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Coolability of Severely Degraded CANDU Cores

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Abstract

Analytical and experimental studies have shown that the separately cooled moderator in a CANDU reactor provides an effective heat sink in the event of a loss-of-coolant accident (LOCA) accompanied by total failure of the emergency core cooling system (ECCS). The moderator heat sink prevents fuel melting and maintains the integrity of the fuel channels, therefore terminating this severe accident short of severe core damage.

Nevertheless, there is a probability, however low, that the moderator heat sink could fail in such an accident. The pioneering work of Rogers (1984) for such a severe accident using simplified models showed that the fuel channels would fail and a bed of dry, solid debris would be formed at the bottom of the calandria which would heat up and eventually melt. However, the molten pool of core material would be retained in the calandria vessel, cooled by the independently cooled shield-tank water, and would eventually resolidify. Thus, the calandria vessel would act inherently as a "core-catcher" as long as the shield tank integrity is maintained.

The present paper reviews subsequent work on the damage to a CANDU core under severe accident conditions and describes an empirically based mechanistic model of this process. It is shown that, for such severe accident sequences in a CANDU reactor, the end state following core disassembly consists of a porous bed of dry solid, coarse debris, irrespective of the initiating event and the core disassembly process.

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The paper describes an improved model for the subsequent heat-up of the debris bed which includes all the significant mechanisms that may affect the thermal behaviour of the debris. the paper also describes a detailed model for the thermal behaviour of the molten pool that might form by eventual melting of the solid debris bed which takes into account internal heat generation and buoyancy-driven circulation in the pool, the formation of solidified crusts on the upper and lower surfaces of the pool, heat generation in the crusts, radiation from the upper crust and radiation absorption, emission and transmission in the steam over the pool, as well as the natural convection and nucleate boiling processes of the shield-tank water on the outer surfaces of the calandria vessel.

Application of these models to a dominant-frequency severe accident sequence in a CANDU 6 reactor is described. Results for reference conditions for the thermal transient in the debris bed show that its heat-up is relatively slow, with melting in the interior of the bed beginning about two hours after heat-up begins. However, the upper and lower surfaces of the debris remain well below the melting point and heat fluxes to the shield-tank water are well below critical heat fluxes for the existing conditions. The calandria vessel remains well-cooled and retains its integrity throughout the transient. No steam explosion is expected. Sensitivity studies in which important parameters are varied over wide ranges yield the same conclusions, with the results indicating that, for larger pore sizes, melting of the debris may not even occur.

Results for the thermal behaviour of the potential subsequent molten pool show that the calandria vessel wall is protected by a thick solid crust below the pool which grows with time. Calandria wall temperatures and heat fluxes to the shield-tank water ensure that the calandria vessel will maintain its integrity in this phase of the transient also.

Again, sensitivity studies varying the important parameters confirm the general validity of this result. An energy balance suggests that there might not be sufficient energy available to form a coherent pool; transient melting and relocation of molten material could result in a geometry of re-solidified material that would be cooled effectively by the shield tank water. Should the shield-tank water eventually boil off the calandria vessel will fail by melt-through, but this will not occur in less than a day, giving the operators adequate time for intervention, such as providing water from emergency supplies to the shield tank. The calandria then will retain the resolidifying core indefinitely.

Contributors to the predicted effectiveness of cooling of a degraded core in a CANDU, in addition to the inherent heat sinks provided by the separate moderator and the shield tank water, are the low power density (about 15.6 MW/Mg of fuel in a CANDU 6, based on the design power) and the extensive dispersion of the debris in the calandria resulting in a shallow molten pool depth of about 1 metre maximum and about 0.65 metre average for the reference case. These factors help to explain the different predicted behaviour of a degraded CANDU core relative to that of an LWR in typical melt-progression scenarios.

The results of this work confirm and provide more confidence in the conclusions of the early studies that the calandria vessel will retain its integrity in severe accidents in a CANDU reactor and will contain a disassembled or partially molten core for a long period without operator intervention, thus acting as an effective core-catcher.

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Refroidissement de Coeurs de Réacteurs CANDU Gravement Détériorés

AECL-11110

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Résumé

Des études analytiques et expérimentales ont démontré que le modérateur refroidi séparément dans un réacteur CANDU assure une source froide efficace en cas d'accident de perte de caloporteur (LOCA) accompagné d'une défaillance totale du système de refroidissement d'urgence du coeur (SRUC). La source froide assurée par le modérateur empêche la fusion du combustible et maintient l'intégrité des canaux de combustible, mettant ainsi un terme à ce grave accident, avant que de graves dommages soient causés au coeur.

Il y a cependant une possibilité, quoique faible, de perte de la source froide assurée par le modérateur lors de ce genre d'accident. Les travaux de recherche, alors totalement nouveaux, entrepris par Rogers (1984) sur ce type d'accident grave avaient démontré, à l'aide de modèles simplifiés, qu'il y aurait défaillance des canaux de combustible et qu'une couche de débris solides et secs se formerait au fond de la cuve, qui surchaufferait et finirait par fondre. Cependant, la masse de débris fondus serait retenue dans la cuve, refroidie par l'eau de la cuve de protection refroidie indépendamment, et pourrait se solidifier de nouveau. Ainsi, la cuve agirait comme un «collecteur de débris du coeur», tant que l'intégrité de la cuve de protection serait maintenue.

Le présent document examine les travaux effectués par la suite sur les dommages causés à un coeur CANDU dans le cas d'accident grave et décrit un modèle mécaniste empirique du processus. Il est démontré que, pour de telles séquences d'accidents graves dans un réacteur CANDU, on trouve après la dislocation du coeur une couche poreuse de débris secs, solides et granuleux, quels que soient l'événement initiateur et le processus de dislocation du coeur.

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NOMENCLATURE

d_p	average pore size in debris bed
F_B	radiation interchange factor in debris bed
F_c	factor to allow for thermal resistance of contacts between fragments in debris bed
k_B	effective thermal conductivity of solid debris bed
k_g	effective thermal conductivity of steam-filled pores in debris bed
k_m	weighted thermal conductivity of solid mterials in debris bed
k_s	thermal conductivity of heavy water steam
L_d	maximum depth of molten pool
p	porosity of debris bed
$Q_{zr}[i]$	heat generation rate from Zircaloy-steam reaction in node i
q_v	actual time-dependent core-average volumetric heat source in fuel material or average volumetric heat source in molten pool
q_{vB}	effective volumetric heat source in debris bed allowing for dilution effect of non-fuel material and for porosity of debris bed
q''	heat flux to shield-tank water
q_d''	heat flux from molten pool to curved lower surface
q_u''	heat flux from molten pool to flat upper surface
R	calandria vessel inner radius
T	absolute temperature
t	time or crust thickness
V_u	volume of UO_2 in debris bed
V_z	volume of ZrO_2 and/or Zr in debris bed
V[i]	total volume of node i in debris bed
w	half-width of molten pool surface
z	position in debris bed measured from top surface
$\bar{z}$	average depth of molten pool
α_B	effective thermal diffusivity of debris bed
ε_B	emissivity of debris bed material
ε_v	porosity of debris bed
θ	half-angle at calandria centre-line subtended by molten pool surface
σ	Stefan-Boltzmann constant

Subscripts

bot	bottom surface of solid debris bed
cadi	inner surface of calandria wall under molten pool
cai	inner surface of calandria wall above molten pool
cbi	inner surface of calandria wall under debris
cbo	outer surface of calandria wall under debris
crd	lower crust
crdm	minimum thickness point on lower crust
cru	upper crust
cti	inner surface of calandria wall above debris
cto	outer surface of calandria wall above debris
d	lower surface of molten pool
m	maximum
max	maximum
top	top surface of solid debris bed
u	upper surface of molten pool

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1. INTRODUCTION

This paper describes the behaviour of CANDU reactor cores in severe accidents involving core disassembly. However, first, the design characteristics of CANDU relevant to severe accidents are described (Snell et al, (1990)).

1.1 CANDU Design Characteristics

CANDU is a horizontal pressure-tube reactor, with the fuel bundles located inside several hundred 10.5-cm diameter, 0.48-cm thick pressure tubes[1]. Twelve 0.5 m-long fuel bundles reside within each pressure-tube. The 37-element fuel bundle is in close proximity to the pressure tube, separated from it by means of 1.1-mm high bearing pads on the outer fuel elements. The heavy-water coolant flows over and through the fuel bundles and is contained by the pressure tubes within the core (Figure 1).

Since the pressure tube operates at approximately the coolant temperature (~300°C), it is thermally insulated during normal operation from the heavy water moderator (~65°C) by the carbon-dioxide-filled annulus formed between the concentric pressure tube and calandria tube. The calandria tube forms the outer boundary between the gas and the moderator (Figure 1, inset). The assembly of fuel, pressure tube, gas annulus and calandria tube is collectively called the fuel channel. The total radial distance between the outer elements of the fuel bundle and the moderator is 1.5 cm.

The zirconium-niobium pressure tube is joined to a stainless-steel end fitting at each end by a rolled joint; the tube material is forced into grooves in the end fitting by rolling from the inside of the pressure-tube during initial installation. The end fitting provides biological shielding to allow access to the reactor vault when the reactor is shut down; permits fuel to be removed and replaced on power by an automatic fuelling machine; and provides a connection to the coolant supply and return pipes (feeders) at each end of the channel (Figure 2).

All large pipes in the CANDU Reactor Coolant System (RCS) are above the core. They consist of headers, or collectors, to which each channel is connected via a 6-cm to 8-cm diameter inlet and outlet feeder pipe; plus pump suction and discharge piping and steam generator inlet and outlet piping. A large break in one of these pipes would cause rapid voiding of the pressure tubes. As with other water-reactor designs, the emergency core cooling (ECC) system provides high-pressure injection of water to refill the core. In CANDU, ECC water is supplied to all the reactor headers.

The heavy-water moderator is contained within a low-pressure tank, called the calandria (Figure 1). During normal operation, about 4.4% of the thermal output of the core is deposited in the moderator, a small amount by heat transfer from the channels, but mostly by direct deposition from the slowing down of neutrons and by fission gamma rays. This heat is removed via dedicated external moderator heat exchangers; external pumps circulate the moderator

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1 Unless otherwise specified, specific numerical values refer to the CANDU 9 reactor. However, the relationships between the values and the conclusions are generic to all CANDUs.

through the heat exchangers and provide momentum to mix the moderator within the calandria. They are powered by normal electrical power (Class IV), backed up by emergency diesel power (Class III) when required.

1.2 Role of Moderator and Shield Tank in Severe Accidents

This paper uses the following definitions:

> A **severe accident** is one in which the fuel heat is **not** removed by either the RCS coolant or by the ECCS water.
>
> Severe core damage is a severe accident in which the core structural integrity is lost.

Because of the heat removal capability of the moderator, a severe accident does not necessarily lead to severe core damage; and because of the heat removal capability of the shield tank, severe core damage does not necessarily lead to calandria vessel melt-through, as will be established later.

The moderator role as an emergency heat sink for the fuel in a severe accident is discussed below. In this role, its active heat removal capability is enough to continuously remove all fuel decay heat following 15 seconds after reactor shutdown. The moderator volume per unit thermal power is typically 8 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) over 5 hours[2] of decay heat from the fuel, assuming no heat removal from the moderator fluid (Snell et al (1990), Hart et al (1994)).

The calandria vessel is in turn contained within a shield tank (or calandria vault), which provides biological shielding during normal operation and maintenance (Figure 3). It is a large steel or concrete tank filled with ordinary water. During normal operation, about 0.4% of the thermal output of the core is deposited in the shield tank and end shields, through heat transfer from the calandria structure and fission heating. This heat is removed via the end shield cooling system, consisting of pumps and heat exchangers.

The shield tank's role as an emergency heat sink for the fuel in a severe core damage accident is discussed below. In this role, its active heat removal capability is enough to continuously remove all fuel decay heat a few days after reactor shutdown. The shield tank volume per unit thermal power is typically 16 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) more then 10 hours[2] of decay heat from the fuel, assuming no heat removal from the shield tank water.

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2 These times are intended to show total heat capacities only. The actual times to lose all liquids will be shorter because of rapid expulsion of liquid as bulk boiling begins in the moderator and in the shield tank water (Rogers, 1984b and 1984c).

Table 1
Capabilities of Moderator and Shield Tank in Severe Accidents

System	Continuous Heat Removal Capability (% full thermal reactor power)	Liquid Volume per Unit Thermal Power at Decay Power	Time to Heat Up and Boil off All By Fuel Decay Power, No Heat Removal[2]
Moderator	4.4%	8 litres/kW @1%	> 5 hours
Shield tank	0.4%	16 litres/kW @ 1% 32 litres/kW @ 0.5%	>10 hours > 20 hours

The moderator and shield tank are inherent heat sinks, in the sense that they are essential to the reactor design and the water inventory is always available. CANDU has in addition a number of heat removal systems designed to remove decay heat under normal shutdown conditions or in accidents, as follows:

1.3 Heat Removal from an Intact RCS

The **main feedwater system** provides feedwater flow to the steam generators during power operation and at decay power. It is supplemented by the **auxiliary steam generator feedwater** pump, which provides decay heat removal capability in normal shutdown conditions and in accidents such as failure of the main feedwater system or loss of Class IV power. Both main and auxiliary feedwater pumps draw on the Group 1 water supplies[3]. The auxiliary steam generator feedwater pump is supplied with Group 1 Class III electrical power in some operating CANDUs; in others it has a dedicated diesel drive.

In addition, the **shutdown cooling system** is provided for normal shutdown heat removal (as an alternative to the steam generators) and for cooldown below 100°C. It can operate in emergencies at full RCS temperature and pressure, and can therefore be used as an emergency heat sink from hot, shutdown, full-pressure conditions, should the steam generators be unavailable.

The third means of heat removal is the **emergency water system** (EWS), seismically qualified to remove heat after a Design Basis Earthquake. It provides a supply of water to the boilers independent of the normal and auxiliary feedwater. Since it is sized to remove decay heat

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3 Modern CANDUs divide safety-related systems into two Groups. Each is capable, by itself, of shutting down the plant, removing decay heat, preventing the release of radioactivity, and monitoring the plant status. Group 1 consists largely of systems used in normal operation, plus two of the special safety systems, usually Shutdown System #1 (see Section 1.5) and the Emergency Core Cooling System. It is supplied by Group 1 Class IV power, backed up by diesel-generated Class III power, and Group 1 water. Group 2 consists of the other two special safety systems, Shutdown System #2 (see Section 1.5) and Containment. It includes sources of seismically-qualified Group 2 power (using separate diesels from Group 1) and seismically qualified water (using separate supplies from Group 1).

shortly after shutdown, it can also be used as an emergency heat sink should normal and auxiliary feedwater, and the shutdown cooling system, all be unavailable. It is supplied by Group 2 electrical power and water. In currently operating CANDUs, the steam generators must be depressurized prior to initiating EWS; in the CANDU 3 and CANDU 9 designs, the EWS has evolved to a complete **Group 2 feedwater system**, and operates at full secondary side pressure.

1.4 Heat Removal for a Loss-of-Coolant Accident

An **emergency core cooling system** refills the headers, and thence the fuel channels following a loss-of-coolant accident (LOCA). To ensure that injection for small breaks is not blocked by high RCS pressure, the main steam safety valves on the main steam lines are opened on a LOCA signal. They are sized to cool down the steam generator secondary side, thereby depressurizing the RCS. Emergency coolant injection in the long term uses recovered water from the reactor building sump. Heat sinks for LOCA include the ECCS heat exchangers, the steam generators, and containment air coolers; the proportion of heat removed by each mechanism depends on the break size. For very small breaks, the shutdown cooling system can also be used.

1.5 Reactor Shutdown

For the normal, emergency and severe accident heat sinks to be effective, the reactor must be shut down. CANDUs have three means of so doing. The normal control system, consisting of absorber rods and light-water zone controllers in the moderator, is capable of shutting the reactor down for most operational transients and accidents, the major exceptions being large LOCAs and some faults in the control system itself.

In addition, there are two independent, dedicated shutdown systems. Shutdown system #1 consists of about 30 gravity-operated, spring-assisted absorber (shutoff) rods, and shutdown system #2 consists of 8 nozzles which inject liquid gadolinium nitrate, at high pressure, into the moderator. Each system is, independently, fully capable of shutting down the reactor for all accidents. Each system has its own detectors, amplifiers, relays, logic, and actuating mechanisms, and is independent of the control system and of the other shutdown system. Because the shutoff mechanisms are inserted into the low-pressure liquid moderator, they can respond very quickly to an accident.

The trip parameters on each system are chosen to provide redundant coverage, where practical, for every accident in the design/licensing set. The provision of dual-independent shutdown systems means that Anticipated Transients Without Scram, as well as accidents without scram, are low enough in probability that they can be ignored for design purposes, as they are a negligible contribution to total risk.

2. REVIEW OF EARLIER RELATED STUDIES

An event sequence in which the fuel heat is not removed by coolant in the primary heat transport system (PHTS) represents an important type of severe accident (Snell, et al (1990)). In most reactor designs other than the CANDU, this event sequence would result in a core melt. However, in a CANDU reactor, the separately cooled moderator provides a potential heat sink in the event of a LOCA accompanied by failure of the emergency coolant injection system (ECIS).

Analytical and experimental investigations were undertaken in the late 1970s and the early 1980s on the consequences of a failure of the ECIS following a large LOCA, to determine the effectiveness of the moderator as a heat sink. These studies showed that there would be no melting of the fuel in such an accident (Rogers (1979); Gordon & Blahnik (1982); Meneley & Hancox (1982); Brown et al (1984); Rogers & Currie (1984a); Howieson (1986); Snell et al (1990)). Although some fuel damage and pressure tube distortion would occur, pressure tube integrity would be maintained and releases of radioactive material to the environment would be within licensing limits, taking into account the expected performance of the containment in such an accident (Snell et al (1990)). An up-date of work in this area is presented by Sanderson et al (1995). The effectiveness of the moderator as an inherent back-up heat sink, together with the use of redundant shut-down systems, contributes to the low frequency of severe core damage calculated in probabilistic risk assessments of the CANDU, in the range of 4.0 to 4.6 x 10^{-6} per reactor-year (Darlington (1987); Snell et al (1990); Allen et al (1990)).

2.1 Studies for the Atomic Energy Control Board

Nevertheless, there is a probability, however low (Allen et al (1990)), that the moderator heat sink would be ineffective in such an accident because of failure of the moderator cooling system, which could occur by events such as loss of moderator heat exchanger service water, loss of moderator flow or failure of moderator system piping. Analytical work was undertaken by Rogers in 1980 on behalf of the Atomic Energy Control Board, the regulatory agency in Canada, on the consequences of the failure of the moderator cooling system following a large LOCA accompanied by loss of emergency coolant injection (LOECI) in a Bruce-A reactor unit. This accident sequence was selected arbitrarily and not as the result of a probabilistic risk assessment. The results of this work (Rogers (1984b); Rogers (1984c); Snell et al (1988); Snell et al (1990)) indicated that core disintegration would occur because of failure of fuel channels uncovered by expulsion and boil-off of the moderator and that a quenched bed of coarse, solid debris would occupy the bottom of the calandria as the last of the moderator was lost from the calandria. The study found that the debris bed would heat up and eventually melt, some 2 to 2 1/2 hours after the start of the accident, with a solid crust forming between the molten debris pool and the calandria wall. The calandria wall, being protected by the solid crust and well cooled by the surrounding shield-tank water (cooled in turn by its own separate cooling system) would maintain its structural integrity. The molten pool of core material would be contained within the calandria vessel and would eventually solidify. The calandria vessel thus would act as an inherent core-catcher in a severe accident of this type in a CANDU reactor (Rogers (1984c)), provided that shield tank cooling were maintained. The study also showed that containment structural integrity would be maintained in this accident sequence.

2.2 Level-2 PRA Study of CANDU 6

In a later level-2 PRA for a CANDU 6 reactor, a severe accident sequence representative of a dominant-frequency category called "late core disassembly" (LCD) was evaluated (Howieson, et al (1988); Allen et al (1990)). The summed frequency of all event sequences in this category for a CANDU 6 was found to be about 5.2 x 10^{-7}. This evaluation, incorporating some of the same computational models used in the study for the AECB, considered a loss of service water with a consequential loss of Class IV power, which causes a loss of feedwater as well as loss of moderator cooling and shield-tank cooling, among other effects. This event eventually leads to the loss of primary coolant through the liquid relief valves and consequent degraded cooling of the fuel and overheating and straining of the pressure tubes, causing some of them to fail. Resulting blow-down of the PHTS results in a drop of pressure which initiates the high-pressure stage of emergency cooling; these events remove stored energy in the fuel and pressure tubes and other components of the PHTS. The fuel and pressure tubes begin to heat up again because of fuel decay heat and, as the temperatures reach higher levels, the oxidation of Zircaloy. Heat is transferred to the moderator but the moderator, lacking cooling, boils off slowly since the decay power is relatively low at this time (1-2 hours after reactor shutdown). Pressure tubes fail as fuel channels are uncovered by the moderator boil-off and once again a coarse solid debris bed is formed in the bottom of the calandria. The debris bed heats up and eventually melts but again a crust protects the calandria wall which continues well-cooled as long as water remains in the shield tank. The study showed that it will take about 25 hours for the shield tank water to boil down to the level of the debris bed, at which time the calandria vessel would be expected to fail. However, obviously there is considerable time for remedial action such as restoring the shield-tank cooling system or arranging temporary water supplies to quench the debris bed or to refill the shield tank. Such actions enable the calandria vessel again to act as a core catcher. A detailed description of this accident sequence is also given by Dick et al (1990).

2.3 MAAP-CANDU Analysis of Darlington NGS

More recently, Blahnik et al (1993) presented the results of an analysis of the response of a Darlington CANDU unit to the loss of all heat sinks resulting from the loss of electric power, using the MAAP-CANDU computer code (Blahnik et al (1991)). Since the accident sequence evaluated by Howieson et al (1988) and Allen et al (1990) also involved a loss of electric power and loss of heat sinks, it is not surprising that the predicted subsequent behaviour in this accident sequence is quite similar to that described in the earlier study. Once again a coarse solid debris bed is formed in the bottom of the calandria vessel which, in this case, dries out in about 14 hours. The debris bed heats up and forms a molten pool separated from the calandria wall by a solid crust, since the calandria is still cooled by the shield-tank water. In this case, calandria cooling by the shield-tank water is suddenly lost at about 27 hours by rupture of a shield-tank seam from over-pressurization resulting from the incapacity of the shield-tank relief valves to relieve the steam generated by boiling of the shield-tank water. This event leads quickly to calandria wall failure. However, once again considerable time is available for operator intervention, which determines the actual outcome of this accident sequence. Restoration of the shield tank cooling system or provision of temporary water supplies to the shield tank within 27 hours of the start of the accident sequence are sufficient to permit the calandria vessel to act as an effective core catcher.

For these three accident sequences the behaviour of the fuel channels is well understood up to and including the point of channel failure. Extensive experimental data are available, covering a wide range of accident conditions, and well-validated analytical models have been developed. See Urbanic (1977), Muzumdar (1982), Rogers and Currie (1982), Muzumdar et al (1983), Brown et al (1984), Hadaller et al (1984), Lau and Blahnik (1984), Akalin et al (1985), Kohn et al (1985), Locke et al (1985), Rosinger et al (1985), Amrouni et al (1986), Gulshani and So (1986), Luxat and Rance (1987), Prater and Courtright (1987), Snell et al (1988).

Subsequent channel disassembly is less well understood because the research emphasis in Canada is on preventing channel failure and subsequent propagation of failure. For examples of relevant work, see Rogers (1984b), Rogers (1984c), Dick et al (1990), Blahnik et al (1991) and Blahnik et al (1993). Nevertheless, logical arguments can be advanced to define an end-state for the core disassembly process, whatever the details of the processes to reach that end-state. These arguments are presented in the next section of this paper.

3. CANDU CORE DISASSEMBLY AND FORMATION OF DEBRIS

At decay power levels CANDU fuel channels will disassemble only if they are uncovered by loss of the heavy water moderator from the calandria. Disassembly of the uncovered horizontal fuel channels is very complex. It involves mechanical, thermal and chemical interactions with steam and hydrogen, the surrounding channels, in-core devices of various types and debris from the disassembly of other channels. The interaction rates are sensitive to the details of the local geometry as well as other local parameters.

3.1 Simple Models of Core Disassembly

In the early study by Rogers (1984b, 1984c), in which it was arbitrarily assumed that a large LOCA, failure of the ECIS and failure of the moderator cooling system all occurred simultaneously, uncovery of fuel channels began at about 20 minutes after the initiating event and was essentially complete by about 45 minutes. Thus, decay power levels were relatively high during this period. As channels were uncovered, rapid oxidation of the Zircaloy calandria tubes occurred by reaction with the heavy-water steam generated by the moderator boil-off. This resulted in very rapid temperature rises of the calandria tubes which, in turn, caused similar rapid temperature rises of the pressure tubes since there was now no heat sink for the heat being transferred to the pressure tubes by radiation and natural convection from the fuel bundles. Actually, during this period heat generally flows from the calandria tubes to the pressure tubes (Rogers, 1984b).

Therefore, within a few tens of seconds after channel uncovery, particularly in the higher power channels, peak calandria tube temperatures reach the melting point of Zircaloy, about 1750°C. At this time, maximum pressure tube temperatures are predicted to be in the range of 1600-1800°C (Rogers, 1984b). At these temperatures some of the unoxidized Zircaloy is molten while solid Zircaloy pressure and calandria tubes have lost much of their strength, have deformed and may have failed by creep-rupture under the imposed gravity loads[4]. While the melting temperature of oxidized Zircaloy is considerably higher than 1750°C, oxidized Zircaloy in the uncovered pressure and calandria tubes is quite brittle and subject to fracture.

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4 By this time, internal pressures in the fuel channels will be close to atmospheric since blowdown of the PHTS would have been completed much earlier.

For this arbitrary initiating event, pressure and calandria tubes are expected to fail over most of their lengths within a few tens of seconds after channel uncovery. At this time, the maximum fuel temperatures in these channels are predicted to be in the range of 2200-2300°C (Rogers, 1984b), considerably below the UO_2 melting temperature of about 2800°C. Therefore, on disassembly of a fuel channel in this case, almost all the fuel is expected to be in the solid state as is oxidized Zircaloy while unoxidized Zircaloy might be molten or solid, depending on its location and environment. Thus, the debris formed on channel disassembly consists mainly of coarse solid pieces of ZrO_2, Zr and UO_2 with a relatively small fraction of molten Zircaloy. While coarse, solid debris may be suspended above the remainder of the liquid moderator for some time after channel disassembly, debris falling to the bottom of the calandria is quenched as it passes through the remaining moderator.

Lacking any knowledge of the behaviour of channels undergoing disassembly, Rogers assumed that debris would fall rapidly to the bottom of the calandria, since this behaviour would result in the most rapid rate of moderator expulsion from the calandria. Eventually, a terminal debris bed composed mainly of coarse solid pieces of UO_2, Zr and ZrO_2 and re-solidified particles of previously molten Zircaloy, quenched to temperatures close to the saturation temperature of the heavy water moderator would be left in the bottom of the calandria as the last of the moderator boiled off (Rogers, 1984b; Rogers, 1984c).

In the representative dominant-frequency LCD accident sequence for a CANDU 6 reactor assessed by Howieson et al (1988), Allen et al (1990) and Dick et al (1990), moderator expulsion and boil-off and consequent channel uncovery begins much later, at about 1.7 hours compared with about 20 minutes in the sequence examined by Rogers (1984b, 1984c). Moderator boil-off also terminates much later in this sequence, at about 5.1 hours compared to about 45 minutes. Therefore, decay powers are much lower than in the earlier study and processes occur more slowly. Channel disassembly is assumed to follow the simple model used by Rogers with channels disintegrating soon after uncovery, but with failure occurring at the relatively low pressure-tube temperature of about 1000°C[5] because of excessive plastic deformation. Debris is assumed to fall directly to the bottom of the calandria vessel (Dick, et al, 1990). This assumption is deemed to be more conservative than assuming debris build-up above the moderator level, supported on the cool submerged channels, because it increases the hydrogen and fission product aerosol source term later in the accident, when containment leakage may be expected. Considering the pressure and calandria tube and fuel temperatures at the time of channel disassembly and the fall of the debris through the remaining moderator, the debris bed at the end of moderator boil-off again consists mainly of coarse, solid pieces of UO_2, ZrO_2 and Zircaloy quenched to the moderator saturation temperature.

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5 The significant difference in the assumed failure temperatures of the calandria and pressure tubes in this scenario compared to that postulated by Rogers makes very little difference to the timing of channel failure because of the very rapid rate of tube temperature rise after uncovery. See Rogers (1984b, 1984c).

3.2 Mechanistic Model of Core Disassembly

The above simple models for debris bed formation following channel disassembly both assumed that debris will fall directly to the bottom of the calandria vessel once channel failure occurs. This assumption is not based on any knowledge of the mechanisms involved but is made to give conservative conditions for later events in the accident sequence.

Recently, Blahnik et al (1993) proposed a mechanistic model for channel disassembly and debris bed formation which is appropriate for channel uncovery beginning several hours after the initiating event. A schematic diagram of the model is shown in Figure 4. As channels are uncovered pressure tube and calandria tube temperatures increase rapidly with resulting plastic deformation (above ~ 1200°C) under gravity loads causing excessive sagging. A sagging channel comes into contact with a lower row which may still be submerged, and thus adequately cooled. The cool channel supports the sagged channel. As the moderator level decreases the lower row is uncovered and sags under its own weight as well as that of the supported channel. As the moderator boils off more channels are uncovered and sag under the accumulating weight of the upper channels. As sagging increases, channel segments separate near individual bundle junctions by a sag-induced local strain when a sufficient displacement distance of about 1 m is available (Blahnik et al (1993)). The suspended debris bed moves downward following the falling moderator liquid level in the calandria vessel. As the mass of suspended debris increases the load on the first submerged channel increases. Each submerged channel can only support about seven other channels; higher debris loading will cause failure by shear at ends of channels, increasing the loading on the channel below. This leads to progressive shear failure of all but some low power peripheral channels resulting in a collapse of the reactor core into the liquid pool in the bottom of the calandria vessel. Figure 5 shows this core disassembly process for the representative severe accident sequence analyzed by Blahnik et al (1993).

The suspended debris at any time may contain large unoxidized Zircaloy surfaces (the outer surfaces of pressure tubes and the inner surfaces of calandria tubes) which are suddenly exposed to steam from the boiling moderator (Blahnik et al (1993). Some Zircaloy oxidizes but the heat generated melts the remaining Zircaloy within a few minutes. This melt tends to be non-wetting since the heat-up rate is too rapid to raise the dissolved oxygen content appreciably. Therefore, most of this melt flows quickly into the liquid pool in the bottom of the calandria vessel, where a small fraction reacts chemically with the heavy water while most is simply quenched. Because of the small amounts of molten material involved and other conditions existing, no energetic fuel-coolant interaction would be expected (Blahnik et al,1993). No appreciable amount of molten core material is present in the suspended debris at the time of core collapse since, as shown in Figure 5, the suspended debris bed builds up quite rapidly to the collapse threshold, limiting the time available to melt unoxidized Zircaloy.

The core collapse predicted by the mechanistic model may be delayed by several hours if the debris does not accumulate on the submerged channels, i.e., if it falls to the bottom of the calandria vessel as soon as channels disassemble. However, the outcome is the same for all disassembly pathways: a solid debris bed located at the bottom of the calandria vessel which eventually dries out.

Thus, the mechanistic model predicts the same state of the terminal debris bed as the last of the moderator is lost from the calandria as that deduced from the simple models: a bed composed mainly of coarse solid pieces of UO_2, ZrO_2 and Zircaloy with smaller particles of re-solidified Zircaloy droplets. The key factor in these models is that they predict that all the UO_2 fuel is well below its melting temperature when channel disassembly occurs.

Since the mechanistic model has no integrated experimental verification, the validity of the conclusions about the state of the terminal debris bed as it dries out can be questioned. However, the likely mechanisms controlling a channel disassembly and core collapse (the sagging and shear failure of composite tubes) are well understood and analytical tools are available to describe them in detail. Based on experimental observations of full-scale fuel assemblies, the hot channel debris is expected to be composed of coarse pieces of ceramic materials that will not readily relocate to the bottom of the calandria vessel (Kohn et al (1985)). Alternative disassembly mechanisms, e.g., a fragmentation of hot tubes or a tube wall melt-through can also be analytically described for sensitivity studies. Uncertainties related to the core disassembly progression stem mainly from scenario-specific descriptions of the channel temperature distributions and of the debris loads imposed on the rows of intact fuel channels. While uncertainties in the mobility of suspended debris affect fission product release and hydrogen generation transients, they do not affect the solid state of the terminal debris bed as it dries out.

Recent studies (Dick et al (1990), Blahnik et al (1991) and Blahnik et al (1993)) indicate that CANDU cores are likely to collapse under accumulated debris from high-elevation channels when the calandria vessel is about half voided. Thus typically, the terminal debris bed is initially submerged in water[6] and so is quenched (Rogers (1984b), Rogers (1984c)). Furthermore, in all such accidents the calandria walls are always externally cooled by the shield-tank water when the terminal debris bed forms. The different disassembly pathways produce a range of solid debris compositions as well as different decay heat rates in the terminal bed. The heat generation rate in the terminal bed at any time can vary by about 40 per cent, depending on the extent of volatile fission product release prior to terminal debris bed dry-out. After bed dry-out, no further decrease of bed heat source resulting from loss of volatiles occurs since the volatiles then remain trapped in the debris.

It is concluded from these studies and arguments that any significant liquefaction of core materials can only occur after the terminal debris bed dries out and heats up. Additional studies of different core disassembly sequences are needed to confirm that this conclusion is generally valid. Nevertheless, without liquefied core materials prior to complete calandria vessel voiding and subsequent heat up of the debris bed, challenges to the integrity of the calandria vessel are avoided during the core disassembly process. In particular, no energetic fuel-coolant interaction is anticipated. The issue of debris retention in the calandria vessel becomes that of adequate heat removal from a rather shallow debris bed to the externally cooled calandria vessel walls.

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6 Accident sequences may also be postulated in which the debris deposits in a fully voided vessel, e.g., a loss of heavy water moderator as an initiating event. In these cases, the earlier studies indicated again that the core debris would be contained in the calandria. (Rogers, 1984b).

4. MODELS FOR THE THERMAL BEHAVIOUR OF DEBRIS BEDS AND MOLTEN POOLS IN CANDU CALANDRIA VESSELS

As described in Section 3, at the end of moderator expulsion and boil-off from the calandria a bed of quenched coarse solid core debris exists at the bottom of the calandria vessel. Considering the nature of the probable mechanisms of channel disintegration, the debris bed is composed mainly of rather large pieces of UO_2, ZrO_2 and some Zr and a small amount of re-solidified Zr droplets. This debris begins to heat up mainly because of the decay heat source in the fuel material and, to a lesser degree, because of the exothermic chemical reaction between any remaining Zircaloy and any steam that is present. Eventually, internal debris temperatures reach levels at which liquefaction of the debris begins and a molten pool may be formed in the calandria. Since, as will be seen, the calandria wall remains well cooled by the shield-tank water during these processes the pool would stabilize and eventually re-solidify as the heat source decays. This section of the paper deals with the models developed to describe the thermal behavior of debris beds and molten debris pools in severe accidents in CANDU reactors.

4.1 Thermal Behaviour of Solid Debris Bed

In the 1984 study, Rogers (1984b,1984c) developed a simple one-dimensional model to represent the transient thermal behaviour of a bed of core material composed of coarse, solid pieces of UO_2 and ZrO_2 located in the bottom of a calandria vessel. A finite-difference computer program, DEBRIS, was developed to analyze the thermal behaviour of the debris bed using this model. Results obtained for the arbitrary severe accident analyzed in the study predicted that melting would begin within the bed about 90 minutes after the start of debris bed heat-up or about 135 minutes after the initiation of the accident. Results also showed that the lower and upper surfaces of the debris bed would be well below bed material melting points throughout the transient. All results were very insensitive to variations in the major parameters including porosity varying from 0.1 to 0.8 and average pore size ranging from 1 to 11 cm. Heat fluxes through the calandria wall from the bottom of the bed to the shield tank water at all times during the transient were well below critical heat fluxes for the shield tank geometry. It was concluded that the calandria wall would remain well-cooled as long as the shield tank cooling system continued to function, with wall inner temperatures below the bed not exceeding 500°C during the transient, so that calandria integrity would be maintained.

DEBRIS was also used in the representative LCD accident sequence in a CANDU 6 analyzed by Howieson et al (1988), Allen et al (1990) and Dick et al (1990). In this case, debris-bed heat-up would begin about 5 hours after the initiating event and melting at a little over 7 hours. Similar conclusions were reached, i.e., the bed upper and lower surface temperatures would remain well below the corium melting temperature, the calandria wall would remain well-cooled and calandria vessel integrity would be maintained throughout the debris-bed heat-up transient.

Recently, improvements have been made to the model and these have been incorporated into a revised version of the computer program, DEBRIS.2. The main features of DEBRIS.2 are as follows:

- The debris forms a uniform porous structure, composed of UO_2 and ZrO_2, and/or Zircaloy in appropriate proportions, with porosity and average pore size specified as inputs, with the dimensions of the debris bed established from the masses and densities of the debris materials, the geometry of the calandria and the specified porosity, assuming a flat upper surface of the debris bed. See Figure 6.
- Heat flow through the debris is one-dimensional in the vertical direction, with the depth of the one-dimensional bed equal to the maximum thickness of the actual debris bed. The one-dimensional model is conservative in that it predicts higher temperatures than would occur in the actual bed because of three-dimensional heat flows. However, allowance is made in the boundary conditions of the debris bed for the different areas of its upper and lower surfaces.
- Heat flow through the bed is treated as conduction through a cubical pore structure with an effective conductivity accounting for conduction through solid materials and radiation and conduction across the pores, which are assumed to be filled with heavy water steam. The effective conductivity of such a heterogeneous structure is given by (Rogers (1984b), Ribaud (1965)):

  $$k_B = k_g \, \varepsilon_v^{1/3} + F_c \, k_m \, (1-\varepsilon_v^{2/3}) \qquad (1)$$

  where k_g, the effective conductivity of the steam-filled pores, is given by:

  $$k_g = k_s + 4 \, \sigma \, F_B \, d_p \, T^3 \qquad (2)$$

  where F_B, the radiation interchange factor for the porous structure, is given by (Rogers, 1984b):

  $$F_B = 3 \, \varepsilon_B/(6 - \varepsilon_B) \qquad (3)$$

  In equation 1, F_c is a factor allowing for imperfect contact conductance between solid pieces in the debris, treated as an input in the program.
- The equivalent thermal conductivity of the solid materials, k_m, is assumed to be the volume-weighted average of the thermal conductivties of the UO_2 and ZrO_2 and/or Zr, assuming random orientation of layers of each and representing this random orientation by assuming that 1/3 of these layers are perpendicular to the heat flow path and 2/3 are parallel to the heat flow path.
- The heat source in the debris is due to fuel decay heat and, as an option, heat generated by the exothermic Zircaloy-water reaction. The decay heat is calculated by a simplified equation, based on the ANS model, appropriate for CANDU reactors (Whittier (1977)). The chemical heat source is based on the reaction rate for solid-state diffusion of oxygen through a zirconium oxide layer using the Urbanic-Heidrick (1978) equation and a heat of reaction of 6444 kJ/kg(Zr), assuming, as input, that a certain fraction of the initial mass of Zircaloy in the core is unoxidized at the time that the debris bed is formed. Another input assumption is the average thickness of the unoxidized Zircaloy fragments in the debris, which yields the

interface area for the reaction. It is assumed that sufficient water is available so that all unoxidized Zircaloy surfaces are readily exposed to water irrespective of their location in the bed, permitting the reaction to proceed at the rate dictated by the Urbanic-Heidrick equation. Any cooling effect of this water is ignored and no additional water is assumed to be available to quench the debris. No credit is taken for the replacement of steam by hydrogen in the thermal analysis of the debris. The Zircaloy-steam reaction rate and corresponding heat source are calculated separately for each node of the debris because of the significantly different temperature histories of the nodes. The volumetric heat source used in the model makes appropriate allowance for the dilution effect of the ZrO_2 and the presence of voids in the bed:

$$q_{vB} = \{q_v \{V_u/(V_u + V_z)\} + Q_{zr}[i]/V[i]\} (1 - \varepsilon_v) \qquad (4)$$

In the reference case, heat generation from the oxidation of Zircaloy is ignored since much of it would have already been oxidized before formation of the debris bed and access of water or steam to the bed after high temperatures are reached would be restricted.

- Heat transfer from the upper surface of the debris bed occurs by thermal radiation to the inner surface of the calandria vessel above the bed and by thermal radiation and natural convection to the steam above the bed. In turn, heat is transferred from the steam by thermal radiation and natural convection to the inner surface of the calandria wall above the bed. The steam above the bed is assumed to be at a uniform temperature. Radiation absorption and emission by the steam above the bed is accounted for because of the relatively long beam length involved. The emissivity of the steam as a function of temperature is estimated for an appropriate beam length and pressure, assuming that only steam is present above the debris, from Holman (1990). Heat is transferred from the inner surface of the calandria wall above the bed to the shield tank water by conduction through the calandria wall in series with either natural convection or nucleate boiling on the outer surface of the wall, depending on the temperature difference between the outer surface and the shield tank water. DEBRIS.2 chooses the appropriate correlation and also allows for a gradual transition between them.

- Heat transfer from the lower surface of the debris bed occurs by conduction through the calandria wall below the bed in series with either natural convection or nucleate boiling on the outer surface of the wall, using the same models as on the surface above the top of the bed.

- DEBRIS.2 provides two options for the shield-tank water cooling system: operating or not operating. For the operating case, the temperature of the shield-tank water is assumed to be held constant throughout the transient. For the non-operating case, the heat transferred from the calandria vessel walls is stored in the shield-tank water so that the shield-tank water temperature increases during the transient until the water saturation temperature is reached. Thereafter, the water temperature is held constant at the saturation value as the moderator boils off. Boil-off of the moderator is not modelled in DEBRIS.2 so that the analysis is valid only until the water boil-off begins to uncover the calandria wall. However, this restriction does not hinder the application of DEBRIS.2 since debris bed melting begins (or peak temperatures are reached in cases of non-melting) before significant boil-off has occurred in all CANDU severe accident cases examined.

- Conservatively, heat loss from the shield-tank water to the concrete walls of the shield tank is ignored.
- Thermal conductivities of UO_2 and ZrO_2 or Zr as functions of temperature and other properties of these materials at appropriate average temperatures are taken from MATPRO (1981). Since limited data are available on heavy water steam, properties of ordinary water steam as functions of temperature from Collier and Thome (1994) are used where necessary. Use of ordinary water steam transport properties will not result in any significant errors.
- Taking into account, as necessary, the foregoing assumptions, a transient heat balance on the debris bed yields the following differential equation:

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha_B}\frac{\partial T}{\partial t} - \frac{q_{vB}}{k_B} \qquad (5)$$

- A finite-difference methodology is used in DEBRIS.2 to solve equation 5 for the given boundary and other conditions. As noted earlier, the relatively large volume of the calandria in a CANDU reactor ensures that any debris bed formed in the calandria will be relatively shallow, as will be seen. Therefore, the number of nodes used to represent the core debris was limited to ten, with the first node on the upper surface of the bed and the tenth node on the lower surface. Sensitivity calculations for a few cases using twenty nodes showed that adequate convergence is obtained using ten nodes. Values of effective bed thermal conductivity at any time, from equation 1, are evaluated at the arithmetic average temperature between two adjacent nodes. The time step used in the program is an input value; to ensure that this choice does not result in mathematical instability in the explicit technique used, the program incorporates a stability check at each time step.

4.2 Transient Melting of Debris Bed in CANDU Calandria

Before considering the ultimate characteristics of a molten pool of corium in the calandria vessel, an assessment of the transient melting process of a debris bed is needed. As we will see in Section 5.1, results obtained using DEBRIS.2 confirm those obtained earlier (Rogers (1984b, 1984c), Dick et al (1990) that the temperatures of the surfaces of the debris bed will be well below the melting temperature of the debris materials and the calandria wall will remain well cooled throughout the bed heat-up. Once melting begins in the solid debris bed, the model in DEBRIS.2 is no longer valid. A model to describe the transient behaviour of the debris bed as it undergoes melting and experimental data on this process are not yet available. Nevertheless, a plausible qualitative description of the melting process can be advanced.

As did the earlier model, DEBRIS.2 predicts that melting begins within the debris bed near the vertical mid-point. As melting begins within the bed, molten material will flow to a lower level and re-solidify. Some of the solid material from the layer above the first molten region will fall into the void left by the downflow of the molten material and will also begin to melt and flow down to the lower level. When this lower layer reaches the melting point, material will again flow down to a lower layer and again re-solidify and solid material from the overlying layer will again drop into the void formed. This process will continue until molten material reaches a level at which the cooling provided by the shield tank water prevents further melting of the debris. Near the outer edges of the debris bed, where the effective depth is small, no melting of the debris is expected at any time. Thus, a layer of solid debris plus re-solidified molten material exists and will be maintained indefinitely between a molten pool and the entire lower part of the calandria wall as long as cooling by the shield tank is effective. This argument assumes that the cooling provided by the shield tank water is adequate to prevent any significant amount of molten corium from coming into contact with the calandria wall during the melting transient. As we will see, the analytical model developed for the thermal behaviour of a molten pool of corium predicts that a thick crust will always exist between the pool and the lower calandria wall for conditions anticipated in severe accidents in a CANDU reactor. This result supports the above argument.

4.3 Thermal Behaviour of a Molten Corium Pool in a CANDU Calandria

The early studies (Rogers (1984b,1984c)) concluded that a molten pool of core material formed in a CANDU calandria in a severe accident would be isolated from the calandria wall by a stable crust that would protect the wall from excessive temperatures. Furthermore, the wall would be well cooled by the shield-tank water, assuming that the separate and independent shield-tank water cooling system continued to function. The calandria vessel would maintain its structural integrity and, eventually, the molten pool would re-solidify. Thus, the calandria vessel in a CANDU reactor would continue to act as core-catcher following debris melting.

The analytical model used in those studies was a simple steady-state model that concentrated on: a) the internal thermal behaviour of the molten pool to establish the upward and downward heat fluxes from the pool to the shield tank water and, b) the potential interaction of molten corium with the calandria wall.

A considerably more detailed and complete model has now been developed to establish the thermal behaviour of a molten pool of corium in a CANDU calandria, although the basic model for heat transfer within the pool is unchanged. The model has been incorporated in a new computer program, MOLPOOL. The main features of the model and the program MOLPOOL are described below:

- At the times that a molten pool of debris would be expected to form in a severe accident in a CANDU, the heat source would be decaying slowly. Thus, quasi-steady-state conditions are assumed to exist.
- A lumped-parameter model is used to represent the molten pool; it is assumed that internal circulation will keep the pool at a fairly uniform temperature except in boundary layers near the surfaces. The decay heat source is the same as that used in DEBRIS.2, as described in Section 4.1, and is assumed to be uniform throughout the pool. There is no heat generation from oxidation of Zircaloy. The pool composition is assumed to be homogeneous; there is no stratification of corium materials. It is assumed that solid crusts exist on both the lower and upper surfaces of the pool. However, the model predicts the thicknesses of the crusts and indicates whether a crust would exist on the upper surface for any given conditions. A two-dimensional model is assumed with heat flows to the end-shields being ignored; the model thus represents conditions near the axial centre-line of the calandria vessel and is conservative for conditions near the end-shields.

- The geometry of the molten pool and solid crusts is determined from the geometry of the calandria, the masses and the liquid and solid densities of the materials involved. See Figure 6.

- The basic pool internal heat transfer mechanisms are natural convection to the nominally flat upper surface and to the curved lower surface. In addition, because of the very high temperatures of the pool, internal thermal radiation is an important mechanism of heat transfer to both surfaces

- For natural convection to the upper surface, the correlation of Kulacki and Goldstein (1972) for average heat transfer to the upper surface of heat generating pools is used. For natural convection to the lower surface a modified correlation, to cover the geometry range (L_d/R) required, was developed from the correlations for average heat transfer rates to the lower curved surface of heat generating pools of Mayinger et al (1976) and Gabor et al (1979). Allowance also is made in the model for the effect of high local heat transfer coefficients at the upper corners of the lower surface (Gabor, 1979).

- Stein et al (1979) showed the necessity of allowing for internal radiation heat transfer in experiments with actual molten pools of UO_2. The approach recommended by Anderson (1976) is used in the model.

- The model uses a heat balance between the heat generation rate in the pool and the heat flows over the upper and lower surfaces to establish the temperature of the pool and the heat fluxes to the upper and lower surfaces. The heat balance is given by:

$$q_v = \left(q_u'' + q_d'' \frac{\theta R}{W} \right) / \bar{z} \tag{6}$$

- It is assumed that the upper and lower surface temperatures of the molten pool are equal to the melting temperature of the pool material.

- Volumetric heat generation, consistent with that in the molten pool at any time, at a uniform rate in both the lower and upper crusts is accounted for, as is thermal conduction in the crusts.

- The change in volume of the molten material as it solidifies into the crusts is taken into account.

- Heat transfer from the upper surface of the molten pool (or the surface of the upper crust) to the shield tank water occurs by the same mechanisms assumed in DEBRIS.2, and the models for these mechanisms used in MOLPOOL are the same as those used in DEBRIS.2, as described in Section 4.1.

- Heat transfer from the lower surface of the lower crust to the shield-tank water occurs by the same mechanisms assumed in DEBRIS.2, and the models for these mechanisms in MOLPOOL are the same as those in DEBRIS.2, as described in Section 4.1.

- Considerable uncertainty exists in the property values of molten core materials, particularly of molten ZrO_2. Also, corium from the meltdown of a CANDU core would have a different composition than that from a typical LWR core; in particular a very low fraction of iron. Property values were selected from several sources. Reference values used for corium and crust material are those of Park et al (1994), with data from Anderson (1976) and Rempe et al (1992) being used to establish sensitivities. Properties of steam were treated in the same manner as in DEBRIS.2.

5. RESULTS

The programs DEBRIS.2 and MOLPOOL were used to assess potential consequences of a severe accident in a CANDU 6 reactor. The accident evaluated was the dominant-frequency accident analyzed earlier by Howieson et al (1988), Allen et al (1990) and Dick et al (1990). These studies indicated that a quenched debris bed composed of coarse, solidified material located in the bottom of the calandria would begin to heat up about 5 hours after the initiating event. Therefore, analyses were made of the thermal behaviour of a debris bed composed of the entire core of a CANDU 6 reactor (2180 MW thermal), 97.3 Mg of UO_2 and 38 Mg of Zr, oxidized to 55.7 Mg of ZrO_2, located in the bottom of the calandria vessel and starting to heat up from a quenched condition at 300 minutes after reactor shutdown. From the results of these analyses, conditions were established for analyses of the thermal behaviour of a molten pool of CANDU 6 core debris in the bottom of the calandria.

5.1 Thermal Behaviour of a Bed of Solid Debris in a CANDU 6 Calandria

Important input data used in the analysis is summarized in Table 2. As mentioned earlier, it is assumed, for the reference conditions, that no water or steam has access to the debris during the heat-up, i.e., that there is no heat generation from the Zircaloy-water reaction.

The values of debris bed porosity and average pore size are reference values which are the same as those used in the earlier studies. These values are based on judgements of the expected nature of the coarse debris resulting from the disassembly processes for a CANDU core in the selected accident sequence, as described in Section 3. However, as in the early study (Rogers (1984b and 1984c)), a sensitivity study was also done to assess the importance of variations of these parameters. The reference porosity of 0.5 results in a maximum debris bed depth of 1.65 m.

Figure 7 shows the temperature history at different points in the debris bed for the reference conditions. Assuming an effective debris melting temperature of 2700°C, the plot of the maximum bed temperature shows that melting of the debris is predicted to begin at about 415 minutes (about 7 hours) after the initiating event or about 115 minutes after the start of debris heat-up. This predicted time is close to that predicted using the older model, DEBRIS, by Dick et al (1990). Figure 7 also confirms the behaviour predicted in the early studies that the upper and lower surface temperatures of the debris bed remain well below the melting temperature throughout the period before melting begins in the interior of the bed. At that time, the upper surface temperature is about 1730°C and the lower surface temperature, is about 380°C.

Table 2
Important Input Data for Analysis of CANDU 6 Debris Heat-Up

Initial reactor power, MW	2180
Mass of UO_2, Mg	97.3
Mass of ZrO_2, Mg	55.7
Inner radius of calandria, m	3.77
Inner length of calandria, m	4.33
Start time, min	300
Fractional decrease of decay power from loss of volatiles	0.2
Porosity of debris bed (Reference value)	0.5
Average pore size, cm (Reference value)	3
Emissivity of calandria	0.3
Initial shield-tank water temperature, °C	60
Shield-tank cooling system operating?	No
Zircaloy + water reaction?	No

The inner and outer surface temperatures of the calandria wall above and below the debris bed during the transient are given in Figure 8 which shows that the maximum internal temperature of the calandria wall during the transient is less than 400°C. The average calandria wall temperature at this point and other positions will be considerably less than this value since the outer surface temperatures do not exceed 140°C, as shown in Figure 8. Thus, calandria wall temperatures are well below the level that would result in significant creep for the stainless steel wall material under the applied stresses.

Figure 9 shows that the maximum heat flux from the calandria wall to the shield-tank water during the transient is only about 13 W/cm^2, well below the critical heat flux (CHF) for the given geometry and sub-cooling (20°C) conditions[7], about 200 W/cm^2. Thus, it would appear, as in the earlier studies, that the calandria vessel would be well cooled and maintain its integrity during the heat-up of the debris bed to the beginning of melting.

However, before a firm conclusion can be reached, the sensitivity of the results to variations in the bed porosity and average pore size must be examined. Figure 10 shows the effect of varying bed porosity from 0.1 to 0.8 on bed temperatures during the transient to the beginning of melting, for the reference average pore size of 3 cm. It can be seen that there is practically no effect on the maximum bed temperature and on the lower surface temperature for this very wide

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7 The critical heat flux on the downward facing lower part of the calandria will not be reduced below values for upward facing or vertical surfaces because the curvature of the surface will permit escape of vapour which will enhance the natural circulation flow pattern set up in the shield-tank water by heat transfer from the calandria vessel (Rogers (1984b), Henry et al (1993)).

range of porosity, which encompasses the maximum range that would be expected in practice. At the time that melting begins, the upper surface temperature increases by about 340°C as porosity increases from 0.1 to 0.8; however, the maximum upper surface temperature is still well below the debris melting point for the entire porosity range.

Figure 11 shows that the heat fluxes to the shield-tank water as a function of time up to the beginning of melting are all less than about 14 W/cm^2, and thus well below CHF, for the whole range of bed porosity for the reference pore size.

The effect of average pore size for the range of possible porosities on the maximum and surface temperatures of the debris is shown in Figure 12 for a time of 410 minutes after the initiating event, i.e., just before the moment when melting is predicted to begin for the reference conditions. Figure 12 shows that the maximum temperature decreases somewhat with an increase of pore size, for all porosities, with maximum bed temperatures at higher pore sizes being definitely less than the bed melting temperature. Figure 12 also shows that bed surface temperatures at 410 minutes increase as pore size increases, for all porosities, but are well below the debris melting temperature. The decrease of maximum temperatures and the increase of surface temperatures as pore size increases reflects a decrease of internal thermal resistance of the debris bed as the effective number of "radiation shields" decreases as pore size increases.

As noted above, Figure 12 shows that the maximum bed temperature at 410 minutes for large pore sizes lies definitely below the debris melting temperature. In fact, the analysis predicts that no melting at all of the debris bed occurs at large pore size, as is shown in Figure 13 for a pore size of 9 cm, at a porosity of 0.5, where the maximum temperature of the debris reaches a value of about 2620°C at about 480 minutes after the initiating event and decreases thereafter. Internal calandria wall temperatures under these conditions reach peak values of about 500°C, with average wall temperatures much lower, and peak values of calandria wall heat fluxes, about 25 W/cm^2, remain well below critical heat flux values even though the shield-tank water has reached saturation conditions at this time. Therefore, calandria integrity will be maintained.

It is possible that a low flow rate of water from the stub-ends of the failed pressure tubes or a slow leak of shield tank water into the calandria above the debris bed could develop during the heat-up of the debris. In this case, a Zircaloy-water reaction would occur on any accessible, exposed, unoxidized Zircaloy in the debris, providing an additional heat source without providing any significant cooling effect. Using the option provided in DEBRIS.2 for heat generation by the Zircaloy-water reaction, the consequences of such an event were investigated for the reference conditions, assuming that one-quarter of the initial Zircaloy in the core was unoxidized at the start of debris heat-up, probably a conservative estimate, and that the average thickness of Zircaloy fragments in the debris was 2 millimetres, about the calandria tube thickness and about half the pressure tube thickness. The results are shown in Figures 14 and 15. Figure 14 shows the maximum and upper and lower surface temperatures of the debris as a function of time compared to the same temperatures assuming no Zircaloy-water reaction in the debris, as given in Figure 7. It can be seen that melting would begin about 35 minutes earlier, at about 380 minutes, but that the upper and lower surface temperatures would remain well below the melting temperature throughout the transient. Figure 15 shows that the effect of the Zircaloy-water reaction would be to increase the heat fluxes to the shield-tank water above and below the debris bed fairly rapidly starting at about 360 minutes but that the resulting peak values would still be well below the critical heat flux value of about 200 W/cm^2. The maximum predicted water flow rate to sustain the Zircaloy-water reaction for these conditions is about 2.5 kg/s or about 2.6 litres per second. Water flow rates above this low value would probably provide some cooling effect and tend to reduce debris temperatures and heat fluxes towards the reference conditions values[8]. Therefore, a low water flow rate onto the top of the debris bed resulting in oxidation of any previously unoxidized Zircaloy would not affect the conclusions of this study.

The reference and sensitivity studies demonstrate that debris bed melting would start at about 415 minutes or so after the initiating event irrespective of porosity or pore size, and might not occur at all if the debris bed effective pore size is large, that the upper and lower surface temperatures of the debris bed would be well below the melting point and that the calandria wall would be well-cooled and maintain its integrity throughout the heat-up transient. Thus, the earlier conclusions obtained using the original code DEBRIS have been confirmed and reinforced by the current analysis using DEBRIS.2.

5.2 Thermal Behaviour of Molten Pool of Core Debris in CANDU 6 Calandria

As discussed above, a model for the transient melting of a debris bed is not yet available, so a conservative approach is taken that assumes that the molten pool is formed instantaneously once melting begins in the debris bed; that is, the transient melting period is ignored. For the reference case, molten pool conditions were calculated using MOLPOOL at a time of 415 minutes after the initiating event with geometry and other relevant conditions taken from the reference case for the debris bed heat-up transient. Key input data and results obtained are summarized in Table 3.

As shown in Table 3, for a molten pool of core material at 415 minutes after the initiating event, MOLPOOL predicts that the calandria wall below the molten pool will be protected by a crust about 15 cm thick on the average, with a minimum thickness of about 11 cm at the upper corners. This rather thick crust limits calandria wall inner surface temperatures below the crust to 437-473°C, with outer surface temperatures about 128°C. Above the pool, the calandria wall average inner surface temperature is about 412°C with the outer surface temperature again about 128°C. The heat fluxes on the calandria wall to the shield-tank water are about 21 W/cm^2 or less, once more below the critical heat flux for the existing conditions. Thus, the structural integrity of the calandria is maintained for these molten debris pool conditions.

The important role of a crust in protecting a reactor vessel wall from molten core material is emphasized by Speis (1995) in a review of the TMI-2 accident.

Table 3 shows that MOLPOOL predicts a relatively thin (about 1.1 cm) upper crust will form over the pool under these conditions. Whether such a thin crust is stable is not certain. The average temperature of the molten pool is about 166°C above the melting point, but is considerably below the expected boiling point temperatures of 3500 to 3700°C

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[8] Analysis undertaken for the CANDU 6 PSA predicts that the core debris can be readily quenched before melting begins by available water supplies (Howieson et al (1988), Allen et al (1990)).

(Anderson, 1976). Table 3 also shows that the proportion of pool heat generation dissipated upwards is more than 70%. Predominance of upward heat dissipation from molten debris is consistent with results obtained by Henry et al (1991) and Rempe (1994).

The foregoing analysis assumes that the molten pool is formed instantaneously as soon as melting begins in the debris bed. An assessment of the conditions that might be more representative of the molten pool characteristics once the melting transient has reached quasi-steady-state conditions can be made by using MOLPOOL to predict such characteristics for times greater than 415 minutes.

Table 3
Key MOLPOOL Input and Results for Reference Conditions

Molten pool maximum temperature, °C	2866
Molten pool surface temperatures, °C	2700
Upper crust surface temperature, °C	1902
Lower crust surface temperature, °C	437
Average steam temperature above pool, °C	753
Calandria wall inner temperature, above pool, °C	412
Calandria wall outer temperature, above pool, °C	128
Calandria wall inner temperature, pool upper corner, °C	473
Calandria wall inner temperature, under pool, °C	437
Calandria wall outer temperature, under pool, °C	128
Shield-tank water temperature, °C	77.4
Upper crust thickness, cm	1.15
Lower crust thickness, cm	14.8
Lower crust minimum thickness @ upper corner, cm	11.3
Maximum depth of pool plus crusts, cm	115
Upward fraction of heat flow	0.73
Heat flux to shield-tank water above pool, W/cm^2	15.8
Heat flux to shield-tank water below pool, W/cm^2	17.2
Maximum heat flux, pool upper corner, W/cm^2	21.1

Results are shown in Figures 16 and 17, for times from 415 minutes to 1600 minutes. The latter is about the time that the calandria vessel would be expected to fail from overheating upon uncovery caused by ejection and boil-off of the shield-tank water, should electric power or emergency water supplies not be restored before then (Dick et al (1990)). Figure 16 shows that the molten pool temperature decreases only slightly over this period, with the outer temperature of the upper crust decreasing to a greater extent. Calandria wall temperatures above and below the molten pool also decrease slowly with time. Figure 17 shows that the upper and lower crusts increase in thickness with time, reaching values of about 22 cm on the average and 18 cm at the minimum for the lower crust and over 3 cm for the upper crust. The analysis also predicts that heat fluxes to the shield-tank water decrease from the values in Table 3 at 415 minutes to about 12 to 15 W/cm^2 on the lower calandria wall and about 8 W/cm^2 on the upper calandria wall at 1600 minutes. Thus, the integrity of the calandria will be maintained over this period.

Sensitivity studies have been undertaken using MOLPOOL to investigate the effects of parameters whose values are uncertain on the behaviour of the molten pool and crusts. These studies were undertaken for a time of 415 minutes.

a) Variation of the emissivity of the upper crust from 0.3 to 0.9 (reference value: 0.9) had essentially no effect on most temperatures and on the heat fluxes to the shield-tank water. Only the thickness of the upper crust, which increases from about 0.6 to 1.15 cm, and the temperature of the crust surface, which decreases from about 2300°C to 1900°C, as the emissivity increases from 0.3 to 0.9, are affected by this variation.

b) Variation of the thermal conductivity of the molten corium from 2 to 10 W/mK (reference value: 3.6 W/mK) affects only the temperature of the molten pool, which decreases from about 2930°C to about 2800°C, without affecting to any important extent other temperatures or calandria wall heat fluxes.

c) Variation of crust thermal conductivity from 4 to 12 W/mK (reference value: 8 W/mK) increases the thickness of the upper crust from about 0.5 cm to about 1.9 cm and the average thickness of the lower crust from about 9.4 cm to about 19 cm. However, the resulting variations in calandria wall temperatures and heat fluxes are not great and the reduced thicknesses of the crusts at low conductivity do not represent a challenge to the integrity of the calandria vessel.

We may conclude that the calandria will remain well-cooled and intact during this accident sequence until it is uncovered by ejection and boil-off of the shield-tank water which should not occur until about 1600 minutes, or about 26 hours, after the initiating event. Therefore, considerable time is available to restore electric power or to provide an emergency water supply to maintain sufficient water in the shield tank to ensure that the calandria is always covered. The present analysis confirms the conclusion of the earlier simpler analyses (Rogers (1984b, 1984c), Dick et al (1990)) that the calandria vessel serves as an effective core-catcher following a severe accident in a CANDU reactor for a molten pool of debris, as well as for a solid debris bed, as long as the shield-tank water level keeps the calandria vessel covered.

5.3 Energy Balance for Molten Pool Conditions

Since a model of the transient melting of a coarse debris bed is not yet available, it has been assumed that a pool of molten debris will eventually form in the calandria once melting of the solid debris begins. The characteristics of such a pool for times greater than 415 minutes, the time when melting is predicted to begin for the reference conditions, have been described in Section 5.2.

However, a comparison of the stored energy which would be necessary for the existence of such a pool including its crusts at any given time with the energy available to form and maintain the pool up to the same time suggests that such a coherent molten pool could not be formed. The energy available consists of the stored energy in the solid debris bed at the time melting begins plus the energy generated by decay heat from the onset of melting to the given time less the energy lost to the shield-tank water over the same period. The energy storage in the molten pool and crusts at any time is calculated in MOLPOOL, the energy stored in the debris bed at the onset of melting is calculated in DEBRIS.2 and the decay energy generated is readily calculated by integration of the decay heat equation over the period. However, to calculate the energy lost to the shield-tank water over the period requires knowledge of the variation with time of heat fluxes from the upper and lower areas of the calandria to the shield-tank water. Since this information is not available for the melting transient, a range of constant time-averaged heat fluxes was assumed which is believed to cover the conditions that might be expected, from results obtained with DEBRIS.2 and MOLPOOL.

A comparison of the stored energy with the available energy at any time for a range of heat fluxes from 8 to 18 W/cm^2 is given in Figure 18. Figure 18 shows that, for time-averaged heat fluxes of 12 W/cm^2 and higher the energy available is always less than the stored energy necessary to form the pool and crusts. Since the heat fluxes at the onset of melting predicted by DEBRIS.2 are generally higher than 12 W/cm^2, and are increasing, and since the weighted average heat fluxes predicted by MOLPOOL for this period are also greater than 12 W/cm^2, we can conclude that there is not sufficient energy available to form a coherent molten pool in the calandria under these conditions.

This finding suggests that, while in general a melting transient will occur as described earlier, the relocation of molten material and its re-solidification results eventually in a geometric arrangement in which the generated heat can be removed to the shield-tank water without further liquefaction of the debris. Development of the analytical model for the melting transient will be necessary to confirm this conclusion.

6. ASSESSMENT AND CONCLUSIONS

The design of the CANDU reactor places the cool moderator about 1.5 cm. away from the outermost part of the fuel bundle. In turn, the calandria containing the moderator is surrounded by a water filled shield tank. Both the moderator and the shield tank are separately-cooled systems, and have the ability to remove decay heat from the fuel in a severe accident - the moderator immediately, and the shield tank in the longer term.

The ability of the moderator to prevent fuel melting and retain fuel within the fuel channels in the absence of coolant has been extensively studied. This paper assumes that both the primary coolant is lost (and not replaced by emergency coolant) and that the moderator heat removal system fails. As the moderator boils off, the fuel channels collapse and form a debris bed in the lower part of the calandria. The models reviewed here for debris bed formation predict that the fuel is not molten when the debris bed is formed, but a molten pool may develop as the bed dries out and heats up. However, the formation of a large coherent molten pool is unlikely, from energy balance considerations. Nevertheless, a detailed model of the debris behaviour predicts that the calandria shell is protected from molten material by a solid crust, and that the decay heat is removed from the bed by heat transfer through the thin calandria wall to the shield tank water. This conclusion is reasonably insensitive to channel failure mechanism, core collapse mechanism, debris porosity, pore size, and heat from zirconium-steam reaction in the bed.

There are a number of uncertainties in this accident sequence, mainly because the structural changes are large. The mechanical/thermal behaviour of the end shields has not been addressed. The capability of the shield tank to relieve steam generated by the boiling shield tank water has not been examined; CANDU 9 has special relief pipes to allow for this, but CANDU 6 does not. There could be local effects in the debris bed or molten pool with the potential to cause hot spots on the calandria shell, with the risk of localized dryout, such as crust cracking and melt penetration. There is no experimental validation of the debris melting transient; however the debris bed behaviour seems to be insensitive to the details of core collapse and bed parameters. There is also uncertainty in the debris bed property values.

Future analytical work should be done to develop a range of models of core collapse (to see if the results are sensitive to the mode of core collapse) and a model of the debris bed melting transient. On the experimental side, demonstration of adequate critical heat flux on a section of the calandria wall containing molten material would be useful to show the sensitivity to local effects.

The predicted core melt behaviour for CANDU is considerably different from that of light-water reactors. Contributors to this difference, in addition to the inherent heat sinks provided by the separate moderator and shield tank water are the low power density (about 15.6 MW/Mg of fuel in a CANDU 6, based on the design power) and the extensive dispersion of the debris in the calandria resulting in a shallow molten pool depth of about 1 metre maximum and about 0.65 metre average for the reference case for CANDU 6. However, the results of the present study may be relevant to recent studies on external cooling of reactor pressure vessels in light water reactors (Henry et al (1993), Park et al (1994).

Of greater importance are the lessons for severe accident management. Whether or not the moderator and shield tank cooling systems are operational, the large volume of water in each system delays the progression of a core melt for hours to days. This allows ample time for restoring electric power or simple mitigation action, such as adding water to the calandria before debris melting begins (Howieson et al (1988), Allen et al (1990)) or to the shield tank at any time.

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8. ACKNOWLEDGEMENTS

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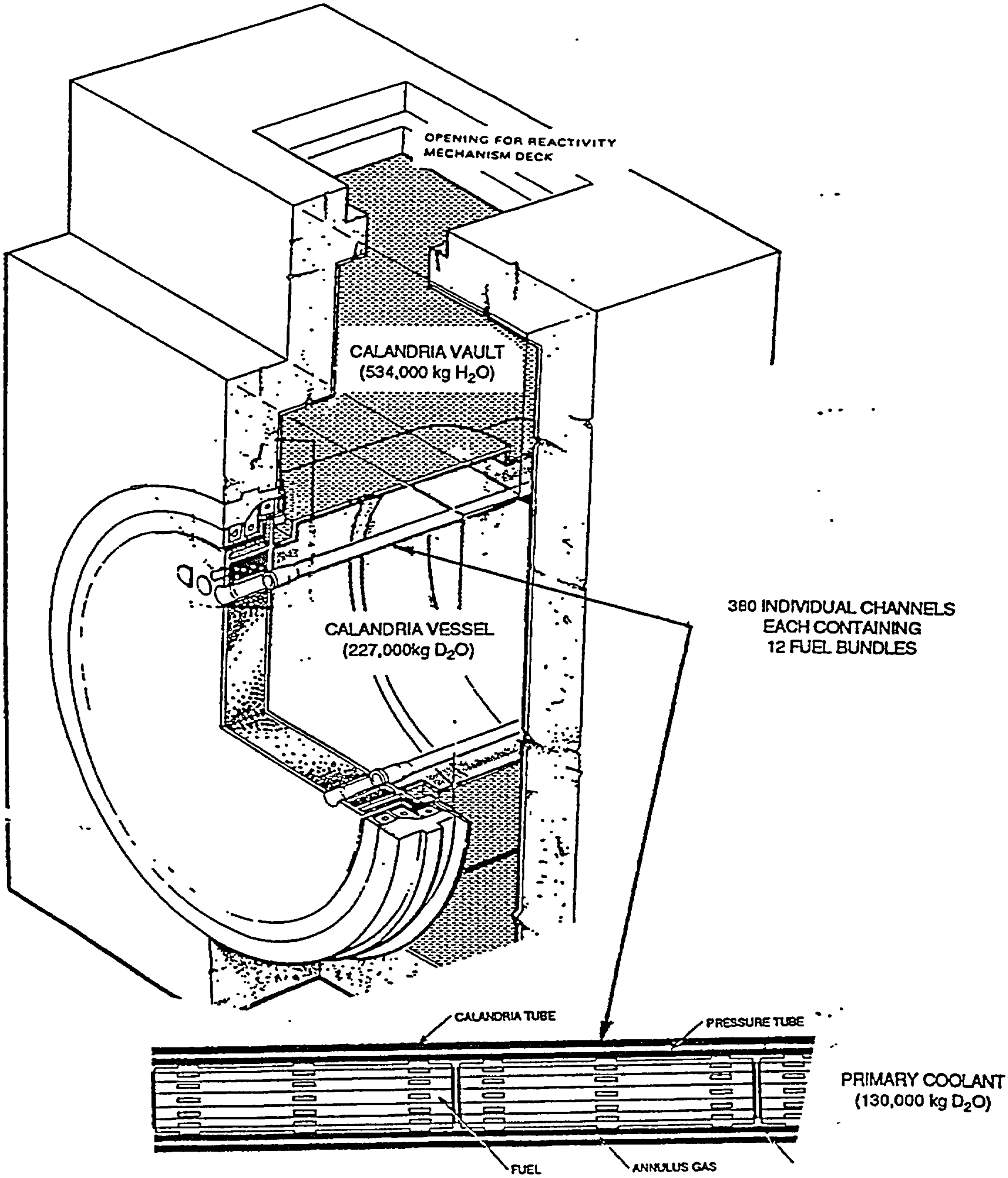


Figure 1 Separate Water Systems Surrounding the Fuel in the CANDU 6 Reactor (From Dick et al 1990)

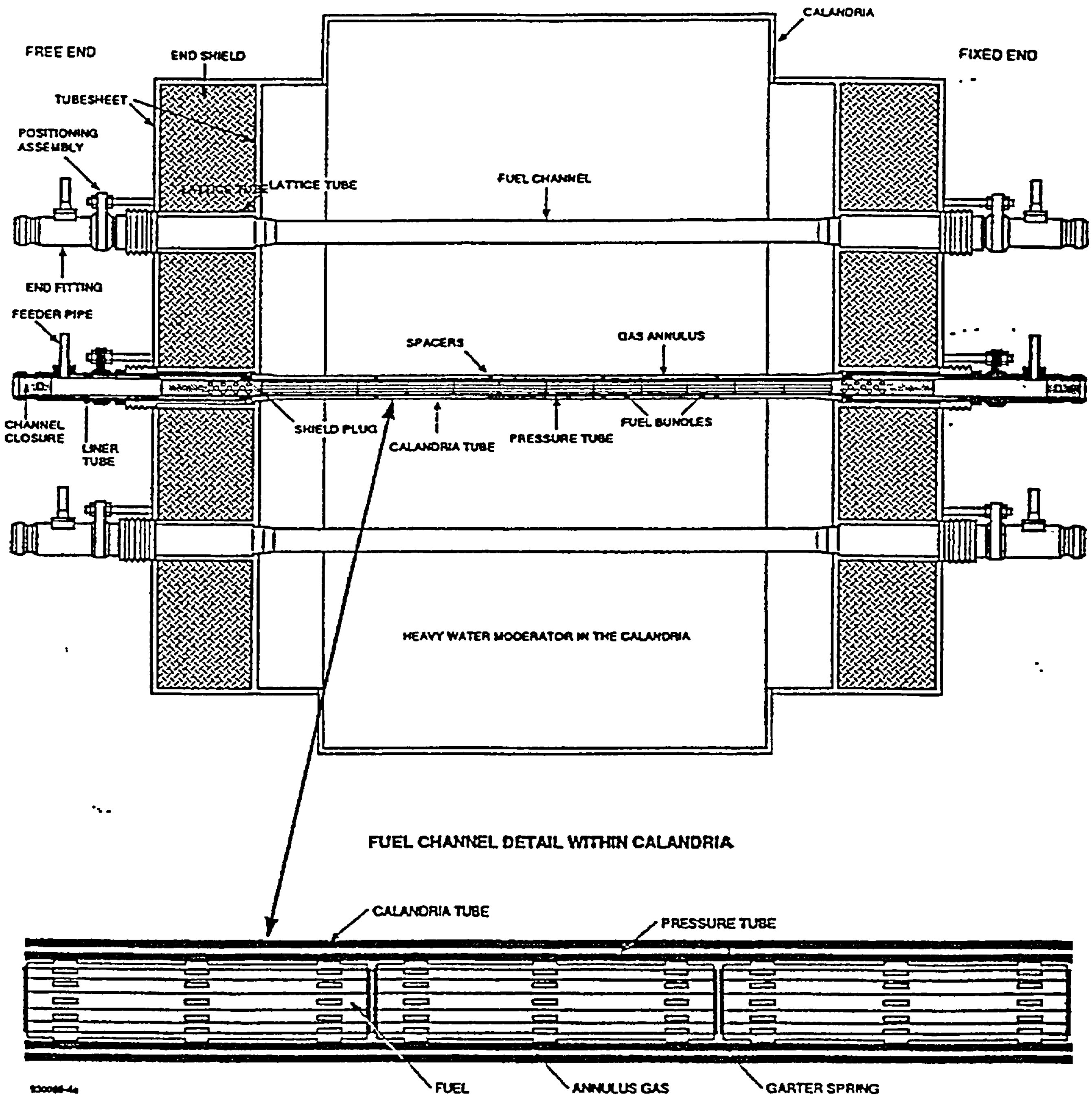


Figure 2 CANDU Reactor – Side View

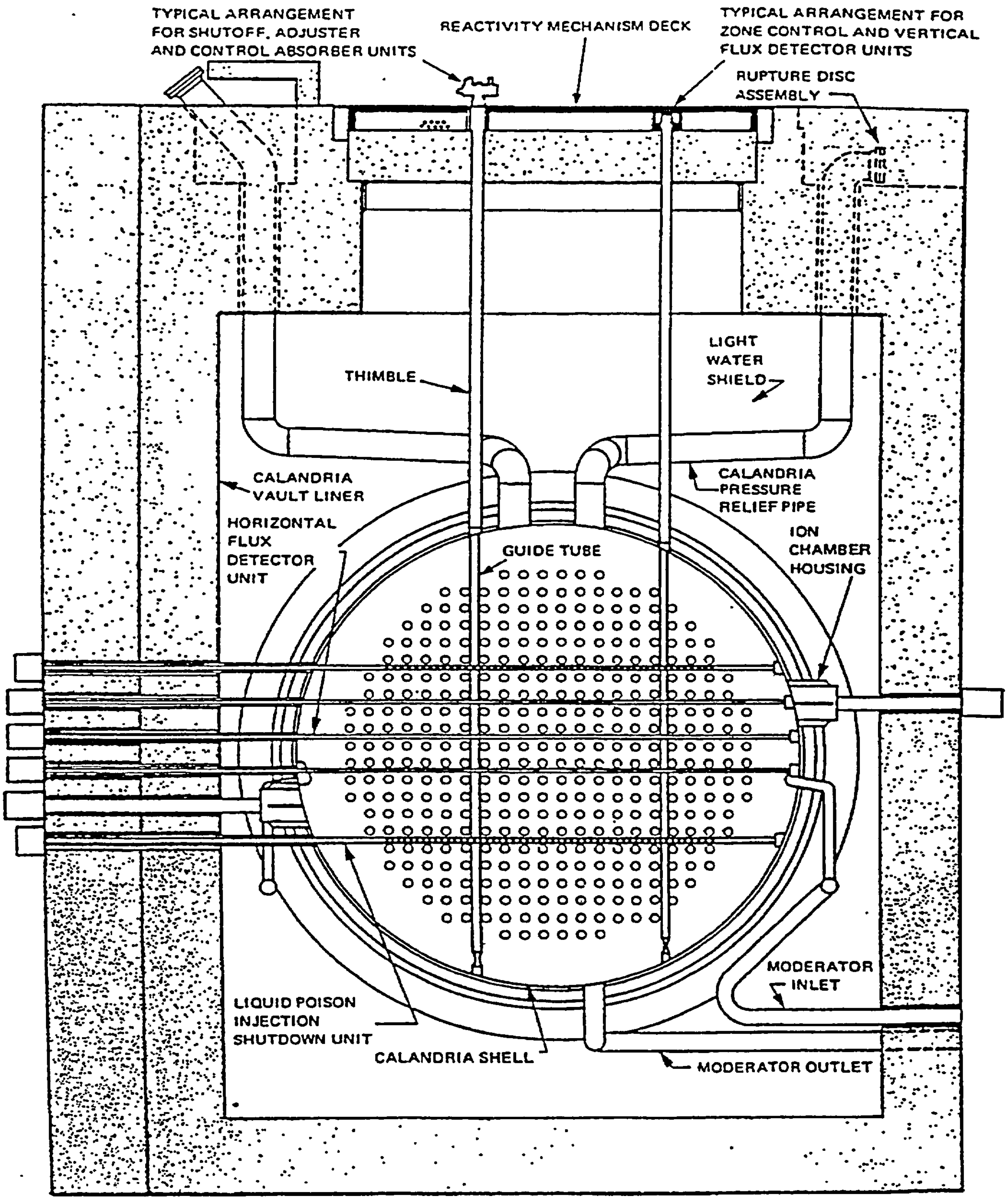
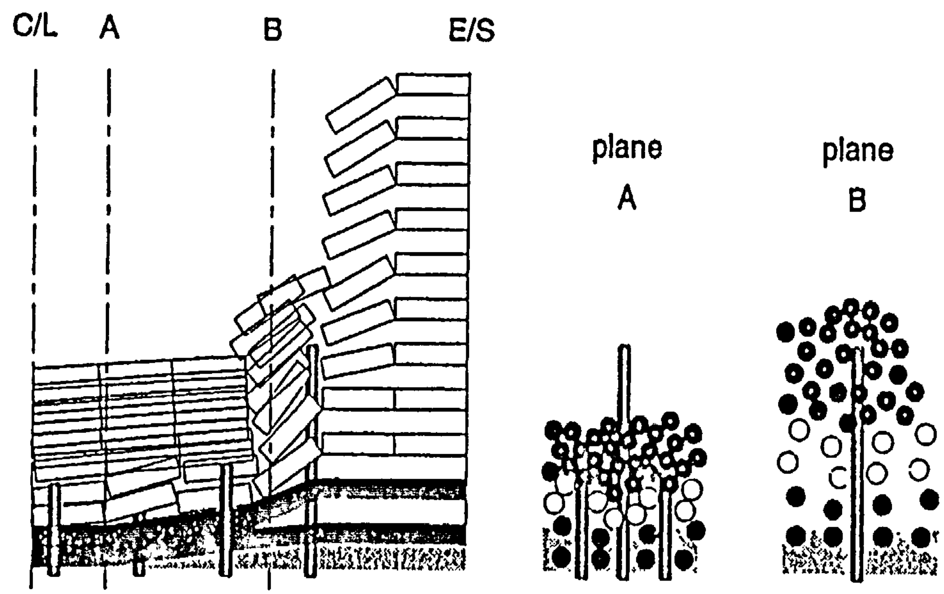


Figure 3 CANDU Reactor – End View

UNCOVERED CHANNELS DEFORM BY SAGGING

SEGMENTS SEPARATE BY MEMBRANE STRETCHING WHEN SUFFICIENT DEFLECTION DISTANCE AVAILABLE

DEFORMATION AT LOCAL TEMPERATURE >1200°C



SEPARATION AT DISTANCE TO LIQUID LEVEL >1 m

SUBMERGED CHANNELS FAIL AT ROLLED JOINT WHEN SUFFICIENT DEBRIS LOAD BUILDS UP (CORE COLLAPSE)

Figure 4 Fuel Channel Disassembly

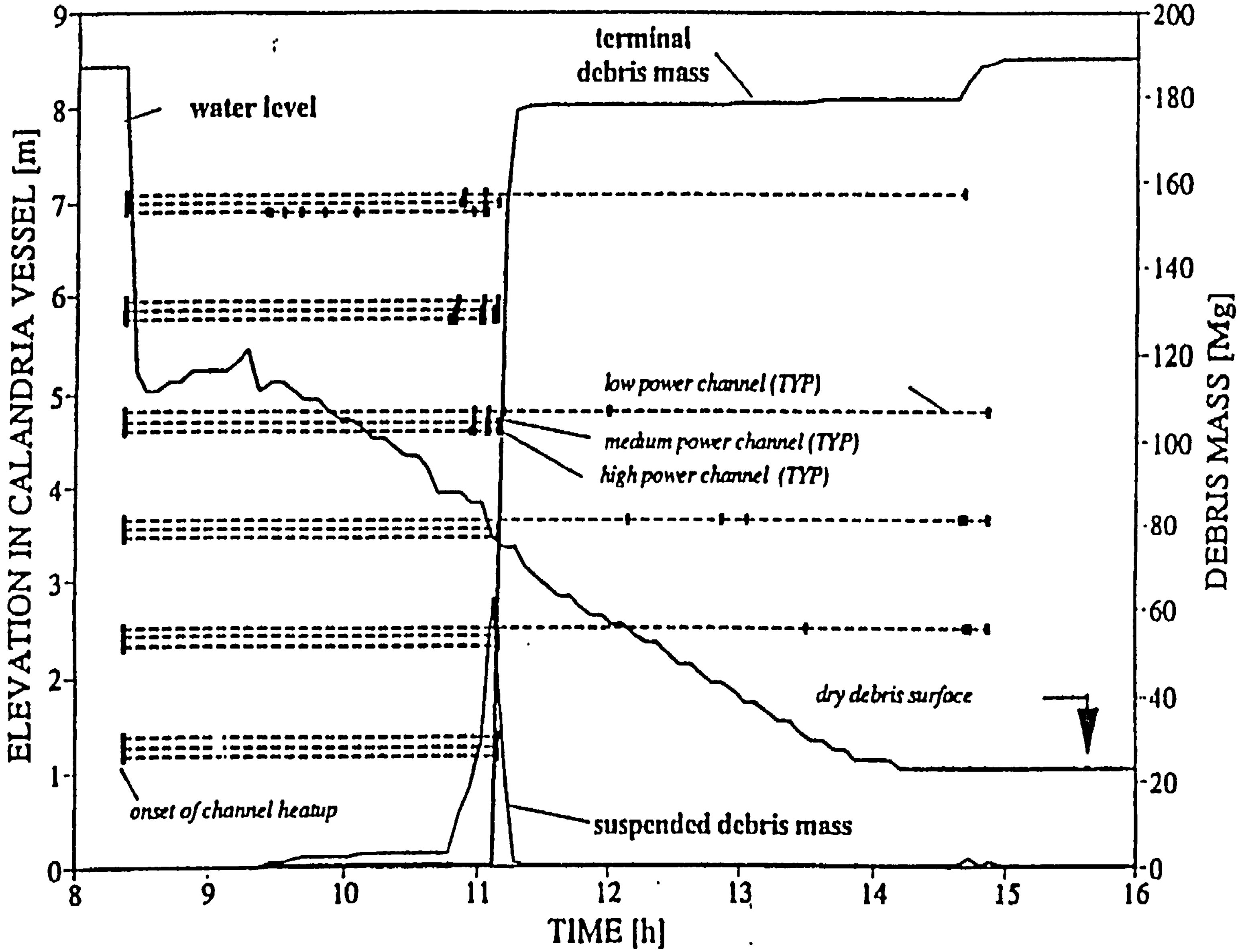
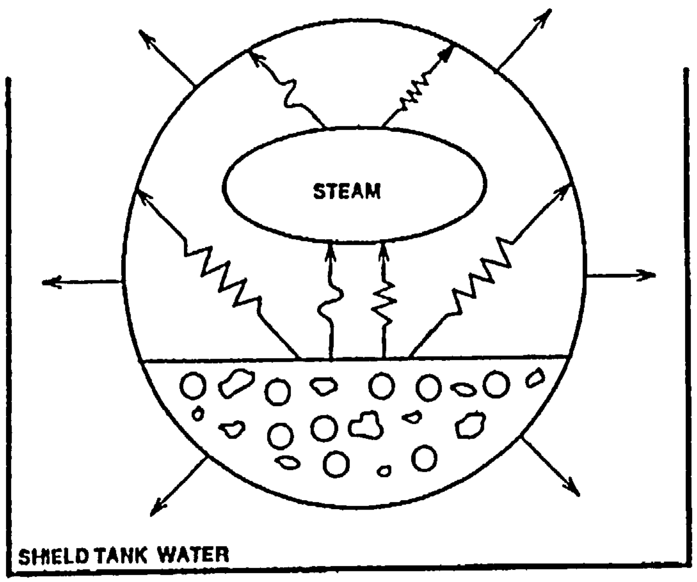
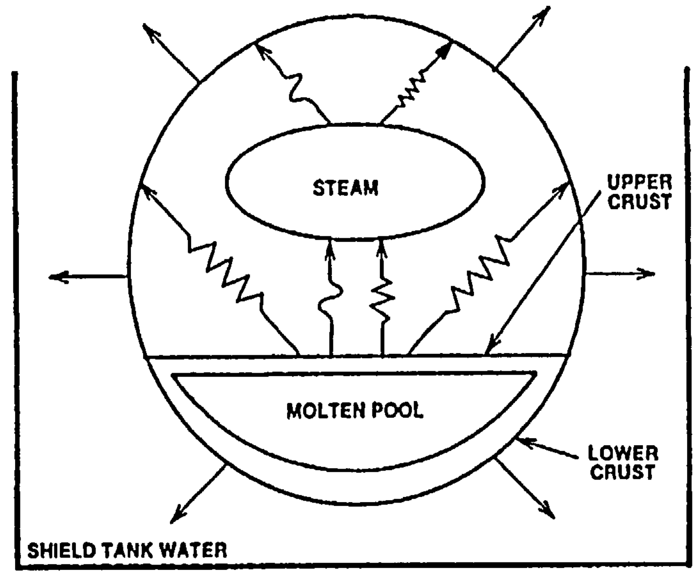


Figure 5 Core Disassembly Transient



a) Debris bed



b) Molten pool and crusts

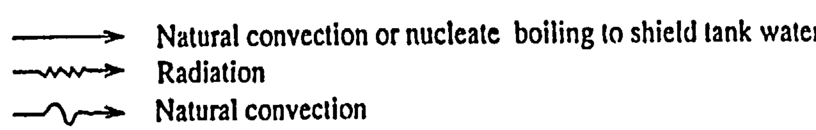


Figure 6 Analytical Model of Debris Bed and Molten Pool

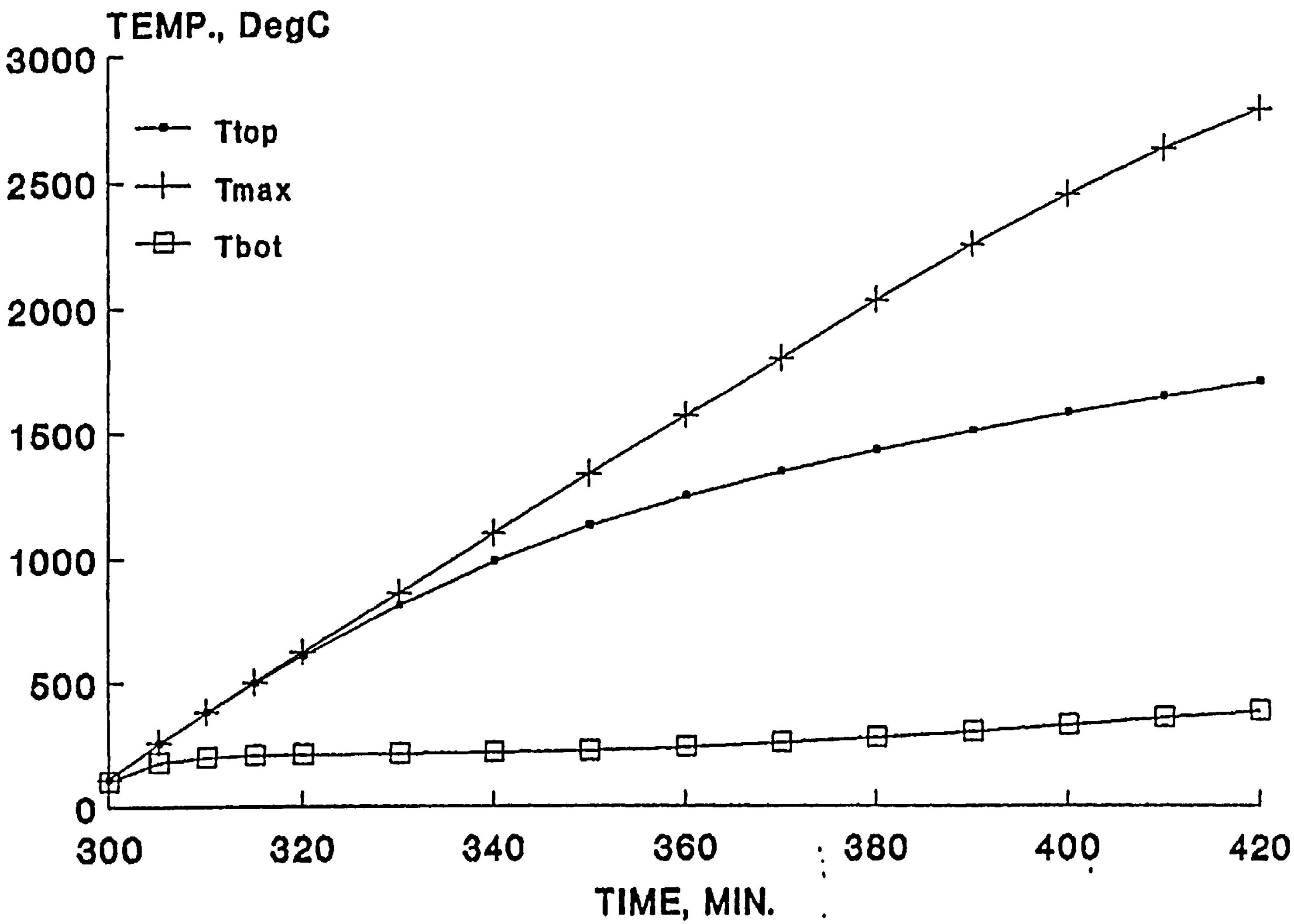
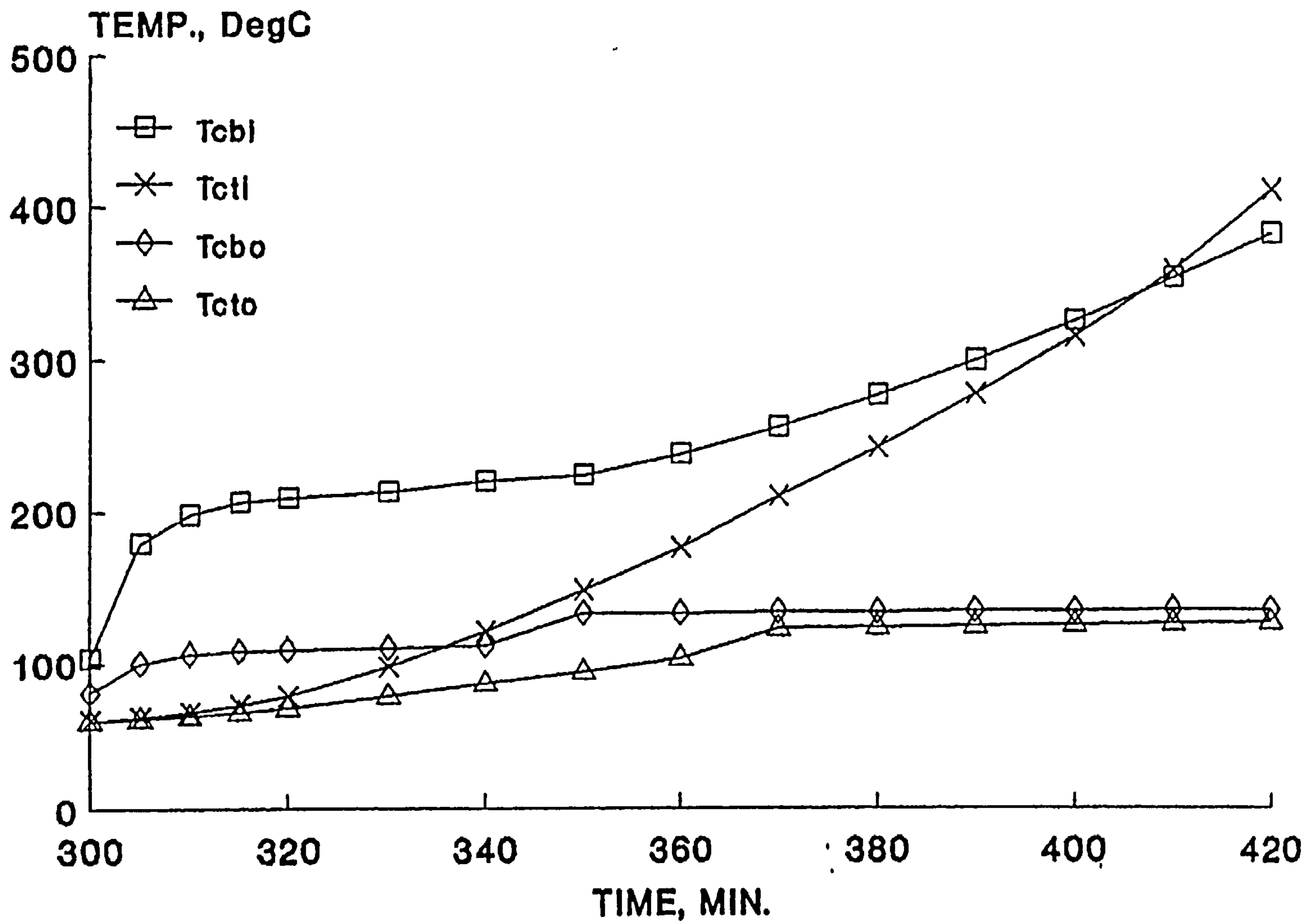
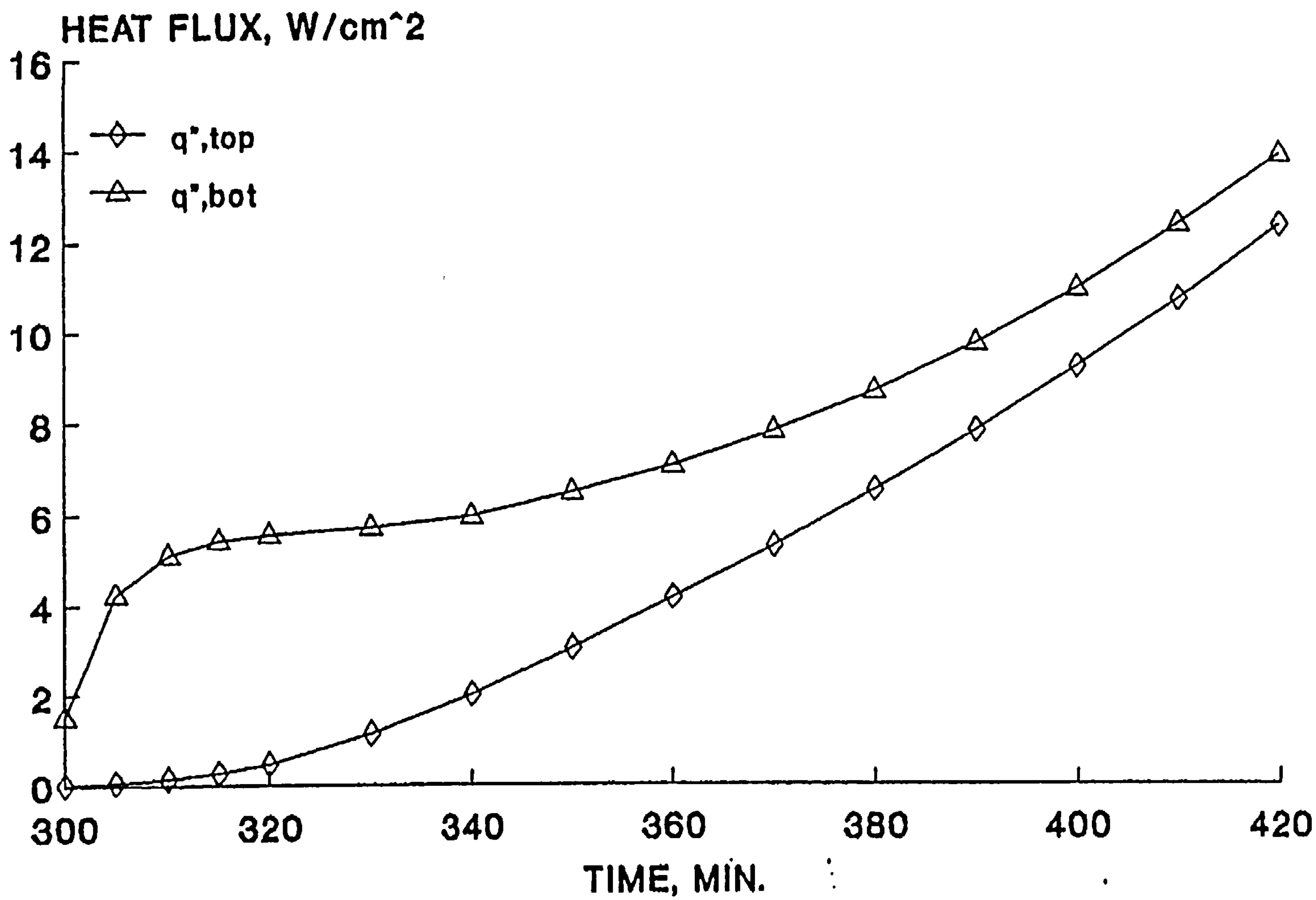


Figure 7 Heat Up of Core Debris in CANDU 6 Calandria, Reference Conditions



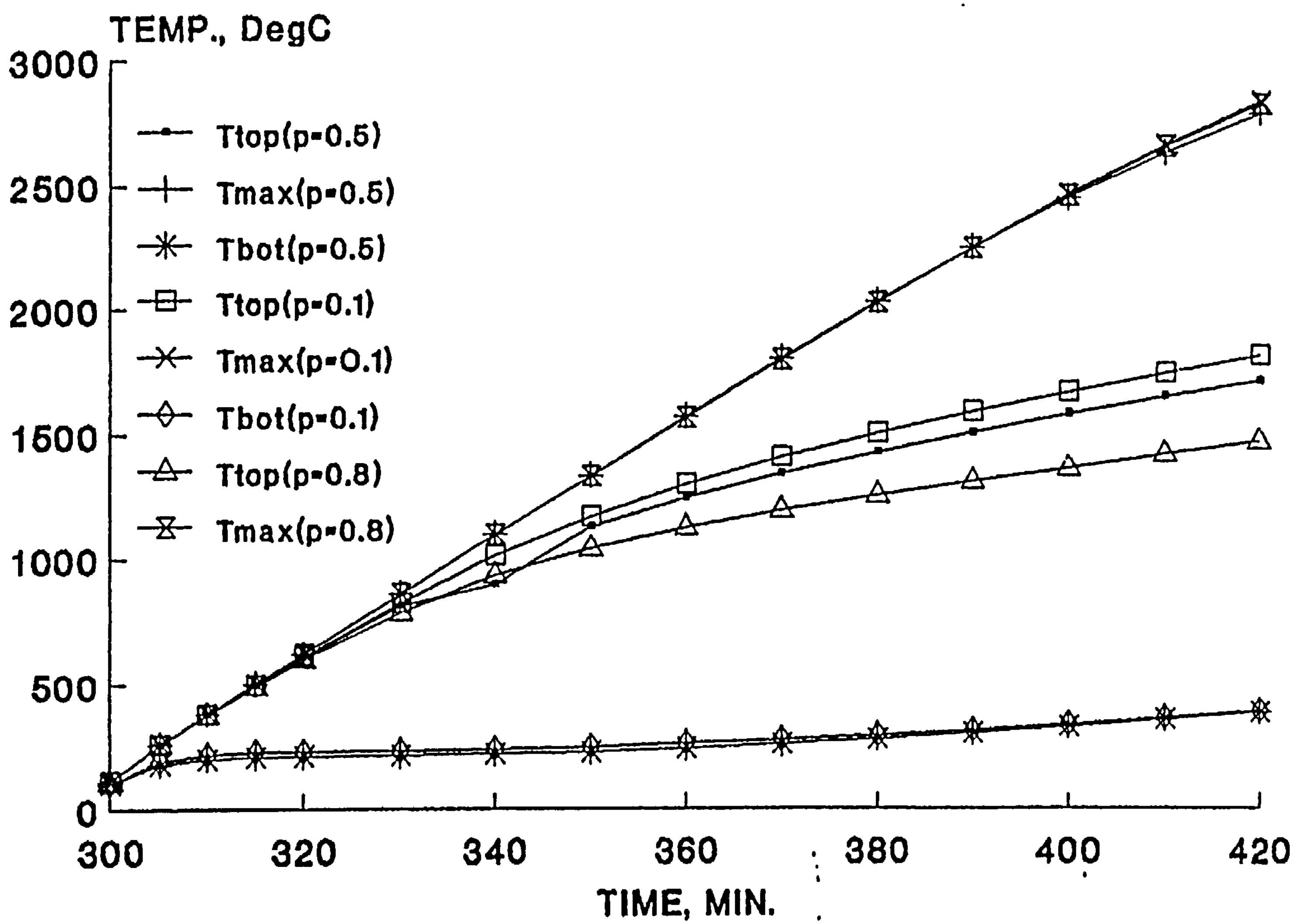
Porosity= 0.5, Pore Size= 3 cm

Figure 8 Calandria Wall Temperatures, Heat Up of Core Debris, CANDU 6 Calandria



Reference Conditions
Porosity = 0.05, Pore Size = 3 cm

Figure 9 Heat Fluxes on Calandria Wall, Heat Up of Debris in CANDU 6 Calandria



Pore Size = 3 cm

Figure 10 Effect of Porosity on Debris Temperature

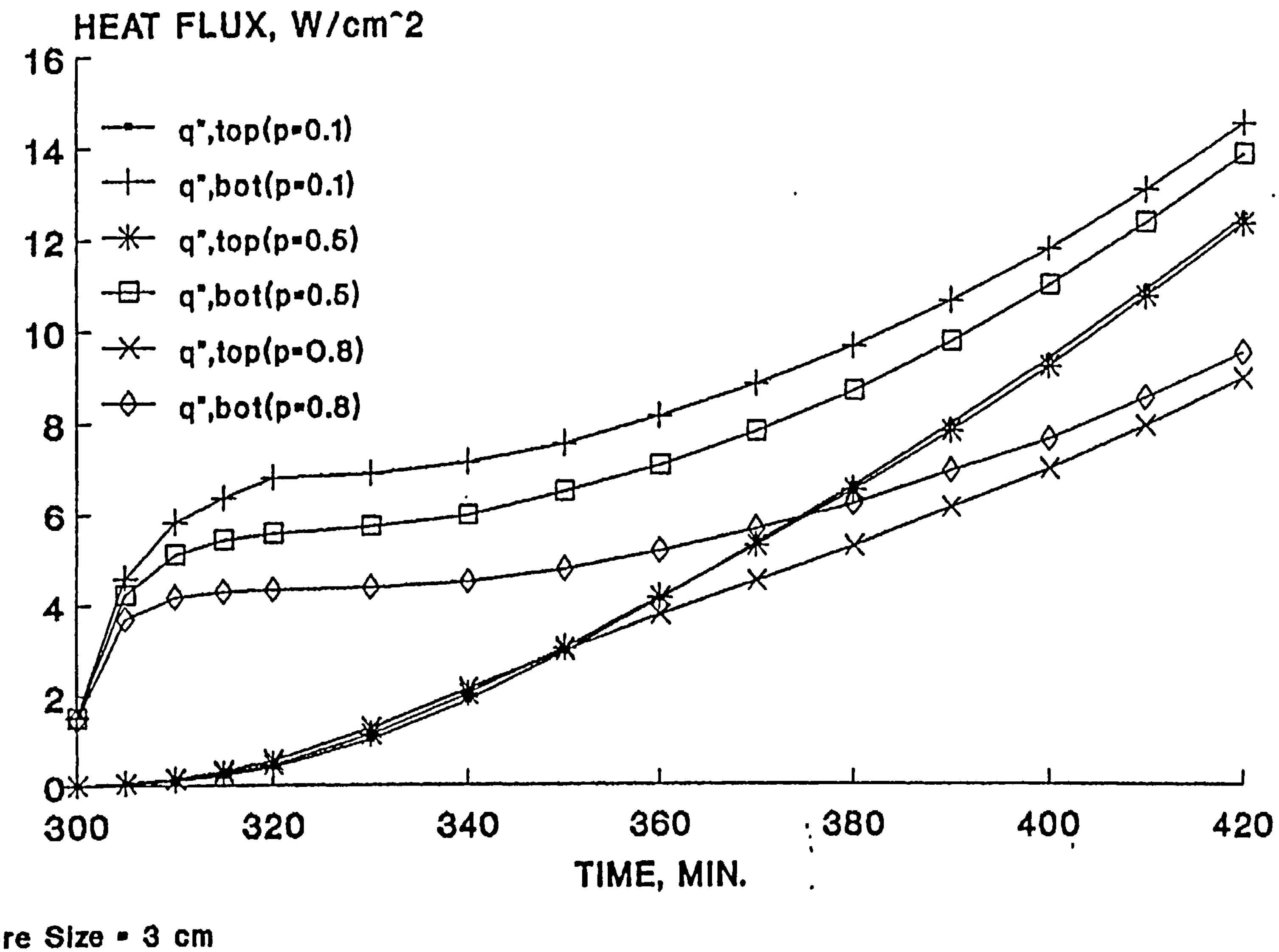


Figure 11 Effect of Porosity on Calandria Wall Heat Fluxes

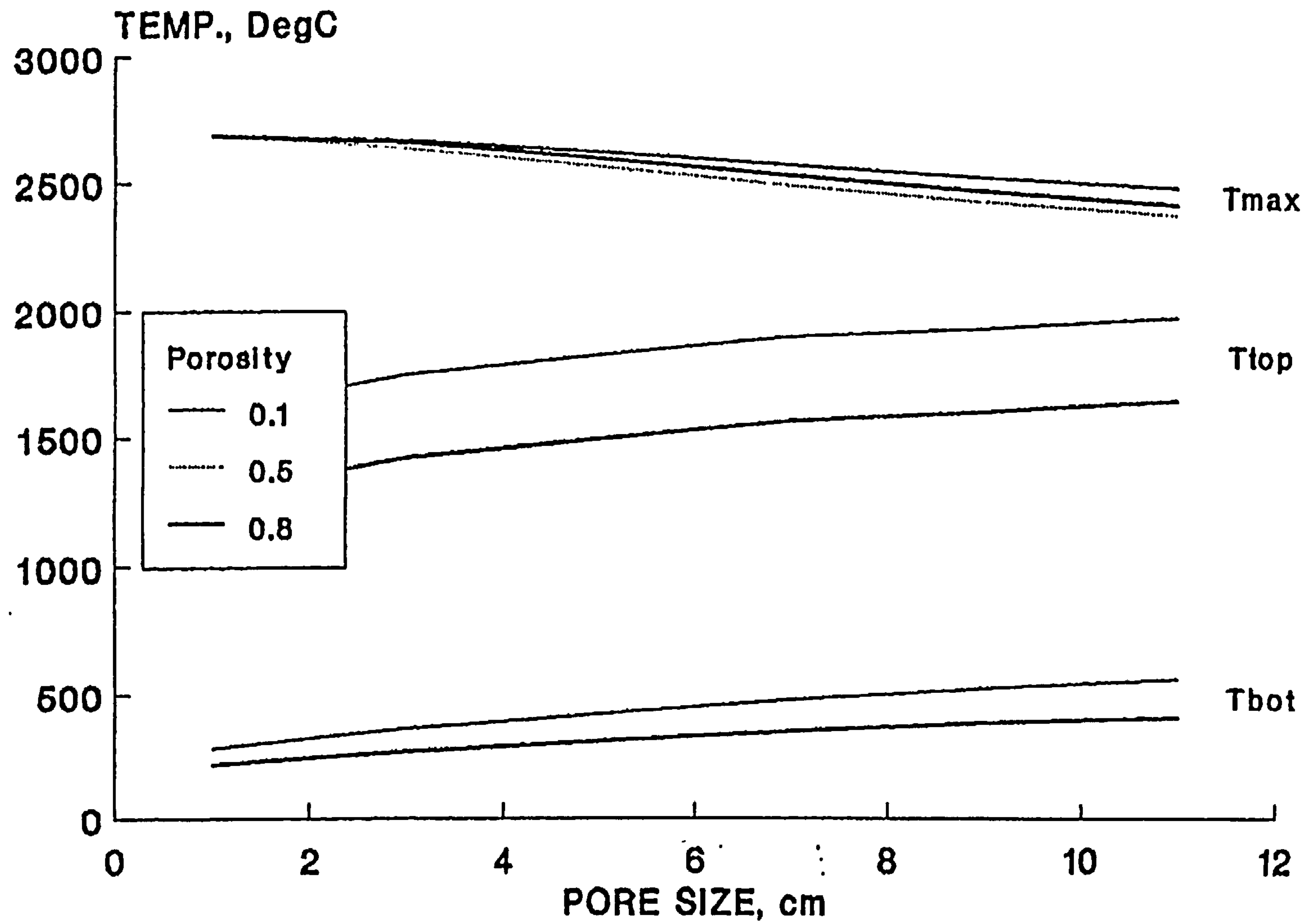
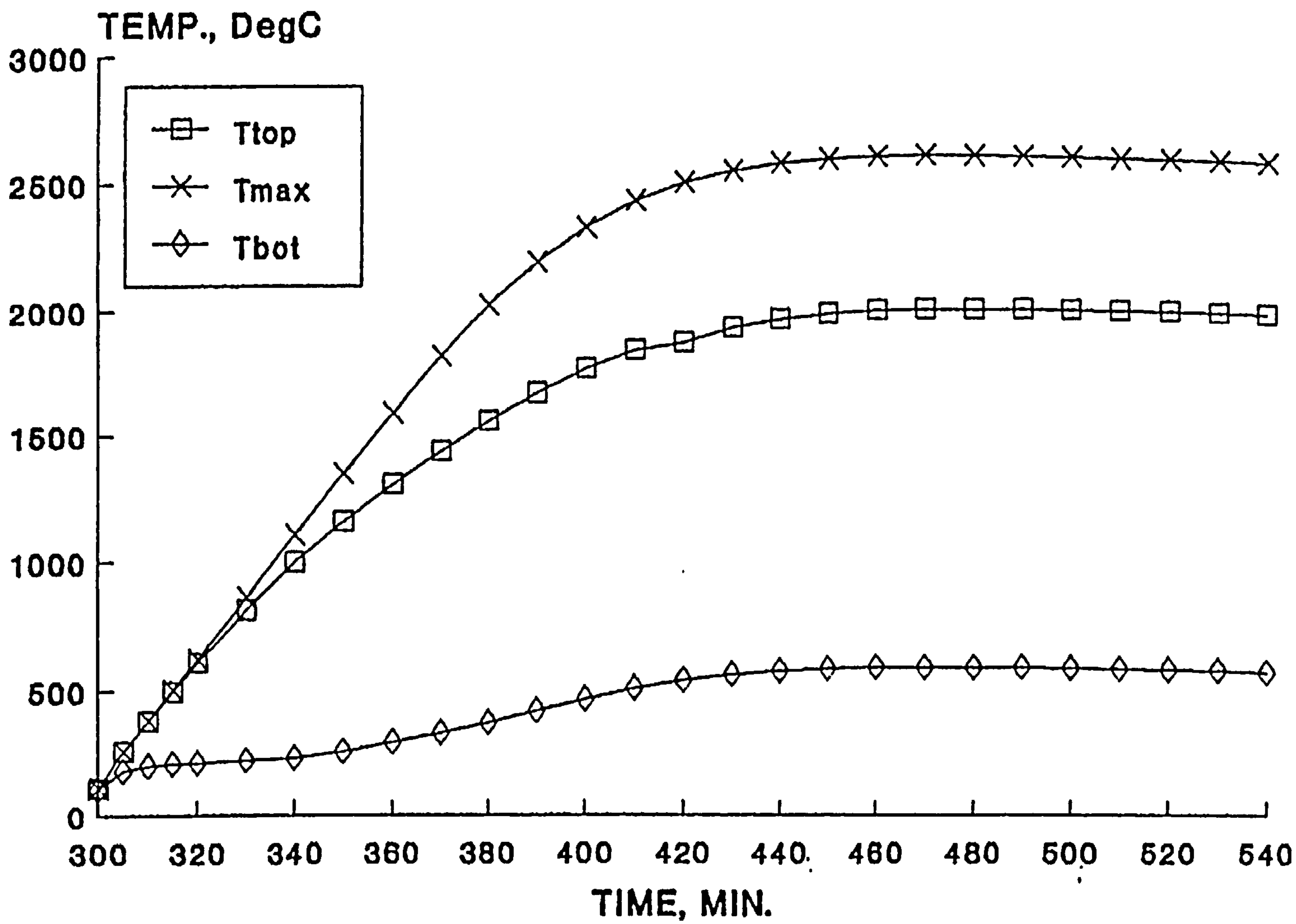
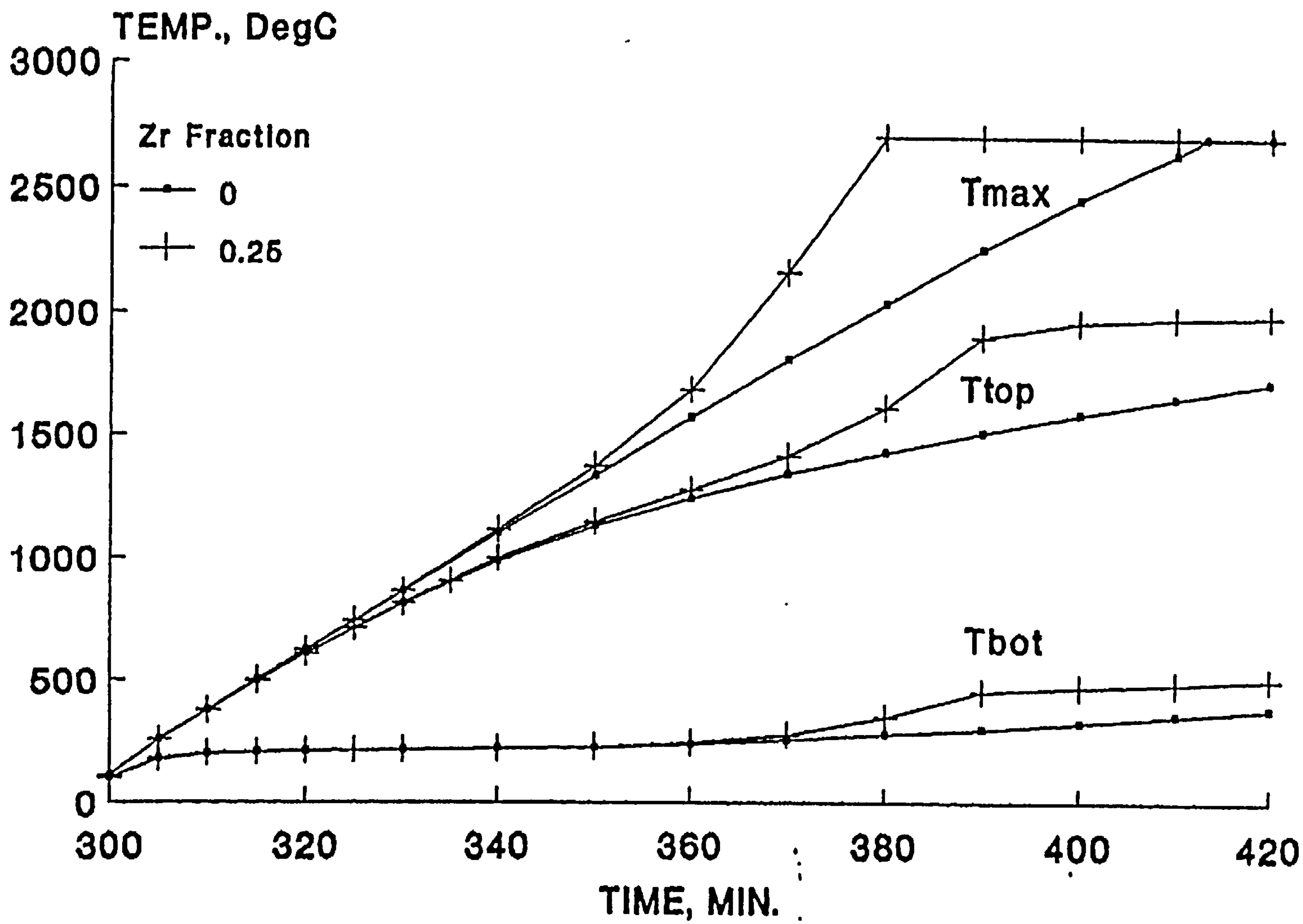


Figure 12 Effect of Pore Size on Maximum Debris Temperature, Time = 410 min



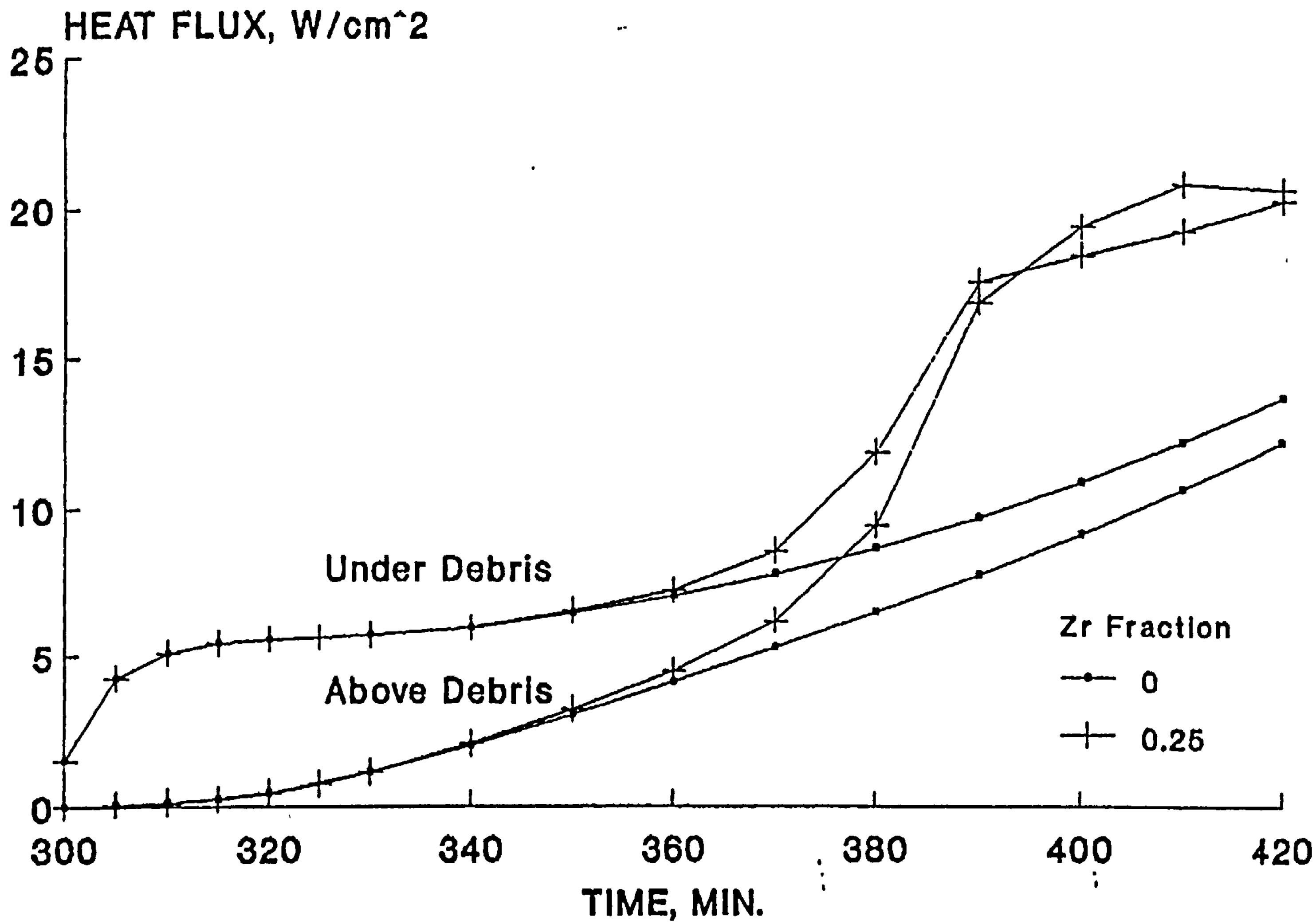
Porosity = 0.5

Figure 13 Heat Up of Core Debris in CANDU 6 Calandria for Pore Size of 9 cm



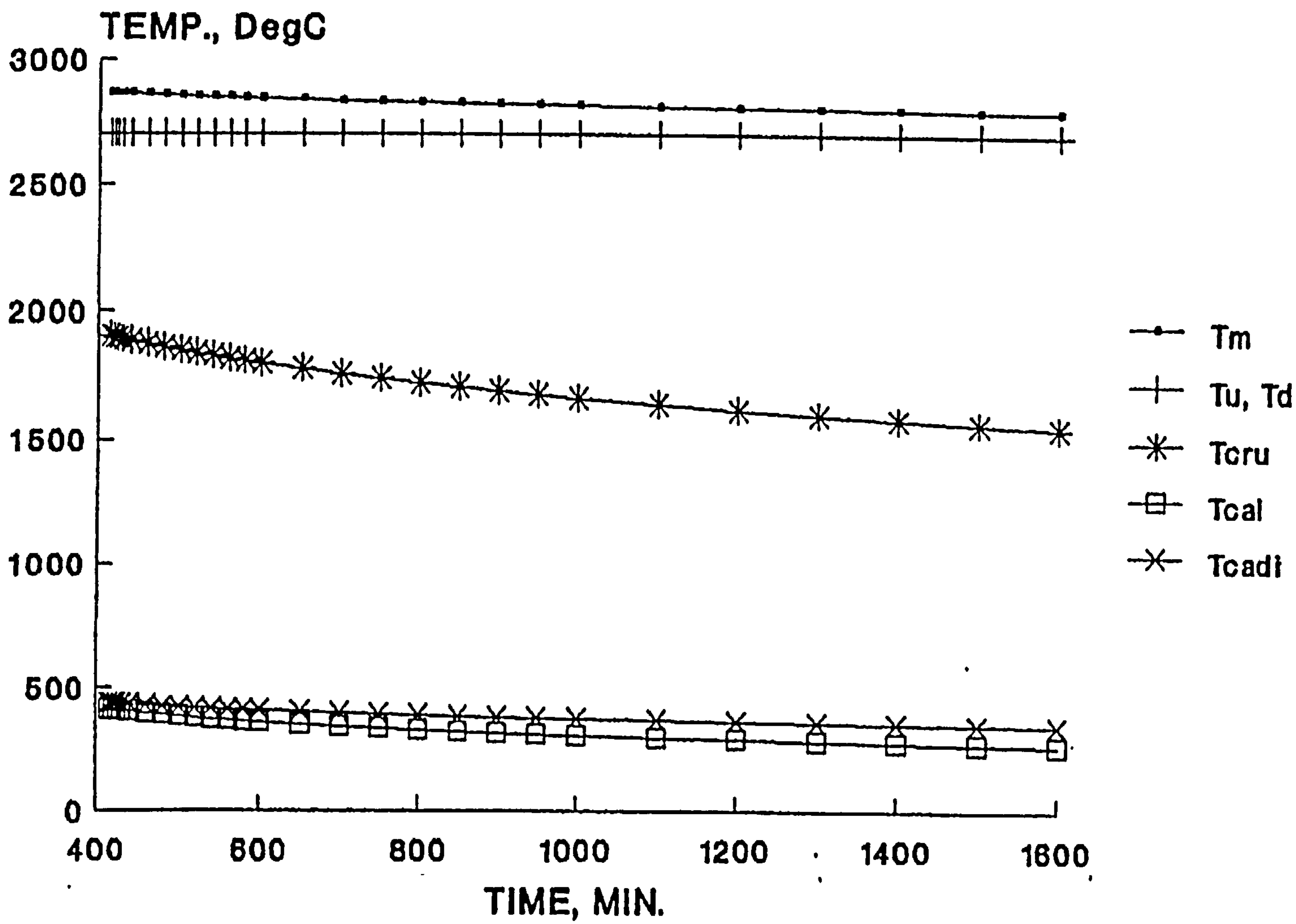
Reaction rate: Urbanic-Heidrick equation

Figure 14 Effect of Zircaloy Oxidation on Debris Thermal Behaviour



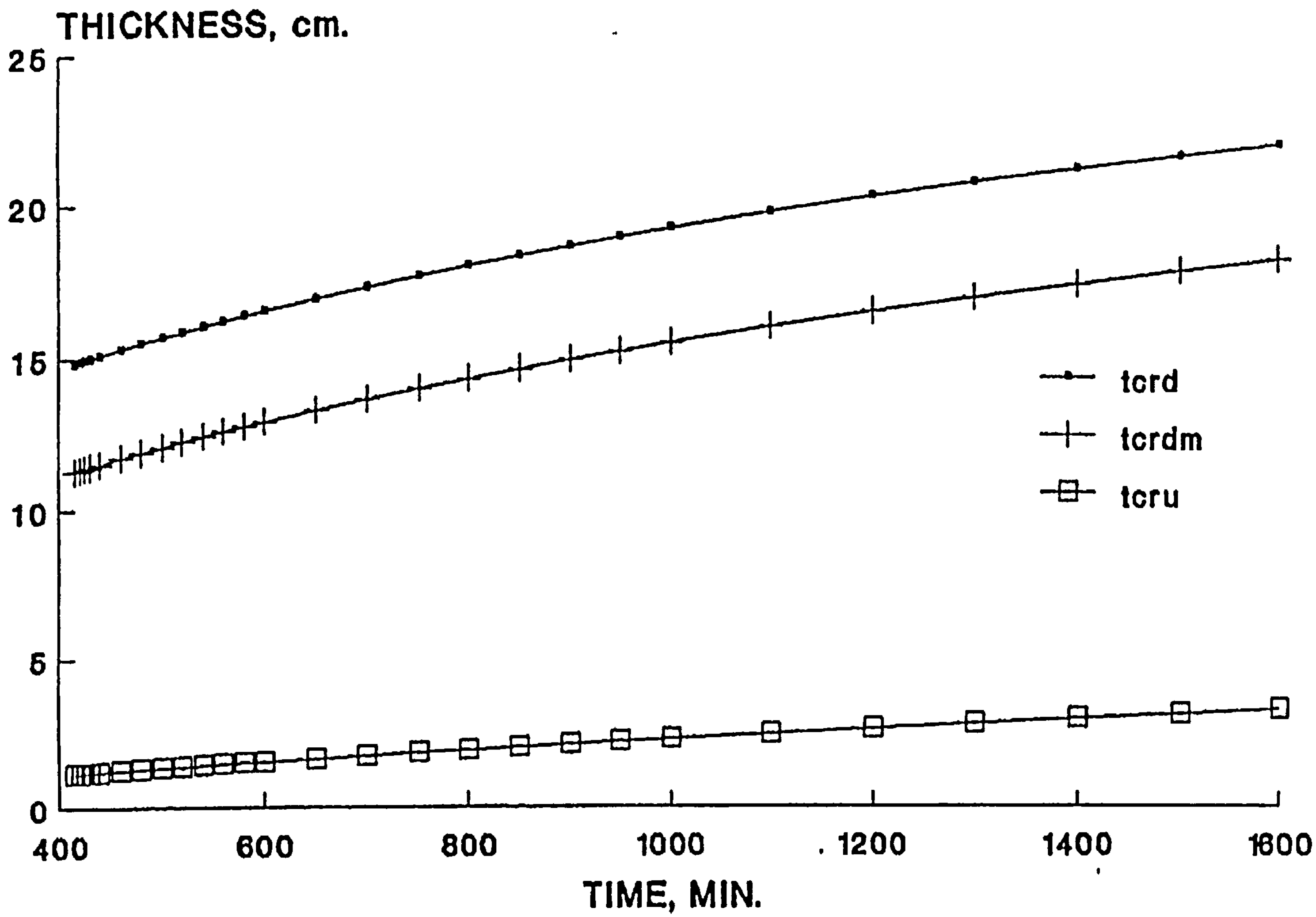
Reaction rate: Urbanic-Heidrick equation

Figure 15 Effect of Zircaloy Oxidation on Debris Thermal Behaviour



Reference Conditions

Figure 16 Molten Core Debris in CANDU 6 Calandria



Reference Conditions

Figure 17 Crust Thickness, Molten Core Debris in CANDU 6 Calandria

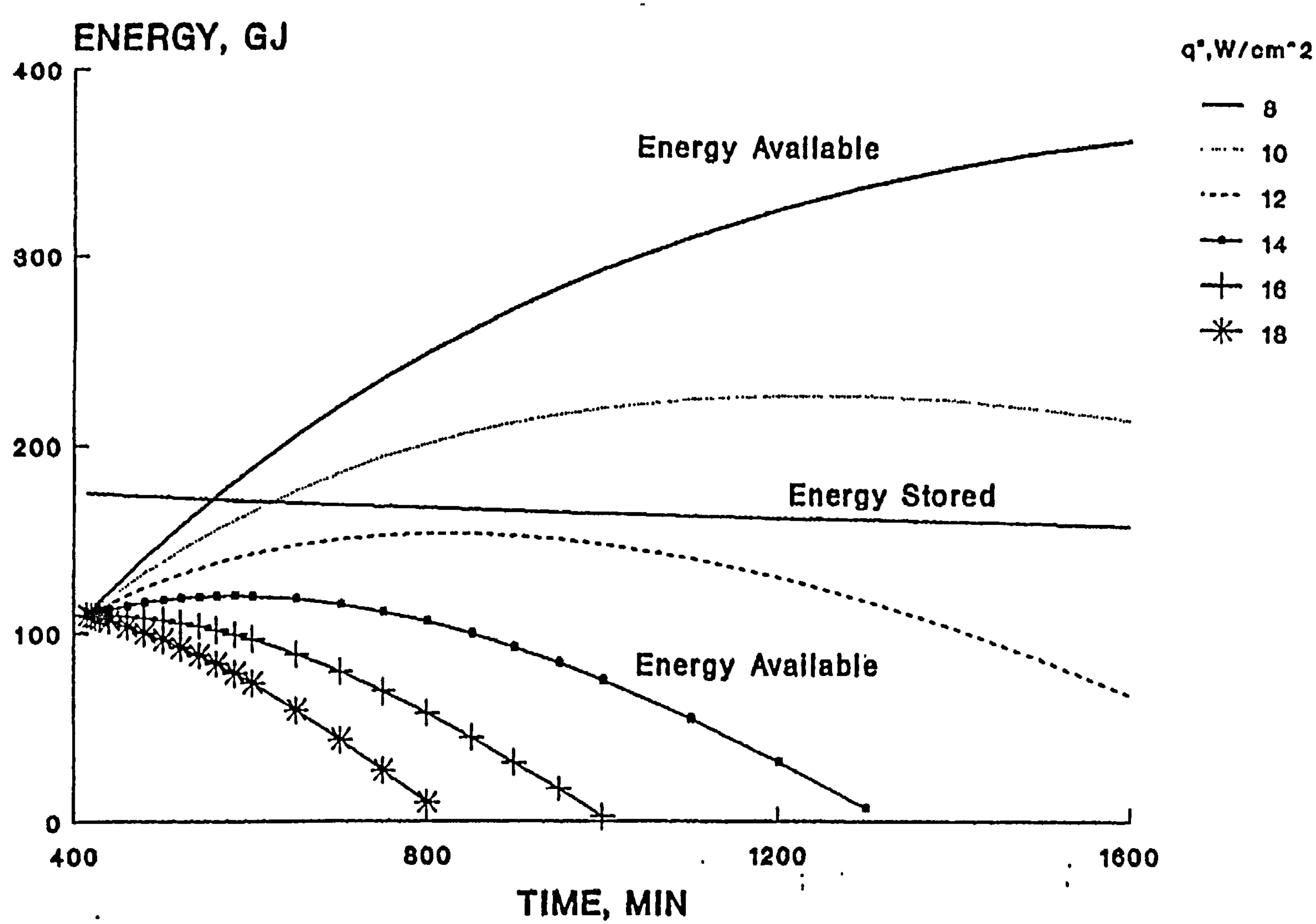


Figure 18 CANDU 6 Molten Core Energy Balance