DEVELOPMENT AND THERMALHYDRAULIC CALCULATIONS OF A SCWR 64-ELEMENT FUEL BUNDLE

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Abstract

The objective of this paper is to design a new fuel bundle for use in a generic pressure-channel SCWR with UO_2 fuel, so that the fuel channel materials, i.e., sheath and fuel, will operate below accepted temperature limits. This was achieved by modifying the flow geometry of a 43-element bundle by increasing a number of fuel elements and by decreasing their outer diameter. The proposed 64-element fuel bundle consists of 63 fuelled elements with an outer diameter of 9.1 mm, and a central element with an outer diameter of 20 mm, which is filled with the burnable poison.

1. Literature survey

SuperCritical Water-cooled Reactors (SCWRs) are one of the six nuclear-reactor concepts currently being developed under the Generation-IV program. Also, other Generation-IV nuclear-reactor options are: Gas-cooled Fast Reactors (GFRs), Lead-cooled Fast Reactors (LFRs), Molten Salt-cooled reactors (MSRs), Sodium-cooled Fast Reactors (SFRs), and Very High-Temperature gas-cooled Reactors (VHTRs). The main advantage of SCWRs, which use supercritical water as the reactor coolant, is an increase in the thermal efficiency from 30-34% (current level of Nuclear Power Plants (NPPs)) to 45-50% for SCW NPPs. This increase in the thermal efficiency is a result of high outlet temperature of the coolant, which can be as high as 625°C at a pressure of 25 MPa. In general, several fuel-bundle designs can be considered for Pressure-Channel (PCh) SCWRs. Some of these bundles are: 37-element, 43-element CANFLEX, 43-element Variant-18 and 43-element Variant-20, which cross sections are shown in Figures 1-4, respectively. Table 1 lists various parameters related to these four fuel-bundle designs.

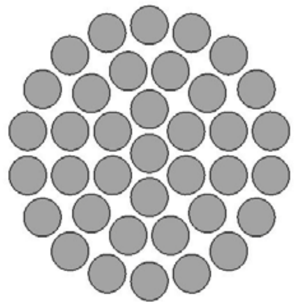


Figure 1 37-element [2].

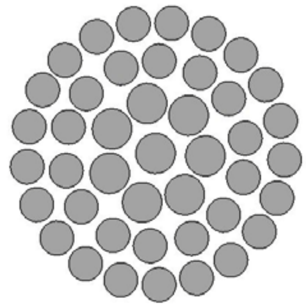


Figure 2 43-element CANFLEX [2].

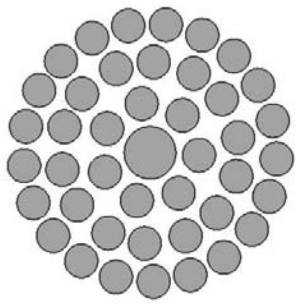


Figure 3 43-element Variant-18 [2].

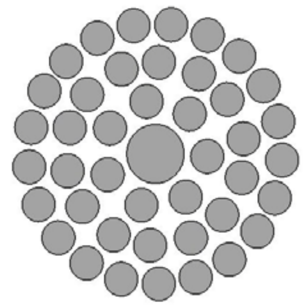


Figure 4 43-element Variant-20 [2].

Table 1. Main Parameters of Fuel Bundles.

	37-Element	CANFLEX	Variant-18	Variant-20
No. of Elements	37	43	43	43
	Element OD (mm)			
Centre Ring (1 element)	13.08	13.5	18.0	20.0
Inner Ring Elements	13.08	13.5	11.5	11.5
Intermediate Ring Elements	13.08	11.5	11.5	11.5
Outer Ring Elements	13.08	11.5	11.5	11.5
Wall Thickness of Elements (mm)	0.47	0.46/0.39	-/0.39	-/0.39
No. of Bundles Per Channel	12			
Heated/Total Bundle-String Length (m)	5.772/5.944			
Heated Area (m^2)	8.76	9.26	8.76	8.76
ID Flow Tube (mm)	103.45			
Flow Area (mm^2)	3449	3625	3788	3729
Hydraulic-equivalent Diameter: D_{hy} (mm)	7.64	7.52	7.98	7.83

2. Research

2.1 Reason behind designing new fuel bundles

Throughout this research project, the 43-element Variant-20 fuel bundle was used as a reference. When uranium dioxide (UO_2) is used as a fuel, the fuel centerline temperature in the 43-element Variant-20 fuel bundle might exceed the industry accepted limit of 1850°C at certain conditions. Thus, either the fuel bundle has to be modified for the use of UO_2 fuel in SCWRs, or the use of different fuels needs to be researched.

The objective of this paper is to analyse the newly designed 64-element fuel bundle for use in a generic PCh SCWR to show that the fuel-channel materials, i.e., sheath and fuel, will operate below the accepted temperature limits.

2.2 The different designs

At the beginning, seven different fuel-bundle designs were proposed, each with either different outside diameters of the elements, inside diameters of the flow tubes, or number of fuel elements.

The seven cross sections below represent the fuel-bundle designs described in Table 2. The fuel bundle selected for the analysis in this paper is the 64-element fuel bundle with an outer diameter of the 42 elements 9.13 mm and the center unheated fuel – 20 mm.

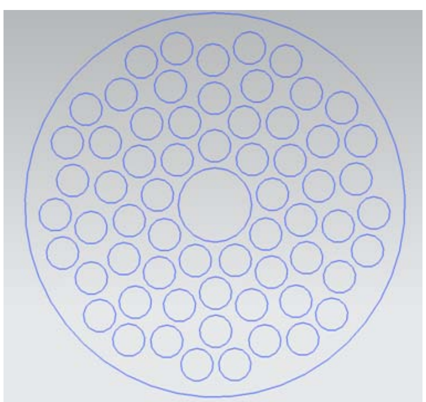


Figure 5 Option 1.

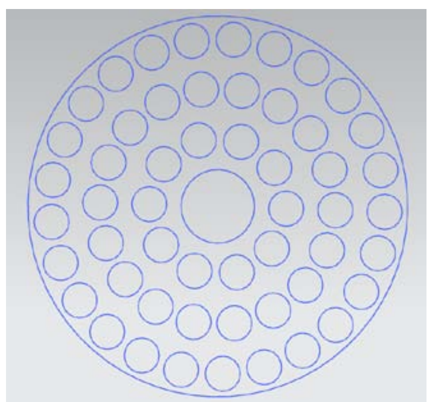


Figure 6 Option 2.

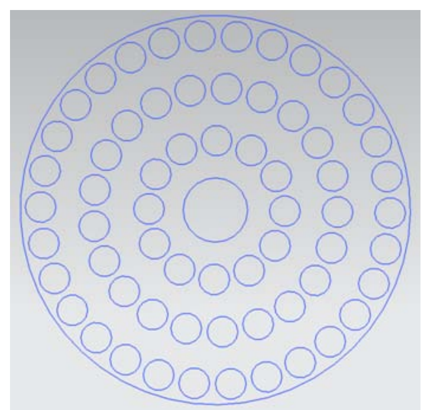
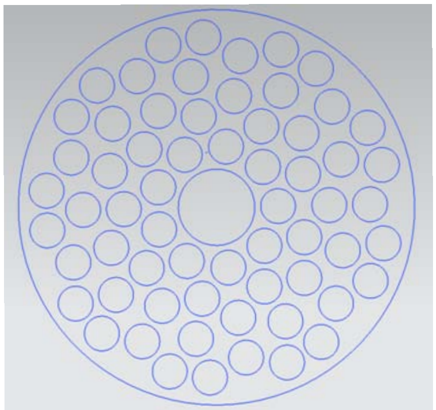


Figure 7 Option 3.



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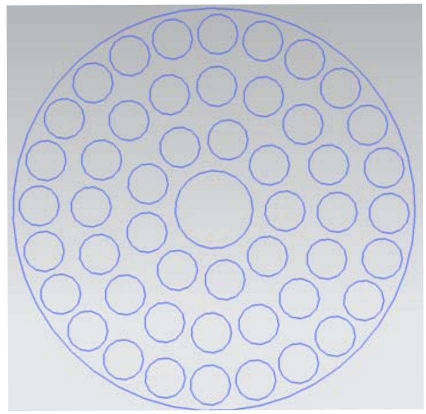

Figure 9 Option 5.

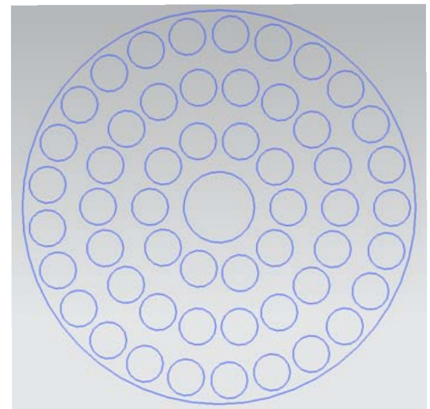

Figure 10 Option 6.

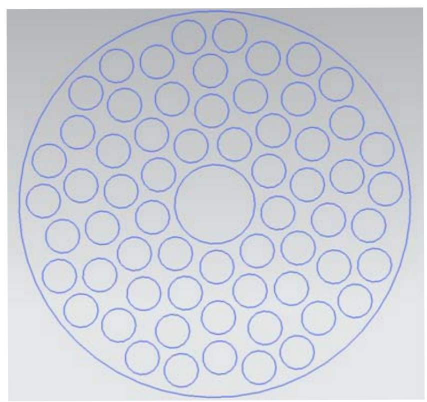

Figure 11 Option 7.

Table 2. Parameters of New Fuel Bundles.

	Variant-20	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
ID Flow Tube (mm)	103.45	103.45	103.45	121.0	103.45	103.45	111	97.4
OD Elements (mm)	11.5	8.80	9.50	9.50	9.127	10.3	10.3	8.50
OD Center Element (mm)	20	20	20	20	20	20	20	20
Number of Heated Elements	42	63	53	63	63	49	53	63
Total Number of Elements	43	64	54	64	64	50	54	64

Fuel-channel design for these bundles is shown in Figure 12. The operating temperature range of the coolant is from 350 to 625°C.

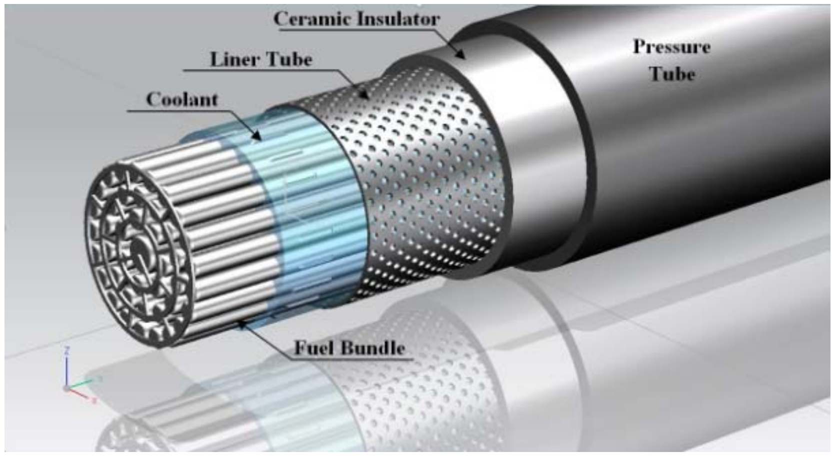

Figure 12 High Efficiency Fuel Channel.

2.3 Analysis of the 64-element fuel bundle

To be able to calculate certain parameters, some restrictions and constant values were stated. The thickness of the fuel elements were kept constant at 0.4 mm, the number of fuel bundles per bundle string was 12, the thermal power per channel was 8.5 MW, the center element was kept unheated with an outer diameter of 20 mm, and the mass flow rate was constant at 4.37 kg/s, for simplicity of the calculations. A restriction that was made on the designs was that the minimum gap between the various element pins would be no less than 1.5 mm to allow for adequate cooling of the fuel and sheath material.

Table 3. Main Parameters of the Seven Fuel Bundle Designs and the Variant-20.

	Variant -20	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**	**Option 7**
	ID_{FT} 103.45 mm	**ID_{FT} 103.45 mm**	**ID_{FT} 121.00 mm**	**ID_{FT} 103.45 mm**	**ID_{FT} 111.00 mm**	**ID_{FT} 103.45 mm**	**ID_{FT} 97.50 mm**	**ID_{FT} 103.45 mm**
	OD_e 11.5 mm	**OD_e 9.50 mm**	**OD_e 9.50 mm**	**OD_e 10.3 mm**	**OD_e 10.3 mm**	**OD_e 8.80 mm**	**OD_e 8.50 mm**	**OD_e 9.127 mm**
Bundle								
Heated Length (m)	0.481							
	Variant -20	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5**	**Option 6**	**Option 7**
Number of Elements	43	54	64	50	54	64	64	64
V_f (cm^3)	1816.57	1578.55	1876.39	1715.56	1855.60	1610.06	1502.15	1731.94

	Variant -20	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
A_h (m^2)	0.73	0.76	0.90	0.76	0.82	0.84	0.81	0.87
A_f (mm^2)	3728.60	4334.34	6719.28	4008.27	4946.62	4259.36	3577.10	3969.30
D_{he} (mm)	7.83	8.80	11.57	8.12	9.30	8.00	6.97	7.24
P_h (m)	1.52	1.58	1.88	1.59	1.71	1.74	1.68	1.81
Heated Diameter (mm)	9.83	10.96	14.29	10.11	11.54	9.78	8.51	8.79
G (kg/m^2s)	1172	1008	650	1090	883	1026	1222	1101
Bundle String								
Heated Length (m)	5.772							
A_h (m^2)	8.76	9.13	10.85	9.15	9.90	10.05	9.71	10.43
q (kW/m^2)	970.5	931.0	783.2	928.8	858.7	845.5	875.4	815.2
V_f (dm^3)	21.8	18.9	22.5	20.6	22.3	19.3	18.0	20.8

* FT: Flow Tube

A three-dimensional model was created of the 64-element fuel bundle using UGS NX 7.5 Software. Three programs were created through Matlab to further analyse the fuel bundle. The first program created used advanced geometry to draw a fuel bundle to the specifications of the user. The program is then linked to two other programs that calculates thermalhydraulic variables according to the bundle modelled in the first program.

To calculate the heat transfer coefficient, the Mokry et al. equation was used:

$$HTC(i) = \frac{k_{bulk}\,(i)}{1000 \cdot D_{hy}} \cdot 0.0061 \cdot \left(\frac{G \cdot D_{hy}}{\mu_{bulk}\,(i)}\right)^{0.904} \mathrm{Pr}_{\mathrm{avg}}\,(i)^{0.684} \cdot \left(\frac{\rho_{wall}\,(i)}{\rho_{bulk}\,(i)}\right)^{0.564} \quad (1)$$

$$\mathrm{Pr}_{\mathrm{avg}}\,(i) = \frac{Cp_{avg}\,(i) \cdot \mu_{bulk}\,(i)}{k_{bulk}\,(i)} \quad (2)$$

As can be seen in Figures 14 and 15, under some conditions the fuel centerline temperature for the reference 43-element Variant-20 fuel bundle with UO_2 as a fuel may exceed the industry accepted limit of 1850°C. However, the fuel centerline temperature in Figure 16 is approximately 1400°C, i.e., 450°C below that of the industry accepted limit. The fuel center line temperature in Figure 17 is approximately 1500°C, i.e., 350°C below that of the industry accepted limit.

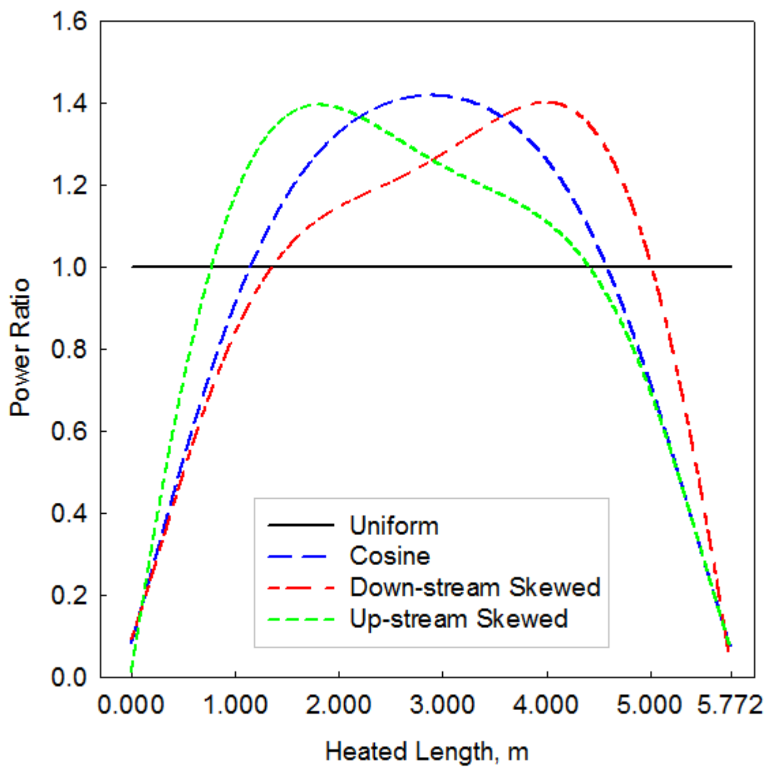

Figure 13 Axial Heat Flux Profiles (AHFPs).

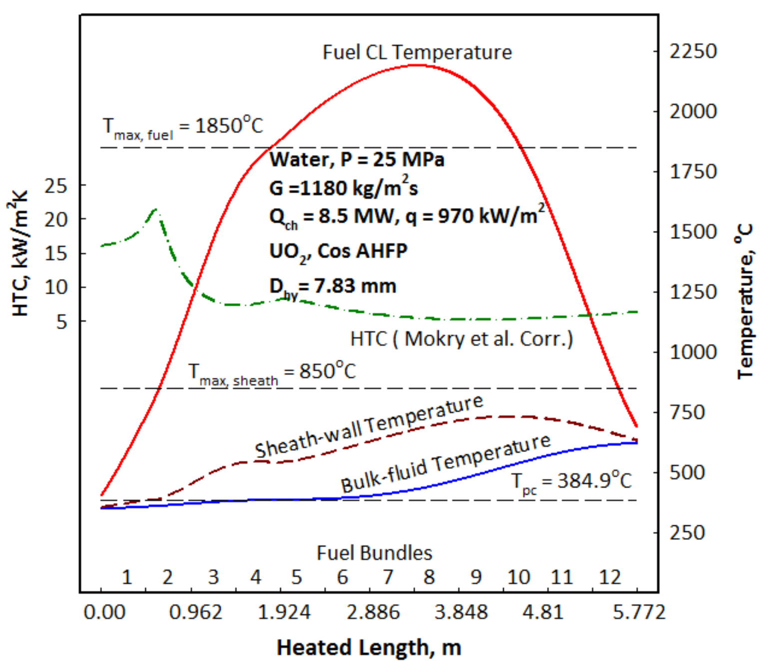

Figure 14 Cosine AHFP, UO_2 fuel, Variant-20 bundle.

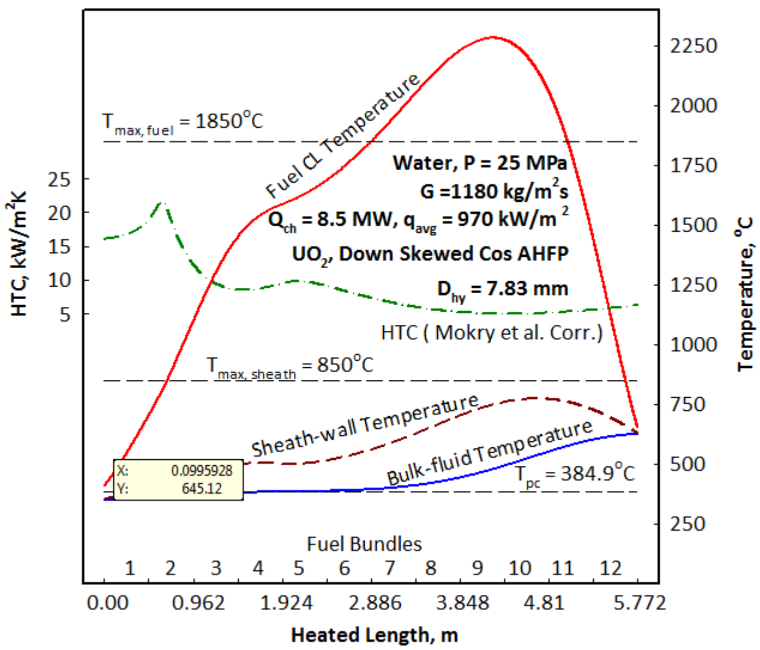

Figure 15 Down-stream Skewed AHFP, UO_2 fuel, Variant-20 bundle.

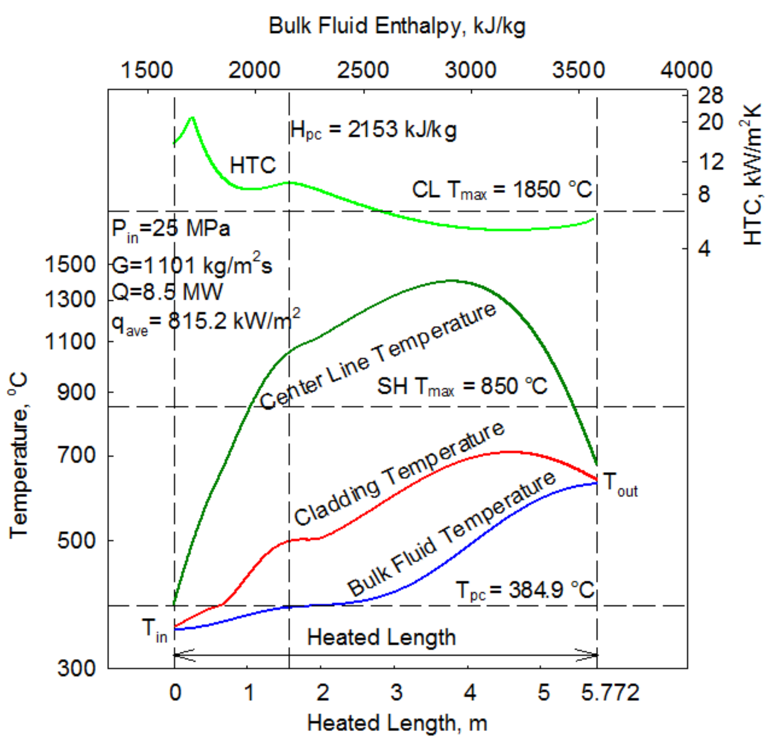

Figure 16 Cosine AHFP, UO_2 fuel, 64-element bundle.

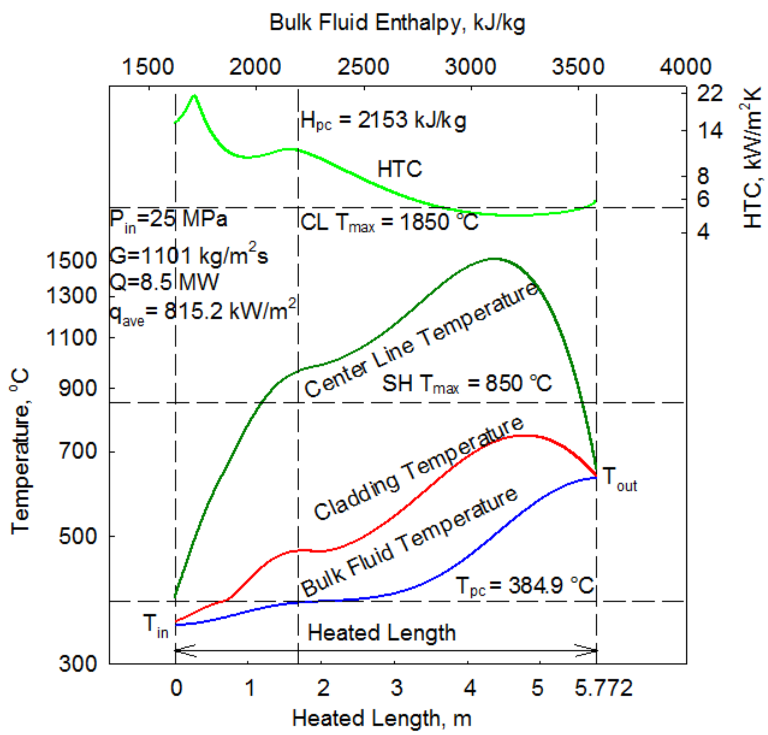

Figure 17 Down-stream Skewed AHFP, UO_2 fuel, 64-element bundle.

3.0 Conclusion

A new 64-element fuel bundle was designed to operate at supercritical-water conditions with an outlet temperature of 625°C at 25 MPa as a replacement for the 43-element Variant-20 fuel bundle, which might not be used at these conditions in application to SCWR, because within certain conditions, such as cosine and downstream-skewed cosine AHFPs, the fuel centerline temperature may exceed the industry accepted limit of 1850°C when UO_2 is utilized as a fuel. The fuel centerline temperatures in the 64-element bundle with smaller OD fuel elements are below the industry accepted limit by 450 and 350°C at cosine and downstream-skewed cosine AHFPs, respectively. These results show that the 64-element fuel bundle can be a potential candidate for implementation in SCWRs.

4.0 Nomenclature

V_f:	Fuel Volume
ID_e:	Inner Diameter of the Elements
N_h:	Number of Heated Elements
A_h:	Heated Area
OD_e:	Outer Diameter of the Elements
A_f:	Flow Area
ID_{PT}:	Inner Diameter of the Perforated Tube
D_{he}:	Hydraulic-Equivalent Diameter
P_w:	Wetted Perimeter
P_h:	Heated Perimeter
G:	Mass Flux
$\dot{m}$:	Mass Flow Rate
q:	Heat Flux
HTC:	Heat Transfer Coefficient

k_{bulk}:	Thermal Conductivity
D_{hy}:	Hydraulic Diameter
μ_{bulk}:	Dynamic Viscosity
ρ_{wall}:	Wall Density
ρ_{bulk}:	Bulk Density
Pr_{avg}:	Average Prandtl Number
Cp_{avg}:	Average Specific Heat

5.0 Abbreviations and Acronyms

SCWR:	SuperCritical Water-cooled Reactor
AHFP:	Axial Heat Flux Profile
UO_2:	Uranium Dioxide
GFRs:	Gas Cooled Fast Reactors
LFRs:	Lead-Cooled Fast Reactors
MSRs:	Molten Salt-Cooled Reactors
SFRs:	Sodium Cooled Fast Reactors
VHTRs:	Very High-Temperature Gas-Cooled Reactors
CANDU:	Canada Deuterium Uranium
REFPROP:	REFerence PROPerties
MATLAB:	MATrix LABoratory
CANFLEX:	CANdu FLEXible Fuelling

6.0 References

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