Establishment of Channel-SpecificChannel and Bundle Power Limits

J.H. Choi[1], D.J. Park[1], H.K. Ahn[1],B.G. Kim[1], C.J. Choi[1], D.W. Kho[2]and S.M. Kim[2]
[1]KEPCO E&C, Daejeon, Rep. of Korea
(jhchoi2@kepco-enc.com)
[2] KHNP-CRI, Daejeon, Rep. of Korea

Abstract

A study on the establishment of channel-specificchannel and bundle power limits for a CANDU 6 plant in Rep. of Korea was done.Rationale for the establishment of channel-specificchannel and bundle power limits and the selection of single channels for detailed safety evaluation, and the results of LOCA analysis with established channel and bundle power limits are included in this paper. A safety evaluation, with final limits for channel-specificchannel and bundle powers,shows that the times to reach acceptance criteria are very close to each other for nine selected single channels in accordance with the basic principles for the establishment of channel and bundle power limits.

1. Introduction

Currently a single power limit for all 380 channels in the core (channel power limit of 7.3 MW and bundle power limit of 935 kW) is specified in the plant technical specification of Wolsong nuclear power plants. This single channel and bundle power limit was established to ensure the safety of high power channels located in the central region of the core. Each fuel channel has a different power and flow in order to have similar fluid conditions at the outlet. Thuslow power channels have a lower flow and therefore should have a lower limit for channel power and bundle power.

Channel-specificchannel and bundle power limits have been used in Canada from the 1990s. The application of similar approach is also considered in Korea. This paper includes the rationale for the establishment of channel-specificchannel and bundle power limits, the selection of single channels for safety evaluation, and the results of safety evaluation with established channel and bundle power limits.

2. Channel-specificChannel and Bundle Power Limits

2.1 Channel-specific Channel Power Limits for Full Power Operation

Channel-specific channel power limits for full power operation are established based on two criteria. The first criterion is to give the same margin to fuel dryout during normal operation. The channel power limit by this criterion is determined from the following equation:

$$CPL_i = Min\ [(7.3 * CCP_i/CCP_{L11}),\ 7.3] \quad (1)$$

Where:

CPL_i = channel power limit of channel i (limited to7.3 MW)

CCP_i = critical channel power of channel i for nominal flux shape

CCP_{L11} = critical channel power of channel L11 for nominal flux shape.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									4408	4702	4682	4681	4703	4407									A
B						4319	4743	5678	5836	5837	6011	6011	5836	5837	5677	4745	4317						B
C					4598	5086	5851	6343	6514	6863	6899	6898	6864	6514	6345	5849	5088	4597					C
D				4640	5398	5966	6542	7216	7300	7300	7300	7300	7300	7300	7215	6541	5964	5401	4638				D
E			4860	5367	6196	6740	7174	7300	7300	7300	7300	7300	7300	7300	7300	7172	6744	6192	5372	4855			E
F			5452	6142	6851	7225	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7221	6857	6135	5459			F
G		5036	5897	6591	7195	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7190	6595	5892	5044		G
H		5550	6433	7193	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7193	6436	5549		H
J	4559	5742	6794	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	6797	5745	4559	J
K	4750	5963	6955	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	6957	5962	4754	K
L	5080	6236	7116	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7115	6239	5080	L
M	5070	6201	7105	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7105	6204	5071	M
N	4989	6076	6958	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	6958	6076	4991	N
O	4817	5828	6822	7168	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7168	6824	5827	4817	O
P		5630	6675	7187	7277	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7277	7185	6678	5627		P
Q		5046	5972	6888	7300	7284	7300	7300	7300	7300	7300	7300	7300	7300	7300	7300	7286	7300	6893	5966	5054		Q
R			5591	6297	7017	7227	7114	7300	7300	7300	7300	7300	7300	7300	7300	7117	7227	6991	6290	5598			R
S			4566	5487	5880	6524	6931	7139	7300	7300	7300	7300	7300	7300	7104	6929	6560	5876	5267	4563			S
T				4536	5141	5751	6230	6756	6848	6891	6890	6891	6890	6849	6791	6231	5720	5115	4534				T
U					3876	4504	5166	5893	5979	6226	6215	6215	6226	5978	5893	5165	4504	3875					U
V						3418	3962	4643	4768	4946	4938	4938	4945	4768	4641	3961	3417						V
W									3697	3794	3950	3950	3793	3695									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 1Channel-specific channel power limits (kW).

The second criterion is the prevention of fuel dryout for moderator inventory drain events for reactors having only one effective trip parameter for this event. The channel power limit by this criterion is determined from the following equation

$$CPL_i^{mod} = CCP_i/DCP_i \quad (2)$$

Where:

CPL_i^{mod} = channel power limit of channel i for moderator inventory drain events (which can cause a top-to-bottom flux tilt)

DCP_i = maximum channel power of channel i,normalized to initial power,during moderator inventory drain events ($DCP_i \geq 1.0$).

The channel-specific channel power limit selectsthelower value from Equations (1) and (2). Figure 1 shows the channel-specific channel power limits established by above rationale for CANDU 6 reactors.

2.2 Channel-specific Bundle Power Limits for Full Power Operation

2.2.1 Bundle power limits by dryout margin and moderator draining

Channel-specific bundle power limits could be established by the same rationale for channel power limits. Figure 2 shows thechannel-specific bundle power limits established for CANDU 6 reactors.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									564.4	602.0	599.5	599.3	602.1	564.4									A
B						553.2	607.7	727.2	747.5	747.4	769.8	769.8	747.3	747.6	727.1	607.9	553.1						B
C					589.5	651.5	749.3	812.4	834.5	878.8	883.6	883.5	878.9	834.4	812.6	749.1	651.7	589.3					C
D				594.7	692.9	765.1	837.6	924.1	935.0	935.0	935.0	935.0	935.0	935.0	924.2	837.5	764.9	692.8	594.4				D
E			622.7	687.7	794.0	863.4	919.1	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	918.7	863.9	793.5	688.2	621.9			E
F			698.3	786.5	877.4	925.3	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	924.8	878.1	785.7	699.1			F
G		644.9	755.1	844.2	921.6	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	920.8	844.5	754.3	645.8		G
H		710.7	823.7	921.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	921.1	824.0	710.4		H
J	583.8	735.2	870.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	870.4	735.7	583.8	J
K	608.1	763.3	890.5	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	890.9	763.5	608.8	K
L	650.5	798.6	911.3	935.0	935.0	935.0	935.0	935.0	934.3	935.0	922.3	924.2	935.0	934.7	935.0	935.0	935.0	935.0	935.0	911.0	798.9	650.5	L
M	649.1	794.3	909.8	935.0	935.0	935.0	935.0	932.8	925.7	916.0	910.5	910.7	916.8	925.1	933.4	935.0	935.0	935.0	935.0	909.8	794.4	649.4	M
N	638.8	778.1	890.9	935.0	935.0	935.0	933.9	925.4	893.9	893.5	883.2	883.0	894.0	893.7	927.7	935.0	935.0	935.0	935.0	891.0	778.1	639.1	N
O	616.7	746.2	873.6	917.8	935.0	935.0	931.4	907.5	885.1	874.6	863.0	862.3	875.5	884.7	909.9	933.8	935.0	935.0	917.9	873.8	746.1	616.7	O
P		721.2	854.8	920.7	931.8	935.0	928.1	909.2	879.0	868.9	862.1	862.2	868.4	880.6	909.1	928.5	935.0	931.9	920.0	855.2	720.5		P
Q		646.1	764.7	882.1	935.0	932.7	911.5	901.7	882.2	881.8	877.0	876.0	881.9	882.1	901.5	910.6	933.0	935.0	882.6	764.0	647.1		Q
R			715.9	806.4	898.6	935.0	905.3	909.1	896.6	898.0	906.0	905.7	897.3	897.5	908.1	904.1	935.0	899.7	805.5	716.9			R
S			590.5	709.6	792.5	861.5	897.3	892.3	915.6	935.0	935.0	935.0	935.0	915.4	892.2	896.3	861.8	792.0	710.0	590.3			S
T				611.4	687.4	757.8	809.0	868.3	875.0	891.6	907.9	907.4	890.2	874.1	868.3	808.4	756.5	687.0	611.2				T
U					539.9	605.9	693.2	789.3	804.3	845.4	859.7	859.4	843.9	802.8	788.7	692.2	604.6	539.0					U
V						478.2	548.0	631.7	650.2	682.0	687.4	686.2	680.9	649.3	630.3	547.1	477.3						V
W									522.4	538.4	561.6	561.0	538.0	521.6									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 2 Initial bundle power limits (kW).

2.2.2 Consideration of bundle enthalpy rise for bundle power limits

Initially Figure 2 was used as the reference for safety analysis. However, some channels showed difficulties meeting the trip coverage acceptance criteria for some events, with channel powers above the corresponding channel power limits (Figure 1) and bundle power limits (Figure 2). It was found that channels with a high maximum bundle enthalpy rise (bundle power limit divided by channel flow) had difficultiesproviding therequired trip coverage for some events.

It was decided to consider an additional constraint, maximum bundle enthalpy rise, to the bundle power limits since the operational margin to bundle power limits is higher than that to channel power limits. Low power channel E3 has a high maximum bundle enthalpy rise but meets the trip coverage acceptance criteria. So, channels O6 (highest power channel) and E3 are selected as the reference channels to generate a correction factor to limit the channel power based onthe channel-specific bundle power limits, which are based on the maximum allowable bundle enthalpy rise.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									575.6	619.1	618.3	616.5	623.2	574.7									A
B						585.8	597.4	695.3	734.4	724.1	757.7	764.2	722.9	741.4	697.7	601.4	588.1						B
C					612.1	628.9	718.0	791.9	836.3	862.4	876.6	880.1	869.8	836.3	797.7	718.4	632.3	614.7					C
D				597.6	654.9	726.8	803.7	898.1	921.3	941.0	937.9	946.6	943.2	928.4	900.7	807.8	726.0	658.6	597.3				D
E			622.7	640.2	780.2	841.5	908.5	942.1	990.1	991.2	998.8	1002.5	1000.5	994.2	949.1	909.6	847.2	782.1	644.4	625.1			E
F			668.7	775.7	849.2	885.7	935.5	985.9	950.8	975.7	938.4	944.3	979.3	957.4	989.5	941.7	884.5	856.9	777.3	673.9			F
G		635.6	741.0	836.1	890.2	926.7	932.8	969.2	970.2	964.5	938.7	935.0	972.6	972.7	976.5	929.4	933.7	892.4	843.0	742.6	641.3		G
H		717.7	805.6	894.8	912.5	931.1	932.4	988.6	964.8	954.9	916.7	917.1	954.4	972.1	991.8	935.2	929.1	919.1	897.3	813.0	719.9		H
J	585.8	698.7	840.1	913.7	965.4	959.5	973.4	985.0	968.6	959.5	917.1	910.8	966.9	970.3	994.4	975.8	967.5	969.2	920.6	840.9	703.0	585.8	J
K	593.3	721.3	847.2	922.0	992.5	963.2	972.7	990.7	962.1	953.9	909.4	910.5	954.6	969.4	994.9	980.6	965.5	1001.9	919.0	851.4	719.4	597.4	K
L	611.3	772.9	863.6	956.6	1027.1	980.5	976.2	988.4	959.6	939.1	904.0	896.5	948.0	960.6	1000.0	977.1	990.9	1030.4	965.5	860.4	779.6	611.3	L
M	637.2	773.9	865.4	958.3	1021.6	992.5	976.1	990.9	1011.5	948.6	921.0	925.4	948.9	1019.5	994.0	980.6	994.0	1029.4	954.9	867.2	772.2	640.1	M
N	640.2	759.9	841.8	935.7	1019.1	977.4	975.0	990.9	973.6	952.3	901.8	896.2	957.8	975.0	998.8	972.2	981.1	1022.4	937.5	838.6	763.8	641.9	N
O	618.6	729.2	817.8	884.3	961.0	934.9	956.7	978.2	969.0	952.0	875.2	877.7	948.3	974.8	977.3	956.8	929.2	963.3	879.8	820.4	728.8	623.6	O
P		711.7	820.2	874.4	941.4	947.4	958.9	977.3	982.1	959.1	918.9	913.7	963.5	984.1	982.6	955.0	949.3	942.9	878.2	823.4	717.4		P
Q		630.7	733.4	832.0	899.5	914.4	929.6	980.7	980.2	976.6	936.2	937.3	979.4	988.5	982.8	932.1	913.0	907.6	834.5	738.8	632.2		Q
R			675.2	774.1	858.4	895.4	908.7	971.0	961.7	948.3	935.9	931.0	951.9	963.1	977.9	905.1	902.5	862.4	780.8	678.1			R
S			600.7	707.2	768.5	815.1	859.8	908.2	964.2	1000.3	988.6	997.1	1004.3	971.1	904.3	862.0	815.7	774.8	710.0	605.2			S
T				626.1	652.3	746.7	782.7	848.6	865.4	902.7	902.3	904.2	908.3	863.4	852.6	780.6	752.7	653.4	630.9				T
U					586.8	619.6	708.4	784.4	795.7	827.3	824.7	831.3	829.9	801.5	787.5	713.9	620.7	591.3					U
V						571.0	605.2	652.7	678.1	701.2	694.1	694.5	706.5	679.7	657.7	607.4	575.9						V
W									597.6	603.5	601.6	606.6	605.7	602.3									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 3 Bundle power limits by maximum bundle enthalpy rise (kW).

For full power operation, channel O6 has a time-averaged channel power of 6,559 kW, a bundle power limit of 935 kW and a channel flow of 25.45 kg/s. So, the maximum bundle enthalpy rise of channel O6 is 36.74 kJ/kg (=935/25.45). The channel-specific bundle power limit, based on maximum bundle enthalpy rise and time-averaged channel power, can be expressed as

$$BPL_i = 36.74\ W_i * F_i * (6559/TACP_i) \qquad (3)$$

Where:

BPL_i =bundle power limit of channel i (kW)
W_i = flow of channel i (kg/s)
F_i= correction factor of channel i
$TACP_i$ = time-averaged channel power of channel i (kW).

Channel E3 has a time-averaged channel power of 3,249 kW, a bundle power limit of 622.7 kW and a channel flow of 13.77 kg/s.The correction factorF_i for channel E3, derived from Equation (3),is 0.6097. By assuming a linear relationship based only on$TACP_i$, between the time-averaged channel powersof channels O6 and E3, the correction factor for channel iis given by

$$F_i = 0.6097 + (1.0-0.6097)\ (TACP_i - 3249) / (6559 - 3249) \qquad (4)$$
$$= 0.2266 + 1.179x10^{-4}\ TACP_i$$

From Equations (3) and (4), channel-specific bundle power limit (kW) is given by a function of time-averaged channel power (kW) and channel flow (kg/s);

$$BPL_i = 36.74\ W_i * (0.2266 + 1.179x10^{-4} TACP_i\ ) * (6559/TACP_i) \qquad (5)$$

Figure 3 shows the channel-specific bundle power limits generated by Equation (5). By selecting the lowestvalue fromFigures 2 and 3, the final channel-specific bundle power limits are determined and shown in Figure 4.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									564.4	602.0	599.5	599.3	602.1	564.4									A
B						553.2	597.4	695.3	734.4	724.1	757.7	764.2	722.9	741.4	697.7	601.4	553.1						B
C					589.5	628.9	718.0	791.9	834.5	862.4	876.6	880.1	869.8	834.4	797.7	718.4	632.3	589.3					C
D				594.7	654.9	726.8	803.7	898.1	921.3	935.0	935.0	935.0	935.0	928.4	900.7	807.8	726.0	658.6	594.4				D
E			622.7	640.2	780.2	841.5	908.5	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	909.6	847.2	782.1	644.4	621.9			E
F			668.7	775.7	849.2	885.7	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	884.5	856.9	777.3	673.9			F
G		635.6	741.0	836.1	890.2	926.7	932.8	935.0	935.0	935.0	935.0	935.0	935.0	935.0	935.0	929.4	933.7	892.4	843.0	742.6	641.3		G
H		710.7	805.6	894.8	912.5	931.1	932.4	935.0	935.0	935.0	916.7	917.1	935.0	935.0	935.0	935.0	929.1	919.1	897.3	813.0	710.4		H
J	583.8	698.7	840.1	913.7	935.0	935.0	935.0	935.0	935.0	935.0	917.1	910.8	935.0	935.0	935.0	935.0	935.0	935.0	920.6	840.9	703.0	583.8	J
K	593.3	721.3	847.2	922.0	935.0	935.0	935.0	935.0	935.0	935.0	909.4	910.5	935.0	935.0	935.0	935.0	935.0	935.0	919.0	851.4	719.4	597.4	K
L	611.3	772.9	863.6	935.0	935.0	935.0	935.0	935.0	934.3	935.0	904.0	896.5	935.0	934.7	935.0	935.0	935.0	935.0	935.0	860.4	779.6	611.3	L
M	637.2	773.9	865.4	935.0	935.0	935.0	935.0	932.8	925.7	916.0	910.5	910.7	916.8	925.1	933.4	935.0	935.0	935.0	935.0	867.2	772.2	640.1	M
N	638.8	759.9	841.8	935.0	935.0	935.0	933.9	925.4	893.9	893.5	883.2	883.0	894.0	893.7	927.7	935.0	935.0	935.0	935.0	838.6	763.8	639.1	N
O	616.7	729.2	817.8	884.3	935.0	935.0	931.4	907.5	885.1	874.6	863.0	862.3	875.5	884.7	909.9	933.8	929.2	935.0	879.8	820.4	728.8	616.7	O
P		711.7	820.2	874.4	931.8	935.0	928.1	909.2	879.0	868.9	862.1	862.2	868.4	880.6	909.1	928.5	935.0	931.9	878.2	823.4	717.4		P
Q		630.7	733.4	832.0	899.5	914.4	911.5	901.7	882.2	881.8	877.0	876.0	881.9	882.1	901.5	910.6	913.0	907.6	834.5	738.8	632.2		Q
R			675.2	774.1	858.4	895.4	905.3	909.1	896.6	898.0	906.0	905.7	897.3	897.5	908.1	904.1	902.5	862.4	780.8	678.1			R
S			590.5	707.2	768.5	815.1	859.8	892.3	915.6	935.0	935.0	935.0	935.0	915.4	892.2	862.0	815.7	774.8	710.0	590.3			S
T				611.4	652.3	746.7	782.7	848.6	865.4	891.6	902.3	904.2	890.2	863.4	852.6	780.6	752.7	653.4	611.2				T
U					539.9	605.9	693.2	784.4	795.7	827.3	824.7	831.3	829.9	801.5	787.5	692.2	604.6	539.0					U
V						478.2	548.0	631.7	650.2	682.0	687.4	686.2	680.9	649.3	630.3	547.1	477.3						V
W									522.4	538.4	561.6	561.0	538.0	521.6									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 4 Channel-specific bundle power limits (kW).

3. Selection of Single Channels for Detailed Analysis

A logical approach is necessary to select typical single channels for detailed safety analysis. Single channels for detailed safety analysis are selected within the core pass 4 (95 channels between reactor inlet header 8 and reactor outlet header 5) because the core pass 4 is assumed as the critical pass in all accidents.

Figure 5 shows the channel enthalpy rise at the channel power limit (channel power limit divided by channel flow). Low power channels running at thechannel power limit have a higher channel enthalpy rise (higher outlet quality) since the channel power limits were established to have the same dryout margin.Of the channels with similar time-averaged channel power, channels with a higher channel enthalpy rise have a higher probability of fuel dryout. High power channel L11 and low power channel L1 are selected based on the channel enthalpy rise.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									350.1	341.7	337.8	338.7	339.6	350.6									A
B						348.3	350.6	345.0	328.2	328.8	322.8	320.1	329.3	325.2	343.6	348.4	346.7						B
C					338.3	343.0	330.2	315.9	302.6	307.2	304.5	303.2	304.7	302.6	313.6	329.9	341.2	336.8					C
D				344.7	343.4	326.4	313.9	304.5	297.6	290.7	292.9	290.3	290.0	295.3	303.5	312.2	326.6	341.6	344.8				D
E			352.9	349.9	315.2	307.6	296.9	288.2	273.1	272.8	272.0	271.0	270.3	272.0	286.1	296.5	305.7	314.2	347.9	351.3			E
F			344.4	315.8	310.7	307.1	289.7	273.2	283.9	277.1	289.0	287.2	276.1	282.0	272.2	287.7	307.3	308.2	314.8	342.3			F
G		347.1	323.1	305.7	306.4	293.9	289.2	277.4	277.9	279.9	287.6	288.8	277.6	277.1	275.3	290.3	291.7	305.4	303.4	322.1	344.5		G
H		324.0	314.6	305.7	299.8	290.7	288.5	271.6	279.2	282.4	294.0	293.9	282.5	277.0	270.7	287.6	291.3	297.6	304.8	311.8	322.8		H
J	352.0	335.6	312.7	300.2	281.5	281.9	276.7	273.1	278.2	281.2	294.4	296.4	279.1	277.7	270.5	276.0	279.5	280.3	297.8	312.4	333.4	352.0	J
K	352.9	331.1	313.3	294.9	272.8	280.6	276.9	271.8	280.3	283.4	298.0	297.6	283.2	278.2	270.6	274.6	279.8	270.2	295.8	311.7	331.6	350.6	K
L	361.3	320.3	312.4	282.6	261.8	274.1	275.4	272.3	281.2	288.3	300.9	303.4	285.6	280.9	269.1	275.1	271.2	260.9	279.9	313.3	317.3	361.1	L
M	346.3	318.0	310.9	281.6	262.5	270.1	275.0	271.4	266.7	285.5	295.5	294.1	285.4	264.6	270.5	273.6	269.6	260.4	282.5	310.1	318.5	344.5	M
N	344.3	320.1	314.7	289.2	263.3	274.0	275.1	271.2	276.8	283.9	301.0	302.9	282.3	276.4	269.0	275.8	272.9	262.3	288.5	315.7	318.1	343.3	N
O	353.4	326.5	321.9	303.2	280.3	286.8	280.4	274.5	277.9	283.4	308.5	307.6	284.5	276.2	274.7	280.3	288.5	279.6	304.6	320.8	326.3	350.3	O
P		332.2	320.8	312.2	288.8	284.8	280.1	274.5	274.1	281.0	293.1	294.7	279.7	273.5	273.0	281.2	284.2	288.2	310.6	319.5	329.1		P
Q		352.4	332.1	322.3	308.8	298.0	290.7	274.3	275.1	276.2	287.9	287.5	275.4	272.7	273.7	289.9	298.5	306.0	321.5	329.2	351.9		Q
R			353.6	328.1	319.0	306.9	292.2	278.0	280.9	284.8	288.9	290.4	283.7	280.4	276.0	293.4	304.4	316.2	324.9	352.5			R
S			350.7	330.1	309.6	311.9	305.3	293.3	280.7	270.1	274.2	271.9	269.0	278.6	293.1	304.4	313.3	306.8	315.6	347.8			S
T				331.8	336.0	311.0	309.8	303.1	297.7	286.1	287.2	286.6	284.2	298.4	303.2	310.6	306.9	333.7	329.0				T
U					307.6	314.5	299.0	297.9	292.4	290.4	291.2	288.9	289.4	290.2	296.7	296.5	313.9	305.1					U
V						298.3	298.6	306.5	294.0	289.7	290.6	290.5	287.5	293.2	303.9	297.4	295.6						V
W									297.2	293.0	301.3	298.8	291.8	294.7									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 5Channel enthalpy rise at channel power limit (kJ/kg).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									44.8	43.8	43.3	43.4	43.5	44.9									A
B						44.6	44.2	42.2	41.3	40.8	40.7	40.7	40.8	41.3	42.2	44.2	44.4						B
C					43.4	42.4	40.5	39.4	38.8	38.6	38.7	38.7	38.6	38.8	39.4	40.5	42.4	43.2					C
D				44.2	41.7	39.8	38.6	37.9	37.6	37.2	37.5	37.2	37.1	37.6	37.9	38.6	39.8	41.7	44.2				D
E			45.2	41.7	39.7	38.4	37.6	36.9	35.0	34.9	34.8	34.7	34.6	34.8	36.6	37.6	38.4	39.7	41.7	45.0			E
F			42.2	39.9	38.5	37.6	37.1	35.0	36.4	35.5	37.0	36.8	35.4	36.1	34.9	36.9	37.6	38.5	39.9	42.3			F
G		43.8	40.6	38.8	37.9	37.3	37.0	35.5	35.6	35.9	36.8	37.0	35.6	35.5	35.3	37.0	37.3	37.9	38.8	40.6	43.8		G
H		41.5	39.4	38.0	37.5	37.1	36.9	34.8	35.8	36.2	36.9	36.9	36.2	35.5	34.7	36.8	37.1	37.5	38.0	39.4	41.3		H
J	45.1	40.8	38.7	37.6	36.1	36.1	35.4	35.0	35.6	36.0	37.0	37.0	35.7	35.6	34.6	35.3	35.8	35.9	37.6	38.6	40.8	45.1	J
K	44.1	40.1	38.2	37.3	34.9	35.9	35.5	34.8	35.9	36.3	37.1	37.1	36.3	35.6	34.7	35.2	35.8	34.6	37.2	38.1	40.0	44.1	K
L	43.5	39.7	37.9	36.2	33.5	35.1	35.3	34.9	36.0	36.9	37.3	37.3	36.6	36.0	34.5	35.2	34.7	33.4	35.9	37.9	39.7	43.4	L
M	43.5	39.7	37.9	36.1	33.6	34.6	35.2	34.7	33.8	35.8	36.9	36.7	35.8	33.5	34.6	35.0	34.5	33.4	36.2	37.9	39.6	43.5	M
N	44.1	40.0	38.1	37.0	33.7	35.1	35.2	34.4	33.9	34.8	36.4	36.6	34.6	33.8	34.2	35.3	35.0	33.6	37.0	38.0	40.0	44.0	N
O	45.2	40.8	38.6	37.4	35.9	36.7	35.8	34.1	33.7	34.0	36.5	36.3	34.1	33.5	34.2	35.9	36.7	35.8	37.4	38.6	40.8	44.9	O
P		42.0	39.4	38.0	37.0	36.5	35.6	34.2	33.0	33.4	34.6	34.8	33.3	33.0	34.0	35.8	36.4	36.9	38.0	39.4	42.0		P
Q		44.0	40.8	38.9	38.0	37.4	36.3	33.9	33.2	33.4	34.6	34.5	33.3	33.0	33.8	36.2	37.4	38.0	38.9	40.8	44.0		Q
R			42.7	40.3	39.0	38.0	37.2	34.6	34.5	35.0	35.9	36.0	34.9	34.5	34.3	37.3	38.0	39.0	40.3	42.7			R
S			45.4	42.6	40.5	39.0	37.9	36.7	35.2	34.6	35.1	34.8	34.5	34.9	36.8	37.9	39.0	40.5	42.5	45.0			S
T				44.7	42.6	40.4	38.9	38.1	37.6	37.0	37.6	37.6	36.7	37.6	38.1	38.9	40.4	42.6	44.4				T
U					42.8	42.3	40.1	39.7	38.9	38.6	38.6	38.6	38.6	38.9	39.7	39.7	42.1	42.4					U
V						41.7	41.3	41.7	40.1	40.0	40.5	40.4	39.6	39.9	41.3	41.1	41.3						V
W									42.0	41.6	42.8	42.4	41.4	41.6									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 6 Maximum bundle enthalpy rise at bundle power limit (kJ/kg).

Figure 6 shows the maximum bundle enthalpy rise (bundle power limit divided by channel flow). The higher bundle enthalpy rise indicates a higher possibility of fuel dryout. High power channels L11 and G5, and low power channel E3 are selected based on bundle enthalpy rise.

The elevation of channels in the core is also considered. Fuel channels located at the top and bottom ofthe core have similar low powers, but the lengths of their inlet and outlet feeders are quite different. Low power channels A9 (top with shortest feeder) and W10 (bottom with longest feeder) are selected based on core elevation and feeder geometry.

Feeder pipes are connected to a reactor inlet or outlet header at three elevations along the surface of header. This connection elevation results in a different effect when flow stratification occurs in the header. During the period of flow stratification, fuel channels with feeder pipes connected to a header above the water level receive only steam, which gives a higher possibility of fuel dryout and heat up. High power channel S10 and low power channel W10 are selected since their feeder pipes are connected to their headers at highest elevation.

The ratio of bundle power limit to channel power limit indicates that the channel power peaking with channel and bundle power limits is assumed to occur at the same time. Fuel channels with a higher power peaking have a higher possibility of fuel dryout. Channels V11 and W10 are selected based on power peaking.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
A									1.397	1.428	1.389	1.389	1.428	1.397									A
B						1.489	1.368	1.438	1.378	1.324	1.352	1.352	1.323	1.378	1.437	1.368	1.488						B
C					1.400	1.304	1.298	1.281	1.245	1.281	1.298	1.298	1.281	1.244	1.281	1.297	1.304	1.399					C
D				1.359	1.310	1.240	1.216	1.253	1.223	1.212	1.234	1.233	1.211	1.223	1.253	1.216	1.239	1.310	1.359				D
E			1.496	1.309	1.279	1.234	1.208	1.174	1.154	1.154	1.177	1.176	1.154	1.154	1.174	1.207	1.234	1.278	1.311	1.496			E
F			1.381	1.290	1.268	1.221	1.164	1.134	1.146	1.154	1.168	1.168	1.154	1.146	1.134	1.164	1.220	1.268	1.289	1.384			F
G		1.420	1.317	1.251	1.252	1.189	1.143	1.125	1.139	1.146	1.147	1.147	1.146	1.139	1.124	1.142	1.189	1.250	1.252	1.315	1.422		G
H		1.371	1.294	1.267	1.212	1.159	1.128	1.119	1.134	1.140	1.138	1.138	1.140	1.134	1.118	1.128	1.158	1.211	1.266	1.294	1.368		H
J	1.405	1.306	1.275	1.225	1.179	1.155	1.135	1.128	1.136	1.143	1.145	1.145	1.143	1.136	1.127	1.134	1.153	1.178	1.223	1.274	1.304	1.405	J
K	1.363	1.271	1.242	1.182	1.160	1.151	1.135	1.132	1.141	1.152	1.164	1.164	1.152	1.141	1.132	1.134	1.149	1.159	1.180	1.240	1.267	1.362	K
L	1.401	1.289	1.238	1.153	1.127	1.124	1.125	1.130	1.144	1.160	1.184	1.183	1.160	1.143	1.129	1.124	1.123	1.125	1.151	1.235	1.285	1.399	L
M	1.403	1.280	1.231	1.145	1.113	1.110	1.117	1.127	1.142	1.161	1.186	1.186	1.161	1.142	1.126	1.115	1.109	1.111	1.142	1.228	1.276	1.400	M
N	1.441	1.293	1.231	1.158	1.115	1.106	1.113	1.123	1.138	1.154	1.173	1.173	1.153	1.137	1.122	1.112	1.105	1.113	1.156	1.228	1.288	1.438	N
O	1.497	1.328	1.272	1.181	1.135	1.113	1.115	1.120	1.133	1.143	1.147	1.147	1.142	1.132	1.119	1.114	1.112	1.134	1.179	1.270	1.323	1.495	O
P		1.400	1.345	1.260	1.192	1.143	1.121	1.115	1.132	1.137	1.133	1.133	1.137	1.131	1.115	1.120	1.142	1.190	1.258	1.343	1.395		P
Q		1.445	1.354	1.327	1.288	1.201	1.151	1.129	1.139	1.141	1.137	1.137	1.141	1.138	1.128	1.150	1.200	1.287	1.327	1.351	1.445		Q
R			1.464	1.375	1.363	1.272	1.160	1.145	1.149	1.148	1.153	1.153	1.148	1.148	1.145	1.160	1.271	1.356	1.373	1.465			R
S			1.482	1.421	1.299	1.260	1.202	1.164	1.157	1.149	1.167	1.167	1.149	1.157	1.157	1.200	1.266	1.297	1.363	1.481			S
T				1.445	1.339	1.261	1.199	1.195	1.155	1.143	1.161	1.161	1.143	1.155	1.200	1.198	1.254	1.331	1.443				T
U					1.289	1.225	1.190	1.214	1.150	1.160	1.165	1.165	1.160	1.149	1.213	1.189	1.224	1.288					U
V						1.340	1.247	1.247	1.169	1.148	1.125	1.125	1.147	1.169	1.246	1.247	1.339						V
W									1.329	1.264	1.264	1.264	1.263	1.328									W
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 7 Ratio of channel power limit to time-averaged channel power.

Figure 7 shows the ratio of channel power limit to time-averaged channel power. It indicates the margin from normal operation to channel power limit. Central high power region has a margin ofabout 15%; however, the outer low-power region has a margin range of 40 to 50%. Channel E3 is selected based on this consideration since it has themaximum deviation from thenormal operating conditions.

Channels L11 and O6 should be considered since they have the lowest critical power ratio (CPR).These channels have ahigher possibility of fuel dryout during the power increase or flow decrease.

Taking into account all considerations mentioned above, a total of 9 channels are selected for detailed analysis. The characteristics ofthe 9 selected single channels are summarized in Table 1.

Table 1 Characteristics of selected 9 single channels.

	Unit	A9M	E3M	G5M	L1M	L11M	O6M	S10M	V11M	W10M
Time-averaged channel power	kW	3155	3249	5747	3625	6168	6559	6352	4388	3002
Channel power limit	kW	4408	4860	7195	5080	7300	7300	7300	4938	3794
Bundle power limit	kW	564.4	622.7	890.2	611.3	904.0	935	935	687.4	538.4
Channel flow	kg/s	12.59	13.77	23.48	14.06	24.26	25.45	27.03	16.99	12.95
Channel enthalpy rise	kJ/kg	350.1	352.9	306.4	361.3	300.9	286.8	270.1	290.6	293.0
Maximum bundle enthalpy rise	kJ/kg	44.8	45.2	37.9	43.5	37.3	36.7	34.6	40.5	41.6
Bundle power peaking	-	0.128	0.128	0.124	0.120	0.124	0.128	0.128	0.139	0.142
Ratio of CPL to time-averaged channel power	-	1.397	1.496	1.252	1.401	1.184	1.113	1.149	1.125	1.264
Elevation in core	-	H	H/M	M	M	M	M	M/L	L	L

4. LOCA Analysis Results

The purpose of safety analysis is to show that all the events included in the Final Safety Analysis Report (FSAR) [2] meet their acceptance criteria with the assumption that single channels are operated initially with their channel and bundle power limits as established in Section 2. The assessment of trip coverage is required to analyze the cases at reduced reactor power as well as full power operation. The assessment of channel refill behavior for large and small break loss of coolant accidents (LOCA),and for singlechannel events (including pressure tube rupture, channel flow blockage, feeder break and end fitting failure),consider only the case of full power operation.

The header boundary condition generated from the circuit analysis (existing FSAR) is applied equally to all single channel analysis. Table 2 is a summary of trip coverage analysis for a

large break LOCA at a reactor inlet header (RIH), with the reactor regulating system (RRS) frozen (i.e., unresponsive). The following four sub-criteria are applied to maintain the integrity of fuel channels for a LBLOCA;

- Stored energy in fuel pellet (E) – 840 kJ/kg
- Fuel centerline melting (CT) – 2817℃
- Fuel sheath melting (ST) – 1760℃
- Pressure tube temperature (PT) – 600℃

Table 2 Trip coverage analysis results for RIH LBLOCA with RRS frozen.

Break Size (%)	Power (%FP)	Violation Time (s)[1]	A9M	E3M	G5M	L1M	L11M	O6M	S10M	V11M	W10M
100	103	**2.2(E)** [2]	2.6	2.5	**2.2**	2.5	**2.2**	**2.2**	**2.2**	2.4	2.6
	75	**2.6(E)**	3.0	2.9	**2.6**	2.9	**2.6**	**2.6**	**2.6**	2.8	3.0
	50	**3.0(E)**	3.4	3.3	3.1	3.3	3.1	**3.0**	**3.0**	3.3	3.4
	25	**4.6(E)**	4.9	4.8	**4.6**	4.8	**4.6**	**4.6**	**4.6**	4.7	4.9
	5	**9.9(E)**	10.1	10.0	**9.9**	10.1	**9.9**	**9.9**	**9.9**	10.0	10.1
50	103	**2.2(E)**	2.7	2.6	2.3	2.6	2.3	**2.2**	**2.2**	2.5	2.7
	50	**3.0(E)**	3.4	3.3	3.1	3.4	3.1	**3.0**	**3.0**	3.3	3.5
	25	**4.5(E)**	4.9	4.8	4.6	4.9	4.6	**4.5**	**4.5**	4.8	4.9
30	75	**2.7(E)**	3.2	3.1	**2.7**	3.2	**2.7**	**2.7**	**2.7**	3.0	3.3
	50	**3.2(E)**	3.7	3.6	3.3	3.6	**3.2**	**3.2**	**3.2**	3.5	3.7
	5	**14.7(E)**	15.1	15.1	**14.7**	15.1	**14.7**	**14.7**	**14.7**	15.0	15.2
20	75	**3.1(E)**	3.9	3.8	3.2	3.8	3.2	**3.1**	**3.1**	3.6	4.0
	25	**8.0(E)**	8.8	8.7	8.1	8.7	8.1	**8.0**	8.1	8.5	8.9
10	103	**6.4(E)**	7.9	7.8	6.8	7.9	6.7	**6.4**	6.5	7.6	8.0
	75	**8.9(E)**	11.4	11.2	9.4	11.2	9.3	**8.9**	**8.9**	10.7	11.5
	50	**14.9(E)**	17.1	16.8	15.2	16.9	15.2	**14.9**	**14.9**	16.2	17.2
	25	**27.0(E)**	27.7	27.6	27.1	27.6	**27.0**	**27.0**	**27.0**	27.5	27.8
5	103	**9.7(E)**	12.3	12.1	10.2	12.2	10.1	**9.7**	9.8	11.7	12.4
	50	**35.6(CT)**	40.8	40.4	35.8(CT)	40.6	**35.6**(CT)	38.7	38.9	38.8	42.0
	25	**55.6(E)**	56.3	56.2	55.7	56.2	55.7	**55.6**	**55.6**	56.1	56.4

(1)Time when any one of the acceptance criteria is violated first from 9 single channels
(2)E – Maximum Stored Energy, CT – Maximum fuel centerline temperature

The values for each single channel in Table 2 are the timeswhen any one of four sub-criteria is reached first. The violation time is the earliest timeof the9 single channels. Channel O6 and S10 have the highest channel power limit of 7.3 MW and the highest bundle power limit (935 kW). Though the earliest timesoccur in channel O6 and S10 for most cases, the differences among thenine channels arevery small. This result agreeswiththe expectations, since the channel and bundle power limits for all 380 channels are determined to have the same safety margin.Trip parameters predicted to occur before theviolation time are considered to be

effective.The full spectrum analysis for LBLOCA with channel and bundle power limits shows a small reduction of trip coverage, but more than two trip parameters for each shutdown system are still effective for the entire spectrum of break size and power level.

The channel refill behaviour, for an LBLOCA with channel and bundle power limits, is also examined. All nine channels show channel refill after emergency core coolant injection and no significant heat upafter the first refill.

Table 3 is a summary of trip coverage analysis for a small break LOCA with the RRS operating. The values for each single channel are the timeswhen the maximum fuel sheath surface temperature reaches 800℃.Like the LBLOCA, the timings are very close to each other among the9 single channels.Channels G5 and L11 are critical channels for most cases.

Table 3 Trip coverage analysis results for SBLOCA with RRS operating.

Break Size(%)	Power (% FP)	A9M	E3M	G5M	L1M	L11M	O6M	S10M	V11M	W10M	Violation Time (s)
3%	103	20.1	20.1	**17.1**	20.1	**17.1**	18.1	19.1	19.1	21.1	**17.1**
	75	99.1	**98.1**	**98.1**	99.2	**98.1**	**98.1**	**98.1**	**98.1**	99.2	**98.1**
	50	112.8	112.8	**111.8**	112.8	**111.8**	**111.8**	**111.8**	**111.8**	112.8	**111.8**
2.5%	103	29.1	28.2	25.1	28.2	**25.0**	26.1	27.1	27.1	30.1	**25.0**
	75	123.3	122.3	**121.2**	122.2	**121.2**	121.3	122.2	122.3	124.3	**121.2**
	50	**137.6**	**137.6**	**137.6**	**137.6**	**137.6**	**137.6**	**137.6**	137.7	138.6	**137.6**
1.5%	103	185.7	183.7	**174.6**	184.8	299.9	178.7	181.6	179.6	193.6	**174.6**
	75	224.6	223.7	**221.6**	223.7	**221.6**	222.6	223.6	223.6	225.7	**221.6**
	50	249.6	249.6	**247.6**	249.6	**247.6**	248.6	249.6	249.6	251.6	**247.6**

5. Conclusion

Channel-specific channel and bundle power limits for anHWR in Korea are established based on the previous experience at CANDU 6 operation in Canada. Maximum bundle enthalpy rise is also considered to establish channel-specificbundle power limits. A logical approach is developed to select single channels for detailed safety analysis, to examine whether the established channel and bundle power limits meet the safety acceptance criteria or not.Of the 95 fuel channels in a critical core pass, 9 fuel channels are selected for detailed safety analysis.

Single channel analysis with channel and bundle power limits is done for all events included in the FSAR. A part of the LOCA analysis results is included in this paper to show the validation of established channel and bundle power limits, and the analysis methodology.The results of trip coverage analysis show that the times to reach acceptance criteria are very close to each other for the 9 selected single channels. It agrees withthe expectationssince the basisfor the establishment of channel and bundle power limits for all 380 channels is to give the same safety margin.

6. References

[1] KHNP, “CANDU 6 Station Reactor Physics Design Manual”, Wolsong NPP 1, 59RF-03310-DM-000 Rev.0, 2009.

[2] KHNP, “Final Safety Analysis Reports”, Wolsong NPP 1, 2013.