MODELING APPROACH FOR ANNULAR-FUEL ELEMENTS USING THE ASSERT-PV SUBCHANNEL CODE

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Abstract

The internally and externally cooled annular fuel (hereafter called annular fuel) is under consideration for a new high burn-up fuel bundle design in Atomic Energy of Canada Limited (AECL) for its current, and its Generation IV reactor.

An assessment of different options to model a bundle fuelled with annular fuel elements is presented. Two options are discussed: 1) Modify the subchannel code ASSERT-PV to handle multiple types of elements in the same bundle, and 2) coupling ASSERT-PV with an external application. Based on this assessment, the selected option is to couple ASSERT-PV with the thermalhydraulic system code CATHENA.

1. INTRODUCTION

AECL is assessing the use of the internally and externally cooled annular fuel for its current, and its Generation IV reactor. This proposed fuel design allows a substantial increase in core power density, while maintaining or improving safety margins. Compared to the traditional solid fuel, which has only one cooling surface that is cooled by the surrounding subchannels, the annular fuel has two cooling surfaces: (i) the outer clad contacting the outer subchannels and (ii) the inner clad contacting the inner subchannel.

Presently, for the thermalhydraulic assessment of a fuel bundle, the nuclear industry uses subchannel codes. ASSERT-PV[1][1] and [2] is the only Canadian code qualified for subchannel analysis of CANDU-type fuel bundles.

The subchannel approach consists in subdividing the cross-sectional flow area of a nuclear fuel bundle into simple parallel and interconnected cells called “subchannels”. Each subchannel is bounded by solid walls of the fuel rods and/or pressure tube and by imaginary boundaries connecting rod centres. Within each subchannel the flow is considered primarily one-dimensional; but the lateral flow between subchannels is also taken into account.

Although the subchannel analysis is suitable to analyse the proposed annular fuel bundle (depicted in Figure 1), ASSERT-PV was developed to model a bundle containing solid-fuel elements only.

[1] ASSERT stands for Advanced Solution of Subchannel Equations in Reactor Thermalhydraulics.

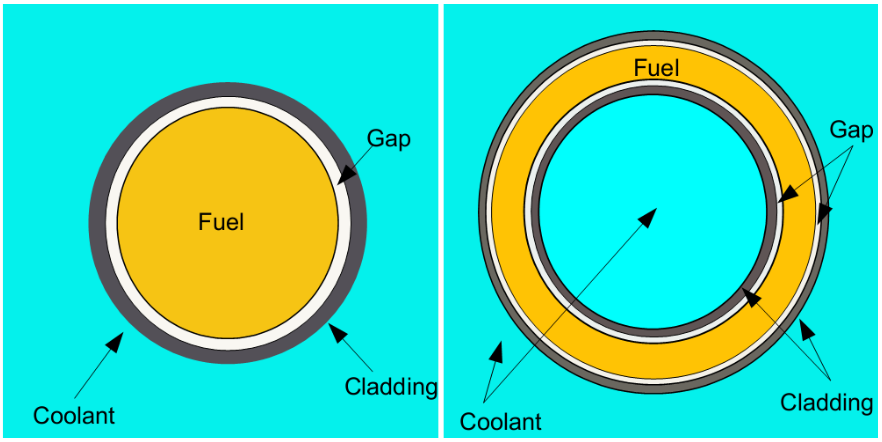


Figure 1: Solid Fuel Element (Left) and Annular Fuel Element (Right)

In light of the previous statement, the goal of this document is to identify possible ways of developing a tool to model and assess the annular fuel using the ASSERT-PV, and recommend one option based on cost effectiveness.

Among the different possible options, the following two are identified:

- Modify ASSERT-PV to handle the annular fuel type, and
- Develop a separate annular fuel element model and couple it to ASSERT-PV.

In the following sections, each option is discussed, presenting its conveniences and its limitations.

2. REVIEW OF PREVIOUS WORK

Annular fuel is not a novel concept or idea; it has been studied in the past and several types of annular fuels were tested and used in different type of reactors. However, this concept was put aside because of a lack of incentive to pursue this type of research, due to either economic reasons or technological limitations. Now that energy economics has changed and the nuclear industry is showing more interest in this concept, it is suggested that the concept of annular fuels be revisited.

This section presents a literature review of relevant analyses carried out to study the tools used to model annular fuels, as well as the methodology used for assessing the thermalhydraulic performance. The analyses reviewed in this section were selected due to their accessibility and relevance to this project.These are two recent analyses by: 1) The Massachusetts Institute of Technology (MIT), and 2) the Korea Atomic Energy Research Institute (KAERI). Both institutions carried out several simulations to assess the feasibility and performance of annular fuel in order to increase the power density in a conventional PWR nuclear reactor.

2.1 Massachusetts Institute of Technology (MIT)

MIT performed a state-of-the-art assessment of using annular fuels in current PWR reactors.Reference [3] presents their methodologies, tools used for their assessments, and conclusions. The MIT report coveredsix different fields: *thermalhydraulic performance, safety analysis performance, neutronic performance, fuel fabrication feasibility, economic feasibility and fuel performance.*

From the thermalhydraulic performance perspective, one of the most important objectives of this study was to identify the most promising fuel assembly arrangement for PWRs to achieve at least 30% increase in power density. Various square array sizes (11x11 to 15x15) that fit in the fixed dimensions of a 17x17 fuel assembly were explored.

To perform this analysis, MIT used the subchannel code VIPRE-01. This code was developed for solid fuel rods, but can also calculate heat conduction in hollow tubes.This option of VIPRE-01 was used for the modeling of fuel bundles with annular fuel elements with inner and outer cooling.The fuel rods were defined as hollow tubes having several material regions with given radial and axial power factors.

MIT found two limiting parameters:(1) pressure drop, which tends to increasedue to larger wetted perimeters; and (2) mass-flow split fraction (inner vs. outer flows).It was observed that the inner subchannel is more susceptible to reach CHF due to the lack of inter-subchannel mixing.

They also concluded that the performance of the annular fuel is more sensitive to operating parameters, such as core flow rate, core power, core inlet temperature, and system pressure. This sensitivity is compensated by the larger critical heat flux ratio (CHFR) margin at rated conditions gained from the new geometry with larger heat transfer area and higher mass flux.

The most promising option was found to be the 13x13 array.Table 1 presents the dimensions of the analysed fuel arrays.

Table 1
Dimensions of Annular Fuel of Various Arrays (cm) [3]

Array	Dcii	Dcio	Dfi	Dfo	Dci	Dco	Pitch
11X11	1.0733	1.1876	1.20	1.700	1.7124	1.8267	1.952
12X12	0.9533	1.0676	1.08	1.540	1.5524	1.6667	1.789
13X13	0.8633	0.9776	0.99	1.410	1.4224	1.5367	1.651
14X14	0.7533	0.8676	0.88	1.294	1.3064	1.4207	1.533
15X15	0.6733	0.7876	0.8	1.1978	1.2102	1.3245	1.431
17X17	Solid Pin	-	-	0.8255	0.8379	0.9522	1.263

Reference [3] states *"The first subscript c and f stand for cladding and fuel respectively; in the second subscript, i and o designate inner cladding and outer cladding, respectively, or* *inner diameter and outer diameter for the fuel ring; and the third subscript denotes the diameters of the cladding (i=inner, o=outer)"*

2.2 Korea Atomic Energy Research Institute (KAERI)

KAERI is also studying the possibility of uprating their PWR design through the use of annular fuels. Their modeling approach differs from MIT because KAERI's subchannel code does not have the option to model hollow tubes (in contrast with VIPRE-01). KAERI developed a thermalhydraulic code, named ANNULAR-AF, used to model the inner flow, linked with its subchannel code MATRA to model the outer flow. The link between the two codes is based on the equalization of pressure drop across the subchannels. The data exchange is via input files.

To assess the adequateness of the code, the KAERI group compared their results against the MIT analyses. In Reference [4] it was stated: "*the pressure drop of a heated length is 150 kPa at the VIPRE-01, while the result of MATRA-AF is 159 kPa, which is about 3.3% higher than that of VIPRE-01.This difference results mainly from applying different correlations to calculate a single-phase friction factor.When the same correlation is used in MATRA-AF, the difference of pressure drop between both codes is within 1% even though different two-phase flow model used in each code.The flow splits (mass flux ratio of inner channel to outer channel) are 1.16 for VIPRE-01 and 1.15 for MATRA-AF.The pressure drop and flow split showed good agreement, except the prediction difference by the two-phase flow correlations."*[2]

Table 2 presents the geometrical data used by KAERI to perform its assessment.

Table 2Fuel Rod Geometrical Data for the Solid Element and the Annular Fuel for Power Uprate [4]

Parameter	Reference Bundle (16X16 solid elements)	Annular 12X12
Pin pitch (cm)	1.285	1.713
Inner clad inner diameter (cm)		0.850
Inner clad outer diameter (cm)		0.966
Pellet inlet diameter (cm)		0.980
Pellet outer diameter (cm)	0.819	1.404
Outer clad inner diameter (cm)	0.836	1.416
Outer clad outer diameter (cm)	0.950	1.590
OPR-1000 and power uprate operating condition		
Nominal reactor power	100%	120%

[2]Quotation from the journal of Nuclear Engineering and Design without any editorial changes.

Reactor power (MW, thermal)	2815	3378
Core flow rate (kg/s)	14 841	14 841
Core inlet temperature (°C)	296	289
Core outlet temperature (°C)	328	328

Observations from the above review are summarized below:

- The KAERI code ANNULAR-AF showed that it is feasible to use a subchannel code linked to an external program to model a bundle with annular fuel.
- The bundle pressure drop can be used as a link parameter between the subchannel code and the annular fuel model.
- Mass-flow and heat-flux split fractions are sensitive parameters, and can be used to verify the convergence of the coupling algorithm.
- In a bundle with annular fuel, the pressure drop is higher than in a bundle with solid elements, this is due to the increase of the wetted perimeter.
- The number of fuel elements in a bundle loaded with annular fuels is lower than the same assembly loaded with solid fuels, when the bundle geometry is fixed. Large fuel elements are used to accommodate inner flows while maintaining the fuel element structural integrity.

3. DEVELOPMENT OPTIONS

This section presents two options for modelling an annular fuel using the subchannel code ASSERT-PV.

3.1 ASSERT-PV as Stand-Alone Code with Built-In Annular Fuel Model

Modifying ASSERT-PV to handle annular fuel elements as a stand-alone code is one option. ASSERT-PV would need to be modified to simultaneously handle two types of elements: (i) the solid fuel element (cooled externally), and (ii)annular fuel element (cooled internally and externally). This would be expensive and time consuming, especially considering the cost associated with the SQA process required for a new version of an Industrial Standard Toolset (IST) code.

The major advantage of modifying ASSERT-PV to handle annular and solid fuel elements together in a single bundle is the flexibility to select the models and correlations that already exist in the code. Furthermore, the simulation time using a modified ASSERT-PV should be much less than that using of an external model coupled with ASSERT-PV, since: (i) there is no need for information exchange between different codes, and (ii) there is no need to start a new ASSERT-PV simulation each and every time information is passed on to ASSERT-PV from the external model.

The major disadvantage of a built-in model is the cost associated with the code development and verification work for a modified version of ASSERT-PV; care must be taken to avoid “unintended” effects of the code changes.

3.2 ASSERT-PV Coupled with an external annular fuel model

The other option is to model the annular fuel elements (and the inner flows) with separate simulationsthat are then coupled with an ASSERT-PV simulation of the external (subchannel) flows. ASSERT-PV would calculate all “open” or outer subchannel flows, while the external code would calculate the inner subchannel flows and the heat-flux split for the annular fuel elements.

Two possible methods exist to couple ASSERT-PV with an external annular fuel element model:(i) the first one is to pass variables directly between ASSERT-PV and the annular fuel element model, with the sequence of execution controlled using multithreading applications (possible use of MPI [9] or PVM [10] subroutines for the coupling); and (ii) the second one is to pass variables outside of ASSERT-PV by updating ASSERT-PV input files with data from the annular fuel element model and extracting from ASSERT-PV output files the required data for the annular fuel element model.The sequence of execution is controlled by another program or script.

The second method has several advantages over the first one

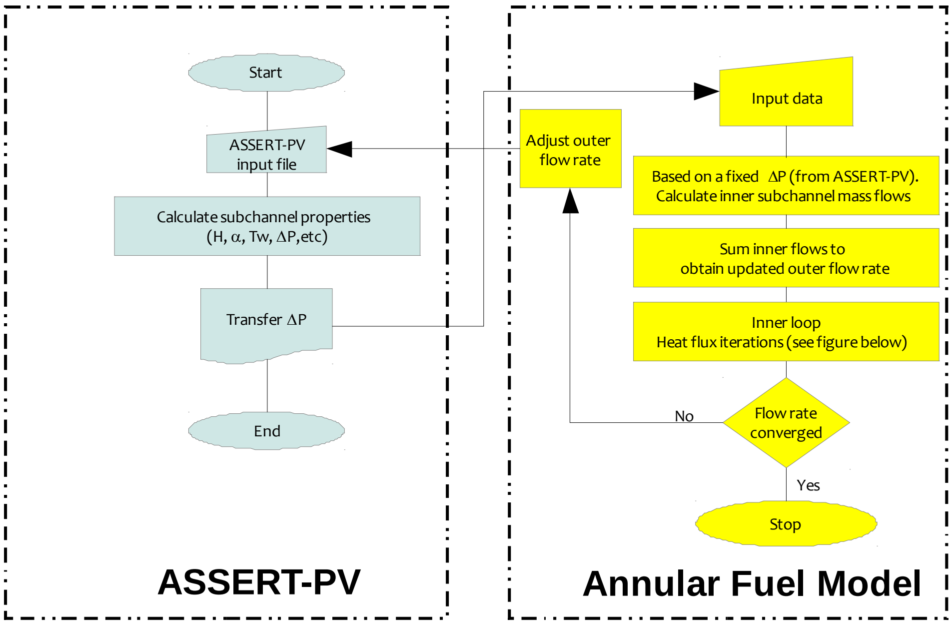
- Easier to maintain because each code is independent from the other.
- No modification to the ASSERT-PV code.In the case of external coupling, there is no need to modify ASSERT-PV; otherwise, it has to be modified to incorporate coupling capability.

However, thedisadvantages are:

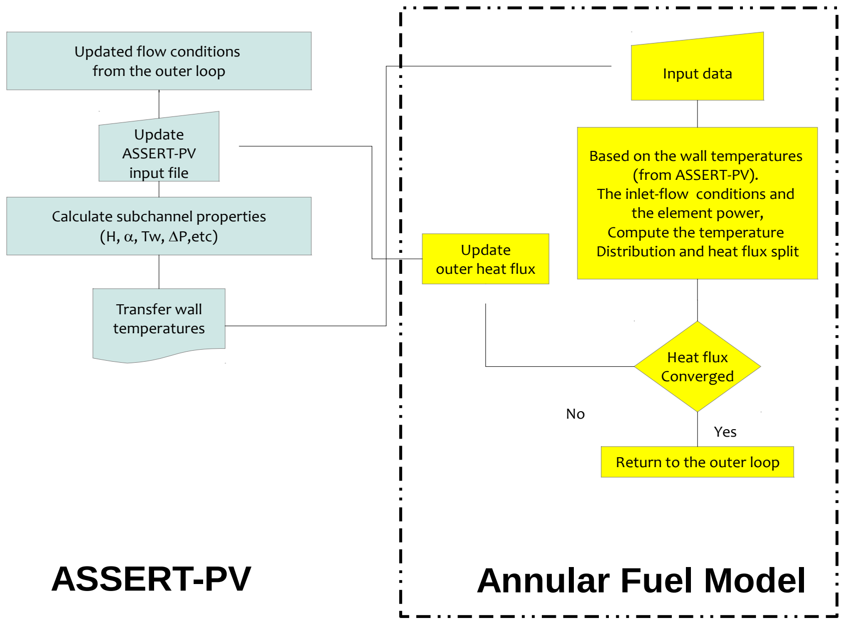
- The program or script that controls the execution must be developed and qualified.
- The simulation time could be much larger.

The convergence of solutions can be obtained by iteratively adjusting the external flow rate until the sum of the inner and outer flows matches a specified bundle total mass flow. This is done while equalizing the channel pressure drop of the ASSERT-PV simulated external flow with that of each and every inner flow.

The heat flux split is performed by the annular fuel model based on the ASSERT-PV predicted wall temperatures, which is obtained first by an initial guess of the fraction of the element power to outer flows.Then, with the total fuel element power and the specified inner flow conditions, the annular fuel model will predict the heat flux to the inner flow, and feedback the information to ASSERT-PV to adjust the heat flux to the outer flows and recalculate the wall temperatures. This “inner” or “heat-flux” iteration will be continued until the predicted heat fluxes converge according to specified convergence criteria. Then, the simulation will move to the “outer” or “flow-rate” iteration to adjust the flow rate to outer flows, as shown in Figure 2.



(a)



(b)

Figure 2:(a) Algorithm for Coupling ASSERT-PV with an External Model, (b) Heat Flux Split Algorithm

3.2.1 Annular Fuel Model Options

There are three options for developing an annular fuel model (including coolant flow inside), as listed below.

3.2.2 Development of an Annular Fuel Model Code

The advantage of developing an annular fuel model is that it can be designed based on the requirements of this specific project. For instance, it can be designed to facilitate the information exchange between this program and ASSERT-PV. However, there is a major drawback: the cost and timeframe associated with developing and qualifying a new code.

3.2.3 Computational Fluid Dynamics

The use of a CFD commercial code (e.g., Fluent or CFX) to model the annular fuel is another option. On one hand, a CFD model may predict a much more detailed single-phase flow and enthalpy distribution and/or pressure drop than a model based on empirical correlations.On the other hand, because of iterations between ASSERT-PV and the CFD model, the coupled solution may become prohibitively time consuming. Furthermore, lack of established two-phase flow and CHF models makes the CFD approach unreliable.

3.2.4 Coupling ASSERT-PV with an Existing Thermalhydraulic Code for Simulation of the Annular Fuel and Inner Flow

In this case, different existing codes can be adapted to model the annular fuel, (e.g., CATHENA [7],and TUF[8]). In contrast with a CFD model, the use of thermalhydraulic code results in a reduced simulation time.

The development of the annular fuel model based on a thermalhydraulic code is limited by its built-in options.

An assessment of the CATHENA built-in options resulted in a suitable platform to develop an annular fuel model.

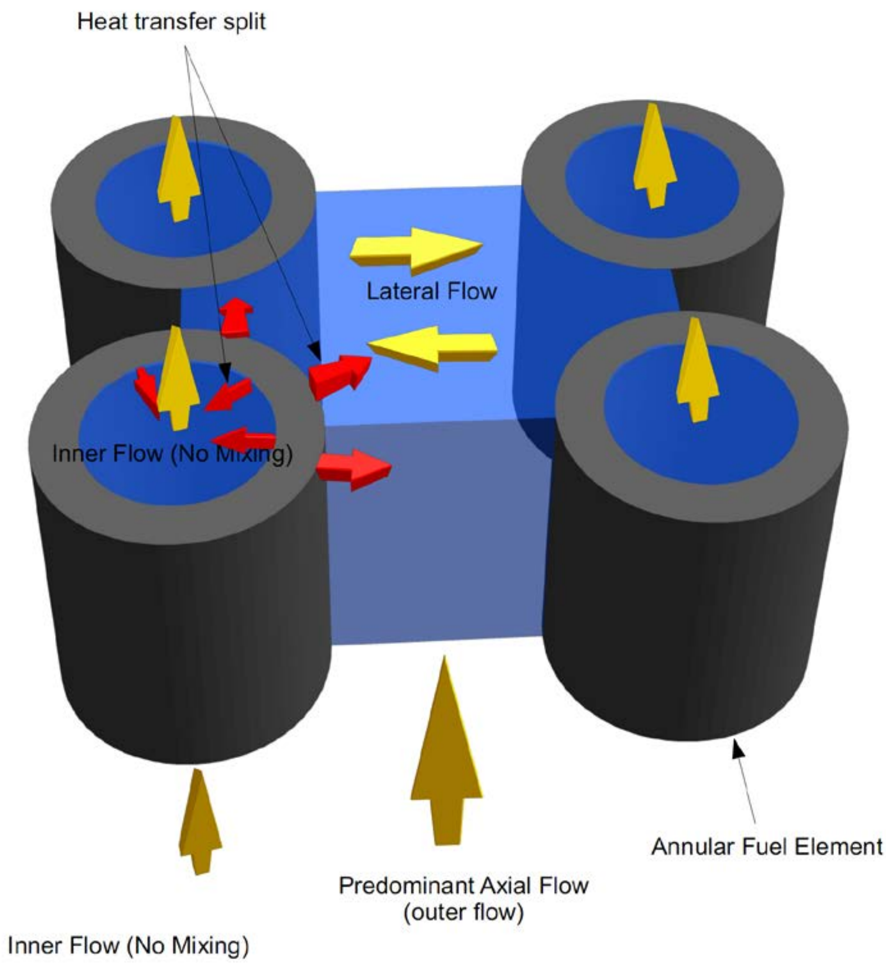


Figure 3: Subchannel Surrounded by Four Annular Fuels

4. PROTOTYPE DEVELOPMENT PLAN

Based on the above options assessment, it is recommended to use ASSERT-PV coupled with an external annular fuel model available in an existing thermalhydraulic code. For the annular fuel model and inner flows, we suggest using CATHENA, a system thermalhydraulic code. CATHENA and ASSERT-PV simulations will be coupled through a script program (see Figure 4).

4.1 Prototype Model Development

The next step is to develop a prototype model, which will be used to implement and test the annular fuel model. The prototype will consist of one ASSERT-PV input file, a CATHENA fuel model input file, and a program or script to control the sequence of execution, information exchange (updating input files), and code convergence. The results obtained from this prototype will be used to further assess the necessity and feasibility of implementing the annular fuel model in a modified version of ASSERT-PV as a standalone code.

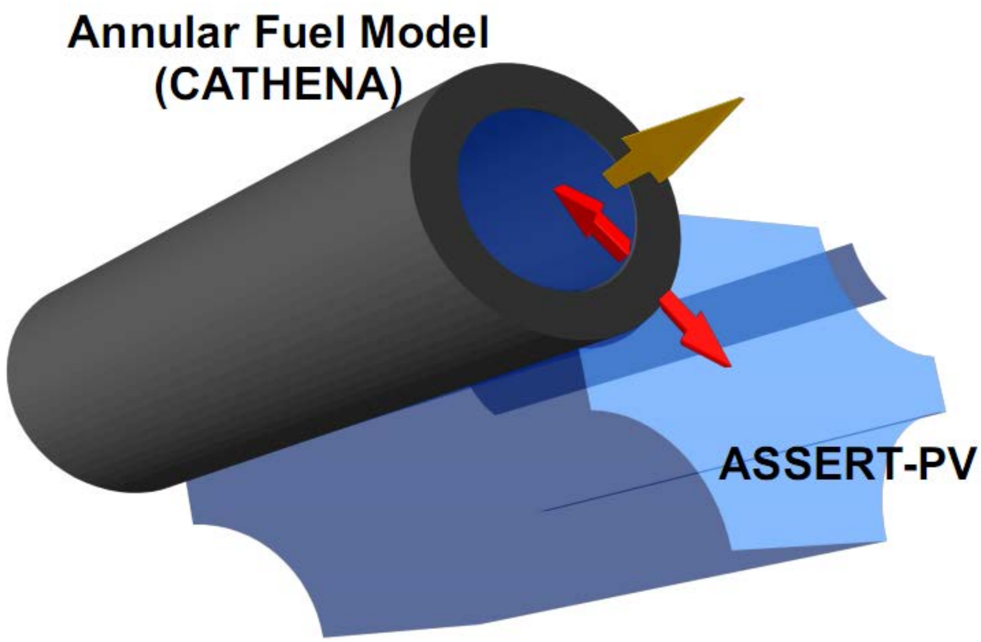


Figure 4: Suggested Prototype

4.2 Prototype Verification and Assessment Plan

During the literature review, a few experimental dataset and analyses were found that can be used to verify prototype model and assess the prototype results:

- MIT analysis performed with the VIPRE-01 code [3]. This analysis was performed using a PWR reactor fuel array.
- KAERI analyses performed with the coupled codes MATRA and ANNULAR [4] and [5]. The results were compared against other thermalhydraulic codes.

Pressure drop, velocity distribution and wall temperature can be used to assess the prototype results and the capability of the prototype program. The assessment of the prototype will be used as a hold point at which the path forward may be revised.

5. RECOMMENDATIONS

The present work outlines possible options to adapt ASSERT-PV code to handle solid and annular fuel elements simultaneously. To further explore these options, the next step is to develop a prototype program that couples an ASSERT-PV simulation of the subchannel flows outside the fuel elements with one or more CATHENA simulations of the annular fuels including the inner flows.

This document also suggests experimental dataset and/or analyses to be used to assess the prototype results.

6. REFERENCES

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