HEAT SINK CONSIDERATIONS DURING SLAR DEFUELLING ACTIVITIES OF THE 1995 MAINTENANCE OUTAGE AT THE POINT LEPREAU G.S.

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In order to conduct the Spacer Locate and Reposition (SLAR) activities, individual fuel channels were de-fuelled using the SLAR tool itself. The presence of the tool in the channel containing fuel caused concerns over channel flow interruption. A methodology was devised to assess the limiting fuel heat up during de-fuelling and during possible prolonged periods of complete flow interruption. Once established, the approach could be used to assess the effect of varying parameters which could effect channel heat-up. Costly delays in SLAR maintenance activities were avoided by ensuring the sequence of channel visits was such that the individual channel powers decayed sufficiently to prevent channel heat up beyond acceptable temperature limits.

1. Background

The main objective of the 1995 Maintenance Outage at the Point Lepreau Generating Station (PLGS) was to conduct a Spacer Locate and Reposition (SLAR) maintenance program. The goal of this program was to relocate spacers between the reactor pressure tubes and calandria tubes to correct a problem of pressure tube to calandria tube contact.

In order to conduct the SLAR activities, individual fuel channels had to be de-fuelled. The SLAR tool itself was used by the fuel delivery machine (D/M) to push fuel out of the core into the receiving fuel machine (FR/M). The fuel was returned to the channel by the other fuel machine before another channel would be visited. Because of its size, the SLAR tool would alter the flow resistance in the channel. As the available head is small under Shutdown Cooling (SDC) conditions, flow is very sensitive to such changes in flow resistance.

The potential for reduced flow led to fuel cooling concerns should the SLAR tool become jammed in the channel. A basic assessment of channel fuel heat up during SLAR defuelling and more detailed assessment of fuel heat up during prolonged channel flow blockages, due to a jammed SLAR tool, were performed. The results of these assessments were used to determine the sequence of channels to be SLARed.

Channel flows could not be monitored during the SLAR de-fuelling process. Therefore the limiting assumption that channel flow is completely interrupted during the SLAR de-fuelling process was made.

An assessment of the likelihood of reaching a bulk (mean) coolant saturation temperature during a routine defuelling was undertaken. While boiling in a channel does not in itself constitute a cooling problem, the presence of the void in a channel complicates the assessment of fuel/sheath temperatures. Avoiding the onset of boiling was deemed to be an appropriate objective providing adequate safety margins.

Only the fuel located between end fitting liner tube flow holes ("Flow Openings" in Figure 1) was considered for the de-fuelling assessments. Fuel bundles within the end fitting would receive adequate cooling flow from the fuel receiving machine. This subcooled water flow provided by the fuelling machine flows past the fuel in the end fitting and exits through liner tube flow holes in each of the end fittings and, in turn, exits through the adjacent feeder.

2. Fuel Cooling Interference During SLAR De-fuelling

The time spent in the channel region during SLAR de-fuelling is different for each bundle. The time required for the coolant surrounding individual bundles to reach saturation temperature was therefore considered. The following simplifying and limiting assumptions were made:

- The coolant and fuel were initially at the same temperature (prior to the start of the SLAR de-fuelling).
- Temperature gradient across the fuel is negligible.
- No heat was transferred out of the channel. All heat generated by the fuel was assumed to be absorbed by the fuel itself and the surrounding coolant.
- Localized boiling is not considered. Only bulk boiling within the fuel channel would lead to the accumulation of vapour which significantly affects heat transfer from the fuel.
- The coolant follows the bundle while it moves, hence no axial heat transfer.
- Reactor rundown power prior to shutdown was not considered (i.e. "trip" or prompt shutdown from full power is assumed).
- The heat transport system is depressurized (required for SLAR). The pressure at the channel is dictated by head of coolant above the channels.

The assumptions made were considered to be limiting enough to account for uncertainties in the predictions of individual channel power prior to the outage and variations in water levels (i.e. level in D_2O Storage Tank).

A bulk coolant heat up time relationship was defined as follows:

$$t = (T_{final}-T_{initial})[(m^*Cp)_{D2O}+(m^*C)_{fuel}] \text{ x } B.P.^{-1} \qquad (1)$$

Where:

- t is time (seconds).
- $T_{initial;final}$ are initial and final temperatures (°C).
- B.P. is bundle power (kW)
- $(m^*Cp)_{D2O}$ is heat capacity of D_2O.
- $(m^*C)_{fuel}$ is heat capacity of fuel.
- for mass (kg), m, and specific heats (kJ/kg.K), Cp,C.

Equation 1 was rearranged to solve for bundle powers which would heat the coolant to saturation given the duration of time each bundle spends in the channel flow region;

$$BP_{SAT} = (T_{sat} - T_{initial}) \text{ x } [(m^*Cp)_{D2O} + (m^*C)_{fuel}] \text{ x } t^{-1} \qquad (2)$$

where:

- BP_{SAT} is the bundle power (kW) at which the temperature of the volume of coolant surrounding the bundle may reach saturation at time t.
- t is the time (s) that fuel bundle is in the channel flow region during the SLAR de-fuelling process.
- T_{sat} is saturation temperature of D_2O at a pressure corresponding to the pressure of the coolant in the fuel channel.

Initial temperatures were defined as corresponding to highest probable channel outlet conditions, the highest nominal temperature in the channel. The initial temperature used for most assessments was 54 °C, which corresponds with the operation limitation imposed on SLAR activities[1].

The duration of time which each bundle spends in the channel flow region has been provided by the Fuel Handling Group. The de-fuelling steps are outlined in Figures 1 through 6.

For the case of a full, depressurized heat transport system, the saturation temperature would correspond to the pressure resulting from the head of the D_2O Storage tank. Ignoring any D_2O Storage Tank cover gas pressure, the pressure at the top row of channels due to fluid head is:

$$P_{upper} = (19.42m)(9.81\ m/s^2)(1033\ kg/m^3)/1000 = 197\ kPa.$$

similarly, the pressure at the bottom fuel channels due to the head of fluid is P_{lower} = 258 kPa.

The D_2O saturation temperatures corresponding to the above pressures[2]:

T_{sat} at 197 kPa = 134.5 °C; T_{sat} at 258 kPa = 140.7 °C.

Equation 2 was solved to determine bundle powers which could heat the surrounding coolant up to saturation. The derived values of bundle power correspond to a particular SLAR de-fuelling time (i.e. corresponding to a bundle position). This step was repeated for the de-fuelling time required of each bundle position. The resulting bundle powers are presented in Table 1.

Three channel/bundle power profiles were defined based on the commonly occurring power distribution within reactor channels[3]. Figures 7, 8 and 9 illustrate examples of the power distribution shapes. The "flat" power profile channels are located in the region surrounding the adjuster rod locations. The "pinched" power profile channels are located in the region of liquid zone control. The remaining channels outside of the reactivity control mechanisms have "cosine" shaped power profiles.

Axial Bundle Power Factors were defined as the ratio of individual bundle powers to average bundle power in that channel as follows:

$$BPF = (BP \times 12)/CP \qquad (3)$$

where:

- BPF is the bundle power factor (ratio).
- BP is the individual bundle power (kW) as determined in Equation 2.
- CP is the channel power (kW).

The axial form factor (FF) was defined as the ratio of peak bundle power (BP_{PEAK}) to average bundle power for a given channel. Sample channels were selected for each power profile region defined above. The sample channels were selected by visually scanning the plots of channel power distribution. The samples were selected to give a range of powers for each region. Power factor ratios were calculated for each bundle in these sample channels.

Of the channels sampled, the bundle power factor ratios of each bundle of the channels with the highest and lowest form factors in each region are listed in Table 2. These represent the limits of possible range of bundle power factors for each region.

Higher bundle power factor (BPF) ratios for a particular bundle position were more limiting in this assessment. The highest bundle power factors for a given bundle position in a given power profile shape are presented in bold type in Table 2. The highest bundle power factors were used to convert the bundle powers of Table 1 to corresponding channel powers using the following expression:

$$\text{Max. C.P.} = (BP_{SAT}/BPF) \times 12 \tag{4}$$

where:

- Max C.P. is the channel power (kW) corresponding to the power of the bundle in question.
- BP_{SAT} is the maximum bundle power calculated in Equation 2. Bundle powers greater than this value for a bundle in this position may cause bulk boiling to occur before the bundle is discharged from the fuel channel.
- BPF is the bundle power factor described in Equation 3.

The maximum channel powers corresponding to individual bundle power maximums are listed in Table 3. The lowest of these channel powers for each channel power profile shape, shown in bold type in Table 3, are the limiting channel powers to prevent bulk boiling at any bundle during the SLAR de-fuelling process.

The lowest maximum allowable channel power is 26.0 kW for "cosine" and "flat" power profile shapes and 27.3 kW for "pinched" power profiles. These corresponded to the saturation powers at 5th bundle position in channels with a "cosine" power distribution and to the saturation powers at the third bundle position for channels with either a "pinched" or "flat" power distribution.

The times after shutdown required for the various channels to decay to the maximum allowable channel powers were determined. An exponential fit of decay power over a range of decay times[4] which approximates the "ANS 5.1" curve of Figure D-1 of reference [5] was used.

$$P = aP_o t_d^{-b} \tag{5}$$

for 10 000 s < t_d < 1 000 000 s

where

- P is the channel decay power at time t_d.
- P_o is the initial channel power before shutdown.
- a and b are calculation constants specific to the range of time, t_d, considered.

This expression was multiplied by a factor of 1.2 so as to match the "ANS 5.1 + 20%" curve of Figure D-1 in reference [5] which has been used in previous safety analyses. The expression was then re-arranged to solve for time in hours as follows:

$$t_d = \frac{\sqrt[b]{1.2\frac{aP_o}{P}}}{3600} \tag{6}$$

This expression is valid for the range 2.78 hrs < t_d <278 hrs (10 000 s <t_d <1 000 000 s).

Using P = 26.0 kW for cosine and flat profiles and P = 27.3 kW for pinched profiles, the resultant time after shutdown at which SLAR de-fuelling can commence without bulk boiling in the channel is listed in Table 4 for various initial channel powers (Po).

3. SLAR Defuelling Interruption

Acceptable sheath temperature limits must not be exceeded if the SLAR tool stops and becomes inoperable or immovable. Specifically, in such an incident, sheath temperatures must remain low enough that fuel failures will not occur in the time required to free the SLAR tool.

The analysis of Reference [6] was used to determine acceptable fuel sheath temperature limits. Two potential sheath failure mechanisms were considered. The first was failure due to oxidation embrittlement whereby oxidation is sufficiently advanced to cause expected sheath failure upon re-wet, subsequent handling, or re-irradiation.

The second failure mechanism considered postulated sheath strain failure due to internal gas pressure. As fuel element temperatures increase the sheath will strain as a result of the increase in fission gas pressure in the gap between the fuel and the sheath. This effect is enhanced by the reduced volume caused by differing fuel and sheath thermal expansions. Simultaneously, the sheath tensile strength decreases as it heats up further contributing to sheath strain. Sheath failure by either high strain rate or overstrain was considered.

The sheath temperatures which could be deemed acceptable depended upon, among other things, pressure and the length of time for which that temperature would be sustained. Sheath temperature acceptance criteria were defined on the basis of preventing fuel failures in the amount of time estimated to free a jammed SLAR tool and on the basis of fuel being acceptable to remain in the reactor for subsequent operation. A maximum sheath temperature of 600 °C was proposed for conditions where the heat transport system was full and depressurized[6]. However, if the fuel was exposed to this temperature for an extended period, such as 5 hours or more, the fuel may not be acceptable for use in subsequent reactor operation.

For some maintenance activities, the Heat Transport System inventory needed to be drained to reactor inlet/outlet header level. In these situations, the acceptable sheath temperature limit was restricted to 550 °C[6].

The analyses of Reference [7] examined the channel void and resultant steady state fuel sheath temperatures which can be expected at various channel decayed powers for the limiting SLAR tool failure position. From this analysis the limiting allowable decayed channel power corresponding to the maximum sheath temperature was determined.

The resulting steady state temperatures vs. decay powers correspond to "cosine shaped" power profiles. The steady state temperature would increase slightly with increasing pressure[7]. When the limiting temperature of 600 °C is applied, at 0.5 MPa, the limiting channel power translates to 23.96 kW. The respective peak bundle power factors are used to determine the limiting power in channels with power profiles other than cosine since the peak temperature is applicable to centre bundles[7]. The power profile of centre bundles is the same for cosine and "pinched" power profiles, hence, the limiting channel powers for each of these profiles is the same.

The peak bundle power at the centre bundles in the cosine power shape channel can be determined by dividing the channel power by 12 and multiplying by the minimum bundle power factor for the centre bundles (BPF = 1.5 from Table 2.). The minimum bundle power factor was used because it is more limiting.

$$Max.B.P. = \frac{Channel Power}{12 bundles/channel} x 1.5 \tag{7}$$

Having thus obtained the maximum bundle power then the above calculation is reversed using the minimum centre bundle power factor of 1.35 from Table 2 to determine the maximum "Flat" profile channel power:

$$MaxC.P. = \frac{CenterB.P.}{1.35} x12 bundles/channel \tag{8}$$

Using Equation 6, the decays times required to reduce the channel powers down to the respective limiting channel powers were calculated. These are presented in Table 5 for 0.5 MPa. This would represent the most limiting situations for SLAR operations while the Heat Transport System is full and depressurized (subject to head of D_2O Storage Tank).

4. Effects on SLAR Procedures

For a given set of system parameters, the more limiting of the above two criteria were applied. A minimum decay time (time since shutdown) was specified for initial (pre-outage) channel powers ranges for each of the power profile shapes defined. These results could be used by the SLAR personnel to define the order in which channels would be de-fuelled for SLAR inspection/repair. The fact that a large number of channels needed to be visited during the outage meant that the selection criteria imposed no additional delays in the SLAR program.

With the above methodology in place, the effect of varying system parameters could be assessed. Other outage activities which impact on channel heat up during SLAR defuelling were considered. For instance, draining of the heat transport system to the headers lowers the saturation temperatures (due to lower pressure at given channel elevations). This influenced the decay times required to prevent bulk boiling during normal SLAR de-fuelling. Table 6 shows the decay times required if the inventory is drained to header level. These limits apply to top channel elevations and would therefore be less restrictive at lower channel elevations.

Certain maintenance activities required deviations from the operational "Guaranteed Shutdown State" (GSS) which ensures no reactor power increases. Potential increases in channel powers up to a specified reactor trip setpoints of 0.1% of full reactor power were considered during the "Approved Overpoisoned Shutdown State" (AOSS) which was established to cater to such activities. These conditions required new decay time limits to be defined by adding the potential increase in reactor power to power (P) in Equation 6. The results are presented in Table 7.

5. Summary

The findings of these assessments were used to assist the SLAR personnel in developing procedures which would allow the SLAR activities to be scheduled according to an optimal sequence of channel visits based on physical location and particular channel decay power history. The resulting procedures completely avoided costly delays in SLAR activities.

The effect of other maintenance work which influenced plant conditions were assessed so that SLAR sequence could be modified if required.

The time delays required after the start of the outage (decay time) were defined for given channel powers and axial power profiles, based on the limiting results of the assessments performed for a given set of plant conditions. Adhering to these decay times provided the assurance that the fuel would remain intact and could be re-used in the reactor.

In the event of a jammed SLAR tool interrupting the coolant flow, fuel would remain sufficiently cool to prevent fuel failures both during the incident and upon subsequent handling of the fuel. Re-use of the fuel would depend on the amount of time the fuel remained in the channel with little or no assured cooling flow.

References:

[1] R. Baker, "SLAR On Reactor Operations - Work Plan 95-55", PLGS, February 1995.

[2] P.G. Hill, R.D. MacMillan, V. Lee, "Tables of Thermodynamic Properties of Heavy Water in S.I. Units", AECL-7531, December 1981.

[3] Memo R.A. Gibb to P. Thompson, "Bundle Power Profile Data", TU-08721-C, 20 September 1988.

[4] M.S. Quraishi, T. Nguyen, T. Chan, "PRESCON VER-0.600 Programmer's Manual", TTR-219, Volume 2, Sept. 1990.

[5] A.C. Whittier, D.W. Black, C.R. Ross, "CANDU Channel Decay Power", AECL-5704, January 1977.

[6] P.J. Reid, "Fuel Sheath Integrity for Fuel Bundles at Decay Power Levels at 600 °C in Steam", PLGS-IR-03553-06 Rev.0, June 1995.

[7] P. Gulshani, "Assessment of Consequences of Flow Interruption During SLAR Channel Defuelling Program at PLGS", AECL TTR-554, June 1995.

Table 1. Maximum Bundle Powers During SLAR (To Prevent Boiling)

Bundle Number (numbered from SLAR tool end)	Time in Channel (seconds)	Saturation Bundle Power; BP_{SAT} (kW)
8 - 12	66	15.96
6 - 7	165	6.38
4 - 5	304	3.46
2 - 3	442	2.38
1	581	1.81

Table 2. Bundle Power Factors

Bundle Number (from SLAR tool end)[*]	Bundle Power Factors					
	Cosine		"Pinched"		"Flat"	
	Max. FF	Min. FF	Max. FF	Min. FF	Max. FF	Min. FF
	V-17	N-17	S-18	K-6	L-16	H-10
7	**1.65**	1.5	**1.65**	1.5	**1.4**	1.35
6	**1.65**	1.5	**1.65**	1.5	**1.4**	1.35
5	**1.6**	1.4	**1.5**	1.4	**1.3**	1.25
4	**1.3**	1.2	1.15	**1.2**	**1.25**	1.25
3	0.95	**1.0**	0.9	**1.05**	**1.1**	1.0
2	0.5	**0.7**	0.6	**0.7**	**0.75**	0.7
1	0.2	**0.3**	0.25	**0.3**	**0.35**	0.3

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[*] Bundles 8 through 12 are were not included in Table 2. because these bundles do not yield limiting in this assessment. These bundles remain in channel for the shortest duration of time and have lower decay power than bundles 6 and 7.

Table 3: Maximum Decay Channel Powers (in kW) Corresponding to Individual Bundles.

Bundle	Max B.P. (kW)	Decay Channel Powers (kW)		
		Cosine Profile	Pinched Profile	Flat profile
7	6.38	46.4	46.4	54.7
6	6.38	46.4	46.4	54.7
5	3.46	**26.0**	27.7	32.0
4	3.46	31.9	34.6	33.3
3	2.38	28.6	**27.3**	**26.0**
2	2.38	40.9	40.9	38.1
1	1.81	72.5	72.5	62.2

Table 4: Decay Time Before SLAR Can Commence to Prevent Reaching Bulk Saturation Temperatures in Coolant.

	Channel Power Profile Shape					
	cosine		pinched		flat	
Initial C.P.(kW)	P/Po	SD hrs	P/Po	SD hrs	P/Po	SD hrs
Po ≤ 7300	0.0036	141	0.0037	123	0.0036	141
Po ≤ 6800	0.0038	113	0.0040	98	0.0038	113
Po ≤ 6000	0.0043	76	0.0045	66	0.0043	75
Po ≤ 5100	0.0051	45	0.0053	39	0.0051	45
Po ≤ 4700	0.0055	35	0.0058	30	0.0055	35
Po ≤ 4300	0.0060	26	0.0063	23	0.0060	26
Po ≤ 3800	0.0068	18	0.0072	15	0.0068	18
Po ≤ 3400	0.0076	13	0.0080	11	0.0076	13

Table 5: Decay Times to Prevent 600 °C Fuel Temperatures at 0.5 MPa.

	Channel Power Profile Shape					
	"cosine"		"pinched"		"flat"	
initial C.P.(kW)	P/Po	SD hrs	P/Po	SD hrs	P/Po	SD hrs
Po ≤ 7300	0.003282	183.1	0.003282	183.1	0.003647	131.0
Po ≤ 6800	0.003524	146.1	0.003524	146.1	0.003915	104.5
Po ≤ 6000	0.003993	98.1	0.003993	98.1	0.004437	70.2
Po ≤ 5100	0.004698	58.5	0.004698	58.5	0.00522	41.8
Po ≤ 4700	0.005098	45.1	0.005098	45.1	0.005664	32.2
Po ≤ 4300	0.005572	34.0	0.005572	34.0	0.006191	24.3
Po ≤ 3800	0.006305	22.9	0.006305	22.9	0.007005	16.4
Po ≤ 3400	0.007047	16.1	0.007047	16.1	0.007829	11.5

Table 6. Limiting Decay Times to Prevent Saturation with PHT Drained to Headers.

Initial C.P.	Decay Ratio	Time
MW	P/Po	hours
Po < 7.3	0.0025	425
Po < 6.8	0.0027	339
Po < 6.0	0.0031	228
Po < 5.1	0.0036	136
Po < 4.7	0.0039	105
Po < 4.3	0.0043	79
Po < 3.8	0.0048	54
Po < 3.4	0.0054	38

Table 7: Decay Times to Prevent 600 °C Fuel Temperatures at 0.5 MPa with 0.1% Increase in Power.

	Channel Power Profile Shape					
	"cosine"		"pinched"		"flat"	
Initial C.P.(kW)	P/Po	SD hrs	P/Po	SD hrs	P/Po	SD hrs
Po ≤ 7300	0.002282	582.0	0.002282	582.0	0.002647	363.2
Po ≤ 6800	0.002524	422.6	0.002524	422.6	0.002915	267.1
Po ≤ 6000	0.002993	245.4	0.002993	245.4	0.003437	158.1
Po ≤ 5100	0.003698	125.2	0.003698	125.2	0.00422	82.3
Po ≤ 4700	0.004098	90.3	0.004098	90.3	0.004664	59.8
Po ≤ 4300	0.004572	63.7	0.004572	63.7	0.005191	42.6
Po ≤ 3800	0.005305	39.7	0.005305	39.7	0.006005	26.8
Po ≤ 3400	0.006047	26.2	0.006047	26.2	0.006829	17.8

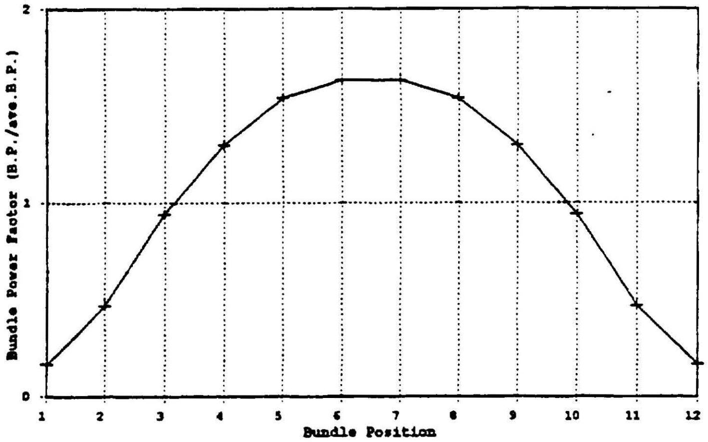

Figure7: Cosine Power Destribution
Channel V-17

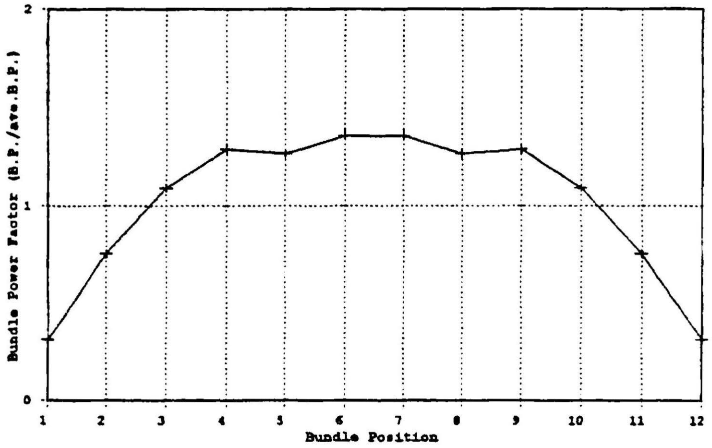

Figure 8: "Flat" Power Destribution
Channel N-8

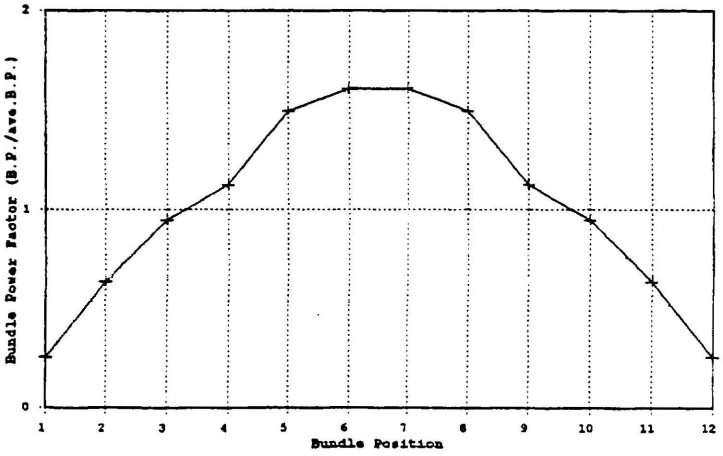

Figure 9: "Pinched" Power Destribution
Channel S-5