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Preliminary no core melt assessment for Canadian SCWR with modified SCTRAN

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Abstract

With developing a two-dimensional conduct solution and incorporating a radiation model, safety analysis code SCTRAN for SCWR is modified to own the ability to evaluate radiation heat transfer in this paper. The verification of code SCTRAN radiation model is carried out through code-to-code comparison with CATHENA. Comparison result shows that the modification of SCTRAN is successful and the calculation accuracy is acceptable. Then SCTRAN is applied to analysis the LOCA with loss of ECCS accident of Canadian SCWR to verify its "no core melt" concept. The results demonstrate that the Canadian SCWR has the potential to accomplish the object of "NO-CORE-MELT".

1. Introduction

AECL is developing the Canadian SCWR[1], which has evolved from the well-established pressure-tube type CANDU reactor. A National Program has been established in Canada to support R&D studies for the Canadian SCWR design[2]. Safety analysis is required to demonstrate an acceptable safety case for any reactor design. Since the radiation heat transfer play an important role in LOCA accident, a two-dimensional conduction and a radiation heat transfer model should be incorporated into code SCTRAN. Then this paper documents the SCTRAN thermal-hydraulic idealization for the Canadian SCWR based on the current conceptual design, which has been described in details by D.F. Wang and S. Wang[3]. The analyses of loss of coolant accident with loss of emergency core cooling (LOCA/LOECC) was performed in this paper to provide some references for the concept development of Canadian SCWR.

2. Modification of SCTRAN

SCTRAN is a safety analysis code developed by Xi'an Jiaotong University, which can be applied to simulate the accident at both subcritical and supercritical pressures. A homogenous model and a four-equation dynamic slip model are implemented into the code as optional modes. The auxiliary models referring to the popular commercial codes like RELAP5 and RETRAN, which consist of water properties, heat transfer coefficient, friction coefficient, critical heat flux and so on, are included. The Jackson correlation is applied in code SCTRAN to evaluate the heat transfer at supercritical pressures. The blowdown experiment from supercritical pressure to subcritical pressure was simulated by SCTRAN in order to make a comparison with code APROS. Besides, the LOFA and LOCA analyses of US SCWR were carried out by code SCTRAN to make a comparison with code RELAP5-3D. The simulation results imply that SCTRAN is capable of carrying out safety analysis for SCWRs[4]. SCTRAN has been applied to analysis the accident consequences of Chinese pressure vessel type concepts, such as CSR1000[5], CGNPC SCWR[6].

Canadian SCWR is a pressure tube type SCWR concept. One of its most distinguish features is that the radiation exchanges between the surfaces in the HEC channels play a very important role when some unlikely events happen, like LOCA/LOECC. In order to simulate such accident scenarios of Canadian SCWR, a radiation heat transfer model should be incorporated into code SCTRAN. The surfaces of the fuels adopt different amount of radiation heat from different directions, which further resulted in a circumferential conduction in the fuel rods. Thus, before the development of radiation heat transfer model, the original one-dimensional conduction in code SCTRAN should be updated to two-dimensional mode firstly. With the known surface temperatures obtained from last time step and the radiation heat transfer model, the radiation exchanges in the HEC channel can be confirmed quantitatively.

2.1 Two-dimensional conduction model

The differential equation of heat conduction problem which owns internal heat source is shown as below:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left[\lambda \nabla T \right] + S \tag{1}$$

The first term at the right side of the equation(1) is the energy variation with space while the last term stands for heat source of the heat structure.

In the two dimensional polar coordinate, the conduction equation can be rewritten as:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda \cdot r \frac{\partial t}{\partial r}) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}(\lambda \frac{\partial t}{\partial \varphi}) + S \tag{2}$$

The symbol r represent the distance in the radial direction and the φ represent the angle in the circumferential direction.

In order to reduce the calculation iteration and guarantee the calculation accuracy simultaneously, the fuel rod is separated into four sectors in the circumferential direction. The mesh layout for the two-dimensional heat conduction is shown in Figure 1. Point P , N, S, W, E need temperature calculation. The material properties and temperatures in a half mesh interval are assumed as constants over a time interval. For the control volume of point P which is shadowed in Figure 1, the internal energy increase equals to the inner heat source plus the heat conducted from the surrounding control volume. Thus the discrete equation can be obtained:

$$\left(\rho c_p\right)_p \frac{(r_n + r_s)}{2} \frac{\Delta r \Delta \theta}{\Delta t}\left(T_p - T_p^0\right) = \left(\frac{r_n \lambda_n (T_N - T_p)}{(\delta r)_n} - \frac{r_s \lambda_s (T_P - T_S)}{(\delta r)_s} \right) \Delta \theta +$$
$$\left(\frac{\lambda_e (T_E - T_p)}{(\delta \theta)_e r_e} - \frac{\lambda_w (T_P - T_W)}{(\delta \theta)_w r_w} \right) \Delta r + S \Delta V \tag{3}$$

The left part of the equation represents the internal energy increase of point P. The first term on the right side of the equation present the heat conducted from point N and S. The second term simulate the heat conducted from point E and W while the last term is the inner heat source.

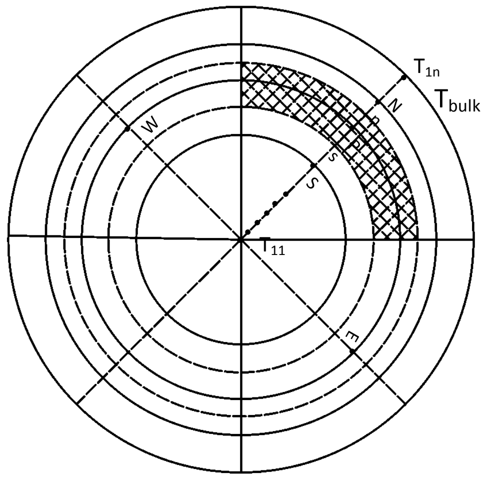

Figure 1 Mesh layout of the heat structure

The equation (3) can be simplified into the following form:

$$a_P T_P = a_E T_E + a_W T_W + a_N T_N + a_S T_S + b \qquad (4)$$

Among them:

$$\Delta V = 0.5(r_n + r_s)\Delta r \Delta\theta,\ a_P^0 = \frac{(\rho c_p)_P \Delta V}{\Delta t}$$

$$b = S\Delta V + a_P^0 T_P^0,\ \Delta r = (r_N - r_S)/2$$

$$a_E = \frac{\lambda_e \Delta r}{(\delta\theta)_e r_e},\ a_W = \frac{\lambda_w \Delta r}{(\delta\theta)_w r_w}$$

$$a_N = \frac{r_n \lambda_n \Delta\theta}{(\delta r)_n},\ a_S = \frac{r_s \lambda_s \Delta\theta}{(\delta r)_s}$$

$$a_P = a_E + a_W + a_N + a_S + a_P^0$$

Every node in the mesh layout owns a heat conduction equation like equation (4). There are five unknown node temperatures in each equation. Uniting the temperature equations for all nodes and solving them together will be absolutely a time consuming task. In order to save computer memory and calculation time, the conduction equations will be solved sector by sector. The node temperature in the radial direction of the sector is solved together assuming that the node properties of the west and east sectors apply values at the last iteration:

$$a_P T_P^{(n)} = a_N T_N^{(n)} + a_S T_S^{(n)} + a_E T_E^{(n-1)} + a_W T_W^{(n-1)} + b \qquad (5)$$

The equation (5) has only three unknown parameters and the temperature node in this sector can be solved by TDMA method with the corresponding boundary conditions. When the solution of this sector is finished, physical properties of the nodes in this sector are updated. The radial heat conduction calculation moves to the next sector in the clockwise direction until all the node temperature satisfy the convergence criterion. In this way, the two-dimensional heat conduction solution is divided into many one-dimensional solutions and the calculation efficiency is greatly promoted.

2.2 Radiation heat transfer model

The radiation heat transfer will be one of the boundary conditions for the heat conduction solution. The cross section of the 64-element HEC channel is illustrated in Figure 2. The outer surface of the central channel, the surfaces of the fuel rods in the inner and outer rings, and the inner surface of the linear tube make up a radiation enclosure. The radiation exchange from different elevations is ignored. Assumptions of the radiation heat enclosure are made firstly:

1. All surfaces in the system are diffusive and grey;
2. The coolant in the pressure tube neither emits nor absorbs radiant thermal energy;
3. Reflectance from a surface is neither a function of incident nor reflected direction nor of radiation frequency.

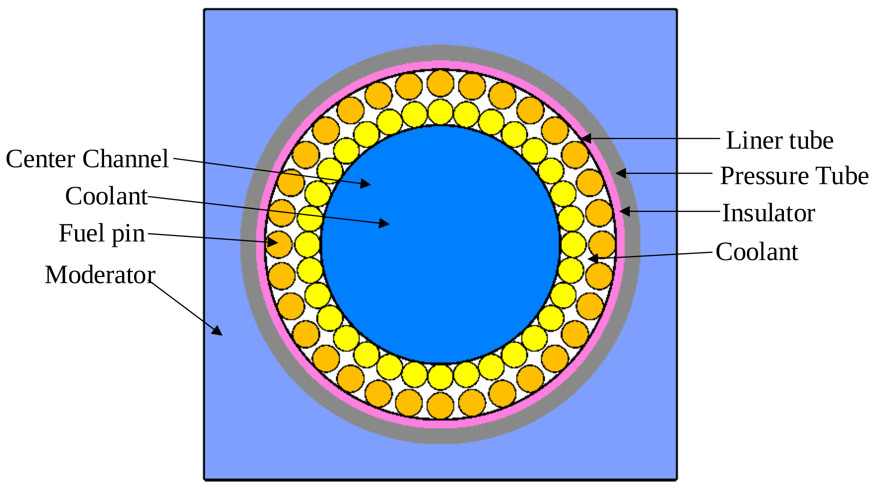

Figure 2 Cross-section of the pressure tube in the latest version

2.2.1 Net heat flux

The radiosity of a surface is the radiant energy flux leaving a surface (i.e., the emitted energy flux plus the reflected energy flux). The energy balance for the i-th surface is:

$$A_i R_i = A_i \varepsilon_i \delta T_i^4 + \rho_i \sum_{j=1}^{n} R_j A_j F_{ji} \qquad (6)$$

$$R_i = \varepsilon_i \delta T_i^4 + \rho_i \sum_{j=1}^{n} R_j \frac{A_j}{A_i} F_{ji} \qquad (7)$$

With considering the conservation of energy, the area times view factor from surface i to any other surface j must equal the area of j times the view factor from j to i:

$$A_i F_{ij} = A_j F_{ji} \qquad (8)$$

Substitute equation (8) into equation (7) and the following form is achieved:

$$R_i = \varepsilon_i \delta T_i^4 + \rho_i \sum_{j=1}^{n} R_j F_{ij} \tag{9}$$

The net heat flux at surface i, Q_i, is the difference between the radiosity for surface i and radiosity throwing to surface i from all surfaces, and it's given by:

$$Q_i = R_i - \sum_{j=1}^{n} R_j F_{ij} \tag{10}$$

Combine equation (9) and equation (10) and the expression for the net heat flux of surface i is obtained:

$$Q_i = \frac{\varepsilon_i}{\rho_i}(\delta T_i^4 - R_i) \tag{11}$$

In equation (11), the reflectivity and emissivity are the basic physical properties of surface I, which are assumed to be independent of surface temperature in this paper. The surface temperature apply the results from last time step. So, the radiosity is the only unknown parameter in the equation (11).

2.2.2 Radiosity solution

On the basis of equation (9), the radiosity of all the surfaces can be calculated by the following equations:

$$\begin{aligned}
&i=1: (1-\rho_1 F_{11})R_1 + (0-\rho_1 F_{12})R_2 + (0-\rho_1 F_{13})R_3 \cdots (0-\rho_1 F_{1n})R_n = \delta \cdot \varepsilon_1 T_1^4 \\
&i=2: (0-\rho_2 F_{21})R_1 + (1-\rho_2 F_{22})R_2 + (0-\rho_2 F_{23})R_3 \cdots (0-\rho_2 F_{2n})R_n = \delta \cdot \varepsilon_2 T_2^4 \\
&\quad\vdots \\
&i=i: (0-\rho_i F_{i1})R_1 + (0-\rho_i F_{i2})R_2 \cdots (1-\rho_i F_{ii})R_i \cdots (0-\rho_i F_{in})R_n = \delta \cdot \varepsilon_i T_i^4 \\
&\quad\vdots \\
&i=n: (0-\rho_n F_{n1})R_1 + (0-\rho_n F_{n2})R_2 + (0-\rho_n F_{n3})R_3 \cdots (1-\rho_n F_{nn})R_n = \delta \cdot \varepsilon_n T_n^4
\end{aligned} \tag{12}$$

Referring to the previous literature[7], the surface emissivity of the central channel and the pressure tube are set 0.34 while the emissivity of the fuel rod is 0.8. The sector distribution of the HEC channel is shown in Figure 3, which is used to generate the view factors of the radiation closure. All the surfaces are divided in a radially symmetrical way with the pressure tube and center pin being divided circumferentially into 32 sectors and all the fuel rods being divided into 4 sectors. The pressure tube and the central channel apply one-dimensional conduction solution because circumferential heat conduction doesn't exists in their conduction solution. That's the reason why they can be separated into arbitrary number of sectors. The view factors are calculated by CATHENA GEOFAC code, which is supplied by AECL.

As one radiation closure is made up of 1 central channel, 64 fuel rods and 1 pressure tube in this paper, there are total 320 unknown radiosity in equation (12), requiring a large amount of computer space and calculation time to solve the linear system of equations. The direct solution of a 320 plus 320 linear equations is not recommended. Since the sector separation is carried out in a radially symmetrical way, the sector radiosity at the same position of each surface are identical. For example, the sector 33, sector 37 and sector 41 own the same radiosity because they are located in the same position of the fuel rods in the circumferential direction. Applying this theory to the whole radiation closure, the original 320 unknown elements in the above equations are greatly reduced to 10 unknown elements, which are separately R_1, R_{33}, R_{34}, R_{35}, R_{36}, R_{161}, R_{162}, R_{163}, R_{164}, R_{289}. The linear equations become smaller and it's easier to get the solution of the radiosity matrix.

With the solved radiosity of each surface, the net heat flux can be obtained through the equation (11).

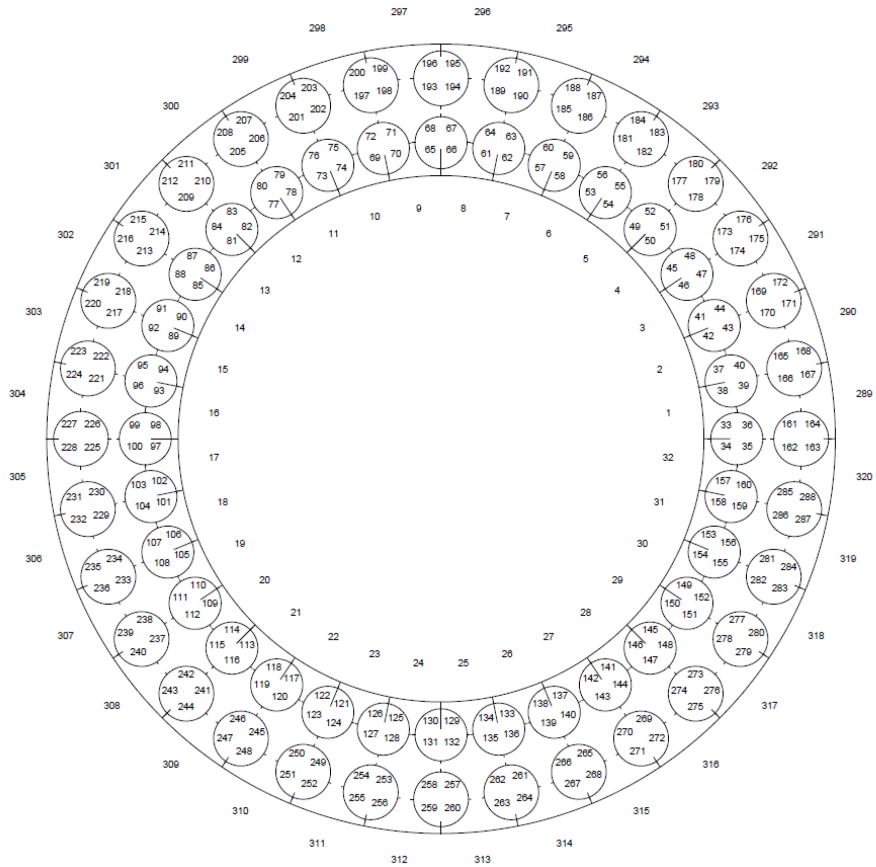

Figure 3 Sector distribution in CATHENA GEOFAC

2.3 Conduction solution with considering the radiation effect

The net heat flux created by the radiation exchange plus the convective heat transfer will be used as the boundary condition of the two-dimensional heat conduction:

$$-k\frac{\partial T}{\partial n}\bigg|_i = h_i(T_i - T_{sk}) + Q_i \qquad (13)$$

The radiation heat Q_i in equation (13) is also a function of surface temperature. In order to simplify the solution, the surface temperatures requiring to figure out the radiation heat of all the surfaces apply the values at last time step. The radiation heat will keep constant in the current time step and the temperature iteration for the radiation heat solution is avoided.

3. Verification of SCTRAN radiation model

Due to the lack of experimental data, the verification of SCTRAN radiation model is carried out by code to code comparison with Canadian system code CATHENA. CATHENA is a one-dimensional, two-fluid thermal-hydraulic computer code. It includes one-dimensional and two-dimensional heat conduction models(GENHTP). Its ability to evaluate the radiation heat transfer has been validated by Lei and Goodman[8].

A 64 fuel bundle HEC channel of the Canadian SCWR is chosen as the analysis object of the verification. The cross-section of the HEC channel is shown in Figure 2. The total power of the fuels is set to 0.75MW, with the inner fuels occupying 44% and outer fuels occupying the left 56%. The detailed structure dimension is included in the paper of D.F. Wang and S. Wang[3]. The situation that the HEC channel is empty of coolant and the fuel power of different level(2%,3%,4%) is transferred to the moderator only by radiation is simulated by both code SCTRAN and CATHENA. Every surface in the HEC channel is marked by a number, as shown in Figure 4. The outer surface of the central channel is marked as S1, the four sectors of the fuels in the inner ring are marked as S2, S3, S4, S5, the four sectors of the fuels in the outer ring are marked as S2, S3, S4, S5 and S10 represents the inner surface of the pressure tube. Only one fuel rod of each ring is shown and other fuel rods are ignored in Figure 4. Figure 5 shows the comparison of fuel surface temperature at the steady state of different power level(2%, 3%, 4%).

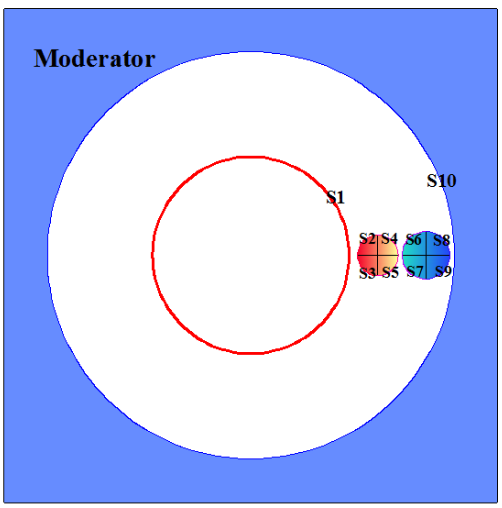

Figure 4 Numberred surfaces of HEC channel

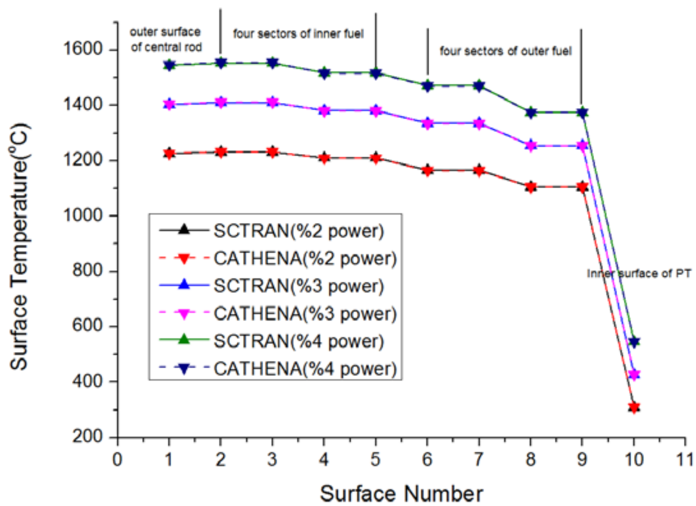

Figure 5 Result comparison between SCTRAN and CATHENA

When the radiation heat conducted by the pressure tube equals to the fuel power, heat transfer of the fuel rod meets a state of dynamic equilibrium. From Figure 5 we can see that surfaces at the axisymmetric position, such as S2/S3, S4/S5, S6/S7, S8/S9, own the same surface temperature. That is because they produce the same nuclear power and emit the same radiation power. The surfaces closing to the pressure tube own a lower surface temperature. Additionally, the higher the power level is, the larger surface temperature becomes.

Figure 5 shows the results of code SCTRAN and CATHENA. The surface temperature obtained from code SCTRAN agree well with the results of code CATHENA. The temperature differences between them can hardly be pointed out from the figure. Table 1 includes the surface temperature of HEC channel at different power level(2%, 3%, 4%) calculated by code SCTRAN and CATHENA. The biggest absolute error and relative error of surface temperature between results of code SCTRAN and

CATHENA are 3.3^{o}C and 0.27%, which is acceptable in temperature prediction. The result comparison shows that the new radiation model in code SCTRAN work quite well and the calculation accuracy can be guaranteed.

Table 1 Surface temperature of the HEC channel at different power level calculated by code SCTRAN and CATHENA

Code	Power(%) \ T(℃)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
SCTRAN	2	1226.2	1232.1	1232.1	1211.1	1211.1	1166.4	1166.4	1106.0	1106.0	309.6
	3	1403.6	1410.3	1410.3	1382.3	1382.3	1336.5	1336.5	1255.5	1255.5	426.8
	4	1545.3	1552.79	1552.7	1518.7	1518.7	1472.5	1472.5	1374.8	1374.8	545.9
CATHENA	2	1227	1233	1233	1210	1210	1165	1165	1106	1106	310
	3	1405	1412	1412	1381	1381	1335	1335	1255	1255	428
	4	1547	1555	1555	1517	1517	1471	1471	1375	1375	547

4. Analysis for LOCA with a loss of ECCS

In order to make sure whether the Canadian SCWR can achieve the potentially "no-core-melt" condition, "LOCA with a loss of ECCS" is simulated by the modified SCTRAN code. When LOCA occurs, the core lose most of its inventory. The core will suffer a terrible cooling condition. With no aids from ECCS simultaneously, the decay heat in the fuels can be transferred by thermal radiation to the liner tube and by the natural circulation of the high-temperature steam. The double-ended break accident at the cold leg is regarded as the analysis target for that it is the most serious LOCA accident. In the simulation of LOCA/LOECC, the emissivity of the linear tube, central channel, and fuel rod are separately set 0.34, 0.34 and 0.8[7].

In the process of LOCA/LOECC, the coolant in the HEC channel become high-temperature steam after the break occurred because of the core heating and depressurization. With the coolant leaking out from the break continuously, the coolant inventory in the HEC channel become less and the cooling condition deteriorate. How to simulate such a bad cooling condition accurately is a very important problem. The Dittus-Boelter correlation is applied to code SCTRAN to evaluate the forced convection heat transfer of the steam. In code SCTRAN, the minimum value of Dittus-Boelter correlation is set as 28 W/m^{2}•K, which means that all the heat transfer coefficient lower than 28 will be set 28 compulsively. If the high-temperature steam in the HEC is regarded as 1000^{o}C, and the fuel cladding temperature is regarded as 1100^{o}C, the natural convection heat transfer coefficient calculated by churchill correlation[9] will be 142 W/m^{2}•K. In the real situation, the temperature difference between the coolant and the fuel cladding is larger and the coeffcient will be larger. In this paper, the high-temperature steam heat tranfer is calcualted by heat transfer coefficient of 28 W/m^{2}•K, which is much lower than the value obtained from churchill correlation, to gurantee conservative simualtion results. The accurate heat transfer condition in the HEC channel should be confirmed by experiment in the future.

As the HP channel owns the largest power fraction and the highest cladding temperature, it's selected to be the main analysis object in the LOCA/LOECC analysis and sensitivity analyses. The maximum surface temperature among the 4 sectors will be considered as the surface temperature of each heat structure and it will be applied to describe the surface temperature variation. Considering that the candidate sheath material for the Canadian SCWR is a stainless steel, the melting temperatures typical varying from 1300^{o}C to 1500^{o}C is the temperature limit of the LOCA/LOECC analysis.

4.1 SCTRAN model of Canadian SCWR

The demension of 64-element bundle is derived from the 62-element bundle. The dimension difference of these two HEC concept is listed in Table 2. The other parameters are the same and the detailed information can be found in the paper of D.F. Wang and S. Wang [3].

Table 2 The dimension difference of 62- and 64-element bundle

		64-element bundle	62-element bundle
Inner ring	pitch circle radius	5.4	5.3
	radius of fuel pins	0.435	0.415
	outer radius of pin cladding	0.475	0.475
Outer ring	pitch circle radius	6.575	6.55
	radius of fuel pins	0.46	0.465
	outer radius of pin cladding	0.5	0.525

The SCTRAN model of Canadian SCWR is shown in Figure 6. The core is divided into four groups of 84 fuel channels. Control volumes 11-20 denote LP; Control volumes 31-40 denote AP; Control volumes 51-60 denote MP; Control volumes 71-80 denote HP. Control volumes 130-190 and 230-290 simulate inlet pipes of the two loops while volumes 410-490 and 510-590 represent outlet pipes. A time dependent junction with temperature of 350 ^{o}C and flowrate of 1254.02 kg/s, as well as a time dependent volume with temperature of 625 ^{o}C and pressure of 25 MPa, are separately set as the boundary conditions of the main coolant line and main steam line. The passive moderator system is also simulated, which is control volume 800, serving as the ultimate heat sink. To simplify the analysis, the moderator temperature is assumed to be kept 80 ^{o}C in all the accident and its heat exchange with the pressure tube will be calculated by a constant coefficient of 1000 W/(m^{2}•K), which indicate that the moderator remove the core heat through natural convection. Turbine stop valves are installed between 430 and 490 as well as between 530 and 590, which will be tripped by the power scram signal in this analysis. The principal operating parameters of Canadian SCWR are listed in Table 3.

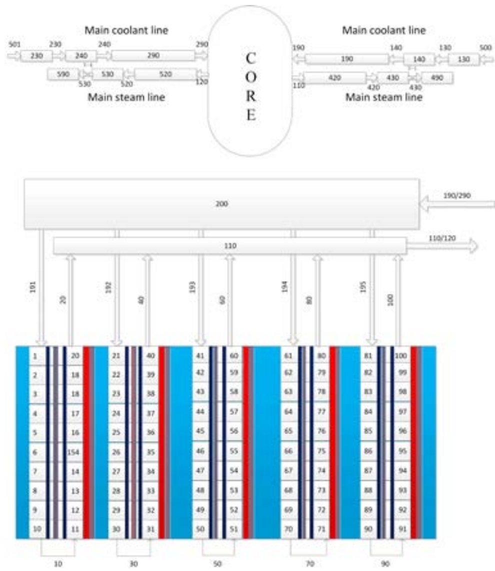

Figure 6 SCTRAN model of PT-SCWR system

Table 3 Operating parameters of Canadian SCWR

Parameters	Design Value	SCTRAN Value	Error
Pressure(Mpa)	25	25	0%
Coolant flow rate(kg/s)	1254	1254.02	0.015%
Thermal power(MW)	2541	2541	0.0%
Inlet/outlet temperature(^{o}C)	350/650	350.7/624.6	0.2%/0.06%

4.2 Results of LOCA with a loss of ECCS

In this LOCA accident, the break at the cold-leg occurred at 0.5s. At 1s, the control rods started to drop and the core power decreased. At the same time, the turbine stop valve was closed. The coolant flowrate from the main coolant pump was maintained in the first 10s and then decreased to zero in 5s(actually decided by the pump inertia).

Figure 7 shows the coolant flowrate through the break at cold leg. When the break occurred, large amount of coolant were drained out through the break at a critical velocity. The core pressure decreased quickly to the subcritical level because of coolant loss. In the first 10s, the main coolant line kept injecting coolant while most of it was directed to the break. The coolant of high temperature in the outlet plenum was directed to flow through the HEC channels and drained out through the break with the coolant in the inlet plenum. The flow scheme in LOCA condition is illustrated in Figure 8. After about 20s, the core pressure was close to the atmospheric pressure and the break coolant flowrate decreased to a low level.

The coolant flowrate in the different power channels are shown in Figure 9. The break located in the cold leg resulted in a big pressure difference between the inlet and outlet plenum. The flow direction were reversed. Large amount of coolant of 625°C from the outlet plenum was directed to the core coolant channel, which resulted in a bad cooling conditions. Therefore the fuel sheath and channel component temperatures increased quickly in this period, as shown in Figure 11.

Figure 10 clearly shows that the power produced by the fuel rods can't be totally removed in the first several seconds and the MCSTs of both rings increased sharply. With the power decreasing and the reversing flow being established, MCSTs kept a slow increasing trend, even had a little temperature drop at about 15s. However, when the coolant in outlet plenum was exhausted, the cooling conditions in the coolant channel deteriorated. The HEC channels were filled with high temperature steam and the radiation exchange became dominant in the heat transfer of HEC at 30s. The radiation exchanges and natural convection in the HEC at this time were not large enough to remove all the core power. In Figure 11, the MCST of the inner and outer ring started to rise again at 20s. Due to the protection from the insulator, the outer surface of the pressure tube remained at a low temperature of 200°C. The temperature decrease of the linear tube at 15s was resulted by the cooling deterioration in the HEC channel.

With time going on, the fuel cladding temperature increased continuously because of the core heating. At about 200s, when MCSTs of the inner and outer ring reached 1296°C and 1253°C respectively, heat transfer of the fuel rods became larger than the decay heat of the fuel rods. The MCST started to decrease slowly, as shown in the Figure 12. The fuel rod would reach a steady state when its net radiation heat equals to the decay heat. However, the decay heat was slowly decreasing with time, which resulted in the continuous temperature decrease of the fuel sheath. Figure 13 illustrated the comparison of the core power and the heat produced by the radiation heat exchanges and natural convection. When the power produced by HP channel was reduced to about 16.9 MW at 200s, the heat transfer of the fuel rods equaled to the decay heat, which means that about 2.5% of the decay power can be totally removed by the radiation heat transfer.

Likewise, performance of the other three channels were similar to that of the HP channel and the MCST variations are shown in Figure 14. The HP channel owned the highest MCST because of its highest core power portion.

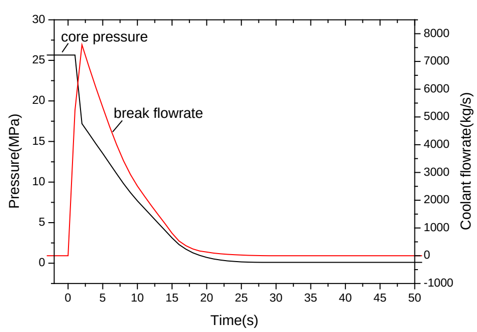

Figure 7 the variations of core pressure and break coolant flowrate in the first 50s of LOCA

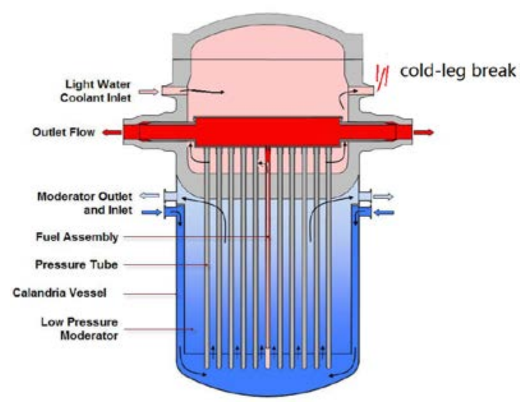

Figure 8 The flow scheme when LOCA occurs

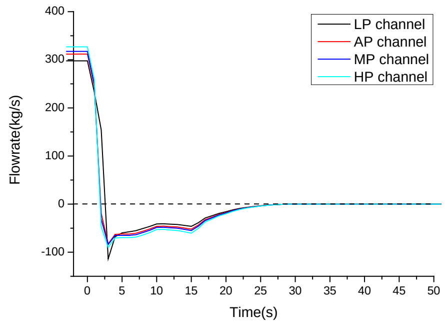

Figure 9 the coolant flowrate in each flow channel

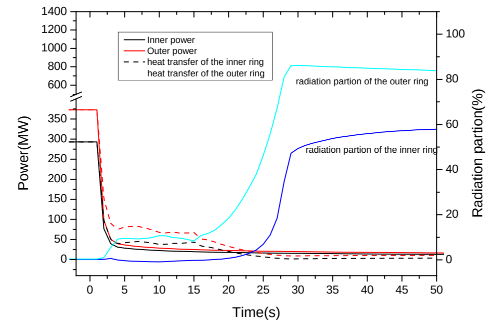

Figure 10 the comparison of core power and heat transfer, the radiation portion variation in the HP channel

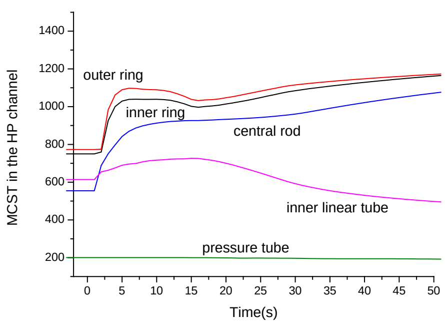

Figure 11 MCST variation in the HP channel in the first 50s

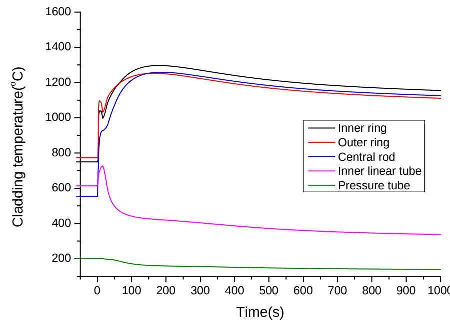

Figure 12 MCST variation in the HP channel

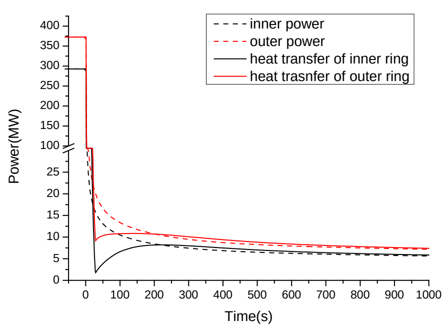

Figure 13 Comparison of radiation heat and the core power in HP channel

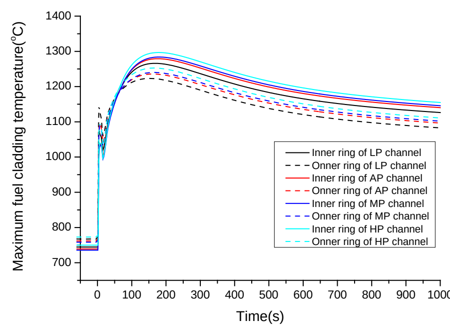

Figure 14 MCST variation in all the coolant channels

4.3 Sensitivity analysis

In the analysis of LOCA/LOECC, different design parameters and hypotheses will influence the core performance in different manners, i.e. the outlet plenum volume, heat transfer coefficient of moderator, natural convection heat transfer coefficient. Sensitivity analyses about these parameters are carried out to identify their effects on the analysis results and provide a reference for the future study.

4.3.1 Outlet plenum volume

In the process of LOCA with loss of ECCS, coolant of 625^{o}C in the outlet plenum flow through the coolant channel reversely. The outlet plenum volume determines how many coolant can be used to cool the heating core. It's an important parameter and three different plenum volumes, which is shown in Table 4, are selected to make a sensitivity analysis about its effects on the fuel sheath temperature. The outlet plenum volume of these three cases are 45.3, 33.97 and 22.65 m^3, respectively. When LOCA occur, the coolant inventory decrease sharply and the flow direction in the HP channel is reversed. Case 1 owned a bigger coolant inventory in the outlet plenum, which results in a larger reversed flowrate in the HP channel. Thus, the MCSTs of the both rings of HP channel are smaller than those of the other two cases. The MCST differences among the three cases exist but it is small, about 8 or 10 ^{o}C, as shown in Table 4. The outlet plenum volume mainly effect the core cooling in the pro-phase of LOCA/LOECC. After experiencing the different MCST peaks, the final MCST variations are identical in the three cases.

Table 4 MCST of different cases in LOCA

Case NO.	Case 1[1]	Case 2	Case 3
Outlet plenum volume(m3)	45.3	33.97	22.65
MCST of the inner ring(^{o}C)	1296.1	1305.8	1313.5
MCST of the outer ring(^{o}C)	1253.1	1261.9	1269.7

4.3.2 Heat transfer coefficient of moderator

In the process of LOCA/LOECC, the moderator pump is also considered to be disabled. Natural convection should be the heat transfer mode between the moderator and the pressure tube. As we all know, heat transfer coefficient of the natural convection ranges from 200 to 1000 W/m^2•K. This heat transfer coefficient may influence the moderator's ability on transferring core decay heat. Thus three different coefficients from 200 to 1000 W/m^2•K are selected to make a primary assessment. The heat transfer coefficients of the moderator of different cases are shown in Table 5. The different heat transfer coefficients resulted in different steady states. Case 1 has the highest sheath temperature of pressure tube and linear tube in the steady state. In the process of LOCA/LOECC, the linear tube sheath temperature of Case 1 is the highest because of the worst convection heat exchange on the moderator side. Due to the mentioned reasons, Case 1 owns the biggest peak cladding temperature, while Case 3 owned the smallest peak cladding temperature. Table 5 shows the different peak cladding temperature of both rings in whole cases. The MCST differences of both rings between Case 1 and Case 3 are separately 12.6^{o}C and 14.8 ^{o}C.

Based on the above analysis, the conclusion can be made that good heat exchange capacity of moderator is helpful for the core cooling in the process of LOCA/LOECC. However, it doesn't make a great change on the MCST of the fuel rods.

[1] The parameters of case * come from the input data of LOCA/LOECC

Table 5 MCSTs of different cases in LOCA

Case NO.	Case 1	Case 2	Case 4*
Heat transfer coefficient from moderator to pressure tuebe(W/m2•K)	200	500	1000
MCST of the inner ring(°C)	1308.7	1300.1	1296.1
MCST of the outer ring(°C)	1267.9	1256.7	1253.1

4.3.3 Natural convection heat transfer

As mentioned in former section, the natural convection heat transfer of the steam in HEC play a important role in the process of LOCA/LOECC. Here a sensitivity analysis about natural convection heat transfer coefficient will be carried out to discuss about effect of the convection heat transfer in LOCA/LOECC. Table 6 shows the different minimum values in 10 cases.

Case 1~5 apply the coefficient of the air natural convetion and Case 10 apply the heat transfer coefficent of fully developed laminar flow. From Table 5, we can see that the natural convection heat transfer is crucial in deciding how much heat can be transferred by convection manner. When the convection heat transfer increase in the HEC channels, the fuel sheath temperature of the inner and outer ring decrease. Conclusion be can made that natural convection heat transfer has a great effect on the fuel sheath temperature. The precise heat transfer coefficient prediction of high-temperature low-velocity steam is necessary.

Table 6 MCSTs of different cases in LOCA

Case No.	Natural convection heat transfer coefficient(W/m^2•K)	MCST in the inner ring(°C)	MCST in the outer ring(°C)	Comment
1	1	1461.3	1384.2	Air natural convection
2	3	1446.7	1372.2	Air natural convection
3	5	1432.8	1360.7	Air natural convection
4	8	1413.5	1344.8	Air natural convection
5	10	1401.4	1335.1	Air natural convection
6	15	1374.2	1312.9	
7	20	1350.2	1293.9	
8	25	1329.1	1277.2	
9*	28	1296.1	1253.1	
10	38	1284.3	1242.8	Fully developed laminar flow

5. Conclusion

In this report, a two-dimensional conduction is developed for SCTRAN. Meanwhile, with the view factors calculated by code CATHENA and the assumption that sector located in the same position of each fuel adopt the same radiation heat from other surfaces, the radiation equation set of each radiation enclosure can be easily solved. The two-dimensional conduction and the radiation heat transfer model are incorporated into code SCTRAN successfully. The result comparison with code CATHENA indicate that the calculation accuracy of SCTRAN is acceptable.

The analysis of LOCA/LOECC of the 64-element Canadian SCWR is carried out to give a preliminary evaluation its inherent safety. The following conclusions can be achieved:

- When LOCA occurs, about 2.5% of the decay power can be totally removed by the radiation heat transferring to the pressure tube even without an intervention of ECCS, which means that the Canadian SCWR has the potential to accomplish the object of "NO-CORE-MELT".

- The HP channel experience the most serious condition because it owns the highest power production. The MCST of the fuel rods in the inner and outer rings of the HP channel are separately 1296.1^{o}C and 1253.1^{o}C, which dosen't has a big safety margin for the cladding material. Core optimization and material study should be carried on.

- The outlet plenum volume has an effect on the performance of LOCA/LOECC. A bigger outlet plenum volume is good for the core cooling in the prophase of cold-leg LOCA.

- Natural convection is the heat transfer mode between moderator and pressure tube. The selection of the corresponding heat transfer coefficient produce an effect on the MCST variation of both rings. The bigger is the heat transfer coefficient, the lower is the linear tube surface temperature, and the lower is the fuel sheath temperature.

- The natural convection heat transfer of high-temperature low-velocity steam in the HEC is crucial in deciding how much heat can be transferred by convection manner. When the convection heat transfer increase in the HEC channels, the fuel sheath temperature of the inner and outer ring decrease. The precise heat transfer coefficient prediction is necessary.

This paper shows that Canadian SCWR is a promising concept, which can achieve the object of "NO-CORE-MELT" in LOCA/LOECC. But the maximum cladding temperature is a little high for the current cladding material in LOCA/LOECC. The selection of the cladding material and the core optimization should be go on.

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