THERMAL BEHAVIOUR OF CANDU FUEL CHANNEL UNDER STEAM FLOW CONDITIONS: AN ALTERNATIVE SOLUTION

HASSAN E. S. FATH*
KHALID M. AL-SABTI**

School of Technical Education,
University of Technology,
Baghdad - Iraq

ABSTRACT

An alternative scheme is proposed to guarantee the safety behaviour of CANDU fuel channels under steam flow conditions. The proposed scheme is based on increasing the annulus gas gap effective thermal conductance during and after the accident. Two transient models (lumped and one-dimensional) are developed to predict the temperature of both pressure tube and calandria tube under the proposed scheme. The results show that the pressure tube temperature increases up to a maximum value after which it drops again. The pressure tube maximum temperature, at the channel vertical midplane, was found to be below 700°C, 500°C, and 430°C when the gap conductivity is 3.0, 4.5, and 6.0 W/m.K respectively. Calandria tube temperature is maintained at 110°C maximum. Therefore, the pressure tube - calandria tube contact is eliminated and a "Coolable Fuel Geometry" is guaranteed.

The moderator subcooling requirements are therefore relaxed and the moderator heat load is fully recovered to the first stage of feedwater heating system.

INTRODUCTION

The CANDU reactor consists of a large horizontal tank (calandria) which contains the low-pressure, low-temperature heavy water moderator. The calandria is penetrated by a large number of calandria tubes which provide "sites" for fuel channels, Figure 1. The pressure tube in which the fuel is located is centrally located inside each calandria tube, and separated by a carbon dioxide filled gas gap. High pressure, high temperature heavy water coolant is pumped through the pressure tube to transfer the heat given off by the fuel to the steam generator. The annulus gas gap between the pressure tube and the calandria tube acts as a thermal insulator that minimizes heat losses from the coolant to the moderator during normal operation.

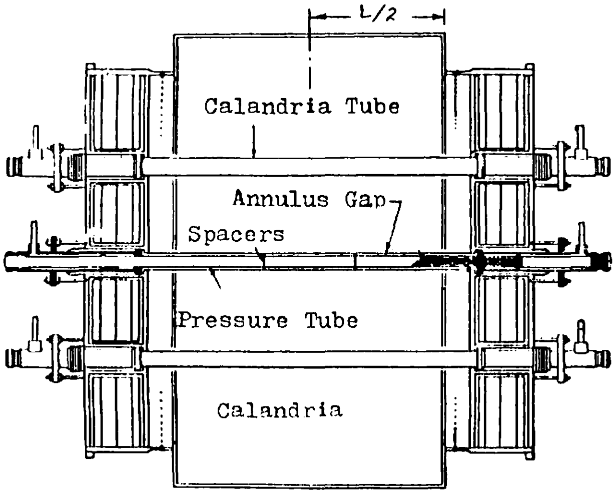

Figure 1 CANDU Reactor Schematic

The present CANDU design has a potential safety feature that prevents the fuel melting under the postulated steam flow conditions. Steam flow conditions can occur in some of the reactor channels during either a postulated Loss Of Coolant Accident (LOCA) with critical break size that causes coolant stagnation or a LOCA associated with Loss Of Emergency Coolant Injection (LOCA + LOECI). Only two conditions are required to cope with this situation, reactor shutdown and continuous removal of the decay heat through the moderator system. With the present design (high thermal resistance of the annulus gas gap), most of the decay heat is transferred to and stored in the pressure tube. The pressure tube temperature rises quickly and the pressure tube strains to contact the calandria tube either by "ballooning", induced by steam pressure, or "sagging", induced by fuel weight. At contact, the sudden release of the large amount of the stored heat through a small contact area can cause calandria tube dryout (i.e. film boiling takes place at the calandria tube outer surface) when the moderator local subcooling is not sufficient. In this case, the calandria tube temperature rises quickly and the tube may fail causing reactor core damage.

Experimental study was carried out at WNRE and indicated that a moderator local subcooling of at least 33°C should be available prior to the accident in order to prevent calandria tube dryout. Economic penalties result from such moderator subcooling because of larger moderator heat exchangers required along with larger amount of heavy water hold up and pumping power. On the other hand, the moderator local temperature, and consequently the moderator subcooling requirements, are uncertain due to the contradicting results obtained by different authors [1 to 3] for the moderator circulation problem. In addition, there are some uncertainties with regard to the ranges of the contact area, contact conductance, and contact heat flux. Moreover, the transient Critical Heat Flux (CHF) was found by Mesler [4] to be about 50% less than the steady-state CHF usually used in CANDU fuel channel analysis.

The foregoing discussion serves to motivate the study that was performed here. A new concept for treating this safety problem is proposed as an alternative safety scheme. The proposed scheme and its safety and economic features will now be presented.

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* Assistant Professor
**Assistant Lecturer

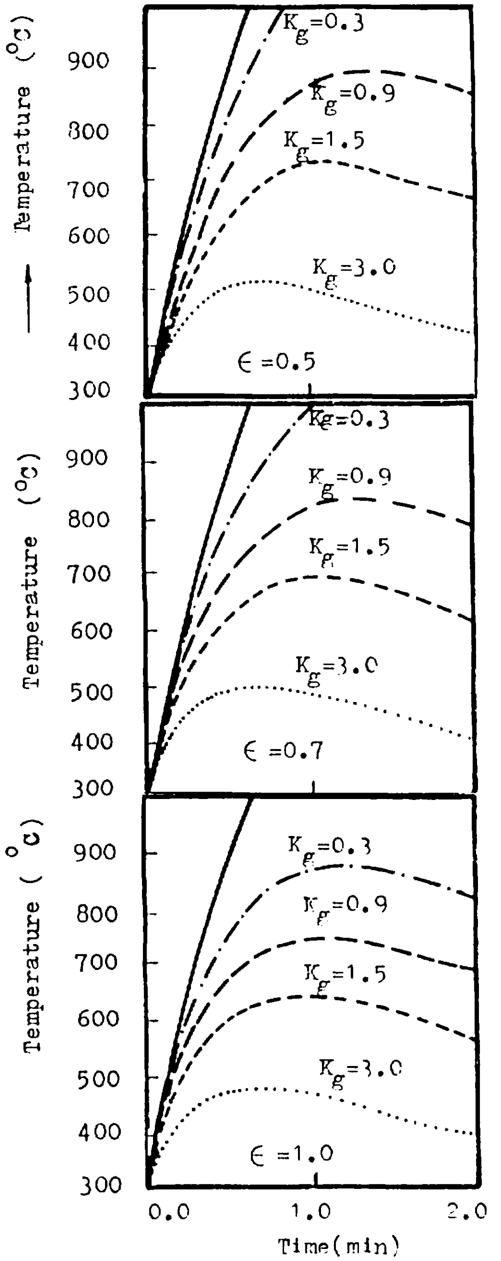

Figure 2 Pressure Tube Transient Temperature Under Different Values Of ϵ and k_g (Lumped Model)

THE PROPOSED SCHEME

The maximum decay heat flux at the beginning of the accident is much less than both steady-state and transient Critical Heat Flux even at zero subcooling. The problem arises from the fact that the high thermal resistance of the annulus gas gap forces the decay heat to be accumulated in the pressure tube instead of being transferred to the moderator as early as the accident starts. The proposed scheme, therefore, is based on increasing the annulus gas heat transfer during and after the accident. A highly reliable combination is to increase the thermal emissivity (ϵ) of the pressure tube and calandria tube (by surface coating) and to increase the equivalent thermal conductivity (k_g) of the annulus gas gap by using circulated helium and additional spacers (see also the Appendix). The additional heat loss from the coolant to the moderator under normal operation, along with the moderator heat load will be fully recovered to the first stage of feedwater heaters.

The thermal behaviour of the pressure tube and calandria tube is presented first, while the moderator heat recovery scheme is presented later.

CHANNEL THERMAL BEHAVIOUR

A preliminary analysis of the channel thermal behaviour was carried out using a lumped model. In this model, the decay heat and channel temperature were assumed to be uniformly distributed along the channel length. The results of this model are shown in Figure 2 for both the present design (solid line) where ϵ = 0.2 and k_g = 0.025 W/m.K and the proposed scheme (dotted lines) where ϵ varies from 0.5 to 1.0 and k_g varies from 0.3 to 3.0 W/m.K. The results show that, for the present design, the pressure tube temperature rises very rapidly so that in few seconds it reaches 1000°C. Increasing the equivalent thermal conductivity of the annulus gas gap, k_g, significantly reduces the pressure tube temperature. The pressure tube temperature increases with time up to a maximum value after which it decreases again. The pressure tube maximum temperature could be controlled below 500°C when the equivalent thermal conductivity is above 3.0 W/m.K and the tubes thermal emissivity is above 0.5. These preliminary results show, in general, the validity of the proposed scheme to limit the pressure tube maximum temperature. More detailed analysis is given below using the one dimensional model.

One Dimensional Model

The fuel channel is assumed to be symmetric around the channel vertical midplane, Figure 1, so that only one half of the channel is modelled. The transient temperatures of both the pressure tube and the calandria tube are obtained from the energy balance of a ring element. The differential equations for both tubes are written as follows,

$$\frac{\partial T_{PT}}{\partial t} = \alpha \frac{\partial^2 T_{PT}}{\partial x^2} + \frac{Q''_{in}}{B_{PT}} - \frac{k_g}{B_{PT}\delta}(T_{PT} - T_{CT}) - \frac{\sigma F_{12}}{B_{PT}}(T^4_{PT} - T^4_{CT}) \qquad (1)$$

$$\frac{\partial T_{CT}}{\partial t} = \alpha \frac{\partial^2 T_{CT}}{\partial x^2} + \frac{k_g}{B_{CT}\delta}(T_{PT} - T_{CT}) + \frac{\sigma F_{12}}{B_{CT}}(T^4_{PT} - T^4_{CT}) - \frac{h}{B_{CT}}(T_{CT} - T_{mod}) \qquad (2)$$

where

T_{PT} = Pressure tube absolute temperature, K

T_{CT} = Calandria tube absolute temperature, K

t = Time, s

α = Tube thermal diffusivity, m^2/s

Q''_{in} = Heat load, W/m^2

d = Tube thickness, m

δ = Annulus gap thickness, m

k_g = Annulus gas gap thermal conductivity, W/m.K

σ = Stefan Boltzman Constant W/m^2.K^4

F_{12} = Gray body configuration factor

B = PT & CT, Tube constant defined as ($B=\rho * C * d$) j/m^2.K

h = Heat transfer coefficient by boiling or convection, W/m^2.K

T_{mod}= Moderator temperature, K

The initial and boundary conditions are written as follows:

$$T_{PT}(0,x) = 300\ ^\circ C \qquad (3)$$

$$T_{CT}(0,x) = 80\ ^\circ C \qquad (4)$$

$$\frac{\partial T_{PT}(t,0)}{\partial x} = \frac{\partial T_{CT}(t,0)}{\partial x} = 0 \qquad (5)$$

$$T_{PT}(t,L/2) = 300\ ^\circ C \qquad (6)$$

$$\frac{\partial T_{CT}(t,L/2)}{\partial x} = 0 \qquad (7)$$

An explicit finite difference method is used to solve the above equations. The results of the pressure tube transient temperatures are shown in Figures 3 and 4. Difference values of ϵ and k_g are also shown in the right hand side of each illustration.

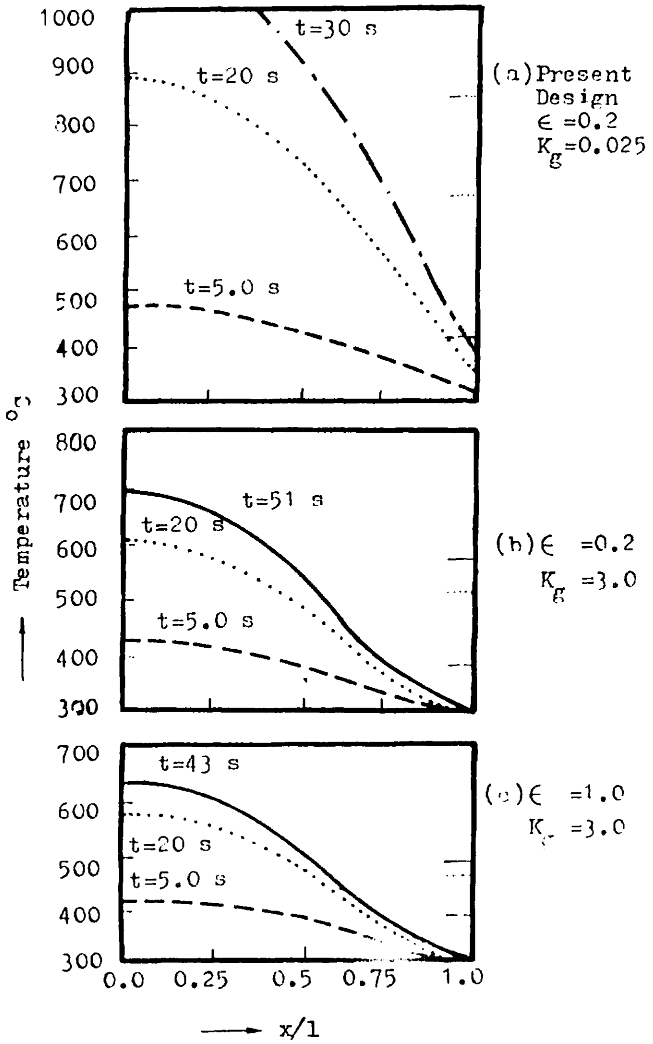

Figure 3 Pressure Tube Transient Temperature

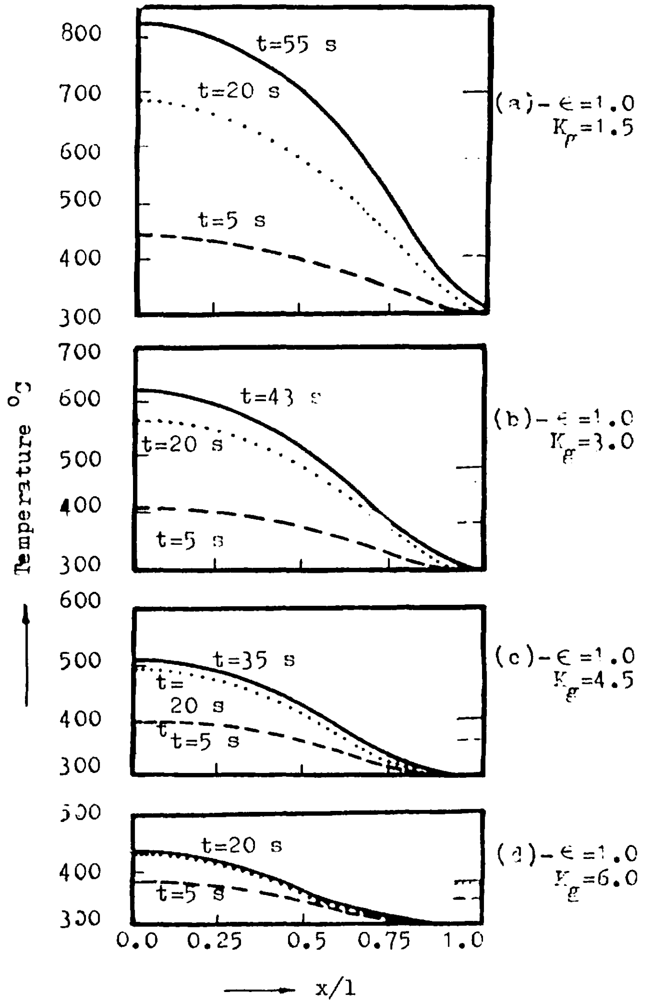

Figure 4 Pressure Tube Transient Temperature

The results in Figure 3(a) show that with the present design values of ϵ and k_g (ϵ = 0.2 and k_g = 0.025 W/m.K), the pressure tube temperature rises very rapidly so that pressure tube - calandria tube contact takes place. Increasing k_g to a value of 3.0 W/m.K, Figure 3(b), limits the pressure tube maximum temperature to 690°C and the average temperature to 570°C. These maximum values occur after 50s from the beginning of the accident, after which the pressure tube temperature decreases with time. The effect of increasing channel emissivity was found to have less influence on both maximum and average temperatures, for example, increasing ϵ to unity, Figure 3(c), limits the pressure tube average temperature to 480°C.

Figure 4 shows the effect of rising k_g from 1.5 W/m.K to 6.0 W/m.K while ϵ is constant. The effect is very apparent in reducing the pressure tube transient temperature significantly. The maximum pressure tube temperatures at the channel midplane are 825°C, 630°C, 505°C, and 430°C while tube average temperature are 705°C, 480°C, 400°C, and 375°C at k_g equal to 1.5, 3.0, 4.5, and 6.0 W/m.K, respectively. In all these cases, the calandria tube transient temperature rises so that nucleate boiling takes place; after that, it rises very slowly. The maximum temperatures of the calandria tube (at the channel midplane) are shown in Figure 5 for some limiting cases.

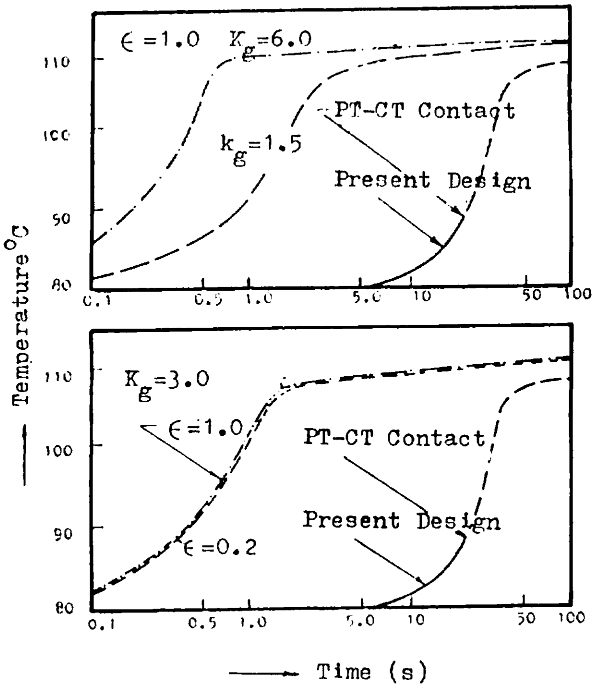

Figure 5 Calandria Tube Transient Temperature At Channel Midplane

It is recommended, however, that more detailed analysis be carried out using the fuel channel codes such as CHAN-II, Reference [5], for the selection of best values of ϵ and k_g.

Advantages Of The Proposed Scheme

The main advantages of the proposed scheme can be summarized as follows:

i) The proposed scheme is simple, passive, and therefore has high reliability. No significant changes in the present design are added since the annulus gas circulation has been adopted for the new reactor designs. In addition, all thermal, mechanical, and nuclear characteristics of the fuel channel remain unchanged.

ii) The pressure tube maximum temperature could be controlled within a specified value so that pressure tube - calandria tube contact is eliminated. This significant safety advantage eliminates the concern of the calandria tube dryout and its possible failure. Therefore, the fuel channel integrity is preserved and a "Coolable Fuel Geometry" is guaranteed.

iii) Maintaining the pressure tube temperature low during the accident will provide a better heat sink for the fuel elements. Therefore, the clad temperature could be maintained at a lower value than that of the present design. This will reduce the Zircaloy-water exothermic reaction and its consequences on clad strength, heat generation, and hydrogen production.

Since the pressure tube - calandria tube contact is eliminated, the moderator subcooling requirements can then be relaxed, i.e. the moderator temperature can be increased. On the other hand, the apparent penalties of losing some of the channel energy will be recovered as given below.

MODERATOR HEAT RECOVERY (MHR)

A large amount of heat is generated within the moderator due to neutron thermalization (moderation) process. The moderator heat load represents about 4% to 5% of the reactor thermal energy and is about 120 MW_{th} in CANDU 600. A moderator cooling system is, therefore, established for the continuous removal of this heat load. The hot moderator water is circulated through the moderator heat exchangers where its heat is transferred to the Recirculating Cooling Water (RCW). Eventually this heat is lost to the environment through the Raw Service Water (RSW). An additional amount of heat will be transferred to the moderator under normal operation using the above proposed scheme and also will be lost, Table 1.

Table 1 Additional Heat Losses, MW(th), to the Moderator during Normal Operation for CANDU 600 using Proposed Scheme

ϵ k_g	0.5	0.7	0.9	1.0
0.3	7.7	8.0	8.7	9.0
0.9	21.8	22.0	22.7	23.0
1.5	35.8	36.0	36.8	37.0

Economic and marketability disadvantages exist with the loss of such large amounts of energy to the environment, while the potential exists for utilizing this energy in the power cycle. The only attempt to recover this energy in power cycle, so far as the author is aware of, has been done by Todorviski and Hemmings [6], where the moderator energy is partially utilized. Their circuit has, however, two main disadvantages. The first is the penalties arising with the lost energy part (30% to 40%). The second is the complex control mechanism required to control the two types of heat exchangers simultaneously (namely, feedwater - moderator heat exchanger, and RCW - moderator heat exchanger).

To overcome these drawbacks, an alternative Moderator Heat Recovery (MHR) circuit will be presented below where all the moderator energy is utilized.

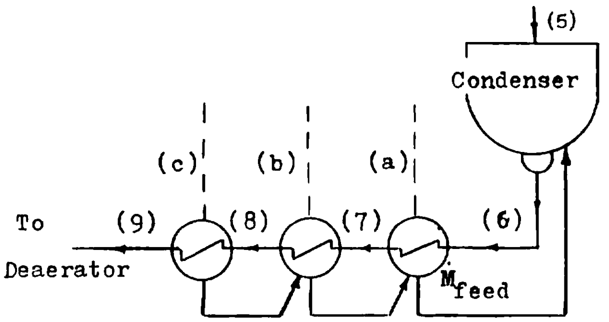

Figure 6 CANDU Secondary Side

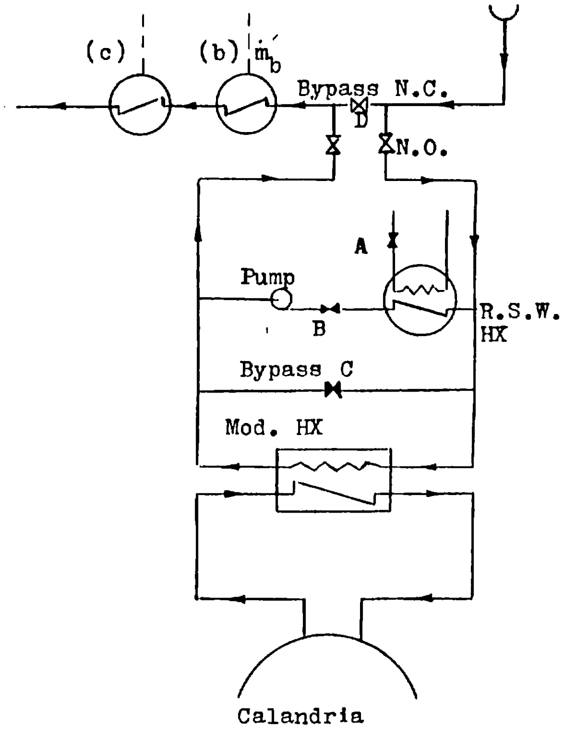

Figure 7 Proposed MHR Circuit

Description of the MHR Circuits

Figure 6 shows a typical CANDU 600 feedwater-condenser arrangement. The proposed MHR circuit is shown in Figure 7, where all moderator energy is transferred to the feedwater.

During normal conditions, all feedwater from the condenser flows through the moderator heat exchangers and then travels back to the other low-pressure feedwater heaters. For the period when feedwater heating is not required (or feedwater is not available), a steady (backup) RSW cooling system is provided to remove the heat load. The RSW system could be sized to remove the maximum heat produced during any expected abnormal (or part load) condition. To maintain the moderator outlet temperature (from the calandria) between the specified upper and lower limits, the following control system is provided:

a) to raise the temperature, the control valve C in the bypass line is opened.

b) to lower the temperature, one of the recirculating water pumps is started and the bypass control valve B and the RSW control valve A are opened.

The moderator temperature determines the degree of the opening of the control valves A, B and C. Figure 7 shows also a feedwater bypass line to allow bypassing the moderator heat exchangers, if necessary. A head tank would be provided in the circuit to cater for contraction and expansion of the fluids due to temperature variations. The MHR circuit would be isolated in the unlikely event of RSW leak into the feedwater. However, leakage, if any, should be into the RSW since pressures are higher on the feedwater side.

Electrical Power Output

Introducing the moderator heat load to the feedwater heating system will save some amount of the bleeding steam required for feedwater heating. The saved amount of bleeding steam will then be used to produce additional electric power in the steam turbine. The steam cycle parameters, Figure 6, are calculated first using an iterative procedure. The important calculated parameters are listed in Table 2.

Table 2 Resultant Parameters For Steam Cycle of CANDU 600 Reactor

Parameter	Value
$\dot{M}_{st}$	1043.0 k_g/s
$\dot{m}_a$	43.4 k_g/s
$\dot{m}_b$	27.5 k_g/s
$\dot{m}_c$	32.5 k_g/s
$\dot{M}_{feed}$	732.0 k_g/s
P_a	0.03 MP_a
P_b	0.07 MP_a
P_c	0.16 MP_a

It was found that the heat transferred to the first Feedwater Heater (FWH) by the bleeding steam is less than the moderator heat load. Therefore, the first FWH can then be eliminated and the amount of bleeding steam required to the second FWH ($\dot{m}_b$) can also be reduced to ($\dot{m}_b'$) calculated as follows:

$$\dot{m}_b' = \frac{\dot{m}_a \cdot i_a + \dot{m}_b \cdot i_b - i_7(\dot{m}_a + \dot{m}_b + \dot{m}_c) - (\dot{Q}_{mod} - \dot{m}_c \cdot i_c)}{(i_b - i_8)} \quad (8)$$

The electric power produced by the saved amount of the bleeding steam is calculated as follows:

$$\text{Power} = \dot{m}_a\ (i_a - i_5) + (\dot{m}_b - \dot{m}_b')\ (i_b - i_5) \quad (9)$$

where, i_a, i_b, i_c, i_5, and i_8 are the specific enthalpy of the steam at points a, b, c, 5, and 8 respectively and $\dot{m}_a$, $\dot{m}_b$, $\dot{m}_c$, are the bleeding steam flow rates at points a, b, and c respectively. The first term in equation (9) represents the power produced from the bleeding steam of the eliminated first FWH, and the second term represents the power produced from the saved steam of the second FWH.

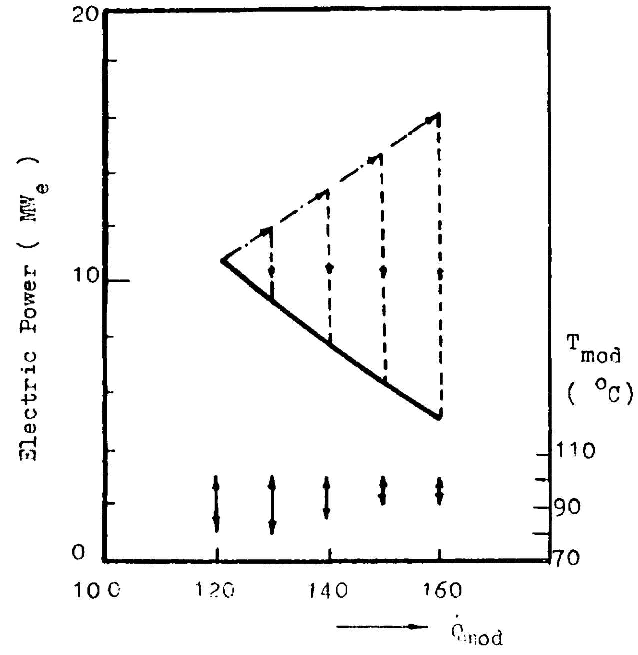

Figure 8 Electric Power Produced

Figure 8 shows the resultant power produced as a function of the moderator heat load, $\dot{Q}_{mod}$. The figure shows the total electric power produced by the recovered moderator heat load (dashed-dot line) which increases as the heat load increases. These values are, however, reduced by an amount equal to the thermal energy lost to the moderator from the fuel channels times the plant thermal efficiency (only when the moderator heat lost is greater than 120 MW_{th}), (downward dotted lines). The net electric power (solid line) is shown to decrease as the moderator heat load increases. The arrows at the bottom represent the range of the moderator outlet temperature (from the calandria) that could be used for each heat load. The results show that the additional power generated is about 5 MW_e to 11 MW_e. These values represent an 0.8 to 1.7% increase in CANDU 600 electric power output. This power has a present worth of 10 to 22 million dollars and results in an increase in the plant thermal efficiency by 0.2% to 0.7%. Such economic advantages would be reduced a small amount by some additional balance of plant equipment required.

Other Advantages of the MHR Circuit

The outstanding features and advantages of the proposed MHR circuit are summarized as:

i) The MHR circuit is simple and therefore has good reliability and requires low maintenance.

ii) At part load, the proposed circuit is self regulating. Since the feedwater flow rate is proportional to the reactor power, the feedwater temperature will remain constant at all reactor powers.

iii) The RSW heat exchangers used as a backup are relatively small. This is due to the high logarithmic mean temperature difference between the moderator and RSW.

iv) The feedwater is clean, so there should be no problem of fouling and corrosion in the moderator heat exchangers.

v) Leakage in the moderator heat exchangers, if any, would be from feedwater to moderator in view of existing pressure differences. Thus the feedwater system would not be contaminated.

vi) The utilization of moderator energy and the increase in the cycle efficiency will add marketing advantages to CANDU systems. The moderator heat will also be eliminated from the loss side of the CANDU heat balance sheet.

CONCLUSION

A simple, and reliable scheme is presented as an alternative solution to the fuel channel behaviour under steam flow conditions. The proposed scheme is based on increasing the annulus gas gap effective thermal conductivity and the channel thermal emissivity; partially under normal operation and fully during the accident. Therefore an early and continuous transfer of the channel decay heat to the moderator takes place during and after the accident. The maximum pressure tube temperature is limited so that pressure tube-calandria tube contact is eliminated. Therefore, the channel integrity is preserved and a "Coolable Fuel Geometry" during and after the accident is guaranteed. The heat loss from the fuel channels to the moderator during normal operation along with the moderator heat load is recovered. A moderator heat recovery circuit is presented for full recovery of the moderator energy to the first stages of feedwater heating system. Safety, economic, and marketing advantages exist with the proposed scheme over the present design. With the proposed scheme, the CANDU reactor will have a safety feature which no other power reactor in the world can claim.

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APPENDIX

Selected Methods To Increase k_g

1. Combined Convection
   a) Replacement of CO_2 by helium
   b) Continuous circulation of helium during and after the accident
   c) Increase the velocity of the gas flow
   d) Swirl flow is preferred
   e) Some additives may be added to the gas during the accident to increase k_g.

It is worth mentioning that combined free and forced convection increases by ten times the gas thermal conductivity as given in Ref. [7].

2. More Conducting Spacers

   a) Introduce more conducting spacers to the fuel channels with suitable number and distribution so that conduction and convection become more efficient while nuclear characteristics do not change.

   b) The spacers should be arranged in such a way that they are in contact only with the calandria tube during normal operation. This will reduce the heat losses from fuel channels during normal operation. Contact of the spacers with pressure tube should be only during the accident.