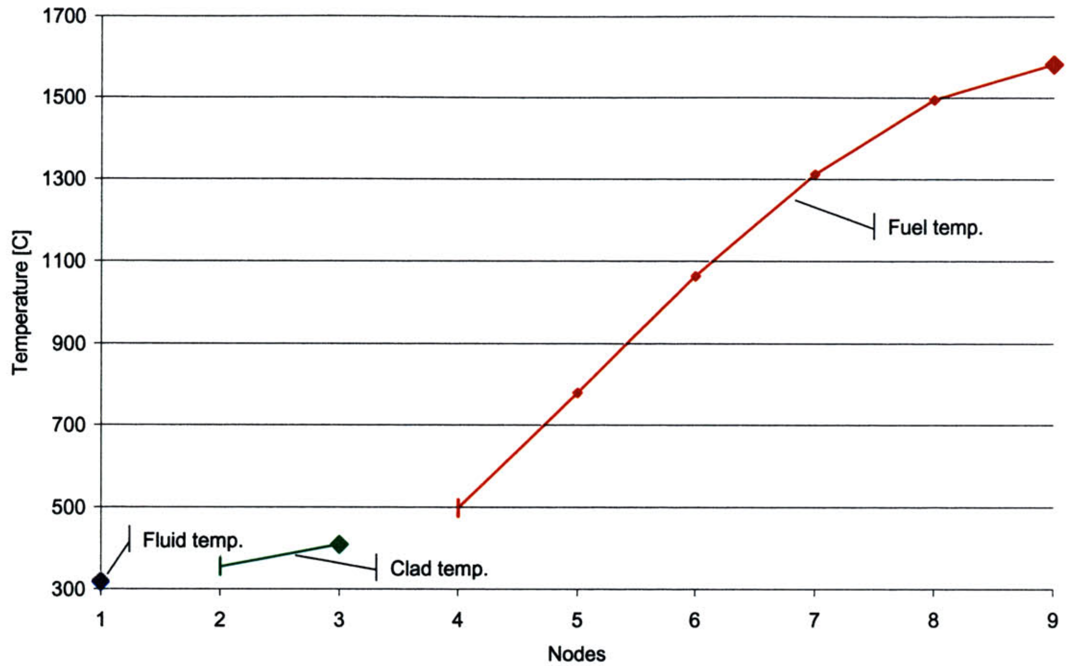


Figure 64 Radial temperature profile in the hottest rod of a PWR assembly

The VIPRE input file for the PWR assembly case follows.

```
                                         input card images

                     1         2         3         4         5         6         7         8
card        12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------------------

            * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            *                                                                   *
            *     vipre-01, PWR assembly input                      05/01/00    *
            *                                                                   *
            * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            1,0,0                                                            *vipre.1
            UO2 homogeneous assembly case( 17x17 )                           *vipre.2
            *
            *  assembly geometry = 17x17 rods
            *
            geom,324,4,16,0,4      *4 different compressed geometry input    *geom.1
            144.,?                                                           *geom.2
            0.,0.5          * default sl = 0.5                               *geom.2 (cont.)
            *     channel dimensions
            *     type I
            4,0.03404,0.2937,0.2937                                          *geom.5
            1,18,307,324                                                     *geom.6
            *     type II
            64,0.06808,0.5875,0.5875                                         *geom.5
            2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17                          *geom.6
            19,36,37,54,55,72,73,90,91,108,109,126,127,144,145,162           *geom.6
            163,180,181,198,199,216,217,234,235,252,253,270,271,288,289,306 *geom.6
            308,309,310,311,312,313,314,315,316,317,318,319,320,321,322,323 *geom.6
            *     type III
            164,0.13616,1.1750,1.1750                                        *geom.5
            20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35                  *geom.6
            38,39,40,41,44,47,50,51,52,53,56,57,62,65,70,71                  *geom.6
            74,75,78,79,80,81,82,83,84,85,88,89,92,95,97,98                  *geom.6
            101,102,104,107,110,113,114,116,119,121,122,125,128,129,130,131 *geom.6
            132,133,134,135,136,137,138,139,140,141,142,143,146,149,152,155 *geom.6
            158,161,164,167,170,173,176,179,182,183,184,185,186,187,188,189 *geom.6
            190,191,192,193,194,195,196,197,200,203,204,206,209,211,212,215 *geom.6
            218,221,223,224,227,228,230,233,236,237,240,241,242,243,244,245 *geom.6
            246,247,250,251,254,255,260,263,268,269,272,273,274,275,278,281 *geom.6
            284,285,286,287,290,291,292,293,294,295,296,297,298,299,300,301 *geom.6
            302,303,304,305                                                  *geom.6
            *     type IV
            92,0.11800,1.2598,0.8812                                         *geom.5
            42,43,45,46,48,49,58,59,60,61,63,64,66,67,68,69                  *geom.6
            76,77,86,87,93,94,96,99,100,103,105,106,111,112,115,117          *geom.6
            118,120,123,124,147,148,150,151,153,154,156,157,159,160,165,166 *geom.6
            168,169,171,172,174,175,177,178,201,202,205,207,208,210,213,214 *geom.6
            219,220,222,225,226,229,231,232,238,239,248,249,256,257,258,259 *geom.6
            261,262,264,265,266,267,276,277,279,280,282,283                  *geom.6
            * Gap input data
            612,3,0,18,0,0                                                   *geom.7
            *     gap type I
            68,0.061,0.496                                                   *geom.8
            1,2,3,5,7,9,11,13,15,17,19,21,23,25,27,29                        *geom.9
            31,33,35,37,70,72,105,107,140,142,175,177,210,212,245,247        *geom.9
            280,282,315,317,350,352,385,387,420,422,455,457,490,492,525,527 *geom.9
            560,562,595,596,597,598,599,600,601,602,603,604,605,606,607,608 *geom.9
            609,610,611,612                                                  *geom.9
            *     gap type II
            444,0.122,0.496                                                  *geom.8
```

```
4,6,8,10,12,14,16,18,20,22,24,26,28,30,32,34                             *geom.9
36,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52                          *geom.9
53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68                          *geom.9
69,71,73,74,75,76,77,78,79,80,83,85,86,89,91,92                          *geom.9
95,97,98,99,100,101,102,103,104,106,108,109,110,111,114,117              *geom.9
118,119,120,121,123,124,125,126,127,129,130,131,134,136,137,138 *geom.9
139,141,143,144,145,146,148,149,150,151,152,153,154,155,156,157 *geom.9
158,159,160,161,162,163,164,165,166,168,169,170,171,172,173,174 *geom.9
176,178,179,182,184,185,188,190,191,194,196,197,200,202,203,206 *geom.9
208,209,211,213,214,216,217,218,219,220,222,223,224,225,226,228 *geom.9
229,230,231,232,234,235,236,237,238,240,241,242,243,244,246,248 *geom.9
249,250,251,252,253,254,255,256,257,258,259,260,261,262,263,264 *geom.9
265,266,267,268,269,270,271,272,273,274,275,276,277,278,279,281 *geom.9
283,284,287,289,290,293,295,296,299,301,302,305,307,308,311,313 *geom.9
314,316,318,319,321,322,323,324,325,327,328,329,330,331,333,334 *geom.9
335,336,337,339,340,341,342,343,345,346,347,348,349,351,353,354 *geom.9
355,356,357,358,359,360,361,362,363,364,365,366,367,368,369,370 *geom.9
371,372,373,374,375,376,377,378,379,380,381,382,383,384,386,388 *geom.9
389,392,394,395,398,400,401,404,406,407,410,412,413,416,418,419 *geom.9
421,423,424,426,427,428,429,430,432,433,434,435,436,438,439,440 *geom.9
441,442,444,445,446,447,448,450,451,452,453,454,456,458,459,460 *geom.9
461,464,466,467,468,469,470,471,472,473,474,475,476,477,478,479 *geom.9
480,481,484,486,487,488,489,491,493,494,495,496,498,499,500,503 *geom.9
505,506,509,511,512,515,518,519,520,521,522,523,524,526,528,529 *geom.9
530,531,532,533,534,535,537,538,539,540,541,543,544,545,546,547 *geom.9
549,550,551,552,553,554,555,556,557,558,559,561,563,564,565,566 *geom.9
567,568,569,570,571,572,573,574,575,576,577,578,579,580,581,582 *geom.9
583,584,585,586,587,588,589,590,591,592,593,594                          *geom.9
*     gap type III
100,0.068,0.496                                                          *geom.8
81,82,84,87,88,90,93,94,96,112,113,115,116,122,128,132                   *geom.9
133,135,147,167,180,181,183,186,187,189,192,193,195,198,199,201 *geom.9
204,205,207,215,221,227,233,239,285,286,288,291,292,294,297,298 *geom.9
300,303,304,306,309,310,312,320,326,332,338,344,390,391,393,396 *geom.9
397,399,402,403,405,408,409,411,414,415,417,425,431,437,443,449 *geom.9
462,463,465,482,483,485,497,501,502,504,507,508,510,513,514,516 *geom.9
517,536,542,548                                                          *geom.9
18,36,54,72,90,108,126,144,162,180,198,216,234,252,270,288       *geom.10
306,324                                                                  *geom.10
*
prop,22,1,1,0      * create table from functions                         *prop.1
203.32,729.1,1800.                                                       *prop.3
*
drag,1,0,1                                                               *drag.1
.18,-.2,0.,64.,-1.,0. * axial friction correlation                       *drag.2
.5,.496   * pitch = .496, kij = .5l/p                                    *drag.5
*
grid,0,1                                                                 *grid.1
.86             *seed, blanket drag factors                              *grid.2
-1,8            *seed channels                                           *grid.4
16.0,1,32.0,1,48.0,1,64.0,1,80.0,1,96.0,1,? * grid loc.                  *grid.6
112.0,1,128.0,1,                                                         *grid.6
0,                                                                       *grid.4
*
corr,1,0,                                                                *corr.1
epri,epri,epri,none,                                                     *corr.2
0.2                                                                      *corr.3
ditb                                                                     *corr.6
w-3l                                                                     *corr.9
0.043,0.066,0.986                                                        *corr.11
*
oper,1,1,-1,0,0,1,0,                                                     *oper.1
* iterate to mdnbr=1.30, fcool=1.95, convergence=0.005
-1.0,1.3,1.95,0.005                                                      *oper.2
0                                                                        *oper.3
2248.1,552.2,202.186,8.825, * operat. cond. 1.587 radial peak            *oper.5
```

```
0                            * no forcing functions                 *oper.12
*
cont                                                                *cont.1
0.,0,20,0,0,1          * direct upflow solution                     *cont.2
0.,0.,0.01,0.05,0.01,0.8                                            *cont.3
0,3,5,3,2,0,1,1,0,0,0,1,1,0                                         *cont.6
1000.,0.,0.,0.,0.,0.,                                               *cont.7
60,153,230       * channels printed                                 *cont.8
115,122,183,483,507 * gaps printed                                  *cont.9
185,201,219
153,230          * dnb results printed                              *cont.11
*
*   rod layout - mixed dummy and conduction rods
*
rods,1,289,1,2,0,0,0,3,                                             *rods.1
*
0.0,0.0,0    * nodal power profile specification                    *rods.2
*
-1           * one entry for each of 16 nodes                       *rods.3
*
1.55 * peak to average peak ratio                                   *rods.5
* compressed rod layout for subchannel (17x17)
25,1,2,5                                                            *rods.19
40,43,46,55,65,88,91,94,97,100,139,142                              *rods.20
145,148,151,190,193,196,199,202,225,235,244,247                     *rods.20
250                                                                 *rods.20
0                                                                   *rods.22
0                                                                   *rods.25
1.000,0.967,0.965,0.973,0.983,0.991,0.991,0.992,0.994,0.992,?
0.991,0.991
0.983,0.973,0.965,0.967,1.000,0.967,0.934,0.940,0.956,0.978,?
1.010,0.983
0.983,1.009,0.983,0.983,1.010,0.978,0.956,0.940,0.934,0.967,?
0.965,0.940
0.964,1.012,1.035,0.000,1.021,1.020,0.000,1.020,1.021,0.000,?
1.035,1.012
0.964,0.940,0.965,0.973,0.956,1.012,0.000,1.051,1.038,0.999,?
0.996,1.024
0.996,0.999,1.038,1.051,0.000,1.012,0.956,0.973,0.983,0.978,?
1.035,1.051
1.027,1.039,1.002,0.999,1.027,0.999,1.002,1.039,1.027,1.051,?
1.035,0.978
0.983,0.991,1.010,0.000,1.038,1.038,0.000,1.030,1.029,0.000,?
1.029,1.030
0.000,1.038,1.038,0.000,1.010,0.991,0.991,0.983,1.021,0.999,?
1.001,1.030
1.000,1.000,1.028,1.000,1.000,1.030,1.001,0.999,1.021,0.983,?
0.991,0.991
0.983,1.019,0.996,0.999,1.029,1.000,1.000,1.029,1.000,1.000,?
1.029,0.999
0.996,1.019,0.983,0.991,0.994,1.009,0.000,1.024,1.027,0.000,?
1.028,1.029
0.000,1.029,1.028,0.000,1.027,1.024,0.000,1.009,0.994,0.991,?
0.983,1.019
0.996,0.999,1.029,1.000,1.000,1.029,1.000,1.000,1.029,0.999,?
0.996,1.019
0.983,0.991,0.991,0.983,1.021,0.999,1.001,1.030,1.000,1.000,?
1.028,1.000
1.000,1.030,1.001,0.999,1.021,0.983,0.991,0.991,1.010,0.000,?
1.038,1.038
0.000,1.030,1.029,0.000,1.029,1.030,0.000,1.038,1.038,0.000,?
1.010,0.991
0.983,0.978,1.035,1.051,1.027,1.039,1.002,0.999,1.027,0.999,?
1.002,1.039
1.027,1.051,1.035,0.978,0.983,0.973,0.956,1.012,0.000,1.051,?
1.038,0.999
```

```
0.996,1.024,0.996,0.999,1.038,1.051,0.000,1.012,0.956,0.973,?
0.965,0.940
0.964,1.012,1.035,0.000,1.021,1.020,0.000,1.020,1.021,0.000,?
1.035,1.012
0.964,0.940,0.965,0.967,0.934,0.940,0.956,0.978,1.010,0.983,?
0.983,1.009
0.983,0.983,1.010,0.978,0.956,0.940,0.934,0.967,1.000,0.967,?
0.965,0.973
0.983,0.991,0.991,0.992,0.994,0.992,0.991,0.991,0.983,0.973,?
0.965,0.967
1.000                                                             *rods.27
17,17,34,51,68,85,102,119,136,153,170,187                         *rods.28
204,221,238,255,272,289                                           *rods.28
1,nucl,0.374,0.3225,6,0.0,0.02244  *UO2 rods                      *rods.62
0,0,0,0,0,3500.0,1.0,0.01 * 3500 btu/hr-ft2-F                     *rods.63
2,dumy,0.482,0.0,0          *control rods                         *rods.68
endd
*
* end of input file
```

Appendix C : SBU INPUT FILE FOR VIPRE

A reference input file for the SBU design is shown below.

```
                              input card images

               1         2         3         4         5         6         7         8
card  12345678901234567890123456789012345678901234567890123456789012345678901234567890
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* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*                                                                   *
*     vipre-01, RTF assembly input                      10/01/99    *
*                                                                   *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
1,0,0                                                          *vipre.1
RTF homogeneous assembly case(11x11 seed 17x17 blanket)        *vipre.2
*
*  assembly geometry = 11 x 11 seed rods 17x17 blanket rods
*
geom,324,9,16,0,9      *9 different compressed geometry input   *geom.1
144.,?                                                         *geom.2
0.,0.5          * default sl = 0.5                             *geom.2 (cont.)
*     channel dimensions
*     type I
4,0.03404,0.2937,0.2937                                        *geom.5
1,18,307,324                                                   *geom.6
*     type II
64,0.06808,0.5875,0.5875                                       *geom.5
2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17                        *geom.6
19,36,37,54,55,72,73,90,91,108,109,126,127,144,145,162         *geom.6
163,180,181,198,199,216,217,234,235,252,253,270,271,288,289,306 *geom.6
308,309,310,311,312,313,314,315,316,317,318,319,320,321,322,323 *geom.6
*     type III
88,0.13616,1.1750,1.1750                                       *geom.5
20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35                *geom.6
38,39,40,41,44,47,50,51,52,53,56,57,70,71,74,75                *geom.6
88,89,92,107,110,125,128,129,142,143,146,161,164,179,182,183   *geom.6
196,197,200,215,218,233,236,237,250,251,254,255,268,269,272,273 *geom.6
274,275,278,281,284,285,286,287,290,291,292,293,294,295,296,297 *geom.6
298,299,300,301,302,303,304,305                                *geom.6
*     type IV
8,0.14811,1.1071,1.1071                                        *geom.5
62,65,130,141,184,195,260,263                                  *geom.6
*     type V
68,0.16006,1.0392,1.0392                                       *geom.5
78,79,80,81,82,83,84,85,95,97,98,101,102,104,113,114           *geom.6
116,119,121,122,131,132,133,134,135,136,137,138,139,140,149,152 *geom.6
155,158,167,170,173,176,185,186,187,188,189,190,191,192,193,194 *geom.6
203,204,206,209,211,212,221,223,224,227,228,230,240,241,242,243 *geom.6
244,245,246,247                                                *geom.6
*     type VI
8,0.123981,1.2258,0.8473                                       *geom.5
59,68,76,87,238,249,257,266                                    *geom.6
*     type VII
24,0.129959,1.1919,0.8134                                      *geom.5
60,61,63,64,66,67,94,105,112,123,148,159,166,177,202,213       *geom.6
220,231,258,259,261,262,264,265                                *geom.6
*     type VIII
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32,0.13594,1.1580,0.7794                                               *geom.5
77,86,96,99,100,103,115,117,118,120,150,151,153,154,156,157            *geom.6
168,169,171,172,174,175,205,207,208,210,222,225,226,229,239,248 *geom.6
*      type IX
28,0.11800,1.2598,0.8812                                               *geom.5
42,43,45,46,48,49,58,69,93,106,111,124,147,160,165,178                 *geom.6
201,214,219,232,256,267,276,277,279,280,282,283                        *geom.6
* Gap input data
612,6,0,18,0,0                                                         *geom.7
*      gap type I
68,0.061,0.496                                                         *geom.8
1,2,3,5,7,9,11,13,15,17,19,21,23,25,27,29                              *geom.9
31,33,35,37,70,72,105,107,140,142,175,177,210,212,245,247              *geom.9
280,282,315,317,350,352,385,387,420,422,455,457,490,492,525,527 *geom.9
560,562,595,596,597,598,599,600,601,602,603,604,605,606,607,608 *geom.9
609,610,611,612                                                        *geom.9
*      gap type II
244,0.122,0.496                                                        *geom.8
4,6,8,10,12,14,16,18,20,22,24,26,28,30,32,34                           *geom.9
36,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52                        *geom.9
53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68                        *geom.9
69,71,73,74,75,76,77,78,79,80,83,85,86,89,91,92                        *geom.9
95,97,98,99,100,101,102,103,104,106,108,109,110,111,134,136            *geom.9
137,138,139,141,143,144,145,146,169,171,172,173,174,176,178,179 *geom.9
206,208,209,211,213,214,216,241,242,243,244,246,248,249,250,251 *geom.9
274,276,277,278,279,281,283,284,311,313,314,316,318,319,321,346 *geom.9
347,348,349,351,353,354,355,356,379,381,382,383,384,386,388,389 *geom.9
416,418,419,421,423,424,426,451,452,453,454,456,458,459,460,461 *geom.9
484,486,487,488,489,491,493,494,495,496,498,500,506,512,518,519 *geom.9
520,521,522,523,524,526,528,529,530,531,532,533,534,535,537,538 *geom.9
539,540,541,543,544,545,546,547,549,550,551,552,553,554,555,556 *geom.9
557,558,559,561,563,564,565,566,567,568,569,570,571,572,573,574 *geom.9
575,576,577,578,579,580,581,582,583,584,585,586,587,588,589,590 *geom.9
591,592,593,594                                                        *geom.9
*      gap type III
44,0.068,0.496                                                         *geom.8
81,82,84,87,88,90,93,94,96,112,113,132,135,180,181,204                 *geom.9
207,215,239,285,286,309,312,320,344,390,391,414,417,425,449,463 *geom.9
485,497,502,504,508,510,514,516,517,536,542,548                        *geom.9
*      gap type IV
56,0.0896,0.496                                                        *geom.8
115,116,122,128,133,147,167,183,186,187,189,192,193,195,198,199 *geom.9
201,205,221,227,233,288,291,292,294,297,298,300,303,304,306,310 *geom.9
326,332,338,393,396,397,399,402,403,405,408,409,411,415,431,437 *geom.9
443,462,465,482,483,501,507,513                                        *geom.9
*      gap type V
176,0.1653,0.496                                                       *geom.8
117,119,121,123,125,127,129,131,149,150,151,152,153,154,155,156 *geom.9
157,158,159,160,161,162,163,164,165,166,168,182,184,185,188,190 *geom.9
191,194,196,197,200,202,203,217,219,220,222,223,224,225,226,228 *geom.9
229,230,231,232,234,235,236,237,238,252,254,255,256,257,258,259 *geom.9
260,261,262,263,264,265,266,267,268,269,270,271,272,273,287,289 *geom.9
290,293,295,296,299,301,302,305,307,308,322,324,325,327,328,329 *geom.9
330,331,333,334,335,336,337,339,340,341,342,343,357,359,360,361 *geom.9
362,363,364,365,366,367,368,369,370,371,372,373,374,375,376,377 *geom.9
378,392,394,395,398,400,401,404,406,407,410,412,413,427,429,430 *geom.9
432,433,434,435,436,438,439,440,441,442,444,445,446,447,448,464 *geom.9
466,467,468,469,470,471,472,473,474,475,476,477,478,479,480,481 *geom.9
*      gap type VI
24,0.1436,0.496                                                        *geom.8
114,118,120,124,126,130,148,170,218,240,253,275,323,345,358,380 *geom.9
428,450,499,503,505,509,511,515                                        *geom.9
18,36,54,72,90,108,126,144,162,180,198,216,234,252,270,288             *geom.10
306,324                                                                *geom.10
*
prop,22,1,1,0      * create table from functions                       *prop.1
```

```
203.32,729.1,1800.                                                *prop.3
*
drag,1,0,1                                                        *drag.1
.18,-.2,0.,64.,-1.,0. * axial friction correlation                *drag.2
.5,.496   * pitch = .496, kij = .51/p                             *drag.5
*
grid,0,2                                                          *grid.1
.86,.86         *seed, blanket drag factors                       *grid.2
100,8           *seed channels                                    *grid.4
77,78,79,80,81,82,83,84,85,86,95,96,97,98,99,100                  *grid.5
101,102,103,104,113,114,115,116,117,118,119,120,121,122,131,132 *grid.5
133,134,135,136,137,138,139,140,149,150,151,152,153,154,155,156 *grid.5
157,158,167,168,169,170,171,172,173,174,175,176,185,186,187,188 *grid.5
189,190,191,192,193,194,203,204,205,206,207,208,209,210,211,212 *grid.5
221,222,223,224,225,226,227,228,229,230,239,240,241,242,243,244 *grid.5
245,246,247,248                                                   *grid.5
16.0,1,32.0,1,48.0,1,64.0,1,80.0,1,96.0,1,? * grid loc.          *grid.6
112.0,1,128.0,1,                                                  *grid.6
224,8           *blanket channels                                 *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                   *grid.5
33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48                   *grid.5
49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64                   *grid.5
65,66,67,68,69,70,71,72,73,74,75,76,87,88,89,90                   *grid.5
91,92,93,94,105,106,107,108,109,110,111,112,123,124,125,126       *grid.5
127,128,129,130,141,142,143,144,145,146,147,148,159,160,161,162 *grid.5
163,164,165,166,177,178,179,180,181,182,183,184,195,196,197,198 *grid.5
199,200,201,202,213,214,215,216,217,218,219,220,231,232,233,234 *grid.5
235,236,237,238,249,250,251,252,253,254,255,256,257,258,259,260 *grid.5
261,262,263,264,265,266,267,268,269,270,271,272,273,274,275,276 *grid.5
277,278,279,280,281,282,283,284,285,286,287,288,289,290,291,292 *grid.5
293,294,295,296,297,298,299,300,301,302,303,304,305,306,307,308 *grid.5
309,310,311,312,313,314,315,316,317,318,319,320,321,322,323,324 *grid.5
16.0,2,32.0,2,48.0,2,64.0,2,80.0,2,96.0,2,? * grid loc.          *grid.6
112.0,2,128.0,2,                                                  *grid.6
0,                                                                *grid.4
*
corr,1,0,                                                         *corr.1
epri,epri,epri,none,                                              *corr.2
0.2                                                               *corr.3
ditb                                                              *corr.6
w-31                                                              *corr.9
0.043,0.066,0.986                                                 *corr.11
*
oper,1,1,-1,0,4,1,0,                                              *oper.1
* iterate to mdnbr=1.30, fcool=1.95, convergence=0.005
-1., 1.3, 1.95, 0                                                 *oper.2
0                                                                 *oper.3
2248.1,552.2,202.186,7.401,    * operating conditions MOC         *oper.5
0                           * no forcing functions                *oper.12
*
cont                                                              *cont.1
0.,0,20,0,0,1          * direct upflow solution                   *cont.2
0.,0.,0.01,0.05,0.01,0.8                                          *cont.3
0,3,5,3,2,0,1,1,0,0,0,1,1,0                                       *cont.6
1000.,0.,0.,0.,0.,0.,                                             *cont.7
60,153,230        * channels printed                              *cont.8
115,122,183,483,507 * gaps printed                                *cont.9
185,201,219
153,230           * dnb results printed                           *cont.11
*
*   rod layout - mixed dummy and conduction rods
*
rods,1,289,1,3,4,0,0,3,                                           *rods.1
*
0.0,0.0,1    * nodal power profile specification                  *rods.2
```

```
*
16          * one entry for each of 16 nodes                          *rods.3
*
0.45373,0.81156,1.05758,1.12688,1.13106,1.12223,1.12083,1.13245 *rods.6
1.15524,1.18175,1.19292,1.18175,1.13013,1.00409,0.73761,0.46019 *rods.6
* compressed rod layout for subchannel (17x17)
25,2,3,5                                                         *rods.19
40,43,46,55,65,88,91,94,97,100,139,142                           *rods.20
145,148,151,190,193,196,199,202,225,235,244,247                  *rods.20
250                                                              *rods.20
1                                                                *rods.22
1,108 *rods type 1 are seed 11x11                                *rods.23
56,57,58,59,60,61,62,63,64,72,73,74                              *rods.24
75,76,77,78,79,80,81,82,89,90,92,93                              *rods.24
95,96,98,99,106,107,108,109,110,111,112,113                      *rods.24
114,115,116,123,124,125,126,127,128,129,130,131                  *rods.24
132,133,140,141,143,144,146,147,149,150,157,158                  *rods.24
159,160,161,162,163,164,165,166,167,174,175,176                  *rods.24
177,178,179,180,181,182,183,184,191,192,194,195                  *rods.24
197,198,200,201,208,209,210,211,212,213,214,215                  *rods.24
216,217,218,226,227,228,229,230,231,232,233,234                  *rods.24
0,0         *end of rods.23 and rods.24                          *rods.24
0                                                                *rods.25
0.600,0.600,0.600,0.668,0.676,0.682,0.678,0.669,0.664,0.669,?
0.678,0.682
0.676,0.668,0.620,0.620,0.620,0.600,0.581,0.581,0.648,0.665,?
0.685,0.666
0.640,0.622,0.640,0.666,0.685,0.665,0.648,0.601,0.601,0.620,?
0.600,0.581
0.572,0.636,0.666,0.000,0.668,0.620,0.000,0.620,0.668,0.000,?
0.666,0.636
0.591,0.601,0.620,0.655,0.636,0.624,0.000,1.637,1.695,1.656,?
1.590,1.546
1.590,1.656,1.695,1.637,0.000,0.647,0.659,0.679,0.663,0.653,?
0.654,1.637
1.508,1.473,1.484,1.470,1.441,1.470,1.484,1.473,1.508,1.637,?
0.678,0.677
0.687,0.669,0.672,0.000,1.695,1.473,0.000,1.421,1.424,0.000,?
1.424,1.421
0.000,1.473,1.695,0.000,0.697,0.693,0.666,0.654,0.656,1.656,?
1.484,1.421
1.446,1.467,1.456,1.467,1.446,1.421,1.484,1.656,0.680,0.677,?
0.690,0.657
0.628,0.608,1.590,1.470,1.424,1.467,1.543,1.612,1.543,1.467,?
1.424,1.470
1.590,0.631,0.651,0.681,0.652,0.610,0.000,1.546,1.441,0.000,?
1.456,1.612
0.000,1.612,1.456,0.000,1.441,1.546,0.000,0.633,0.675,0.657,?
0.628,0.608
1.590,1.470,1.424,1.467,1.543,1.612,1.543,1.467,1.424,1.470,?
1.590,0.631
0.651,0.681,0.666,0.654,0.656,1.656,1.484,1.421,1.446,1.467,?
1.456,1.467
1.446,1.421,1.484,1.656,0.680,0.677,0.690,0.669,0.672,0.000,?
1.695,1.473
0.000,1.421,1.424,0.000,1.424,1.421,0.000,1.473,1.695,0.000,?
0.697,0.693
0.663,0.653,0.654,1.637,1.508,1.473,1.484,1.470,1.441,1.470,?
1.484,1.473
1.508,1.637,0.678,0.677,0.687,0.655,0.636,0.624,0.000,1.637,?
1.695,1.656
1.590,1.546,1.590,1.656,1.695,1.637,0.000,0.647,0.659,0.679,?
0.588,0.569
0.560,0.618,0.648,0.000,0.650,0.602,0.000,0.602,0.650,0.000,?
0.648,0.618
0.573,0.583,0.602,0.588,0.569,0.569,0.630,0.646,0.666,0.647,?
```

```
0.622,0.604
0.622,0.647,0.666,0.646,0.630,0.583,0.583,0.602,0.587,0.588,?
0.588,0.649
0.657,0.662,0.659,0.650,0.645,0.650,0.659,0.662,0.657,0.649,?
0.602,0.602
0.601                                                              *rods.27
17,17,34,51,68,85,102,119,136,153,170,187                          *rods.28
204,221,238,255,272,289                                            *rods.28
1,nucl,0.3307,0.30315,6,0.1575,0.013775  *seed rods                *rods.62
0,1,0,0,0,1000000.,1.,0.01 *No gap very high btu/hr-ft2-F          *rods.63
2,hrod,0.374,0.0,3          *bkt. rods 3 regions:fuel+gap+clad     *rods.68
6,2,0.161,0.99,1,3,0.0034,0.0,3,4,0.02244,0.01*blanket rods        *rods.69
3,dumy,0.482,0.0,0          *control rods                          *rods.68
1,25,1183.01,seed                                                  *rods.70
80.33,0.0642,13.1439,?
170.33,0.0642,13.1575
260.33,0.0642,13.1702,?
350.33,0.0642,13.182
440.33,0.0642,13.1928,?
530.33,0.0642,13.2027
620.33,0.0642,13.2117,?
710.33,0.0642,13.2197
800.33,0.0642,13.2267,?
890.33,0.0642,13.2329
980.33,0.0642,13.238,?
1070.33,0.0642,13.2423
1160.33,0.0642,13.2456,?
1250.33,0.0642,13.2479
1340.33,0.0642,13.2493,?
1430.33,0.0642,13.2498
1520.33,0.0642,13.2493,?
1610.33,0.0642,13.2479
1700.33,0.0642,13.2456,?
1790.33,0.0642,13.2423
1880.33,0.0642,13.238,?
1970.33,0.0642,13.2329
2060.33,0.0642,13.2267,?
2150.33,0.0642,13.2197
2240.33,0.0642,13.2117
2,25,638.256,blan                                                  *rods.70
80.33,0.0764,5.356,?
170.33,0.0764,4.902
260.33,0.0764,4.520,?
350.33,0.0764,4.192
440.33,0.0764,3.909,?
530.33,0.0764,3.662
620.33,0.0764,3.444,?
710.33,0.0764,3.251
800.33,0.0764,3.078,?
890.33,0.0764,2.923
980.33,0.0764,2.782,?
1070.33,0.0764,2.655
1160.33,0.0764,2.538,?
1250.33,0.0764,2.432
1340.33,0.0764,2.334,?
1430.33,0.0764,2.243
1520.33,0.0764,2.159,?
1610.33,0.0764,2.082
1700.33,0.0764,2.010,?
1790.33,0.0764,1.942
1880.33,0.0764,1.879,?
1970.33,0.0764,1.820
2060.33,0.0764,1.765,?
2150.33,0.0764,1.712
2240.33,0.0764,1.663
3,1,1.0,bgap                                                      *rods.70
```

```
1,100,6.8 *gap condty.=2000Btu/hr.ft2.F*0.0034 ft
4,13,409.0,bcld
80.33,0.0671,7.330,?
260.33,0.07212,8.1158
692.33,0.07904,9.8016,?
1502.33,0.08955,13.2923
1507.73,0.11988,13.3211,?
1543.73,0.14089,13.5166
1579.73,0.14686,13.7172,?
1615.73,0.1717,13.9231
1651.73,0.1949,14.1347,?
1687.73,0.18388,14.3519
1723.73,0.1478,14.5752,?
1759.73,0.112,14.8047
1786.73,0.085,14.9810
endd
*
* end of input file
```

Appendix D : WSB INPUT FILES FOR VIPRE

A reference input file for the WSB-A design follows.

```
                                   input card images

                   1         2         3         4         5         6         7         8
card      12345678901234567890123456789012345678901234567890123456789012345678901234567890
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          * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
          *                                                                   *
          *     vipre-01, Checkerboard array input Ver 3          03/10/00    *
          *                                                                   *
          * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
          1,0,0                                                         *vipre.1
          Checkerboard array case(1 assembly seed + 1 assembly blanket)   *vipre.2
          *
          *  assembly geometry = 11 x 11 seed rods 17x17 blanket rods
          *
          geom,289,8,16,0,8      *8 different compressed geometry input   *geom.1
          144.,?                                                        *geom.2
          0.,0.5          * default sl = 0.5                            *geom.2 (cont.)
          *     channel dimensions
          *     type I
          32,0.13445,1.1669,0.7884                                      *geom.5
          37,38,40,41,54,55,57,58,73,74,88,89,90,91,105,106             *geom.6
          184,185,199,200,201,202,216,217,232,233,235,236,249,250,252,253 *geom.6
          *     type II
          64,0.15809,1.1669,0.7884                                      *geom.5
          20,21,22,23,24,25,36,39,42,53,56,59,70,71,72,75               *geom.6
          76,87,92,93,104,107,108,109,110,121,122,123,124,125,126,127   *geom.6
          163,164,165,166,167,168,169,180,181,182,183,186,197,198,203,214 *geom.6
          215,218,219,220,231,234,237,248,251,254,265,266,267,268,269,270 *geom.6
          *     type III
          37,0.14712,1.1131,1.1131                                      *geom.5
          5,8,26,43,60,69,77,94,111,120,128,138,139,140,141,142         *geom.6
          143,144,145,146,147,148,149,150,151,152,162,170,179,196,213,221 *geom.6
          230,247,264,282,285                                           *geom.6
          *     type IV
          4,0.11801,1.2598,0.8812                                       *geom.5
          1,17,273,289                                                  *geom.6
          *     type V
          126,0.13616,1.1750,1.1750                                     *geom.5
          10,11,12,13,14,15,16,27,28,29,30,31,32,33,34,44               *geom.6
          45,46,47,48,49,50,51,61,62,63,64,65,66,67,68,78               *geom.6
          79,80,81,82,83,84,85,95,96,97,98,99,100,101,102,112           *geom.6
          113,114,115,116,117,118,119,129,130,131,132,133,134,135,136,154 *geom.6
          155,156,157,158,159,160,161,171,172,173,174,175,176,177,178,188 *geom.6
          189,190,191,192,193,194,195,205,206,207,208,209,210,211,212,222 *geom.6
          223,224,225,226,227,228,229,239,240,241,242,243,244,245,246,256 *geom.6
          257,258,259,260,261,262,263,274,275,276,277,278,279,280       *geom.6
          *     type VI
          2,0.15260,1.0821,1.0821                                       *geom.5
          19,271                                                        *geom.6
          *     type VII
          16,0.12897,1.1979,0.8193                                      *geom.5
          3,4,6,7,35,52,86,103,187,204,238,255,283,284,286,287          *geom.6
          *     type VIII
```

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8,0.14164,1.1440,1.1440                                                  *geom.5
2,9,18,137,153,272,281,288                                               *geom.6
* Gap input data
544,4,0,17,0,0                                                           *geom.7
*     gap type I
188,0.1614,0.496                                                         *geom.8
6,8,10,12,14,16,36,37,38,39,40,41,42,43,44,45                            *geom.9
46,47,48,49,67,69,70,73,75,76,79,81,82,100,102,103                       *geom.9
105,106,107,108,109,111,112,113,114,115,133,135,136,137,138,139 *geom.9
140,143,145,146,147,148,166,168,169,172,175,176,177,178,179,180 *geom.9
181,199,201,202,204,205,206,207,208,209,210,211,212,213,214,232 *geom.9
234,235,236,237,238,239,240,241,242,243,244,245,246,247,284,286 *geom.9
288,290,292,294,296,314,316,317,318,319,320,321,322,323,324,325 *geom.9
326,327,328,329,347,349,350,351,352,353,354,355,356,359,361,362 *geom.9
380,382,383,384,385,388,391,392,393,394,395,413,415,416,417,418 *geom.9
420,421,422,423,424,425,426,427,428,446,448,449,452,454,455,458 *geom.9
460,461,479,481,482,484,485,486,487,488,490,491,492,493,494,512 *geom.9
514,515,516,517,518,519,520,521,522,523,524,525                          *geom.9
*     gap type II
260,0.1220,0.496                                                         *geom.8
1,2,17,19,20,21,22,23,24,25,26,27,28,29,30,31                            *geom.9
32,33,50,52,53,54,55,56,57,58,59,60,61,62,63,64                          *geom.9
65,66,83,85,86,87,88,89,90,91,92,93,94,95,96,97                          *geom.9
98,99,116,118,119,120,121,122,123,124,125,126,127,128,129,130   *geom.9
131,132,149,151,152,153,154,155,156,157,158,159,160,161,162,163 *geom.9
164,165,182,184,185,186,187,188,189,190,191,192,193,194,195,196 *geom.9
197,198,215,217,218,219,220,221,222,223,224,225,226,227,228,229 *geom.9
230,231,248,250,251,252,253,254,255,256,257,258,259,260,261,262 *geom.9
263,264,266,268,270,272,274,276,278,280,298,299,300,301,302,303 *geom.9
304,305,306,307,308,309,310,311,312,313,331,332,333,334,335,336 *geom.9
337,338,339,340,341,342,343,344,345,346,364,365,366,367,368,369 *geom.9
370,371,372,373,374,375,376,377,378,379,397,398,399,400,401,402 *geom.9
403,404,405,406,407,408,409,410,411,412,430,431,432,433,434,435 *geom.9
436,437,438,439,440,441,442,443,444,445,463,464,465,466,467,468 *geom.9
469,470,471,472,473,474,475,476,477,478,496,497,498,499,500,501 *geom.9
502,503,504,505,506,507,508,509,510,511,528,529,530,531,532,533 *geom.9
534,535,536,544                                                          *geom.9
*     gap type III
40,0.0877,0.496                                                          *geom.8
5,11,68,71,72,74,77,78,80,104,110,141,142,144,167,170                    *geom.9
171,173,174,203,357,358,360,363,386,387,389,390,419,450,451,453 *geom.9
456,457,459,462,483,489,539,542                                          *geom.9
*     gap type IV
56,0.1417,0.496                                                          *geom.8
3,4,7,9,13,15,18,34,35,51,84,101,117,134,150,183                         *geom.9
200,216,233,249,265,267,269,271,273,275,277,279,281,282,283,285 *geom.9
287,289,291,293,295,297,315,330,348,381,396,414,429,447,480,495 *geom.9
513,526,527,537,538,540,541,543                                          *geom.9
*
17,34,51,68,85,102,119,136,153,170,187,204,221,238,255,272      *geom.10
289                                                                      *geom.10
*
prop,22,1,1,0      * create table from functions                         *prop.1
203.32,729.1,1800.                                                       *prop.3
*
drag,1,0,1                                                               *drag.1
.18,-.2,0.,64.,-1.,0. * axial friction correlation                       *drag.2
.5,.496   * pitch = .496, kij = .51/p                                    *drag.5
*
grid,0,2                                                                 *grid.1
.86,.86        * seed, blanket loss coef.                                *grid.2
161,8          * Seed and boundary channels                              *grid.4
1,2,3,4,5,6,7,8,9,18,19,20,21,22,23,24                                   *grid.5
25,26,35,36,37,38,39,40,41,42,43,52,53,54,55,56                          *grid.5
57,58,59,60,69,70,71,72,73,74,75,76,77,86,87,88                          *grid.5
89,90,91,92,93,94,103,104,105,106,107,108,109,110,111,120       *grid.5
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121,122,123,124,125,126,127,128,137,138,139,140,141,142,143,144 *grid.5
145,146,147,148,149,150,151,152,153,162,163,164,165,166,167,168 *grid.5
169,170,179,180,181,182,183,184,185,186,187,196,197,198,199,200 *grid.5
201,202,203,204,213,214,215,216,217,218,219,220,221,230,231,232 *grid.5
233,234,235,236,237,238,247,248,249,250,251,252,253,254,255,264 *grid.5
265,266,267,268,269,270,271,272,281,282,283,284,285,286,287,288 *grid.5
289                                                             *grid.5
16.0,1,32.0,1,48.0,1,64.0,1,80.0,1,96.0,1,? * grid loc.         *grid.6
112.0,1,128.0,1,                                                *grid.6
128,8        * Blanket channels                                 *grid.4
10,11,12,13,14,15,16,17,27,28,29,30,31,32,33,34                 *grid.5
44,45,46,47,48,49,50,51,61,62,63,64,65,66,67,68                 *grid.5
78,79,80,81,82,83,84,85,95,96,97,98,99,100,101,102              *grid.5
112,113,114,115,116,117,118,119,129,130,131,132,133,134,135,136 *grid.5
154,155,156,157,158,159,160,161,171,172,173,174,175,176,177,178 *grid.5
188,189,190,191,192,193,194,195,205,206,207,208,209,210,211,212 *grid.5
222,223,224,225,226,227,228,229,239,240,241,242,243,244,245,246 *grid.5
256,257,258,259,260,261,262,263,273,274,275,276,277,278,279,280 *grid.5
16.0,2,32.0,2,48.0,2,64.0,2,80.0,2,96.0,2,? * grid loc.         *grid.6
112.0,2,128.0,2,                                                *grid.6
0,                                                              *grid.4
*
corr,1,0,                                                       *corr.1
epri,epri,epri,none,                                            *corr.2
0.2                                                             *corr.3
ditb                                                            *corr.6
w-31                                                            *corr.9
0.043,0.066,0.986                                               *corr.11
*
oper,1,1,-1,0,0,1,0,                                            *oper.1
* iterate to mdnbr=1.00, fcool=1.95, convergence=0.005
-1., 1.3, 1.95, 0                                               *oper.2
0                                                               *oper.3
2248.1,552.2,202.186,7.079, * (7.401*264/276)op. cond. MOC      *oper.5
0                          * no forcing functions               *oper.12
*
cont                                                            *cont.1
0.,0,20,0,0,1          * direct upflow solution                 *cont.2
0.,0.,0.01,0.,0.,0.8                                            *cont.3
2,3,5,0,2,0,1,1,0,0,0,1                                         *cont.6
1000.,0.,0.,0.,0.,0.,                                           *cont.7
19,64,254      * channels printed                               *cont.8
51,150,271,291,480 * gaps printed                               *cont.9
64,254         * dnb results printed                            *cont.11
*
*   rod layout - mixed dummy and conduction rods
*
rods,1,324,0,3,0,0,0,0,0,0,0                                    *rods.1
*
0.0,0.0,1    * nodal power profile specification                *rods.2
*
16           * one entry for each of 16 nodes                   *rods.3
*
0.45373,0.81156,1.05758,1.12688,1.13106,1.12223,1.12083,1.13245 *rods.6
1.15524,1.18175,1.19292,1.18175,1.13013,1.00409,0.73761,0.46019 *rods.6
* normal rod layout for checkerboard
1,3,0.00000000,1,1,0.25
2,1,1.21700000,1,1,0.25,2,0.25
3,1,1.14500000,1,2,0.25,3,0.25
4,3,0.00000000,1,3,0.25,4,0.25
5,1,1.09100000,1,4,0.25,5,0.25
6,1,1.08100000,1,5,0.25,6,0.25
7,3,0.00000000,1,6,0.25,7,0.25
8,1,1.06300000,1,7,0.25,8,0.25
9,1,1.05800000,1,8,0.25,9,0.25
10,1,0.53400000,1,9,0.25,10,0.25
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11,1,0.54000000,1,10,0.25,11,0.25
12,1,0.55900000,1,11,0.25,12,0.25
13,1,0.55300000,1,12,0.25,13,0.25
14,1,0.55900000,1,13,0.25,14,0.25
15,1,0.58000000,1,14,0.25,15,0.25
16,1,0.58600000,1,15,0.25,16,0.25
17,1,0.62700000,1,16,0.25,17,0.25
18,3,0.00000000,1,17,0.25
19,1,1.21700000,1,1,0.25,18,0.25
20,1,1.10800000,1,1,0.25,2,0.25,18,0.25,19,0.25
21,2,1.66400000,1,2,0.25,3,0.25,19,0.25,20,0.25
22,2,1.64000000,1,3,0.25,4,0.25,20,0.25,21,0.25
23,2,1.57800000,1,4,0.25,5,0.25,21,0.25,22,0.25
24,2,1.56600000,1,5,0.25,6,0.25,22,0.25,23,0.25
25,2,1.59300000,1,6,0.25,7,0.25,23,0.25,24,0.25
26,2,1.55700000,1,7,0.25,8,0.25,24,0.25,25,0.25
27,2,1.61800000,1,8,0.25,9,0.25,25,0.25,26,0.25
28,1,0.53200000,1,9,0.25,10,0.25,26,0.25,27,0.25
29,1,0.54200000,1,10,0.25,11,0.25,27,0.25,28,0.25
30,1,0.55300000,1,11,0.25,12,0.25,28,0.25,29,0.25
31,1,0.55800000,1,12,0.25,13,0.25,29,0.25,30,0.25
32,1,0.56400000,1,13,0.25,14,0.25,30,0.25,31,0.25
33,1,0.57200000,1,14,0.25,15,0.25,31,0.25,32,0.25
34,1,0.58300000,1,15,0.25,16,0.25,32,0.25,33,0.25
35,1,0.60400000,1,16,0.25,17,0.25,33,0.25,34,0.25
36,1,0.62700000,1,17,0.25,34,0.25
37,1,1.14500000,1,18,0.25,35,0.25
38,2,1.66400000,1,18,0.25,19,0.25,35,0.25,36,0.25
39,2,1.57000000,1,19,0.25,20,0.25,36,0.25,37,0.25
40,2,1.57200000,1,20,0.25,21,0.25,37,0.25,38,0.25
41,2,1.51100000,1,21,0.25,22,0.25,38,0.25,39,0.25
42,2,1.50300000,1,22,0.25,23,0.25,39,0.25,40,0.25
43,2,1.54000000,1,23,0.25,24,0.25,40,0.25,41,0.25
44,2,1.50200000,1,24,0.25,25,0.25,41,0.25,42,0.25
45,2,1.57500000,1,25,0.25,26,0.25,42,0.25,43,0.25
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47,1,0.54000000,1,27,0.25,28,0.25,44,0.25,45,0.25
48,1,0.55100000,1,28,0.25,29,0.25,45,0.25,46,0.25
49,1,0.55800000,1,29,0.25,30,0.25,46,0.25,47,0.25
50,1,0.56300000,1,30,0.25,31,0.25,47,0.25,48,0.25
51,1,0.56800000,1,31,0.25,32,0.25,48,0.25,49,0.25
52,1,0.57500000,1,32,0.25,33,0.25,49,0.25,50,0.25
53,1,0.58300000,1,33,0.25,34,0.25,50,0.25,51,0.25
54,1,0.58600000,1,34,0.25,51,0.25
55,3,0.00000000,1,35,0.25,52,0.25
56,2,1.64000000,1,35,0.25,36,0.25,52,0.25,53,0.25
57,2,1.57200000,1,36,0.25,37,0.25,53,0.25,54,0.25
58,3,0.00000000,1,37,0.25,38,0.25,54,0.25,55,0.25
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61,3,0.00000000,1,40,0.25,41,0.25,57,0.25,58,0.25
62,2,1.52400000,1,41,0.25,42,0.25,58,0.25,59,0.25
63,2,1.56100000,1,42,0.25,43,0.25,59,0.25,60,0.25
64,1,0.52400000,1,43,0.25,44,0.25,60,0.25,61,0.25
65,1,0.53800000,1,44,0.25,45,0.25,61,0.25,62,0.25
66,1,0.54900000,1,45,0.25,46,0.25,62,0.25,63,0.25
67,1,0.55600000,1,46,0.25,47,0.25,63,0.25,64,0.25
68,1,0.56100000,1,47,0.25,48,0.25,64,0.25,65,0.25
69,1,0.56400000,1,48,0.25,49,0.25,65,0.25,66,0.25
70,1,0.56800000,1,49,0.25,50,0.25,66,0.25,67,0.25
71,1,0.57200000,1,50,0.25,51,0.25,67,0.25,68,0.25
72,1,0.58000000,1,51,0.25,68,0.25
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75,2,1.51100000,1,53,0.25,54,0.25,70,0.25,71,0.25
76,2,1.53700000,1,54,0.25,55,0.25,71,0.25,72,0.25
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79,2,1.53200000,1,57,0.25,58,0.25,74,0.25,75,0.25
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94,2,1.53400000,1,71,0.25,72,0.25,88,0.25,89,0.25
95,2,1.54600000,1,72,0.25,73,0.25,89,0.25,90,0.25
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99,2,1.53300000,1,76,0.25,77,0.25,93,0.25,94,0.25
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321,3,0.00000000,1,286,0.25,287,0.25
322,1,1.14500000,1,287,0.25,288,0.25
323,1,1.21700000,1,288,0.25,289,0.25
324,3,0.00000000,1,289,0.25
0                                                          *rods.9
1,dumy,0.374,0.0,0          *blanket rods                  *rods.68
2,dumy,0.3346,0.0,0         *seed rods                     *rods.68
3,dumy,0.482,0.0,0          *control rods                  *rods.68
endd
*
* end of input file
```

A reference WSB-B input file for VIPRE is given below.

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                              input card images

                 1         2         3         4         5         6         7         8
 card   12345678901234567890123456789012345678901234567890123456789012345678901234567890
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   1    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   2    *                                                                     *
   3    *     vipre-01, Checkerboard array input Ver 3         03/10/00       *
   4    *                                                                     *
   5    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   6    1,0,0                                                           *vipre.1
   7    Checkerboard array case(1 assembly seed + 1 assembly blanket)   *vipre.2
   8    *
   9    *  assembly geometry = 11 x 11 seed rods 17x17 blanket rods
  10    *
  11    geom,289,8,16,0,8      *8 different compressed geometry input   *geom.1
  12    144.,?                                                          *geom.2
  13    0.,0.5          * default sl = 0.5                              *geom.2 (cont.)
  14    *     channel dimensions
  15    *     type I
  16    32,0.13445,1.1669,0.7884                                        *geom.5
  17    37,38,40,41,54,55,57,58,73,74,88,89,90,91,105,106               *geom.6
  18    184,185,199,200,201,202,216,217,232,233,235,236,249,250,252,253 *geom.6
  19    *     type II
  20    64,0.15809,1.1669,0.7884                                        *geom.5
  21    20,21,22,23,24,25,36,39,42,53,56,59,70,71,72,75                 *geom.6
  22    76,87,92,93,104,107,108,109,110,121,122,123,124,125,126,127     *geom.6
  23    163,164,165,166,167,168,169,180,181,182,183,186,197,198,203,214 *geom.6
  24    215,218,219,220,231,234,237,248,251,254,265,266,267,268,269,270 *geom.6
  25    *     type III
  26    37,0.14712,1.1131,1.1131                                        *geom.5
  27    5,8,26,43,60,69,77,94,111,120,128,138,139,140,141,142           *geom.6
  28    143,144,145,146,147,148,149,150,151,152,162,170,179,196,213,221 *geom.6
  29    230,247,264,282,285                                             *geom.6
  30    *     type IV
  31    4,0.11801,1.2598,0.8812                                         *geom.5
  32    1,17,273,289                                                    *geom.6
  33    *     type V
  34    126,0.13616,1.1750,1.1750                                       *geom.5
  35    10,11,12,13,14,15,16,27,28,29,30,31,32,33,34,44                 *geom.6
  36    45,46,47,48,49,50,51,61,62,63,64,65,66,67,68,78                 *geom.6
  37    79,80,81,82,83,84,85,95,96,97,98,99,100,101,102,112             *geom.6
  38    113,114,115,116,117,118,119,129,130,131,132,133,134,135,136,154 *geom.6
  39    155,156,157,158,159,160,161,171,172,173,174,175,176,177,178,188 *geom.6
  40    189,190,191,192,193,194,195,205,206,207,208,209,210,211,212,222 *geom.6
  41    223,224,225,226,227,228,229,239,240,241,242,243,244,245,246,256 *geom.6
  42    257,258,259,260,261,262,263,274,275,276,277,278,279,280         *geom.6
  43    *     type VI
  44    2,0.15260,1.0821,1.0821                                         *geom.5
  45    19,271                                                          *geom.6
  46    *     type VII
  47    16,0.12897,1.1979,0.8193                                        *geom.5
  48    3,4,6,7,35,52,86,103,187,204,238,255,283,284,286,287            *geom.6
  49    *     type VIII
  50    8,0.14164,1.1440,1.1440                                         *geom.5
  51    2,9,18,137,153,272,281,288                                      *geom.6
  52    * Gap input data
  53    544,4,0,17,0,0                                                  *geom.7
  54    *     gap type I
  55    188,0.1614,0.496                                                *geom.8
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6,8,10,12,14,16,36,37,38,39,40,41,42,43,44,45                   *geom.9
46,47,48,49,67,69,70,73,75,76,79,81,82,100,102,103              *geom.9
105,106,107,108,109,111,112,113,114,115,133,135,136,137,138,139 *geom.9
140,143,145,146,147,148,166,168,169,172,175,176,177,178,179,180 *geom.9
181,199,201,202,204,205,206,207,208,209,210,211,212,213,214,232 *geom.9
234,235,236,237,238,239,240,241,242,243,244,245,246,247,284,286 *geom.9
288,290,292,294,296,314,316,317,318,319,320,321,322,323,324,325 *geom.9
326,327,328,329,347,349,350,351,352,353,354,355,356,359,361,362 *geom.9
380,382,383,384,385,388,391,392,393,394,395,413,415,416,417,418 *geom.9
420,421,422,423,424,425,426,427,428,446,448,449,452,454,455,458 *geom.9
460,461,479,481,482,484,485,486,487,488,490,491,492,493,494,512 *geom.9
514,515,516,517,518,519,520,521,522,523,524,525                 *geom.9
*     gap type II
260,0.1220,0.496                                                *geom.8
1,2,17,19,20,21,22,23,24,25,26,27,28,29,30,31                   *geom.9
32,33,50,52,53,54,55,56,57,58,59,60,61,62,63,64                 *geom.9
65,66,83,85,86,87,88,89,90,91,92,93,94,95,96,97                 *geom.9
98,99,116,118,119,120,121,122,123,124,125,126,127,128,129,130   *geom.9
131,132,149,151,152,153,154,155,156,157,158,159,160,161,162,163 *geom.9
164,165,182,184,185,186,187,188,189,190,191,192,193,194,195,196 *geom.9
197,198,215,217,218,219,220,221,222,223,224,225,226,227,228,229 *geom.9
230,231,248,250,251,252,253,254,255,256,257,258,259,260,261,262 *geom.9
263,264,266,268,270,272,274,276,278,280,298,299,300,301,302,303 *geom.9
304,305,306,307,308,309,310,311,312,313,331,332,333,334,335,336 *geom.9
337,338,339,340,341,342,343,344,345,346,364,365,366,367,368,369 *geom.9
370,371,372,373,374,375,376,377,378,379,397,398,399,400,401,402 *geom.9
403,404,405,406,407,408,409,410,411,412,430,431,432,433,434,435 *geom.9
436,437,438,439,440,441,442,443,444,445,463,464,465,466,467,468 *geom.9
469,470,471,472,473,474,475,476,477,478,496,497,498,499,500,501 *geom.9
502,503,504,505,506,507,508,509,510,511,528,529,530,531,532,533 *geom.9
534,535,536,544                                                 *geom.9
*     gap type III
40,0.0877,0.496                                                 *geom.8
5,11,68,71,72,74,77,78,80,104,110,141,142,144,167,170           *geom.9
171,173,174,203,357,358,360,363,386,387,389,390,419,450,451,453 *geom.9
456,457,459,462,483,489,539,542                                 *geom.9
*     gap type IV
56,0.1417,0.496                                                 *geom.8
3,4,7,9,13,15,18,34,35,51,84,101,117,134,150,183                *geom.9
200,216,233,249,265,267,269,271,273,275,277,279,281,282,283,285 *geom.9
287,289,291,293,295,297,315,330,348,381,396,414,429,447,480,495 *geom.9
513,526,527,537,538,540,541,543                                 *geom.9
*
17,34,51,68,85,102,119,136,153,170,187,204,221,238,255,272      *geom.10
289                                                             *geom.10
*
prop,22,1,1,0      * create table from functions                *prop.1
203.32,729.1,1800.                                              *prop.3
*
drag,1,0,1                                                      *drag.1
.18,-.2,0.,64.,-1.,0. * axial friction correlation              *drag.2
.5,.496   * pitch = .496, kij = .51/p                           *drag.5
*
grid,0,3                                                        *grid.1
.6,2.3,2.3   * seed, blanket loss coef., blanket inlet         *grid.2
161,8         * Seed and boundary channels                      *grid.4
1,2,3,4,5,6,7,8,9,18,19,20,21,22,23,24                          *grid.5
25,26,35,36,37,38,39,40,41,42,43,52,53,54,55,56                 *grid.5
57,58,59,60,69,70,71,72,73,74,75,76,77,86,87,88                 *grid.5
89,90,91,92,93,94,103,104,105,106,107,108,109,110,111,120       *grid.5
121,122,123,124,125,126,127,128,137,138,139,140,141,142,143,144 *grid.5
145,146,147,148,149,150,151,152,153,162,163,164,165,166,167,168 *grid.5
169,170,179,180,181,182,183,184,185,186,187,196,197,198,199,200 *grid.5
201,202,203,204,213,214,215,216,217,218,219,220,221,230,231,232 *grid.5
233,234,235,236,237,238,247,248,249,250,251,252,253,254,255,264 *grid.5
265,266,267,268,269,270,271,272,281,282,283,284,285,286,287,288 *grid.5
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289                                                                     *grid.5
16.0,1,32.0,1,48.0,1,64.0,1,80.0,1,96.0,1,? * grid loc.                 *grid.6
112.0,1,128.0,1,                                                        *grid.6
128,8          * Blanket channels                                       *grid.4
10,11,12,13,14,15,16,17,27,28,29,30,31,32,33,34                         *grid.5
44,45,46,47,48,49,50,51,61,62,63,64,65,66,67,68                         *grid.5
78,79,80,81,82,83,84,85,95,96,97,98,99,100,101,102                      *grid.5
112,113,114,115,116,117,118,119,129,130,131,132,133,134,135,136 *grid.5
154,155,156,157,158,159,160,161,171,172,173,174,175,176,177,178 *grid.5
188,189,190,191,192,193,194,195,205,206,207,208,209,210,211,212 *grid.5
222,223,224,225,226,227,228,229,239,240,241,242,243,244,245,246 *grid.5
256,257,258,259,260,261,262,263,273,274,275,276,277,278,279,280 *grid.5
16.0,2,32.0,2,48.0,2,64.0,2,80.0,2,96.0,2,? * grid loc.                 *grid.6
112.0,2,128.0,2,                                                        *grid.6
128,1          * Inlet Blanket channels                                 *grid.4
10,11,12,13,14,15,16,17,27,28,29,30,31,32,33,34                         *grid.5
44,45,46,47,48,49,50,51,61,62,63,64,65,66,67,68                         *grid.5
78,79,80,81,82,83,84,85,95,96,97,98,99,100,101,102                      *grid.5
112,113,114,115,116,117,118,119,129,130,131,132,133,134,135,136 *grid.5
154,155,156,157,158,159,160,161,171,172,173,174,175,176,177,178 *grid.5
188,189,190,191,192,193,194,195,205,206,207,208,209,210,211,212 *grid.5
222,223,224,225,226,227,228,229,239,240,241,242,243,244,245,246 *grid.5
256,257,258,259,260,261,262,263,273,274,275,276,277,278,279,280 *grid.5
0.0,3                                                                   *grid.6
0,                                                                      *grid.4
*
corr,1,0,                                                               *corr.1
epri,epri,epri,none,                                                    *corr.2
0.2                                                                     *corr.3
ditb                                                                    *corr.6
w-31                                                                    *corr.9
0.043,0.066,0.986                                                       *corr.11
*
oper,1,1,-1,0,4,1,0,                                                    *oper.1
* iterate to mdnbr=1.00, fcool=1.95, convergence=0.005
-1., 1.3, 1.95, 0                                                       *oper.2
0                                                                       *oper.3
2248.1,552.2,202.186,7.079, * (7.401*264/276)op. cond. MOC              *oper.5
0                            * no forcing functions                     *oper.12
*
cont                                                                    *cont.1
0.,0,750,50,3,0         * iterative upflow solution                     *cont.2
*0.,0,20,0,0,1          * direct upflow solution                        *cont.2
*0.,0.,0.01,0.,0.,0.8                                                   *cont.3
0.,0.,0.001,0.,0.,0.3,1.5,0.8                                           *cont.3
5,3,5,0,2,0,1,1,0,0,0,1,1                                               *cont.6
1000.,0.,0.,0.,0.,0.,                                                   *cont.7
17,64,254       * channels printed                                      *cont.8
51,150,271,291,480 * gaps printed                                       *cont.9
17,254          * dnb results printed                                   *cont.11
*
*   rod layout - mixed dummy and conduction rods
*
rods,1,324,1,3,4,0,0,0,0,0,0                                            *rods.1
*
0.0,0.0,1    * nodal power profile specification                        *rods.2
*
16           * one entry for each of 16 nodes                           *rods.3
*
0.45373,0.81156,1.05758,1.12688,1.13106,1.12223,1.12083,1.13245 *rods.6
1.15524,1.18175,1.19292,1.18175,1.13013,1.00409,0.73761,0.46019 *rods.6
* normal rod layout for checkerboard
1,3,0.00000000,1,1,0.25
2,1,1.54200000,1,1,0.25,2,0.25
3,1,1.53800000,1,2,0.25,3,0.25
4,3,0.00000000,1,3,0.25,4,0.25
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5,1,1.52700000,1,4,0.25,5,0.25
6,1,1.52000000,1,5,0.25,6,0.25
7,3,0.00000000,1,6,0.25,7,0.25
8,1,1.53500000,1,7,0.25,8,0.25
9,1,1.61200000,1,8,0.25,9,0.25
10,1,0.49700000,1,9,0.25,10,0.25
11,1,0.51000000,1,10,0.25,11,0.25
12,1,0.51800000,1,11,0.25,12,0.25
13,1,0.52200000,1,12,0.25,13,0.25
14,1,0.52300000,1,13,0.25,14,0.25
15,1,0.52400000,1,14,0.25,15,0.25
16,1,0.53000000,1,15,0.25,16,0.25
17,1,0.55000000,1,16,0.25,17,0.25
18,3,0.00000000,1,17,0.25
19,1,1.54200000,1,1,0.25,18,0.25
20,1,1.49400000,1,1,0.25,2,0.25,18,0.25,19,0.25
21,2,1.49000000,1,2,0.25,3,0.25,19,0.25,20,0.25
22,2,1.53300000,1,3,0.25,4,0.25,20,0.25,21,0.25
23,2,1.48000000,1,4,0.25,5,0.25,21,0.25,22,0.25
24,2,1.47400000,1,5,0.25,6,0.25,22,0.25,23,0.25
25,2,1.52000000,1,6,0.25,7,0.25,23,0.25,24,0.25
26,2,1.49100000,1,7,0.25,8,0.25,24,0.25,25,0.25
27,2,1.60900000,1,8,0.25,9,0.25,25,0.25,26,0.25
28,1,0.49700000,1,9,0.25,10,0.25,26,0.25,27,0.25
29,1,0.51000000,1,10,0.25,11,0.25,27,0.25,28,0.25
30,1,0.51900000,1,11,0.25,12,0.25,28,0.25,29,0.25
31,1,0.52200000,1,12,0.25,13,0.25,29,0.25,30,0.25
32,1,0.52300000,1,13,0.25,14,0.25,30,0.25,31,0.25
33,1,0.52400000,1,14,0.25,15,0.25,31,0.25,32,0.25
34,1,0.52800000,1,15,0.25,16,0.25,32,0.25,33,0.25
35,1,0.53700000,1,16,0.25,17,0.25,33,0.25,34,0.25
36,1,0.55000000,1,17,0.25,34,0.25
37,1,1.53800000,1,18,0.25,35,0.25
38,2,1.49000000,1,18,0.25,19,0.25,35,0.25,36,0.25
39,2,1.48800000,1,19,0.25,20,0.25,36,0.25,37,0.25
40,2,1.53200000,1,20,0.25,21,0.25,37,0.25,38,0.25
41,2,1.48100000,1,21,0.25,22,0.25,38,0.25,39,0.25
42,2,1.47600000,1,22,0.25,23,0.25,39,0.25,40,0.25
43,2,1.52100000,1,23,0.25,24,0.25,40,0.25,41,0.25
44,2,1.49000000,1,24,0.25,25,0.25,41,0.25,42,0.25
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46,1,0.49700000,1,26,0.25,27,0.25,43,0.25,44,0.25
47,1,0.51000000,1,27,0.25,28,0.25,44,0.25,45,0.25
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49,1,0.52200000,1,29,0.25,30,0.25,46,0.25,47,0.25
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55,3,0.00000000,1,35,0.25,52,0.25
56,2,1.53300000,1,35,0.25,36,0.25,52,0.25,53,0.25
57,2,1.53200000,1,36,0.25,37,0.25,53,0.25,54,0.25
58,3,0.00000000,1,37,0.25,38,0.25,54,0.25,55,0.25
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60,2,1.53600000,1,39,0.25,40,0.25,56,0.25,57,0.25
61,3,0.00000000,1,40,0.25,41,0.25,57,0.25,58,0.25
62,2,1.53600000,1,41,0.25,42,0.25,58,0.25,59,0.25
63,2,1.61000000,1,42,0.25,43,0.25,59,0.25,60,0.25
64,1,0.49700000,1,43,0.25,44,0.25,60,0.25,61,0.25
65,1,0.51100000,1,44,0.25,45,0.25,61,0.25,62,0.25
66,1,0.51900000,1,45,0.25,46,0.25,62,0.25,63,0.25
67,1,0.52300000,1,46,0.25,47,0.25,63,0.25,64,0.25
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70,1,0.52300000,1,49,0.25,50,0.25,66,0.25,67,0.25
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79,2,1.54300000,1,57,0.25,58,0.25,74,0.25,75,0.25
80,2,1.48500000,1,58,0.25,59,0.25,75,0.25,76,0.25
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93,2,1.47600000,1,70,0.25,71,0.25,87,0.25,88,0.25
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0                                                                 *rods.9
2,nucl,0.3346,0.2967,6,0.22126,0.01575  *UO2 seed rods           *rods.62
0,0,0,0,0,3500.0,.97,0.0                                          *rods.63
1,hrod,0.374,0.0,3          *bkt. rods 3 regions:fuel+gap+clad  *rods.68
6,2,0.161,0.99,1,3,0.0034,0.0,3,4,0.02244,0.01*blanket rods      *rods.69
3,dumy,0.482,0.0,0          *control rods                         *rods.68
1,25,1183.01,seed                                                 *rods.70
80.33,0.0642,13.1439,?
170.33,0.0642,13.1575
260.33,0.0642,13.1702,?
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2240.33,0.0642,13.2117
2,30,638.256,blan                                    *rods.70
80.33,0.0764,5.356,?
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2960.33,0.0774,1.352,?
3140.33,0.0776,1.292
3,1,1.0,bgap                                         *rods.70
1,100,6.8 *gap condty.=2000Btu/hr.ft2.F*0.0034 ft
4,13,409.0,bcld
80.33,0.0671,7.330,?
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692.33,0.07904,9.8016,?
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