Assessment of Fuel Fitness-for-Service After Standing-Start Process Under Gentilly-2 Shutdown Conditions *

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ABSTRACT

During a planned annual outage at Gentilly 2, primary and back-up heat sinks are provided for removing decay heat from fuel. The primary heat sink is provided by either the steam generators or the shutdown cooling system heat exchangers. Forced coolant flow transports the decay heat to these heat sinks. The backup heat sink is provided by coolant subcooling, end-shield and moderator coolants, piping metal mass, and the steam generators. Intermittent buoyancy-induced flow (IBIF) of the coolant or standing-start process transports the decay heat to these heat sinks.

The analysis in this paper assesses fuel and fuel channel fitness-for-service after repeated standing start cycles when only the back-up heat sink is assumed available. This analysis defines a set of suitable conditions for return to full-power operation, without any inspection or analysis after the fuel and fuel channels have been subjected to repeated IBIF cycles. Two temperature limits are used in the analysis: the fuel sheath temperature is limited to 450 °C, and the pressure tube temperature is limited to 400 °C in IBIF cycles.

The analysis uses the computer programs THERMOSS-III for calculating the number of IBIF cycles, the channel-coolant temperature and heatup times in each of the cycles, HOTSPOT for calculating the transient sheath-to-coolant heat-transfer coefficient and the pressure tube temperature transient, ELESTRES for generating initial conditions of a fuel element, and ELOCA.Mk6 for assessing the transient thermal-mechanical behaviour of the fuel element. A set of stringent criteria for fuel bundles and pressure tubes to return to service are defined, justified, and examined. Whenever possible, fuel sheath and pressure tube degradation mechanisms are quantified using the temperature limits and the results calculated by the computer codes.

A 450 °C fuel sheath temperature map is constructed. This map defines the operation envelope for fuel sheath remaining below 450 °C, should a loss of forced coolant circulation occur in a shutdown state. If the fuel sheath temperature limit is not exceeded, the pressure tube temperature will be below 400 °C during IBIF cycles. With these limits, the results of the analysis show that the fuel and the fuel channel are suitable for returning to full power after repeated IBIF cycles.

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INTRODUCTION

In a planned annual outage at Gentilly 2, primary and back-up heat sinks are provided for removing decay heat from fuel. The primary heat sink is provided by either the steam generators or the shutdown cooling system heat exchangers. Forced coolant flow, supplied by either the heat transport system or by shutdown cooling system pumps, transports the decay heat to these heat sinks. The backup heat sink is provided by coolant subcooling, end-shield and moderator coolants, piping metal mass, and the steam generators. Intermittent buoyancy-induced flow (IBIF) of the coolant or standing-start process transports the decay heat to these heat sinks. The standing start refers to the period from the shutdown of the reactor to its restart.

The analysis in this paper assesses fuel and fuel channel fitness-for-service after repeated IBIF cycles when only the back-up heat sink is assumed available. Previous analyses [1,2] have defined fuel acceptance criteria as showing that no fuel failure will result if the back-up heat sink is used. These acceptance criteria did not consider whether there would be an increased risk of fuel or channel failures under normal operation or accident conditions if the affected fuel and fuel channel were returned to service.

This analysis defines a set of suitable conditions for return to full power operation without any inspection or analysis after the fuel and fuel channels have been subjected to repeated IBIF cycles. The analysis uses an improved methodology and updates the previous analyses to account for the cumulative effects of IBIF cycles on fuel and fuel channel behaviour. This analysis considers various fuel sheath and pressure tube degradation mechanisms, defines the acceptance criteria for fitness-for-service, and verifies the suitability of these criteria for the affected fuel and fuel channel to return to service.

COOLANT, FUEL, AND FUEL CHANNEL BEHAVIOUR

During a shutdown state with the primary heat transport system either full or drained to the headers and with forced channel coolant flow, the fuel and fuel sheath are well cooled. The fuel sheath temperature is slightly above the coolant temperature. A gap may open up between the fuel pellets and the sheath because of thermal contraction of the fuel after the reactor is shut down. The radial gap increases resistance to fuel-to-coolant heat transfer, resulting in a relatively large temperature difference between the fuel pellet and the sheath.

If forced coolant flow is lost, the subcooled coolant in a fuel channel will stagnate. Starting from this condition, the channel coolant heats up to the saturation temperature and boils. The steam that is generated rises to the upper parts of the channel while water remains at the bottom of the channel. The steam-water phase separation causes the upper fuel elements and pressure tube to become exposed to steam and to heat up. The steam partitions in the channel centre and flows towards the end fittings. The steam condenses in the cold water in the end fittings and on the cold end-fitting surfaces. Once the upper parts of the end fittings heat up to the saturation temperature, the steam can reach the vertical parts of the feeders and vent to the feeders where it condenses. The resulting net hydrostatic head in the feeders (fluid density difference between the feeders) generates a flow that refills the channel and restores adequate fuel and fuel channel cooling.

This cycle of channel-coolant stagnation, heatup, venting, and refill can repeat itself. In a standing-start cycle, maximum fuel and fuel channel temperatures occur at the time of steam venting. An important parameter that determines these maximum temperatures is the time interval between the start of channel coolant boiling and steam venting. This duration is determined by channel power, pressure, and coolant subcooling [1]. The temperatures of the coolant and the end fittings increase as the IBIF cycles continue. Therefore, the duration of channel heatup decreases from the longest time in the first cycle to a negligibly small time in the last cycle. Consequently, the maximum fuel and fuel channel temperatures decrease in the subsequent IBIF cycles.

At the time of steam venting, the maximum fuel and fuel channel temperatures occur in the upper part of the channel at the channel axial centre because this location has the highest bundle power and is the first to be exposed to steam, and the heat transfer is largely by thermal radiation from the fuel to pressure tube.

Fission products produced in the fuel during normal operation may pressurize the gap between the fuel pellets and the fuel sheath. The value of the gas pressure depends on fuel irradiation time, i.e., fuel burnup. If the gas pressure is greater than the coolant pressure, the fuel sheath can lift off the fuel pellets. The sheath lift-off decreases fuel-to-sheath heat transfer, resulting in higher fuel temperatures during the channel heatup transient. When the fuel temperature increases sufficiently during an IBIF cycle, additional fission products may diffuse from the fuel matrix into the gap, thereby, increasing the gas pressure in the gap. At higher temperatures, the sheath yield strength is reduced. The reduced strength and higher gas pressure can cause the sheath to strain radially outward. This strain increases the gap volume, thereby reducing the gas pressure in the gap and eventually establishing a mechanical balance between the gas pressure and the coolant pressure. The resulting sheath plastic strain may cause the sheath to fail by a variety of mechanisms, or it may be at a point where the affected fuel bundles are no longer fit for continued service under normal operation. The plastic sheath strain in repeated IBIF cycles is cumulative.

The pressure tube heats up non-uniformly under stratified two-phase coolant conditions in the channel in an IBIF cycle. At a given channel axial location, the temperature around the pressure tube circumference decreases from its maximum value at the top of the tube to the saturation temperature at the location of the water level. At sufficiently high temperature and channel pressure, the pressure tube may start to deform during an IBIF cycle. Thermal stress in the pressure tube occurs because of heatup and quenching in each IBIF cycle. This stress may lead to fatigue failure or crack initiation and growth in repeated IBIF cycles.

After steam venting and channel refilling, the stagnant channel coolant may be subcooled. The coolant will take sometime to heat up to the saturation temperature. During this time period, the fuel elements and the pressure tube cool down before another IBIF cycle starts. Therefore, the time period when the coolant is heating up to the saturation temperature is also an important parameter that affects the behaviour of the fuel and fuel channel. This period is shortest at the channel axial centre where the coolant first heats up to the saturation temperature.

ANALYSIS METHODOLOGY

The analysis presented in this paper limits the fuel sheath and pressure tube temperatures to, respectively, 450°C and 400°C in each IBIF cycle, to allow the fuel and fuel channel to return to service at full power without inspection or analysis. The 400°C temperature limit is the pressure tube stress relief temperature used in manufacturing. A sheath temperature limit of 600°C was shown to ensure fuel sheath integrity for fuel bundles at decay power levels in the Point Lepreau Generating Station [2]. This higher sheath temperature limit was shown to prevent fuel failure, but fuel fitness-for-service was not investigated. The analysis in this paper examines fuel and fuel channel degradation mechanisms to justify that the 450°C and 400°C temperature criteria are sufficient for the fuel and fuel channel to return to service after IBIF cycles.

The analysis uses the following approach:

- The computer program THERMOSS-III [1] is used to calculate the time required to heat up the subcooled coolant to the saturation temperature (coolant heatup time), the time for the upper fuel elements and pressure tube to heat up in steam (channel heatup time), the channel coolant temperature at the end of each IBIF cycle, and the total number of IBIF cycles for a given set of initial conditions.
- The results calculated by THERMOSS-III are used in the HOTSPOT code to calculate the transient pressure tube temperature and effective sheath-to-coolant heat transfer coefficient assuming a stagnant, saturated steam environment in a cross section of the channel.
- A time interval of 0.01 s is used for the rapid refilling phase of an IBIF cycle. To compute the fuel and sheath temperatures in the time period when the subcooled coolant is heating up to the saturation temperature at the start of an IBIF cycle, a sheath-to-coolant heat-transfer coefficient of 0.427 kW/(m^2•K) is used. This value is based on the work of Sparrow et al., which is cited in [3], for a laminar flow parallel to a bank of circular tubes with constant coolant thermal conductivity. The coolant temperature is assumed to increase linearly with time during the period when the channel is filled with liquid coolant.
- The computer code ELESTRES Version M13B CY7 [4,5] is used to generate initial conditions for a fuel element.
- The results calculated by THERMOSS-III, HOTSPOT and ELESTRES are used in ELOCA.Mk6 Mod 2.1 [6] to assess thermal-mechanical behaviour of a fuel element. For each set of conditions, a coolant history input deck required by ELOCA is generated, which accounts for repeated coolant phase (liquid or vapour) changes starting from the first cycle to the last cycle. With these cyclic input boundary conditions on the outside surface of the fuel sheath, the thermal-mechanical responses of the fuel and fuel sheath are also cyclic. In this way, the effect of repeated thermal processes on plastic sheath strain is accumulated.
- The fuel and fuel channel assessment examines various degradation mechanisms to support the two selected temperature limits for fuel fitness-for-service.

The analysis is performed over a range of channel power (0.1% to 3% of 7.3 MW), coolant pressure (0.2 MPa to 10 MPa), initial coolant subcooling (80°C to 271°C), and fuel burnup (50, 140, and 230 MW•h/kg U).

RESULTS OF THE ANALYSIS

Fuel and Channel Responses to IBIF Cycles

Table 1 shows samples of the THERMOSS-III calculated coolant and channel heatup times during each IBIF cycle and the coolant temperature at the end of each IBIF cycle. A finite number of IBIF cycles were calculated. In reality, the cycles may continue after the last cycle reported in Table 1. The subsequent cycles after the last cycle listed in the table will allow the coolant temperature to approach its saturation, resulting in shorter time periods for channel and coolant heatup. These subsequent cycles have a negligible effect on fuel and fuel channel behaviour. Therefore, the calculated results at the end of the last IBIF cycle, provided by THERMOSS-III can be referred to as the results after all IBIF cycles.

Figure 1 shows typical sheath-to-coolant heat-transfer coefficient and coolant temperature transients in repeated IBIF cycles that were used as input to ELOCA.Mk6. The coolant temperature is constant at the (steam) saturation value during channel heatup, it decreases rapidly on channel refill, and it increases linearly to the saturation temperature after refill.

Figure 2 shows the fuel, sheath, and pressure tube temperature transients predicted by, respectively, ELOCA.Mk6 and HOTSPOT in repeated IBIF cycles for the conditions given in Figure 1. The sheath temperature increases to a maximum at the end of each IBIF cycle and decreases rapidly on channel refill. The fuel temperature is slightly higher than the sheath temperature during channel heatup and is significantly higher during subcooled coolant heatup. The pressure tube temperature follows the sheath temperature. For the conditions shown in Figure 2, the predicted maximum sheath temperature exceeds the sheath temperature limit of 450°C in the first two cycles. The maximum pressure tube temperature is far below the temperature limit of 400°C.

Figure 3 shows the sheath plastic strain and fuel-sheath gap transients predicted by ELOCA.Mk6 in repeated IBIF cycles for the conditions given in Figure 1. At the end of the last IBIF cycle, the sheath plastic strain is 0.003%, which does not present a concern for returning the fuel to service even though the sheath temperature exceeds the temperature criterion in the first two cycles. This result indicates that the sheath temperature criterion is conservative.

The results for other initial conditions are similar to those shown in Figures 2 and 3 and shown the following expected trends. At either higher fuel burnup, power, or initial coolant subcooling, the fuel and pressure tube temperatures and sheath plastic strain are higher. At higher channel pressure, the sheath temperature is higher.

Results of the Fuel and Fuel Channel Assessment

The analysis examined the effects of various fuel, fuel sheath, and pressure tube degradation mechanisms, and these results are given below.

- Oxidation embrittlement

  A fuel sheath that has oxide in excess of 0.7 wt% in half of the wall thickness during the heatup in all IBIF cycles may fail on cooldown during channel refill. The maximum total channel heatup time for all IBIF cycles was predicted to be 10.5 h. If the sheath is assumed to be held at 450°C for 10.5 h, the oxide thickness will be about 0.5 μm. Therefore, sheath oxidation during IBIF cycles is of no concern for returning fuel to service if the sheath temperature limit of 450°C is not exceeded.

- Beryllium-assisted Crack Penetration

  Beryllium brazes at the fuel bundle bearing and spacer pads assist crack penetration of the sheath at elevated temperatures exceeding 740°C [6]. Since the maximum sheath temperature is limited to 450°C in this analysis, this degradation mechanism does not impede returning fuel to service after it has been exposed to IBIF cycles.

- Longitudinal Ridge

  Longitudinal ridges on the sheath may form as a result of sheath collapse onto the fuel pellets, caused by high coolant pressure. Such ridges can introduce localized plastic sheath strain that may cause either the sheath to fail immediately or fail from fatigue during thermal cycling. For all initial conditions considered and for all cases with the maximum sheath temperature of less than 450°C, no longitudinal ridges were predicted, indicating that this degradation mechanism does not prevent returning fuel to service.

- Collapse of Sheath into Axial Gap

  The possibility of instantaneous sheath collapse into a concentrated axial gap was considered. This concern is similar to the phenomenon of sheath collapse into a large diametral gap, to form longitudinal ridges. Collapse of sheath into axial gaps can introduce localized plastic sheath strain, which may cause either immediate sheath failure or a fatigue failure during thermal cycling. Axial gaps exist in a shutdown state because of thermal contraction of the fuel. Small fuel chips lodged between the fuel pellets and between the fuel pellet and the end cap can also result in axial gaps. It is very unlikely that this total amount of axial gap will occur at one particular axial location. In the ELOCA.Mk6 calculation, an initial concentrated axial gap of 2.5 mm is assumed in this analysis.

  No sheath collapse into the concentrated axial gap was predicted, for all cases within the sheath temperature limit, using a modified empirical correlation of Westinghouse Canada Inc. and test data for sheath collapse into axial gaps for temperatures between 300°C and 750°C.

- Plastic Sheath Strain

  Sheath strain consequences are a concern when the fuel is returned to power. If a large positive strain has occurred on the fuel sheath during IBIF cycles, the diametral gap increases. As a result, the fuel-to-sheath heat-transfer coefficient is reduced. This reduction in the heat-transfer coefficient causes the fuel temperature to rise under normal operating conditions. If a negative sheath strain has occurred during IBIF cycles, the diametral gap decreases and the fuel-to-sheath heat transfer is improved. Therefore, the negative plastic sheath strain is not a concern in terms of fuel centreline temperature increase.

It is necessary to define how much positive plastic sheath strain can be tolerated during a standing-start process without compromising the fuel safety and performance when it is returned to service. This criterion can be determined by setting a limit to the increase in fuel centreline temperature after return of fuel to service. An uncertainty in fuel centreline temperature has been estimated to be ±160°C on the basis of manufacturing tolerances. A suggested acceptance criterion is that the fuel that had been exposed to repeated IBIF cycles should have a fuel centreline temperature upon return to service that is similar to that of the fuel that has not undergone the IBIF cycles. This criterion is interpreted as a requirement that the fuel centreline temperature be within the uncertainty once the fuel is returned to power. A further more stringent criterion demands that the calculated fuel centreline temperatures increase by no more than half of the uncertainty, i.e., 80°C. The 80°C fuel centreline temperature increase can be converted to an equivalent plastic sheath strain increment using ELOCA.Mk6. This estimated strain increment is about 0.17% for the fuel with a burnup of 200 MW•h/kg U. Therefore, this analysis uses the plastic sheath strain increment of 0.17% as a limiting criterion for fuel to return to service.

No plastic sheath strain increment cumulated after all IBIF cycles was predicted to exceed 0.17% for cases where the calculated sheath temperature was below 450°C. For such conditions, the fuel after the IBIF cycles behaves thermally the same way as if no IBIF cycles had occurred.

- Thermal Stress and Plastic Strain Fatigue

  Thermal stresses on the fuel and fuel sheath were calculated by ELOCA.Mk6. The calculation was performed under transient conditions, which include a series of heatup and cooldown phases. Fatigue of the fuel sheath under repetitive thermal cycling was not considered in ELOCA.Mk6. Of many factors influencing the thermal fatigue life of the sheath, ductility of Zircaloy-4 at high irradiation levels is the predominant one. The sheath is designed to collapse into contact with the UO_2 fuel under operating conditions and to undergo some plastic deformations during reactor cycling between shutdown and full-power operation. Predicting fatigue lifetime involves the cumulative effect of numerous small-scale events taking place over many cycles of stress and strain under various service environments. According to the information in MATPRO [7], low cycle (plastic strain) fatigue for Zircaloy-4 can be expressed as $\Delta\varepsilon = C N_f^{-\alpha}$, where $\Delta\varepsilon$ is the plastic strain range, N_f is the number of cycles to failure, C and α are material parameters given in [7]. This equation was used to estimate N_f under IBIF conditions.

  The assessment assumed that a maximum strain range of 2% was maintained in each of the IBIF cycles. Thus, N_f was estimated to be 517. This result means that the sheath will fail as a result of plastic strain fatigue if the number of IBIF cycles during a shutdown exceeds 517, and if the strain range remains constant at 2% in each IBIF cycle. In spite of these conservative assumptions, the estimated N_f value is much greater than the maximum number of IBIF cycles calculated by THERMOSS-III. Therefore, thermal stress fatigue in IBIF cycles does not need to be considered if the sheath temperature is maintained below or equal to 450°C.

- Sheath Hydriding and Hydride Precipitation

  Zircaloy-4 is used in fuel sheath production because of its low neutron absorption, and because of its good corrosion and hydrogen-deuterium pickup performance under CANDU® coolant conditions. The amount of hydrogen-deuterium absorption is generally related to the amount of oxidation. Because the sheath temperature is limited to 450°C, sheath oxidation is very slow at such low temperatures. Thus, the hydrogen-deuterium pickup during IBIF cycles is expected to be low. Hydrogen dissolution and re-precipitation of hydride during thermal cycling in IBIF cycles were not taken into consideration at this stage in this study.

- Other Fuel and Fuel Bundle Degradation Mechanisms

  Other degradation mechanisms, such as fuel bundle deformation and possible deterioration of the CANLUB layer at the inner surface of the sheath at high temperatures during IBIF cycles, were not analyzed in this study. However, qualitative assessments were performed indicating these degradation mechanisms may not impede returning fuel to service after repeated IBIF cycles.

- Thermal Shock and Thermal Stress Fatigue on the Pressure Tube

  A finite-element analysis was performed to estimate the stresses induced by an assumed steady-state temperature gradient in the pressure tube, which is typically encountered in an IBIF cycle. Thermal shock to the pressure tube induced by the sudden incoming of cold coolant to the inside surface of the pressure tube during each IBIF cycle was also estimated. The estimated thermal stresses on the pressure tube were assumed to be alternating as the IBIF cycles continue. The cyclic temperature and stress behaviour of the pressure tube may result in fatigue crack initiation. The allowable number of stress cycles to fatigue crack initiation has been correlated to an alternating stress for irradiated cold-worked Zr-2.5 Nb pressure tubes and given in the fitness-for-service guidelines for CANDU pressure tubes.

  In a typical case suitable for IBIF conditions, the allowable number of stress cycles was estimated to be over 400 based on an estimated maximum pressure tube alternating stress. The maximum number of IBIF cycles calculated by THERMOSS-III was 31, which is a small fraction (0.08) of the allowable number of stress cycles. Therefore, thermal stress fatigue is not a concern for fatigue crack initiation in the pressure tube, as long as the pressure tube temperature is limited to below or equal to 400°C in IBIF cycles.

<u>Temperature Maps</u>

From the foregoing results it is concluded that the fuel and fuel channel can be returned to service without performing any inspection or analysis after a loss of forced coolant circulation occurs in a reactor shutdown, provided that the fuel sheath temperature does not exceed 450°C and that the pressure tube temperature does not exceed 400°C. This section identifies the range of the initial coolant subcooling, pressure, fuel burnup, and power level conditions for which these two temperature limits are not exceeded in IBIF cycles.

Figure 4 shows such a temperature map for 450°C sheath temperature limit at a fuel burnup of 50 MW•h/kg U. Each line in Figure 4, i.e., for a given pressure, gives the values of channel power and initial coolant subcooling for which the sheath temperature is 450°C in IBIF cycles. For values of power and subcooling above the line, the sheath temperature is above 450°C. For values of power and subcooling below the line, the sheath temperature is below 450°C. The solid lines in the region of low initial subcooling are extrapolated. Caution must be taken when these extrapolated results are used.

The 450°C sheath temperature maps for fuel burnups of 140 and 230 MW•h/kg U are shown in Figures 5 and 6, respectively. A comparison of Figures 4, 5, and 6 shows that the clusters of temperature lines are moving to the left side of each plot, i.e., the low-power side, as fuel burnup increases. Therefore, the 450°C sheath temperature map for the fuel burnup of 230 MW•h/kg U is most restrictive.

The plastic sheath strain increment that reaches the maximum allowable value of 0.17% at the end of the last IBIF cycle is also shown in Figures 5 and 6 by symbols without connecting lines. The locations of all these symbols are towards the upper and right corner, away from the temperature lines. These results indicate that the plastic sheath strain increment will not reach 0.17% when the sheath temperature limit is maintained.

Figure 7 compares the 450°C sheath temperature curve with the 400°C pressure tube temperature curve for one coolant pressure. The pressure tube temperature limit allows higher initial coolant subcooling values than the sheath temperature limit does. This difference indicates that the sheath temperature limit is more limiting because it requires an envelope further towards the low-power and low-coolant subcooling conditions. Therefore, only the 450°C sheath temperature map needs to be used to define a fuel fitness-for-service envelope.

CONCLUSIONS

An analysis was performed on the behaviour of fuel and fuel channels after a succession of standing-start cycles was performed. A 450°C fuel sheath temperature map in terms of channel power level and initial coolant subcooling for a range of fuel burnups was constructed. This map defines the operation envelope for fuel sheath remaining below 450°C, should a loss of forced coolant circulation occur in a shutdown state. If the fuel sheath temperature limit is not exceeded, the pressure tube temperature will be below 400°C during standing-start cycles. Assessment of various fuel degradation mechanisms indicates that the fuel is suitable for returning to power if its sheath temperature has remained below or equal to 450°C during IBIF cycles. The fuel channel is also considered fit for service if the pressure tube temperature does not exceed 400°C during IBIF cycles.

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Table 1
Samples of the Results Calculated by THERMOSS-III
(coolant pressure of 0.2 MPa, coolant initial subcooling of 100°C)

% of 7.3 MW Power	IBIF Cycle																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Coolant heatup time (time required to heat up the subcooled coolant to the saturation temperature) (s)																			
0.1	1356	1201	1064	942	834	738	654	579	513	454	402	356	315	279	247	219	194	172	
1.0	126	103	85	69	57	47	38	31	26	21	17								
Channel heatup time (time for the upper part of fuel elements and the pressure tube to heat up in steam) (s)																			
0.1	1659	1469	1301	1152	1020	903	800	708	627	555	492	435	386	341	302	268	237	210	186
1.0	260	213	175	144	118	97	79	65	53	44	36	30							
Coolant temperature at the end of each cycle (°C)																			
0.1	20	32	42	51	59	66	72	78	82	87	91	94	97	100	102	104	106	108	109
1.0	20	38	53	65	75	83	90	95	100	103	106	109							

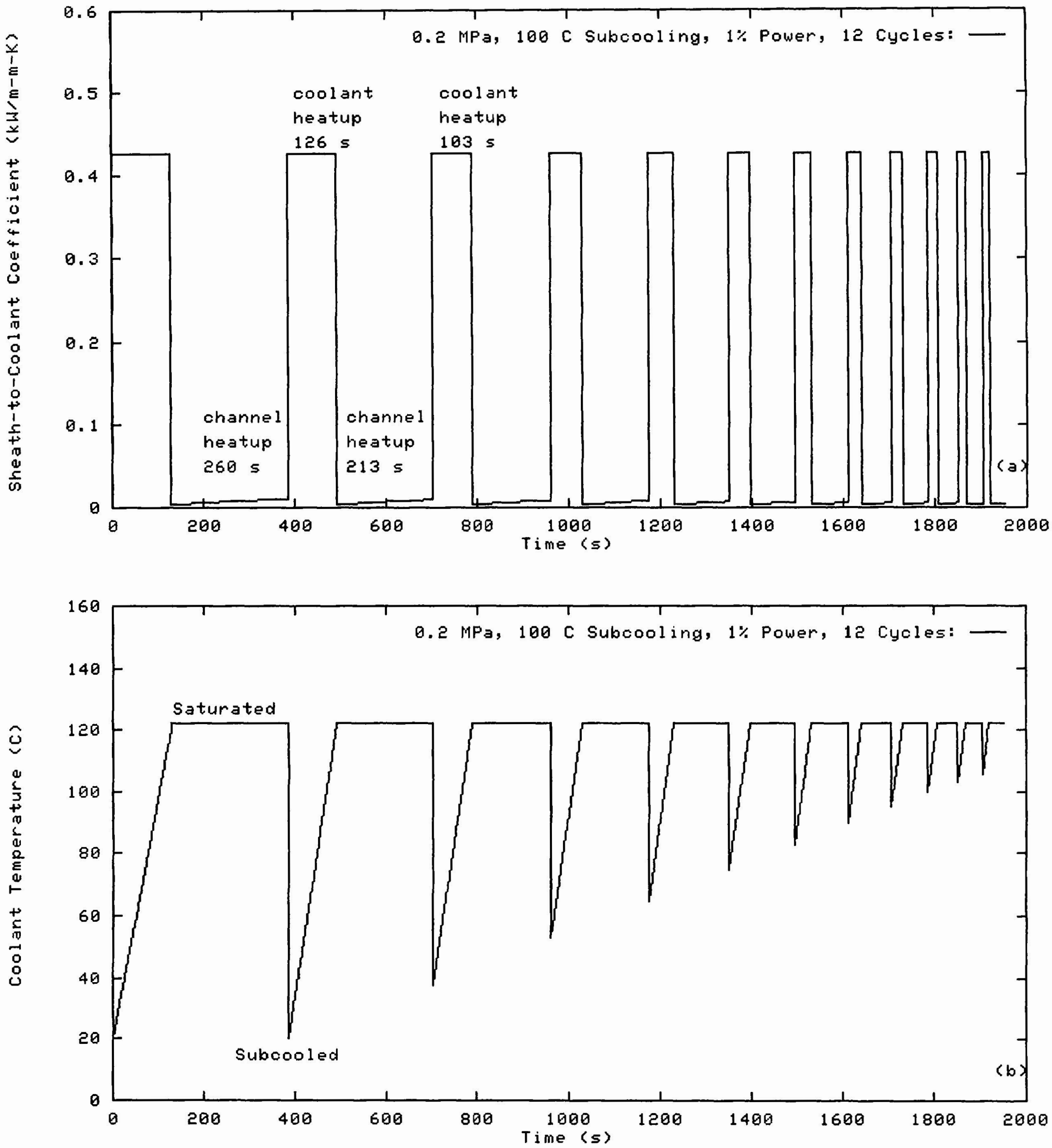

Figure 1 Sample coolant history input to ELOCA.Mk6: (a) sheath-to-coolant heat-transfer coefficient and (b) coolant temperature in IBIF cycles

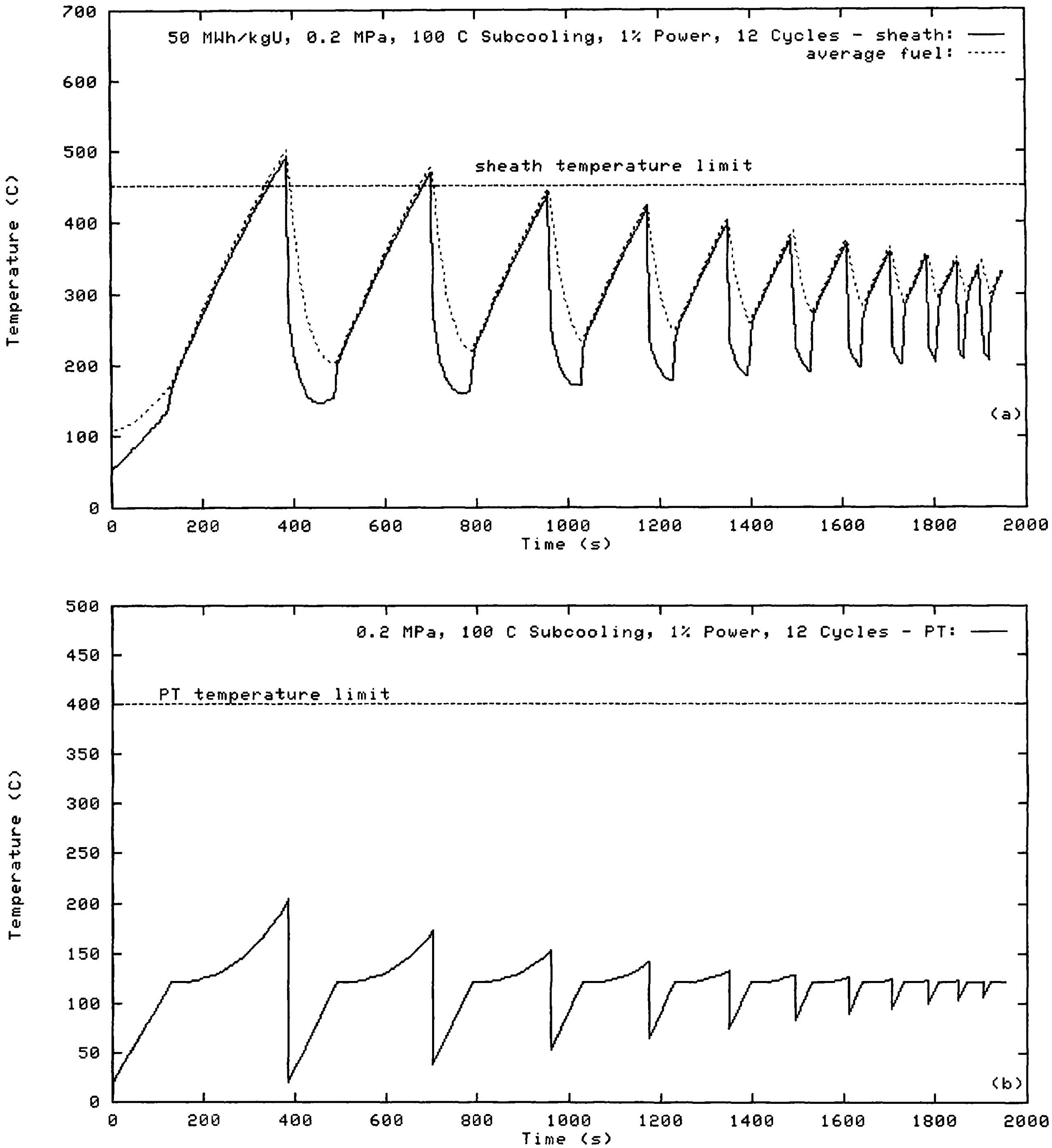

Figure 2 ELOCA.Mk6-calculated (a) average fuel and sheath temperatures and (b) HOTSPOT-calculated average pressure tube temperature at the top (50 MW•h/kg U, 0.2 MPa, 100°C subcooling, 1% of 7.3 MW channel power, 12 cycles)

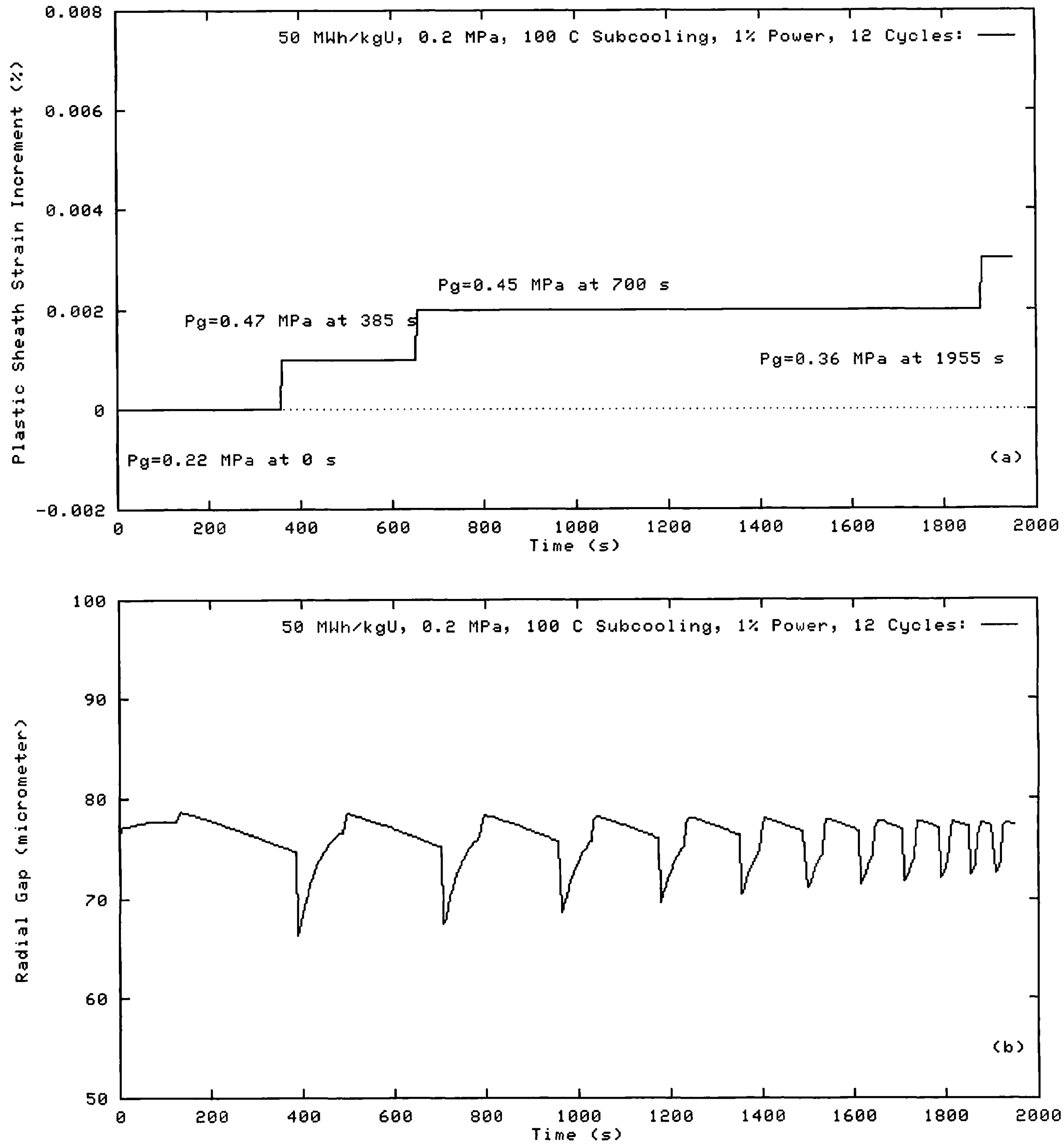

Figure 3 ELOCA.Mk6-calculated (a) plastic sheath strain increment (current strain - initial strain) and (b) radial fuel-to-sheath gap (50 MW•h/kg U, 0.2 MPa, 100°C subcooling, 1% of 7.3 MW channel power, 12 cycles)

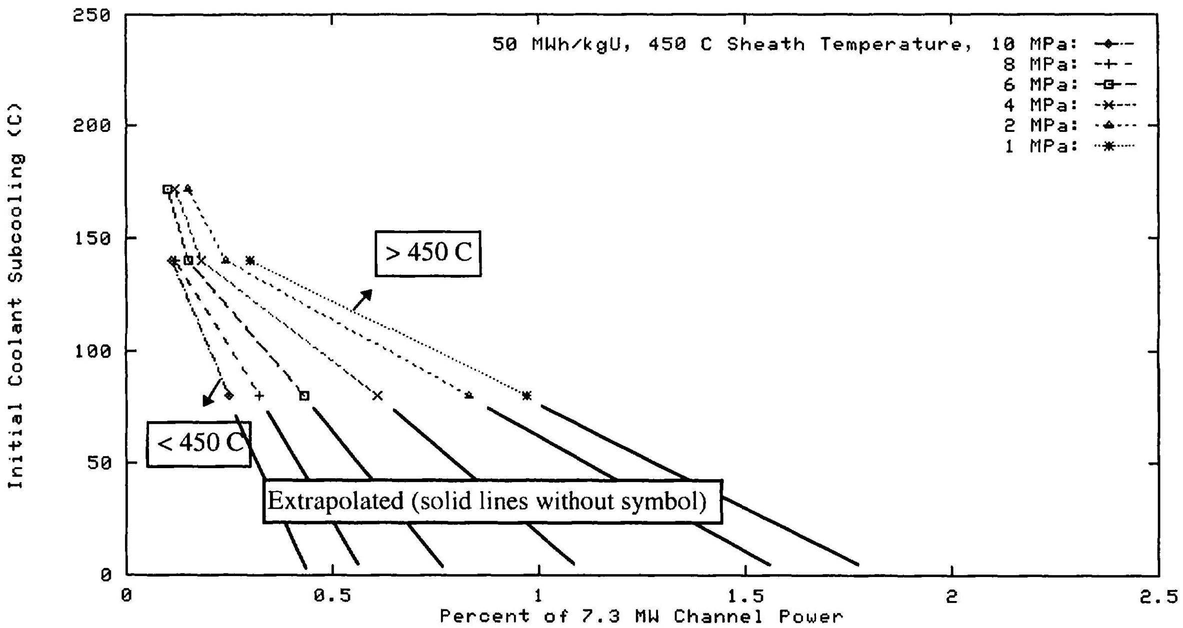

Figure 4 450°C sheath temperature map relating initial coolant subcooling to percent of 7.3 MW channel power and channel pressure for a fuel burnup of 50 MW•h/kg U

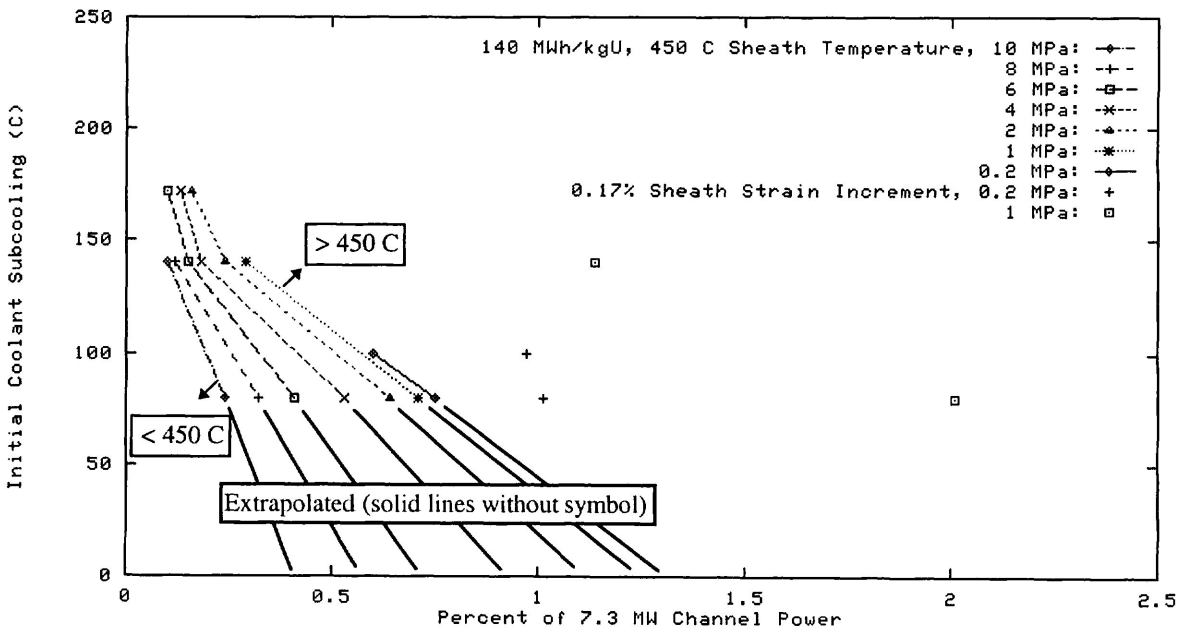

Figure 5 450°C sheath temperature map relating initial coolant subcooling to percent of 7.3 MW channel power and channel pressure for a fuel burnup of 140 MW•h/kg U (symbols without connecting lines represent the plastic sheath strain increment of 0.17% at the end of IBIF cycles)

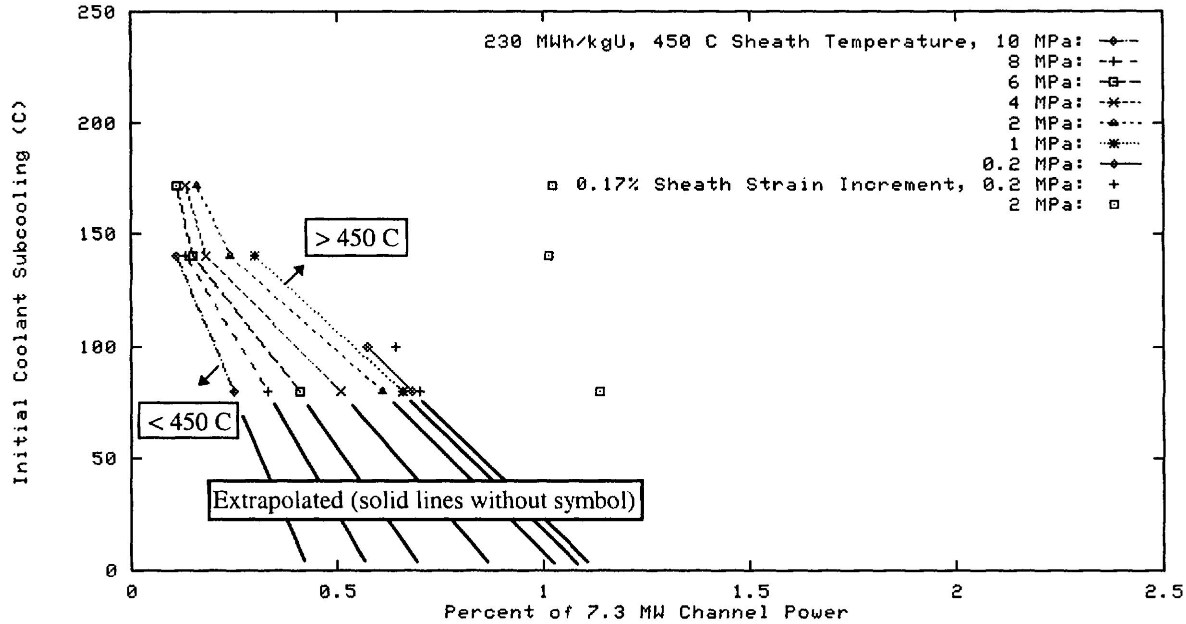

Figure 6 450°C sheath temperature map relating initial coolant subcooling to percent of 7.3 MW channel power and channel pressure for a fuel burnup of 230 MW•h/kg U (symbols without connecting lines represent the plastic sheath strain increment of 0.17% at the end of IBIF cycles)

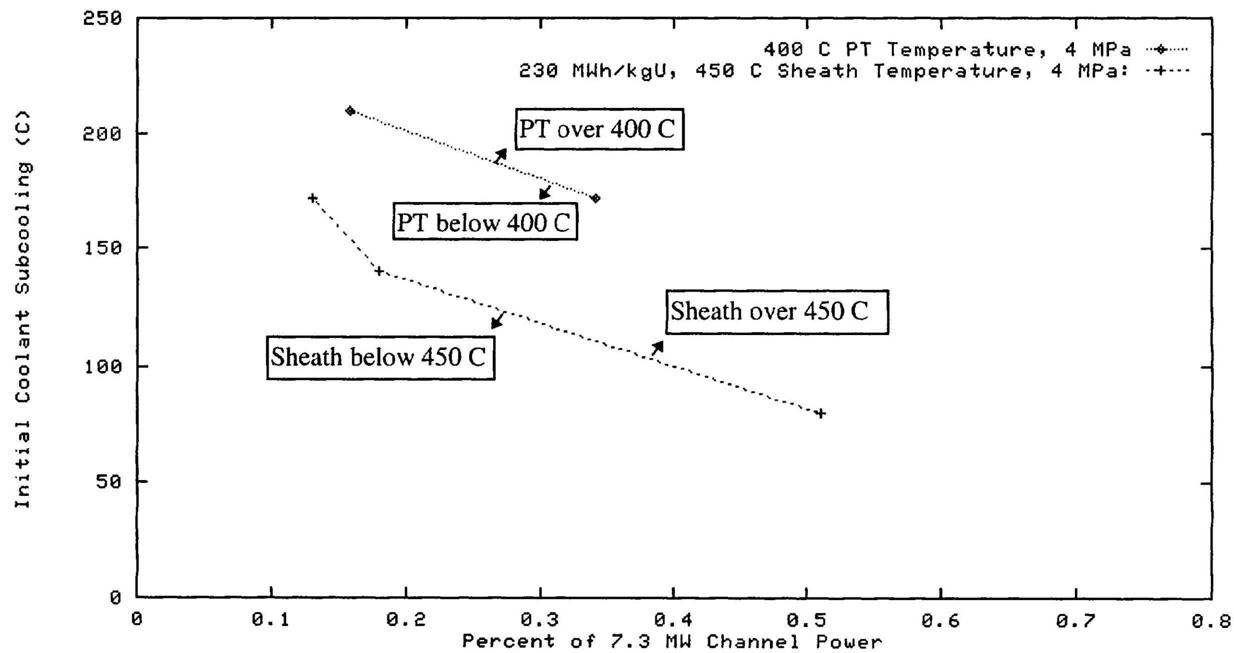

Figure 7 Comparison of the 450°C sheath temperature curve with the 400°C pressure tube temperature curve