Indian Point 2 Model – Steam Generator Tube Rupture Sequences

Table 1 shows the top 100 SGTR sequences with the failed split fractions for each sequence.

Each sequence includes an SISF split fraction that simply indicates that the sequence involves a loss of coolant from the primary system. This split fraction is a flag and has no quantitative value. It should also be noted that the sequences are shown in groups of two with the only difference being the inclusion of a SWS1 split fraction in one sequence of each pair. This SWS1 split fraction is required to properly reflect the fact that Indian Point 2 has two separate service water headers, either of which could be aligned to the essential or non-essential header at a given time. The two sequences therefore represent identical scenarios except that in one sequence, service water pumps 21, 22 and 23 are aligned to the essential header and in the other sequence, service water pumps 24, 25 and 26 are aligned to the essential header. Since either plant configuration is equally likely, the value of SWS1 is 0.5 and the sum of the two sequences represents the complete scenario.

Those sequences which are assigned to Plant Damage State 48A represent core damage sequences with an un-isolated secondary side while those sequences assigned to Plant Damage State 48B represent core damage sequences with the release through a modulating relief valve allowing radionuclide deposition and partitioning. Based on the expected core inventory release fractions associated with the two plant damage states, Plant Damage State 48A can be considered a large early release, while Plant Damage State 48B involves sufficient deposition and partitioning to preclude it from being a large early release. The Plant Damage State totals in the baseline model are 1.35E-7 for PDS 48A and 8.7E-7 for PDS 48B.

Table 2 provides a more detailed description of the failures and successes included in the dominant SGTR sequences. Figure 3.1-5 of the Indian Point 2 IPE provides the SGTR event tree and the top events included in that tree. Those events are:

RW Refueling Water Storage Tank availability
HP High Pressure Injection
L1 Auxiliary Feedwater
O3 Operator cools down and depressurizes without AFW
OS Operator stops AFW to ruptured SG and isolates generator
O4 Operator cools down and depressurizes with AFW before overfill – EARLY
O5 Operator cools down and depressurizes following overfill – LATE
SO Isolation of the steam generator after overfill
MU RWST makeup following successful depressurization
AS Accumulator availability
LP Low Pressure Injection
LR Low Pressure Recirculation (Shut Down Cooling)
RH Recirculation Heat Removal

SO & OS

ONLY SEQ WHERE ISOLATION FAILS GO TO LERF!

OR NO AFW

C/22

Table 1

Rank	Baseline SGTR CDF	Conditional SGTR CDF	Failed Split Fractions	Plant Damage State
1	2.54E-07	2E-05	//SISF/O41*O5A	PDS48B
2	2.54E-07	2E-05	//SWS1*SISF/O41*O5A	PDS48B
3	8.59E-08	6.6E-06	//SWS1*SISF/OS1*O5E	PDS48B
4	8.59E-08	6.6E-06	//SISF/OS1*O5E	PDS48B
5	5.06E-08	3.9E-06	//SISF/HP3*O41*O5G	PDS48B
6	5.06E-08	3.9E-06	//SWS1*SISF/HP3*O41*O5G	PDS48B
7	3.03E-08	2.3E-06	//SISF/OS1*SO1*LR2	PDS48A
8	3.03E-08	2.3E-06	//SWS1*SISF/OS1*SO1*LR2	PDS48A
9	2.18E-08	1.7E-06	//SWS1*SISF/HP3*L14	PDS48B
10	2.18E-08	1.7E-06	//SISF/HP3*L14	PDS48B
11	7.23E-09	5.6E-07	//SISF/OS1*O5E*SO3	PDS48A
12	7.23E-09	5.6E-07	//SWS1*SISF/OS1*O5E*SO3	PDS48A
13	6.48E-09	5E-07	//SWS1*SISF/RW2*OS1	PDS48A
14	6.48E-09	5E-07	//SISF/RW2*OS1	PDS48A
15	6.31E-09	4.9E-07	//SISF/OS1*SO1*MU1	PDS48A
16	6.31E-09	4.9E-07	//SWS1*SISF/OS1*SO1*MU1	PDS48A
17	4.89E-09	3.8E-07	//SWS1*SISF/RW2*O41	PDS48B
18	4.89E-09	3.8E-07	//SISF/RW2*O41	PDS48B
19	4.85E-09	3.7E-07	//SISF/L11*O31	PDS48A
20	4.85E-09	3.7E-07	//SWS1*SISF/L11*O31	PDS48A
21	3.18E-09	2.4E-07	//SISF/HP3*OS1*SO1	PDS48A
22	3.18E-09	2.4E-07	//SWS1*SISF/HP3*OS1*SO1	PDS48A
23	2.27E-09	1.7E-07	//SISF/O41*SO2*LR2	PDS48A
24	2.27E-09	1.7E-07	//SWS1*SISF/O41*SO2*LR2	PDS48A
25	2.23E-09	1.7E-07	//EA1B*SISF/O41*O5A	PDS48B
26	2.23E-09	1.7E-07	//EA1B*SWS1*SISF/O41*O5A	PDS48B
27	2.23E-09	1.7E-07	//EB1B*SISF/O41*O5A	PDS48B
28	2.23E-09	1.7E-07	//EB1B*SWS1*SISF/O41*O5A	PDS48B
29	2.00E-09	1.5E-07	//EA1B*EBCB*SISF/HP6*O41*O5G	PDS48B
30	2.00E-09	1.5E-07	//EA1B*EBCB*SWS1*SISF/HP6*O41*O5G	PDS48B
31	1.30E-09	1E-07	//SISF/L11*SO4	PDS48A
32	1.30E-09	1E-07	//SWS1*SISF/L11*SO4	PDS48A
33	1.30E-09	1E-07	/MC26C1/SISF/O41*O5A	PDS48B
34	1.30E-09	1E-07	/MC26C1/SWS1*SISF/O41*O5A	PDS48B
35	9.89E-10	7.6E-08	//SISF/L11*LR4L	PDS48B
36	9.89E-10	7.6E-08	//SWS1*SISF/L11*LR4L	PDS48B
37	9.21E-10	7.1E-08	//SWS1*SISF/HP3*OS1*O53	PDS48B
38	9.21E-10	7.1E-08	//SISF/HP3*OS1*O53	PDS48B
39	9.03E-10	6.9E-08	//SISF/O41*O5A*SO2	PDS48A
40	9.03E-10	6.9E-08	//SWS1*SISF/O41*O5A*SO2	PDS48A
41	8.65E-10	6.7E-08	//EA1B*EBCB*SISF/HP6*L14	PDS48B
42	8.65E-10	6.7E-08	//EA1B*EBCB*SWS1*SISF/HP6*L14	PDS48B
43	7.55E-10	5.8E-08	//EA1B*SISF/OS1*O5E	PDS48B
44	7.55E-10	5.8E-08	//EA1B*SWS1*SISF/OS1*O5E	PDS48B
45	7.55E-10	5.8E-08	//EB1B*SISF/OS1*O5E	PDS48B
46	7.55E-10	5.8E-08	//EB1B*SWS1*SISF/OS1*O5E	PDS48B
47	6.08E-10	4.7E-08	//SWS1*SISF/HP3*OS1*LR2	PDS48B
48	6.08E-10	4.7E-08	//SISF/HP3*OS1*LR2	PDS48B
49	4.73E-10	3.6E-08	//SISF/O41*SO2*MU1	PDS48A
50	4.73E-10	3.6E-08	//SWS1*SISF/O41*SO2*MU1	PDS48A
51	4.56E-10	3.5E-08	/MC26A1/SISF/OS1*SO1*LRF	PDS48A
52	4.56E-10	3.5E-08	/MC26A1/SWS1*SISF/OS1*SO1*LRF	PDS48A
53	4.56E-10	3.5E-08	/MC26B1/SISF/OS1*SO1*LRF	PDS48A

54	4.56E-10	3.5E-08	/MC26B1/SWS1*SISF/OS1*SO1*LRF	PDS48A
55	4.45E-10	3.4E-08	//EA1B*SISF/HP3*O41*O5G	PDS48B
56	4.45E-10	3.4E-08	//EA1B*SWS1*SISF/HP3*O41*O5G	PDS48B
57	4.45E-10	3.4E-08	//EB1B*SISF/HP3*O41*O5G	PDS48B
58	4.45E-10	3.4E-08	//EB1B*SWS1*SISF/HP3*O41*O5G	PDS48B
59	4.39E-10	3.4E-08	/MC26C1/SISF/OS1*O5E	PDS48B
60	4.39E-10	3.4E-08	/MC26C1/SWS1*SISF/OS1*O5E	PDS48B
61	4.28E-10	3.3E-08	//SWS1*SISF*CC1/OS1*SO1*RHF	PDS48A
62	4.28E-10	3.3E-08	//SISF*CC1/OS1*SO1*RHF	PDS48A
63	3.48E-10	2.7E-08	//EA1B*EBCB*SISF/HP6*OS1*LP10	PDS48B
64	3.48E-10	2.7E-08	//EA1B*EBCB*SWS1*SISF/HP6*OS1*LP10	PDS48B
65	3.38E-10	2.6E-08	/X31*G2F/SISF/O41*O5A	PDS48B
66	3.38E-10	2.6E-08	/X31*G2F/SWS1*SISF/O41*O5A	PDS48B
67	3.14E-10	2.4E-08	/W21*G2F/SISF/O41*O5A	PDS48B
68	3.14E-10	2.4E-08	/W21*G2F/SWS1*SISF/O41*O5A	PDS48B
69	2.66E-10	2E-08	//EA1B*SISF/OS1*SO1*LR2	PDS48A
70	2.66E-10	2E-08	//EA1B*SWS1*SISF/OS1*SO1*LR2	PDS48A
71	2.66E-10	2E-08	//EB1B*SISF/OS1*SO1*LR2	PDS48A
72	2.66E-10	2E-08	//EB1B*SWS1*SISF/OS1*SO1*LR2	PDS48A
73	2.59E-10	2E-08	/MC26C1/SISF/HP3*O41*O5G	PDS48B
74	2.59E-10	2E-08	/MC26C1/SWS1*SISF/HP3*O41*O5G	PDS48B
75	1.92E-10	1.5E-08	//EA1B*SISF/HP3*L14	PDS48B
76	1.92E-10	1.5E-08	//EA1B*SWS1*SISF/HP3*L14	PDS48B
77	1.92E-10	1.5E-08	//EB1B*SISF/HP3*L14	PDS48B
78	1.92E-10	1.5E-08	//EB1B*SWS1*SISF/HP3*L14	PDS48B
79	1.80E-10	1.4E-08	//SISF/HP3*O41*O5G*SO2	PDS48A
80	1.80E-10	1.4E-08	//SWS1*SISF/HP3*O41*O5G*SO2	PDS48A
81	1.72E-10	1.3E-08	//SWS1*SISF/HP3*L14*SO5	PDS48A
82	1.72E-10	1.3E-08	//SISF/HP3*L14*SO5	PDS48A
83	1.55E-10	1.2E-08	/MC26C1/SISF/OS1*SO1*LR2	PDS48A
84	1.55E-10	1.2E-08	/MC26C1/SWS1*SISF/OS1*SO1*LR2	PDS48A
85	1.28E-10	9.8E-09	/Z61*X3F*G2F*G3E*A6F*A3F*MC26BF*MC26CF*MC27F/SWS1*SISF/L13*LRF	PDS48B
86	1.27E-10	9.8E-09	/Z61*X3F*G2F*G3E*A6F*A3F*MC26BF*MC26CF*MC27F/SISF*SAF/L13*LRF	PDS48B
87	1.27E-10	9.8E-09	//SWS1*SISF/HP3*OS1*AS1	PDS48B
88	1.27E-10	9.8E-09	//SISF/HP3*OS1*AS1	PDS48B
89	1.25E-10	9.6E-09	//SISF/HP3*O41*LR2	PDS48B
90	1.25E-10	9.6E-09	//SWS1*SISF/HP3*O41*LR2	PDS48B
91	1.24E-10	9.5E-09	//SISF/OS1*SO1*RH1	PDS48A
92	1.24E-10	9.5E-09	//SWS1*SISF/OS1*SO1*RH1	PDS48A
93	1.15E-10	8.8E-09	/X31*G2F/SISF/OS1*O5E	PDS48B
94	1.15E-10	8.8E-09	/X31*G2F/SWS1*SISF/OS1*O5E	PDS48B
95	1.13E-10	8.7E-09	//EA1B*EBCB*SISF/HP6*OS1*SO1	PDS48A
96	1.13E-10	8.7E-09	//EA1B*EBCB*SWS1*SISF/HP6*OS1*SO1	PDS48A
97	1.12E-10	8.6E-09	/MC26C1/SISF/HP3*L14	PDS48B
98	1.12E-10	8.6E-09	/MC26C1/SWS1*SISF/HP3*L14	PDS48B
99	1.06E-10	8.2E-09	/W21*G2F/SISF/OS1*O5E	PDS48B
100	1.06E-10	8.2E-09	/W21*G2F/SWS1*SISF/OS1*O5E	PDS48B

Table 2

Sequence	Sequence CDF	Discussion of Split Fractions

//SISF/O41*O5A
 	
//SWS1*SISF/O41*O5A
	2.54E-07
	
	2.54E-07
		In this sequence, the operator has successfully isolated the SG and terminated auxiliary feedwater flow to the ruptured steam generator (Top Event OS).
		
		Following successful isolation, the operator must still depressurize and cool down the RCS (Split Fraction O41). In this sequence, he fails to do so prior to overfill.
		
		Split Fraction O5A represents the continued attempt to depressurize and cool down the RCS after the initial failure in O41 and prior to RWST depletion. The relief and safety valves are again challenged (Top Event SO) during this time with the condition of two phase flow increasing the likelihood of the safety valve failing to re-close.
		
		In this sequence, depressurization (O5) is not successful but isolation prior to RWST depleti (SO) is successful. As a result, primary to secondary leakage is assumed to continue throug the modulating relief valve and eventually the RWST is depleted. Since makeup flow to the RWST is insufficient for this tube rupture flow rate and the RCS remains at high pressure ar cannot be transitioned to shutdown cooling, core damage occurs.
		
		Since the releases are through a modulating valve, this sequence allows enough source term reduction through deposition and partitioning to keep releases below the LERF level and is assigned to Plant Damage State 48B.

//SWS1*SISF/OS1*O5E
 	
//SISF/OS1*O5E
	8.59E-08
	
	8.59E-08
		In this sequence, split fraction OS1 fails, which represents failure of the operator to isolate a terminate feedwater flow to the ruptured SG prior to overfill.
		
		Split Fraction O5E represents late depressurization (following overfill and prior to RWST depletion). This split fraction differs from O5A, however, since there are no previously successful top events involving operator action and cognitive errors must therefore be incluc
		
		As in the previous sequence, depressurization is not successful but isolation prior to RWST depletion is successful, core damage occurs, releases are through a modulating relief valve a the sequence is assigned to Plant Damage State 48B.

//SISF/HP3*O41*O5G
 	
//SWS1*SISF/HP3*O41*O5G
	5.06E-08
	
	5.06E-08
		Split Fraction HP3 represents initial failure of high pressure injection.
		
		Split Fraction O41 is the same action described above.
		
		The operators will continue cool down and depressurization actions under top event O5 and since high pressure injection is not available, they will at a certain point be directed to initia rapid cool down of the RCS to achieve core cooling recovery using the low pressure injectic system. Split fraction O5G models this action including the additional equipment needed to accomplish the more rapid cool down.
		
		In this sequence, depressurization to allow low pressure injection is not successful, but isola prior to core damage is successful. As a result, releases following core damage are through modulating relief valve and this sequence is assigned to Plant Damage State 48B.

//SISF/OS1*SO1*LR2
 	
//SWS1*SISF/OS1*SO1*LR2
	3.03E-08
	
	3.03E-08
		In this sequence, split fraction OS1 fails, which represents failure of the operator to isolate t various leakage paths to and from the ruptured steam generator and terminate feed water flo the ruptured SG prior to overfill.
		
		Split fraction SO1, which represents inability to isolate following overfill, also fails.
		
		Top event O5, depressurization and cool down the RCS to the point where shutdown coolin can be implemented, prior to RWST depletion, is successful. However, split fraction LR2 f which represents the inability to actually implement shutdown cooling following depressurization. It should be noted that the current model assumes that both RWST makeu (MU) and shut down cooling (LR) are required to prevent core damage following successfu depressurization. This is a substantial conservatism since with successful makeup, the exten time available would make any failure of shutdown cooling highly likely to be recoverable a with successful implementation of shutdown cooling, little or no additional makeup is requi
		
		Given the current modeling, this sequence represents core damage with a continuously open path to the environment and is assigned to Plant Damage State 48.

//SWS1*SISF/HP3*L14
 	
//SISF/HP3*L14
	2.18E-08
	
	2.18E-08
		Split Fraction HP3 represents initial failure of high pressure injection.
		
		Similar to sequences 5 and 6 above, this sequence represents failure to depressurize to recov core injection following a failure of the high pressure injection system. In this case, howeve the failure to depressurize is a result of failure of the Auxiliary Feedwater System (Split Fraction L14) under the more demanding success criteria for this action (both motor driven AFW pumps required).
		
		Although depressurization to allow low pressure injection is not successful resulting in core damage, isolation prior to core damage is successful. As a result, releases following core damage are through a modulating relief valve and this sequence is assigned to Plant Damag State 48B.

//SISF/OS1*O5E*SO3
 	
//SWS1*SISF/OS1*O5E*SO3
	7.23E-09
	
	7.23E-09
		In this sequence, split fraction OS1 fails, which represents failure of the operator to isolate a terminate feed water flow to the ruptured SG prior to overfill.
		
		Split Fraction O5E represents late depressurization (following overfill and prior to RWST depletion). Split fraction SO3, which represents inability to isolate following overfill, accounting for dependencies with O5E, also fails.
		
		Since both depressurization and isolation prior to RWST depletion are failed, core damage occurs with a continuously open path to the environment and is assigned to Plant Damage S 48A.

//SWS1*SISF/RW2*OS1
 	
//SISF/RW2*OS1
	6.48E-09
	
	6.48E-09
		In this sequence, split fraction RW2, the Refueling Water Storage Tank supply to the core injection systems, fails. This fails high pressure injection and eliminates the ability to recov core cooling by depressurizing and using low pressure injection.
		
		Split fraction OS1 also fails, representing operator failure to isolate and terminate feed wate flow to the ruptured SG, allowing continued loss of primary coolant. Given failure of all injection, early core damage is assumed and later actions to depressurize (O5) and isolate (S are bypassed.
		
		Since core damage occurs with a continuously open path to the environment, this sequence assigned to Plant Damage State 48A.

//SISF/OS1*SO1*MU1
 	
//SWS1*SISF/OS1*SO1*MU1
	6.31E-09
	
	6.31E-09
		In this sequence, split fraction OS1 fails, which represents failure of the operator to isolate t various leakage paths to and from the ruptured steam generator and terminate feed water flo the ruptured SG prior to overfill.
		
		Split fraction SO1, which represents inability to isolate following overfill, also fails.
		
		Top event O5, depressurization and cool down the RCS to the point where shutdown coolin can be implemented, prior to RWST depletion, is successful. Switchover to shutdown cooli has not yet been challenged and the model assumes some make up to the RWST is required Split fraction MU1 represents the inability to provide that make up and this sequence theref leads to core damage.
		
		Since this sequence represents core damage with a continuously open path to the environme it is assigned to Plant Damage State 48A.

//SWS1*SISF/RW2*O41
 	
//SISF/RW2*O41
	4.89E-09
	
	4.89E-09
		In this sequence, split fraction RW2, the Refueling Water Storage Tank supply to the core injection systems, fails. This fails high pressure injection and eliminates the ability to recov core cooling by depressurizing and using low pressure injection.
		
		Steam generator isolation (Split fraction OS1) succeeds but split fraction O41, depressurizat and cool down, fails, allowing continued loss of primary coolant. Given failure of all inject early core damage is assumed.
		
		Since core damage occurs with releases through a modulating relief valve, this sequence is assigned to Plant Damage State 48B.

//SISF/L11*O31
 	
//SWS1*SISF/L11*O31
	4.85E-09
	
	4.85E-09
		In this sequence, auxiliary feed water (split fraction L11) fails along with the operator actior depressurize and cool down in the absence of auxiliary feed water (split fraction O31).
		
		This is assumed to lead directly to core damage and this sequence is assigned to Plant Dama State 48A.

//SISF/HP3*OS1*SO1
 	
//SWS1*SISF/HP3*OS1*SO1
	3.18E-09
	
	3.18E-09
		In this sequence, high pressure injection (HP3) has failed as well as steam generator isolatio (split fractions OS1 and SO1).
		
		This is assumed to lead directly to core damage with a continuously open path to the environment and this sequence is assigned to Plant Damage State 48A.

//SISF/O41*SO2*LR2
 	
//SWS1*SISF/O41*SO2*LR2
	2.27E-09
	
	2.27E-09
		In this sequence, the operator has successfully isolated the SG and terminated auxiliary feed water flow to the ruptured steam generator (Top Event OS). Early depressurization and coo down of the RCS (Split Fraction O41) fails, however. Split fraction SO2, which represents inability to isolate following overfill, also fails.
		
		Top event O5, depressurization and cool down the RCS to the point where shutdown coolin can be implemented, prior to RWST depletion, is successful. However, split fraction LR2 f which represents the inability to actually implement shutdown cooling following depressurization.
		
		This sequence represents core damage with a continuously open path to the environment an assigned to Plant Damage State 48A.

//EA1B*SISF/O41*O5A
 	
//EA1B*SWS1*SISF/O41*O5A
 	
//EB1B*SISF/O41*O5A
 	
//EB1B*SWS1*SISF/O41*O5A
	2.23E-09
	
	2.23E-09
	
	2.23E-09
	
	2.23E-09
		These sequences are identical to sequences 1 and 2 except that they include failure of autom SI actuation signals.
		
		Since there is no dependence on automatic SI for the O41 and O5A functions, these sequenc simply represent the complement of the above sequences, since RISKMAN modeling accou for the success probability of the SI actuation in those sequences
		
		Consistent with sequences 1 and 2, these sequences are assigned to Plant Damage State 48B

//EA1B*EBCB*SISF/HP6*O41 *O5G
 	
//EA1B*EBCB*SWS1*SISF/H P6*O41*O5G
	2.00E-09
	
	2.00E-09
		These sequences are identical to sequences 5 and 6 except that they include failure of both trains of automatic SI actuation signals. Since top event HP represents high pressure injecti which has a dependency on the automatic actuation signal, the split fraction used (HP6) refl the failure probability of high pressure injection in the absence of the automatic actuation signal.
		
		Consistent with sequences 5 and 6, these sequences are assigned to Plant Damage State 48B

//SISF/L11*SO4
 	
//SWS1*SISF/L11*SO4
	1.30E-09
	
	1.30E-09
		In these sequences, AFW fails (L11) but the operator successfully depressurizes and cools d (O31) using the ruptured steam generator and a Pressurizer PORV, avoiding steam generato overfill.
		
		Early operator action to stop AFW is not required given failure of L11 and top event OS is bypassed. Isolation is challenged in SO and fails in this sequence. Although RWST makeu and shutdown cooling are possible since depressurization and cool down is successful, they not credited in these sequences.
		
		This is conservatively modeled as a core damage sequence and, given failure of SO, this sequence is assigned to Plant Damage State 48A.

//SISF/O41*O5A
 	
//SWS1*SISF/O41*O5A
	1.30E-09
	
	1.30E-09
		These sequences are identical to sequences 1 and 2 except that they include failure of autom SI actuation signals.
		
		Since there is no dependence on automatic SI for the O41 and O5A functions, these sequenc simply represent the complement of the above sequences, since RISKMAN modeling accou for the success probability of the SI actuation in those sequences
		
		Consistent with sequences 1 and 2, these sequences are assigned to Plant Damage State 48B