Risk Assessment of Operational Events

HANDBOOK

Volume 5 – Risk Analysis of Containment-Related Events (LERF)

(Currently contains only Consequential SGTR Events)

DRAFT

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Acronyms

AFW	auxiliary feedwater
ASP	Accident Sequence Precursor (Program)
BOP	balance-of-plant
BWR	boiling-water reactor
CCF	common-cause failure
CCCG	common-cause component group
CCDP	conditional core damage probability
CCW	component cooling water
CDF	core damage frequency
CDP	core damage probability
C-SGTR	Consequential SGTR
DBA	Design Basis Accident
ECA	event and condition assessment
EDG	emergency diesel generator
EFPY	Effective Full Power Years
EFW	emergency feedwater
EOP	emergency operating procedure
EPIX	Equipment Performance and Information Exchange (database)
FSG	Faulted Steam Generator
gpm	gallons per minute
HDL (H/D/L)	High/Dry/Low (High RCS pressure/Dry SG/Low Secondary side pressure)
HEP	human error probability
HFE	human failure event
HRA	human reliability analysis
IA	instrument air
IMC	Inspection Manual Chapter
LER	licensee event report
LSC	loop seal cleared
LOCA	loss-of-coolant accident
LOIA	loss of instrument air
LOOP	loss of offsite power
LPI	low-pressure injection
MD	management directive
MFW	main feedwater
NPP	nuclear power plan
NR	non-recovery
PCS	power conversion system

PD	performance deficiency
PORV	power-operated relief valve
PRA	probabilistic risk assessment
PSF	performance shaping factor
PWR	pressurized-water reactor
p(csgtr)	Conditional C-SGTR probability given a SG tube challenge
p(lerf)	Conditional LERF probability given C-SGTR
RADS	Reliability and Availability Data System
RASP	Risk Assessment Standardization Project
RCIC	reactor core isolation cooling
RHR	residual heat removal
ROP	Reactor Oversight Process
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SBO	station blackout
SDP	Significance Determination Process
SGTR	Steam Generator Tube Rupture
SPAR (model)	Standardized Plant Analysis Risk (model)
SRA	senior reactor analyst
SRV	safety relief valve
SSC	structures, systems and/or components
SW	service water
T/M	test or maintenance
TS	Technical Specifications

1.0 Introduction

1.1 Objectives

The first objective of the Risk Assessment of Operational Events Handbook (sometimes known as "RASP Handbook" or "handbook") was to document methods and guidance that NRC staff could use to achieve more consistent results when performing risk assessments of operational events, and to evaluate licensee performance issues.

The second objective was to provide analysts and Standardized Plant Analysis Risk (SPAR) model developers with additional guidance to ensure that the SPAR models used in the risk analysis of operational events represent the as-built, as-operated plant to the extent needed to support the analyses.

This handbook represents best practices based on the feedback and experience from the analyses of over 600 precursors in the Accident Sequence Precursor (ASP) Program (since 1969) and numerous Significance Determination Process (SDP) Phase 3 analyses (since 2000).

1.2 Scope of the Handbook

The scope of the handbook is provided below.

- ***Applications.*** The methods and processes described in the handbook can be primarily applied to risk assessments for Phase 3 of the SDP, the ASP Program, and event assessments in accordance with Management Directive 8.3, "NRC Incident Investigation Program." The guidance for the use of SPAR models and Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) software package can be applied in the risk analyses for other regulatory applications, such as the Generic Safety Issues Program and special risk studies of operational experience.

- ***Relationships to program requirements.*** This handbook is intended to provide guidance for implementing requirements contained in program-specific procedures, such as Inspection Manual Chapter (IMC) 0609, "Significance Determination Process," and IMC 0309, "Reactive Inspection Decision Basis for Reactors." It is not the scope of this handbook to repeat program-specific requirements in the handbook, since these requirements may differ between applications and may change as programs evolve. Program-specific requirements supersede guidance in this handbook.

- ***Deviations from methods and guidance.*** Some unique events may require an enhancement of an existing method or development of new guidance. Deviations from methods and guidance in this handbook may be necessary for the analysis of atypical events. However, such deviations should be adequately documented in the analysis to allow for the ease of peer review. Changes in methodologies and guidance may be reflected in future revisions of this handbook.

1.3 Audience for the Handbook

The principal users of this handbook are senior reactor analysts (SRAs) and headquarters analysts involved with the risk analysis of operational events. It is assumed that the analysts using this handbook have received PRA training at the SRA qualification level. The analyst using this handbook should be familiar with the risk analysis of operational events, SAPHIRE software package, and key SPAR model assumptions and technical issues. Although, this handbook could be used as a training guide, it is assumed that the analyst either has completed the NRC course “Risk Assessment in Event Evaluation (Course Number P-302) or has related experience.

2.0 Consequential SGTR Events

2.1 Introduction and LERF Method

This section provides an introduction and a simplified model for estimating consequential steam generator tube rupture (C-SGTR) LERF fraction.

2.1.1 Introduction

Accidents involving steam generator (SG) tube ruptures can be contributors to plant risk, mainly because of their potential for causing a release outside containment (containment bypass sequences). This section addresses consequential steam generator tube rupture events; i.e., events in which SG tubes leak or fail as a consequence of the high differential pressures or elevated temperatures during accident sequences for SGs with U-tubes. Once through SGs are not the subject of this section since they are not susceptible to the challenges discussed here (Refer to Section 6.4 of NUREG-2195).

C-SGTR can occur in two sets of accident sequences: severe accidents and design basis accidents (DBAs). Some core damage severe accidents involve sequences, where after the onset of core damage, the primary pressure is high (generally at the set point of the primary relief valves), and at least one SGs is dry (no secondary heat removal) with its secondary side depressurized (i.e. near atmospheric pressure). These severe accident sequences are referred to as HDL (or H/D/L) which stands for high primary pressure and dry steam generator(s) with low secondary side pressure. DBAs involve initiating conditions, where the pressure across the tubes is significantly higher than nominal pressure during operation. These sequences include: steam line break, feed line break, stuck open SG safety valve or atmospheric dump valve, and anticipated transients without scram.

Thermally-induced SGTR refers to those events caused post-core damage mainly due to creep rupture. The term pressure-induced SGTR is used for those C-SGTR events prior to core damage, and are caused by a sudden increase of pressure difference across the SG tubes without necessarily involving high temperature ranges for creep rupture.

This section provides a method to estimate LERF resulting from a C-SGTR event. The main references for this work are NUREG-2195 and NUREG-1750. The basic premise of the method is to avoid (or minimize) modifying the event tree and fault tree models in a PRA, where C-SGTR is not originally modeled. The method focuses on estimating the C-SGTR frequency, and its LERF based on analyzing individual dominant accident sequences, whenever possible.

In this section, calculations of 2 quantitative measures are discussed:

1. Conditional probability of C-SGTR, p(csgtr), given a SG tube challenge
2. Conditional probability of LERF [1], p(lerf), given the occurrence of C-SGTR.

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[1] Definition of LERF from NUREG-2122: <u>Large Early Release Frequency</u>: The frequency of a rapid, unmitigated release of airborne fission products from the containment to the environment that occurs before effective implementation of offsite emergency response, and protective actions, such that there is a potential for early health effects.

These quantitates may be used for one accident sequence at a time, or used for a set of accident sequences with similar characteristics.

The key equations for the LERF model due to C-SGTR are given in Section 2.4.1, and are labeled as *Equations 1 and 2*.

The supporting requirement LE-D6 of the ASME/ANS PRA Standard requires inclusion of induced SGTR analysis. For example, for capability category I, it states:

> "PERFORM a conservative analysis of thermally induced SGTR that includes plant-specific procedures…"

It should be noted that this report is not intended to provide best practices about how to model C-SGTR in a PRA. Rather, the guidance in here is intended to calculate LERF fraction once C-SGTR and core damage occur.

2.1.2 A Simplified method to estimate C-SGTR LERF fraction

Appendix 2-F provides a simplified method to estimate C-SGTR LERF.

For a more in-depth calculation of the C-SGTR LERF, refer to the example calculation in Appendix 2-D.

2.2 Assumptions and Ground Rules

This section summarizes major assumptions and ground rules used in the estimates and assessment described in the subsequent sections.

1. Definition of leak size for SGTR

SGTR is defined as the total leakage area from one or more tube leaks equal to the area of a single SG tube guillotine break.

For thermally-induced SGTR, where core damage already occurred, C-SGTR is defined as the SGTR that occurs prior to failure of an "other RCS component", such as hot leg or surge line. See "benevolent failures" in item 3 below.

Size example:

If the SG tube inner radius is 0.984 cm (0.388 in), the tube flow area is 3.04 cm^2 (0.472 in^2). The total flow area equivalent to a double ended guillotine break of a tube is 2 * 3.04 = 6.1 cm^2 (0.943 in^2).

This area may differ considerably from one SG to another one. For example, for a tube inner radius of 0.823 cm, the total leakage area equivalent to a guillotine break of a single tube will be 4.256 cm^2.

Both of these examples are taken from actual SGs.

2. Definition of favorable and unfavorable SG designs

For U-tube SGs, the design of the SG lower plenum and its connection to the hot leg affects p(csgtr). For the purposes of this document, SGs are considered in two categories:

i) Favorable design (applicable to Westinghouse plants)
ii) Unfavorable design (applicable to CE plants)

See Appendix 2-A to determine which type the SG in question may be favorable or unfavorable. It is assumed that the SGs installed currently in domestic NPPs fall into these 2 categories by vendor. Future SG designs must be evaluated on their merits.

The calculations in this report do not apply to B&W once-through SGs.[2]

3. Hot leg and surge line materials and welding

Credit is taken for "benevolent failures"[3] in calculation of p(csgtr). These are failures of other RCS components (other than SG tubes), such as hot leg and surge line, whose failure preceding SG tube failures will mitigate C-SGTR. Improvements in materials and welding of other RCS components will cause p(csgtr) to go up. Estimating the changes in p(csgtr) in cases where the other RCS components are improved is out of the scope of this document.

4. LERF model

If C-SGTR and core damage occur, large early release of fission products is postulated. Thus, the numerical value of LERF is the same as the numerical value of CDF followed by C-SGTR.

This applies to all sequences in which both core damage and C-SGTR occur, regardless of which one occurs first.

See Appendix 2-B for a discussion on LERF. See Section 2.4.1 for LERF equations for C-SGTR.

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[2] Vigorous natural circulation flows are not expected due to the elevations and design of the hot legs and steam generators. These plants have not been part of the recent severe accident induced failure studies.

[3] *Benevolent failure*: A failure of an active or passive system component or a structural member of the reactor or containment pressure boundary that alters accident progression in a manner that reduces the severity of the current reactor or containment status or mitigates the consequences of subsequent events. An example is the failure of a safety/relief valve to reclose on demand, causing unintentional depressurization of the reactor coolant system (RCS). This event has the beneficial effect of reducing reactor vessel pressure, thereby reducing the potential for adverse creep rupture of the reactor coolant system (e.g., induced steam generator tube rupture) and (later in time) high-pressure failure of the reactor pressure vessel lower head. Such failures are often precluded from consideration in the Level 1 PRA, but can be credited in the Level 2 analysis to facilitate a more realistic assessment of severe accident progression, especially when there is a clear link to severe accident conditions causing the failure.

5. RCP Loop seal clearing

In a core damage sequence in which a thermally-induced SGTR challenge exists, if a RCP Loop seal (water plug upstream the RCPs) is cleared, then p(csgtr) = 1.0.

In H/D/L core damage sequences with RCP seal leakage of 300 gpm/pump or greater, RCP Loop seal is modeled as cleared, thus p(csgtr) = 1.0.

See Figure C-1 in Appendix 2-C depiction of a RCP Loop seal.

See Figure C-2 for countercurrent natural circulation, which allows possibility of hot leg failures prior to SG tube failures.

The clearing of a loop seal eliminates the counter-current flow pattern and creates a challenging environment for SG tubes. Loop seal clearing (along with a clearing of the fluid in the RV lower downcomer region) results in a direct natural circulation path around the coolant loop (RV, HL, SG, cold leg). Loop seals are more likely to clear when the water in the loop seals is heated and a rapid depressurization occurs. If loop seals are cleared and full loop natural circulation is established, the hot steam from the RV challenges the integrity of the SG tubes.

Sequences with loop seal clearance are assigned to the containment bypass fraction (e.g. C-SGTR is postulated) with a p(csgtr) value of 1.0. Thermal & hydraulic (T&H) analyses indicated that the probability that the loop seal is cleared is almost certain[4] if the RCP leakage is about 450 gpm per pump. For RCP seal leakage of 300 gpm, the TH analysis predicted no possibility that the loop seal is cleared. For the purpose of a bounding analysis, the probability of loop seal clearing may be considered to be 1.0 for core damage sequences with RCP seal leakage of 300 gpm/pump or greater.

In summary, the model used in this document postulates that loop seal clearing will occur for both Westinghouse and CE cases in severe accident sequences where a 300–480 gpm/pump leakage exists. These leakage sequences are generally well delineated in PRA studies. Such sequences are assumed to lead to consequential steam generator tube rupture end state.

6. SG tube materials

2 types of currently used SG tube materials are considered:

- Thermally-Treated Alloy 600
- Thermally-Treated Alloy 690

As discussed in Section 6 of Reference 1, the SG tube material type affects the number of flawed tubes and their flaw types.

2.3 SG flaw distributions and large flaws

[4] Especially if the 450 gpm/pump leak occurs later in the sequence.

In Appendix 2-E, Section E-3 contains an example for quickly estimating the conditional C-SGTR fraction for different SG ages; this example is also given in Reference 5 (C-SGTR for RASP Handbook Worksheet estimate C-SGTR due to SG ages; ML17318A002).

2.4 Estimate p(csgtr) and LERF for an accident sequence

In this section, a simple LERF model is provided. Then accident sequences that could lead to C-SGTR and LERF are classified according to relevance to C-SGTR. Finally, tables of recommended p(csgtr) values are given,

2.4.1 LERF model and equations

If core damage and C-SGTR occur, containment bypass occurs and it is postulated to lead to LERF. The LERF fraction p(lerf) after a containment bypass due to C-SGTR is assigned a value of 1.0 for the purposes of this report. Appendix 2-B discusses the assumptions involved and other potential factors that could be considered.

For a thermally-induced C-SGTR sequence (i) with a CDF of f_i, the LERF equation can be written as:

$LERF(i) = f_i * p(csgtr) * p(lerf) = f_i * p(csgtr) * 1.0,$ *Equation 1*.

p(csgtr) values are given in Tables 2.4-1 and 2.4-2 for favorable and unfavorable SG types.

For a pressure-induced C-SGTR that occurs early in the accident sequence for some DBA events, LERF equation can be formally written as

$LERF(j) = f(iev)_j * p(csgtr) * ccdp_j * p(lerf) = f(iev)_j * p(csgtr) * ccdp_j * 1.0,$ *Equation 2.*

where j refers to an initiating event (iev), such as ATWS, or a large secondary-side break (SSB).

In existing PRA models, such as SPAR models, C-SGTR is not included in the event tree models; thus $ccdp_j$ in Equation 2 is not readily available. Therefore, Tables 2.4-1 and 2.4-2 provide bounding p(csgtr) values for specific sequences in cells marked in yellow.

2.4.2 Sequences not subject to C-SGTR

Some accident sequences do not pose a C-SGTR challenge. These are assigned a p(csgtr) value of 0 in Tables 2.4-1 and 2.4-2.

2.4.3 Thermally-induced C-SGTR sequence

Thermally-induced C-SGTR challenge applies to those severe accident sequences already modeled as core damage. These severe accident sequences are defined in categories (cat-1, cat-2, and cat-3) in Tables 2.4-1 and 2.4-2:

Cat-1: HDL sequences with no RCP loop seal clearing
Cat-2: HDL sequences with RCP loop seal clearing
Cat-3: Non-HDL sequences with potential faulted steam generator (FSG) (not explicitly queried in an ET node).

p(csgtr) values are given for these categories.

Output table showing CDF sequences a PRA model (such as a SPAR model) can be examined to identify sequences in each of these categories; it is sufficient to examine only the dominant sequences (e.g. top 100, top 95% CDF). The remaining sequences, the residue, then is assumed to behave, in aggregate, the same way as the sequences examined; or it can be conservatively assigned a p(csgtr) value of 1.0. This is illustrated later with an example in Section 2.5.

Some practical rules in assignment of categories to CDF sequences that are candidates for thermally-induced challenges are as follows:

1. If AFW fails, and RCS is not depressurized, classify the sequence as HDL.

2. If RCS seal LOCA greater than 300 gpm occurs (B1 and B2 seal clearing in the current SPAR models for W high temperature seals), and the sequence is also HDL, classify the sequence as HDL with RCS loop seal cleared.

3. If AFW is not queried, or is successful, and RCS is not depressurized, classify the sequence as Non-HDL with potential FSG.

If RCP seal LOCA occurs in models with N9000 or non-GEN III SDS (seal failure), assume loop clearing. This assumption is conservatively made in the absence of further information and analysis about these seal failures.

2.4.4 Pressure-induced C-SGTR sequence

There are 2 initiating events where a credible pressure-induced C-SGTR challenge may occur at the beginning of the event due to potential high pressure difference across the SG tubes. These are

- ATWS event with failure of pressure control (leading to a rapid pressure spike in RCS)
- Large secondary-side break events (LSSB)

These 2 events are labeled as categories 4 and 5 in Tables 2.4-1 and 2.4-2.

Treatment and modeling of these 2 types of events are discussed in Reference 1. In this report, the following simple practical suggestions are offered for potential C-SGTR CDF sequences for these events, without implementing detailed modeling.

ATWS and failure of pressure relief sequences:

These sequences are usually sent to the core damage end state and can be captured in the list of CDF sequences (see Appendix 2-D for an example.) In that case, their CDF can be identified and multiplied by p(csgtr) provided in Table 2.4-1 or 2.4-2 to obtain their C-SGTR CDF. See row labeled 4 in Table D-2 for an example.

Large SSB sequences:

SSB initiating events may or may not be already modeled in a PRA. If they are not modeled, then one may:

1. Ignore its contribution, if the ratio of CDF of already collected C-SGTR susceptible CDF sequences to the total CDF is at the order of 20%: in such cases, the additional contribution from SSB events is not expected to contribute enough to affect the overall LERF.

2. Make a simple estimate of the CDF for the sequence defined as: IEV-SSB occurs and C-SGTR occurs and plant response fails, leading to CDF:

   CDF(large SSB with csgtr) = IEV-FREQ * p(csgtr) * CCDP(large SSB with csgtr)

   Example:

   IEV-FREQ = 1E-03/year (rare event not expected to occur in the lifetime of a plant.)

   P(csgtr) = 0.02 (from Table 2.4-1 or 2.4-2)

   CCDP(large SBB with csgtr) = 2 * CCDP(IEV-SGTR)

   CCDP of SGTR can be taken from the PRA in question. It is increased by a factor of 2 to account for potential HEP effects due to the occurrence of SBB and SGTR together. It may be useful to inspect SGTR CDF cutset to see how important HEPs are.

   For an example calculation, using a CCDP of 1.5E-04[5]:

   CDF(large SSB with csgtr) = 1E-03 * 0.02 * 2 * 1.5 E-04 = 6E-09/year.

   This value supports the assertion that the contribution is small.

2.4.5 Recommended p(csgtr) values

In Tables 2.4-1 and 2.4-2, 5 categories of sequences/initiating events are defined as susceptible to C-SGTR challenge:

Cat-1: HDL with no RCP loop seal clearing (CD already occurred)
Cat-2: HDL with RCP loop seal cleared (CD already occurred)
Cat-3: Non HDL CD sequences with subsumed FSG and AFW isolation to the FSG
Cat-4: ATWS sequences with initial high delta P across SG tubes
Cat-5: Large SSB sequences with initial high delta P across SG tubes.

In the same tables, recommended p(csgtr) values for each category of sequences are given, one for "favorable" SG, the other for "unfavorable" SG configurations.

[5] In the PRA example given in Appendix 2-D, the following CCDP is found: IEV(SGTR)=2.07E-03/year; CCDP(SGTR)=7.25E-05; CDF(SGTR)=1.5E-07/year.

	Table 2.4-1 Recommended p(csgtr) values for Accident Sequences For a favorable SG (Westinghouse SG-like)		
	Initiator or Sequence Category	**Description or Comment**	**p(csgtr)**
1	HDL	No RCP loop seal clearing	0.024
2	HDL	With RCP loop seal clearing (1)	1
3	Non-HDL (2)	Non-HDL with potential FSG	0.0013
4a	Transients/SLOCA/MLOCA --> ATWS (3)	IE*RPS*/PR-REL*AFW	0.01
4b	Transients/SLOCA/MLOCA --> ATWS (3)	IE*RPS*PR-REL	0.05
4c	IE-SSB --> ATWS (3)	IE-SSB*RPS	0.05
5a	Large SSB (4)	IE-SSB*/RPS*PI-SGTR	0.02
5b	All transients --> consequential SSB	IE*/RPS…-->CSSB	0.02
	IE-SGTR	All	0
	IE-LLOCA/XLOCA/ISLOCA	All	0

(1) In sequences with RCP seal LOCA > 300 gpm/pump

(2) FSG is not explicitly accounted for in the sequence frequency. Use 0.13 for FSG occurring * 0.01 for p(csgtr) to get an effective p(csgtr)= 0.0013 for the sequence, as given in the table. Adjust 0.13 FSG probability for secondary side valve opening/leakage) as needed, if necessary.

(3) p(csgtr) below 3200 psia was calculated in NUREG-2195 as 0.01; after 3200 psia, other RCS components become vulnerable to failure. It is postulated that 95% of the time other RCS components will fail (leak) precluding C-SGTR; thus a p(csgtr) = 0.5 is used for the CD sequences with ATWS and failure of pressure relief.

(4) The majority of the reported events classified as SSB are smaller size leaks that did not actuate automatic reactor trip, but eventually required a manual reactor trip. In such cases, the C-SGTR challenge is not expected.

IE = Initiating Event
RPS = Reactor Protection System (fails) /RPS = RPS successful.
PR-REL = Primary System Pressure Relief fails. /PR-REL = PR-REL successful.
SSB = Secondary-Side Break
LLOCA (MLOCA, SLOCA) = Large (Medium, Small) LOCA

Recommendation: Use these p(CSGTR) values regardless of the total number of SG tubes in the plant.

	Table 2.4-2 Recommended p(csgtr) values for Accident Sequences For an unfavorable SG (CE SG-like)		
	Initiator or Sequence Category	**Description or Comment**	**p(csgtr)**
1	HDL	No RCP loop seal clearing	0.2
2	HDL	With RCP loop seal clearing (1)	1
3	Non-HDL (2)(5)	Non-HDL with potential FSG	0.0013
4a	Transients, SLOCA, MLOCA --> ATWS (3)	IE*RPS*/PR-REL*AFW	0.01
4b	Transients, SLOCA, MLOCA --> ATWS (3)	IE*RPS*PR-REL	0.05
4c	IE-SSB --> ATWS (3)	IE-SSB*RPS	0.05
5a	Large SSB (4)	IE-SSB*/RPS*PI-SGTR	0.02
5b	All transients --> consequential SSB	IE*/RPS…-->CSSB	0.02
	IE-SGTR	All	0
	IE-LLOCA, XLOCA, ISLOCA	All	0

(1) In sequences with RCP seal LOCA > 300 gpm/pump.

(2) FSG is not explicitly accounted for in the sequence frequency. Use 0.13 for FSG occurring * 0.01 for p(csgtr) to get an effective p(csgtr)= 0.0013 for the sequence, as given in the table. Adjust 0.13 FSG probability for secondary side valve opening/leakage) as needed, if necessary.

(3) p(csgtr) below 3200 psia was calculated in NUREG-2195 as 0.01; after 3200 psia, other RCS components become vulnerable to failure. It is postulated that 95% of the time other RCS components will fail (leak) precluding C-SGTR; thus a p(csgtr) = 0.5 is used for the CD sequences with ATWS and failure of pressure relief.

(4) The majority of the reported events classified as SSB are smaller size leaks that did not actuate automatic reactor trip, but eventually required a manual reactor trip. In such cases, the C-SGTR challenge is not expected.

(5) This probability is left as in favorable SG type since the race between hot leg and SG tubes is not relevant for pressure-induced challenges.

IE = Initiating Event
RPS = Reactor Protection System (fails) /RPS = RPS successful.
PR-REL = Primary System Pressure Relief fails. /PR-REL = PR-REL successful.
SSB = Secondary-Side Break
LLOCA (MLOCA, SLOCA) = Large (Medium, Small) LOCA.

Recommendation: Use these p(CSGTR) values regardless of the total number of SG tubes in the plant.

2.5 C-SGTR LERF for a PRA model already quantified

2.5.1 Overview

Since the ASME/ANS PRA Standard (Reference 3) supporting requirement LE-D6 requires an assessment of LERF due to C-SGTR, one would expect that an existing PRA model will address this LERF contribution in some manner.

A comprehensive assessment is expected to include C-SGTR sequences in categories such as:

- HDL CDF sequences
    - No RCP loop seal clearing
    - With RCP loop seal clearing (LSC)
- ATWS and failure of pressure relief
- Large secondary side breaks.

In addition, for those non-HDL CDF sequences in which a FSG occurs and AFW is isolated to the FSG, there may be lesser intensity C-SGTR tube challenges. Such a sequence may not be explicitly queried in event trees and may be subsumed in an existing non-HDL CDF sequence. Such sequences may be categorized as;

- Non-HDL CDF sequences with FSG and AFW isolation to the FSG.

The expected contribution of each of these categories to the CDF of sequences susceptible to C-SGTR is likely to be ranked as:

1. HDL CDF sequences without loop seal clearance
2. ATWS and failure of pressure relief CDF sequences

Followed by (in no particular order)

- HDL CDF sequences with loop seal clearance
- Large secondary side breaks leading to C-SGTR and CDF
- Non-HDL CDF sequences with FSGs subsumed

The total CDF of sequences susceptible to C-SGTR may be at the order of 20% of the total plant CDF. One sanity check would be to see if such a ratio is obtained or not in a PRA when C-SGTR frequency is estimated.

For a PRA model, a table of dominant CDF sequences can be readily obtainable. A reviewer or a PRA analyst can evaluate such a table categorizing CDF sequences by their susceptibility to C-SGTR challenges. This would constitute the first step of a 3-step process to estimate the LERF due to C-SGTR. Such a process may be used either to make the estimate for the first time, or to check the validity of an existing estimate. An example of this 3-step process is given in Appendix 2-D of this report.

For ATWS and Large SSB sequences, the uncertainties are large due to lack of supporting analyses:

- For ATWS sequences, T&H analyses that can be used as inputs to estimate p(csgtr) are not available.

- For ATWS sequences, information about the failure of other RCS components (other than SG tubes) is not readily available for high-pressure RCS scenarios (e.g. p. 3000 psia) to evaluate whether those components or SG tubes will leak first.

- For SSBs, the initiating event frequencies available from events are heavily skewed towards small secondary side leaks, which may not create a serious challenge to the SG tubes. Thus, a "large" SSB event must be postulated. The size requirement and frequency of such events are not readily available.

- For SSB events, T&H analyses to be used to calculate p(csgtr) are not readily available.

For the pressure-induced scenarios like for ATWS and Large SSBs, p(csgtr) can be calculated by using a tool such as the Calculator (NUREG-2195), if the following information is available:

- T&H input for the scenario (pressures and temperatures)

- Failure model of other RCS components (especially for pressure-induced failures), for a given set of SG tube flaws that are postulated to exist at the time of the accident

2.5.2 Example LERF Calculation for an Existing PRA

Appendix 2-D provides an example of LERF estimate for an already-quantified PRA which does not include C-SGTR. This example is for a Westinghouse PWR with a favorable SG type. p(csgtr) values from Table 2.4-1 are used.

In this example:

- No SBB initiating event was modeled in the PRA. An estimate is provided.

- Only internal event during power operation are considered.

2.5.3 Further Examples

Additional examples can be found in the following documents in ADAMS. These documents, which contain proprietary information, are not publicly available.

- ML13052A643: A Risk Assessment of C-SGTR, March 2009.
- ML14210A630: 005-CSGTR Probability for a sample plant, July 2014.
- ML15313A407: Estimation of C-SGTR CDF Frequency for PRA Level 2 Analysis, December 2016.

2.6 Additional Considerations

2.6.1 C-SGTR Estimates for PRA All Hazard Models

Assessment of C-SGTR for PRA models containing other hazard categories in addition to internal events can be made in a similar manner, as the example given in Appendix 2-D. Special attention may be needed to ensure minimal cutsets are used to identify significant CDF sequences and their percentage contribution to the plant CDF.

2.7 References

1. NUREG-2195: Consequential SGTR Analysis for Westinghouse and Combustion Engineering Plants with Thermally Treated Alloy 600 and 690 Steam Generator Tubes, draft, March 2017. Draft report ADAMS Accession No. ML16134A029.

2. NUREG-1570: Risk Assessment of Severe Accident-Induced Steam Generator Tube Rupture, March 1998. ADAMS Accession No. ML070570094.

3. ASME/ANS RA-Sb-2013, “Standard for Level 1/ Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications," September 2013.

4. ML17318A001: EXCEL Workbook - C-SGTR RASP Handbook worksheet CDF sequences to estimate LERF.

5. ML17318A002: EXCEL Workbook - C-SGTR for RASP Handbook Worksheet estimate C-SGTR due to SG ages.

Appendix 2-A. SG Classification for C-SGTR

In this report, SGs are classified in two categories:

Category 1: favorable SG (Typical Westinghouse SG design).
Category 2: unfavorable SG (Reduced Mixing).

For HDL core damage sequences, the conditional probability of C-SGTR is considerably different between these 2 categories. If no other information is available, the following rule of thumb should be used:

- Westinghouse and similar replacement SGs used in Westinghouse PWRs at the time of this report are considered to be in category 1. Those with the hot leg relatively closer to the tube sheet, such as the CE plant modeled, are considered to be in category 2.

In plant-specific cases, if available, information about the geometry of the lower plenum of the SG could be taken into account. Especially with new plant and SG designs, the clear distinction between the typical Westinghouse design and reduced mixing SGs solely based on the PWR type (W or CE) may be blurred.

The relatively shallow inlet plenum design of the steam generator under consideration for the CE plant has a reduced distance for mixing of the hot leg gasses prior to entering the tube sheet, as shown in Figure A-1 below. The reduced mixing creates a higher thermal load on the tubes. The steam generator considered for the CE plant was a replacement steam generator. The earlier work on Westinghouse plants focused on the Zion Nuclear Power Plant (ZNPP) with the associated Westinghouse Model 51 steam generators. To qualify, the applicability of these Westinghouse predictions for Westinghouse plants with replacement steam generators, the NRC's Office of Nuclear Regulatory Research (RES) has worked with the NRC's Office of Nuclear Reactor Regulation (NRR) to acquire plant specific inlet plenum design information from a few plants with replacement steam generators. Although it was not practical to get design information for as many plants as desired, three sets of drawings were obtained. These included steam generator drawings from the Donald C. Cook Nuclear Plant, the Diablo Canyon Power Plant, and Prairie Island Nuclear Generating Plant. RES staff studied the dimensions for the inlet plenum region and found only small differences in the mixing path and overall lower plenum geometry between the new designs and the previously studied Model 51 design. The expectation is that thermal mixing in the inlet plenums would not be significantly impacted by the new steam generator designs for the sample plants considered.

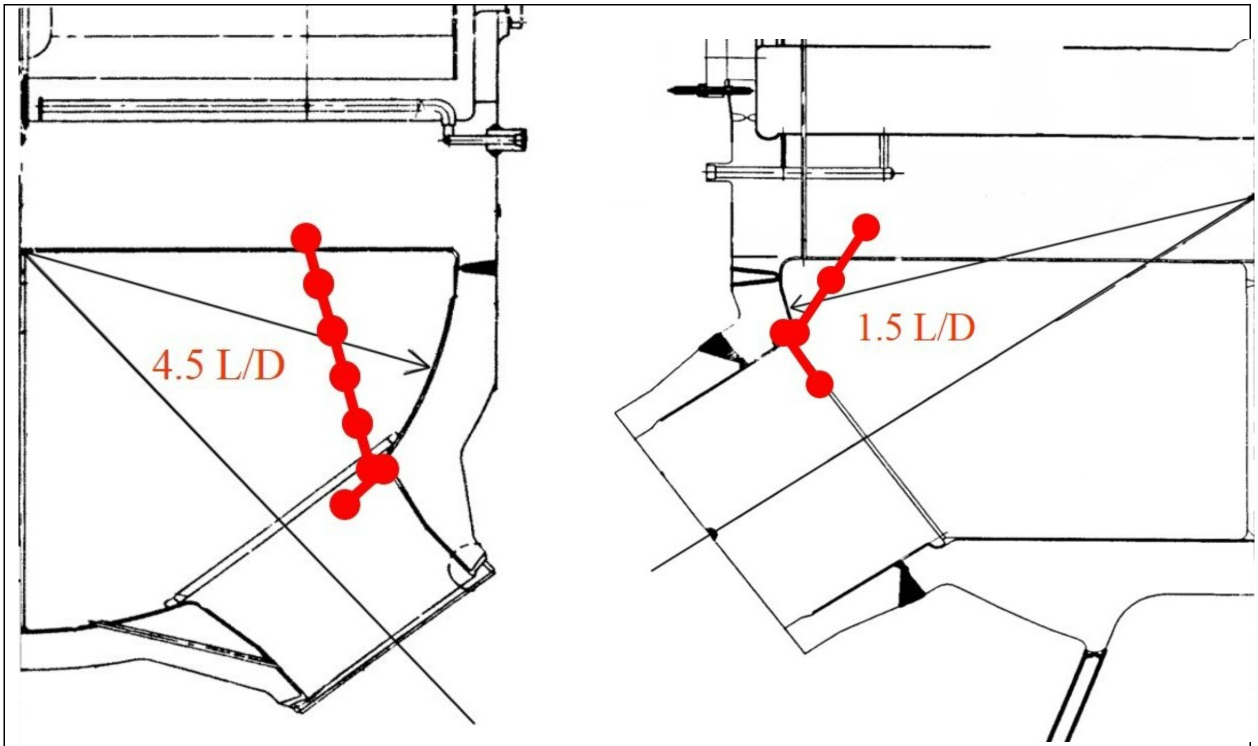
Furthermore. CE C-SGTR behavior differs from Westinghouse plants. This is caused by less mixing of hot gases before reaching SG tubes in the CE SGs, mainly due to:

– A relatively reduced distance from the hot leg exit to the tube sheet entrance, especially for some replacement SGs

Thus, in a CE SGTR, it is predicted that at the entrance to the tube sheet, some SG tubes are exposed to gas temperatures that are similar to the hottest temperatures exiting the hot legs.

Because of this reduced inlet plenum mixing, the thermal challenge to CE SG tubes is relatively higher than Westinghouse SG tubes. There is a greater likelihood that tubes in a CE steam generator will fail earlier relative to the tubes in Westinghouse plants.

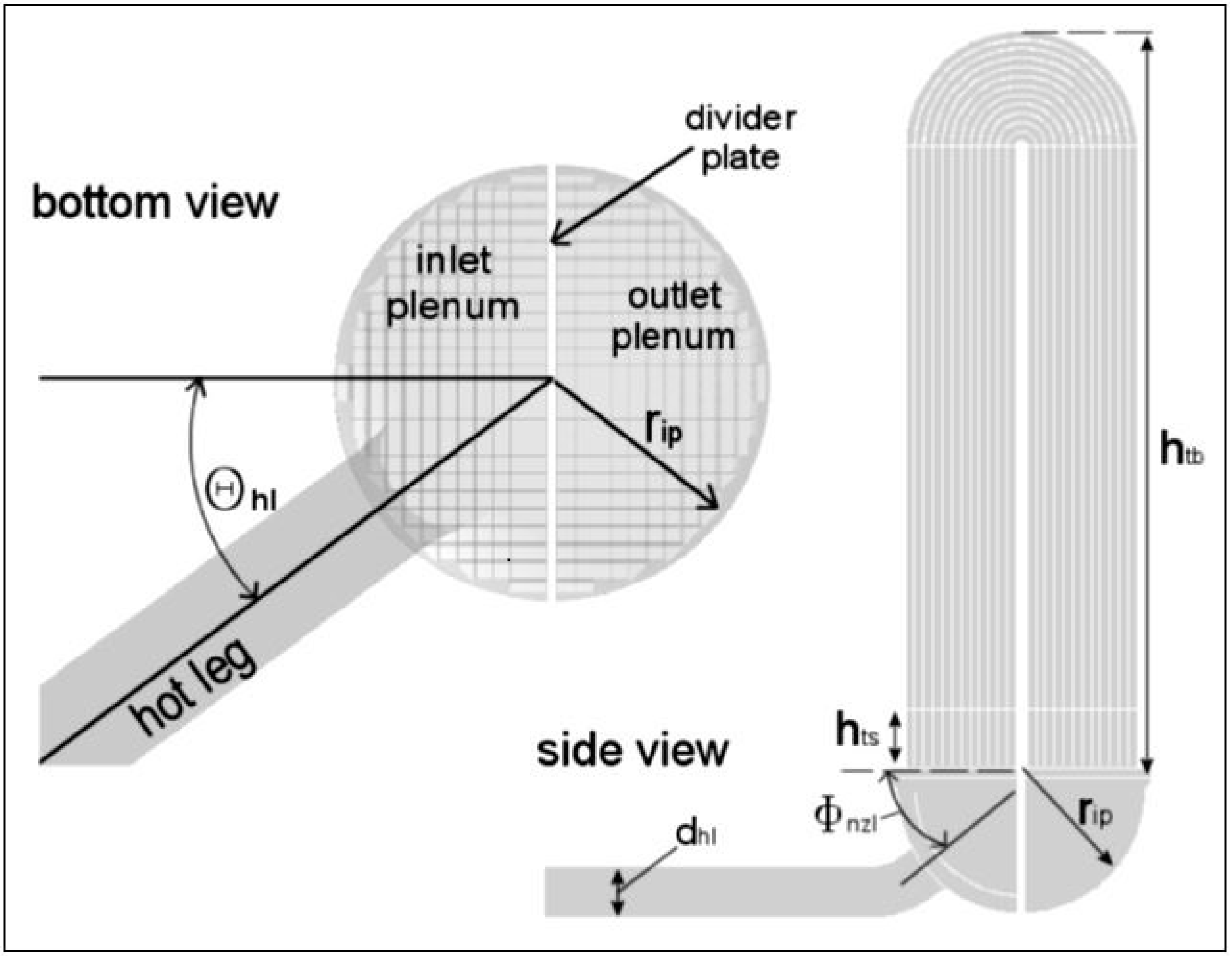
Under certain conditions, unflawed tubes could rupture before hot legs. Unlike for the rupture of a flawed tube, multiple unflawed tubes could potentially reach the failure condition nearly simultaneously resulting in a rupture large enough to depressurize the RCS sufficiently fast to prevent failure of other RCS components.



Favorable SG type (side view, inlet plenum)	Unfavorable SG type (side view, inlet plenum)

Figure A-1. Example CE inlet plenum compared to W model 51

- Note: L/D for illustration purposes only. L represent the distance from the HL exit to the tube sheet entrance. D represents ¼ of the HL diameter which is used to estimate the diameter of the hot plume exiting the hot leg.



divider plate
bottom view
inlet plenum
outlet plenum
r_{ip}
Θ_{hl}
hot leg
side view
h_{tb}
h_{ts}
Φ_{nzl}
d_{hl}
r_{ip}

Figure A-2

Appendix 2-B. LERF Model Assumptions

In this document, a simple LERF model is used:

> If a C-SGTR equivalent to approximately guillotine break of a single SG tube occurs anytime during the evolution of a core damage sequence, and the other RCS components do not fail prior to this SG tube rupture, then LERF is postulated. Thus the LERF fraction p(lerf) for any such sequence is 1.0.

This may be considered to be a pessimistic (an upper bound or conservative) estimate because:

1. A secondary side opening releasing the fission products is assumed;
2. Timing of the fission product release is always assumed to lead to LERF;
3. No credit for severe accident management strategies is given;
4. No credit for completion of evacuation before the fission product release is given.

This LERF model is equally applicable to core damage sequences for other hazard categories (such as large intensity seismic events), as it is applicable to internal events, where the completion of evacuation may be achieved in a shorter time.

Considering the large number of underlying uncertainty sources in T&H, in material failures models, and in PRA-related input, use of this pessimistic LERF fraction model is deemed to be prudent. Taking further credit to lower the LERF fraction is not recommended without revisiting other model assumptions leading to conditional C-SGTR fractions given in Tables 2.4-1 and 2.4-2.

Appendix 2-C. Additional Information

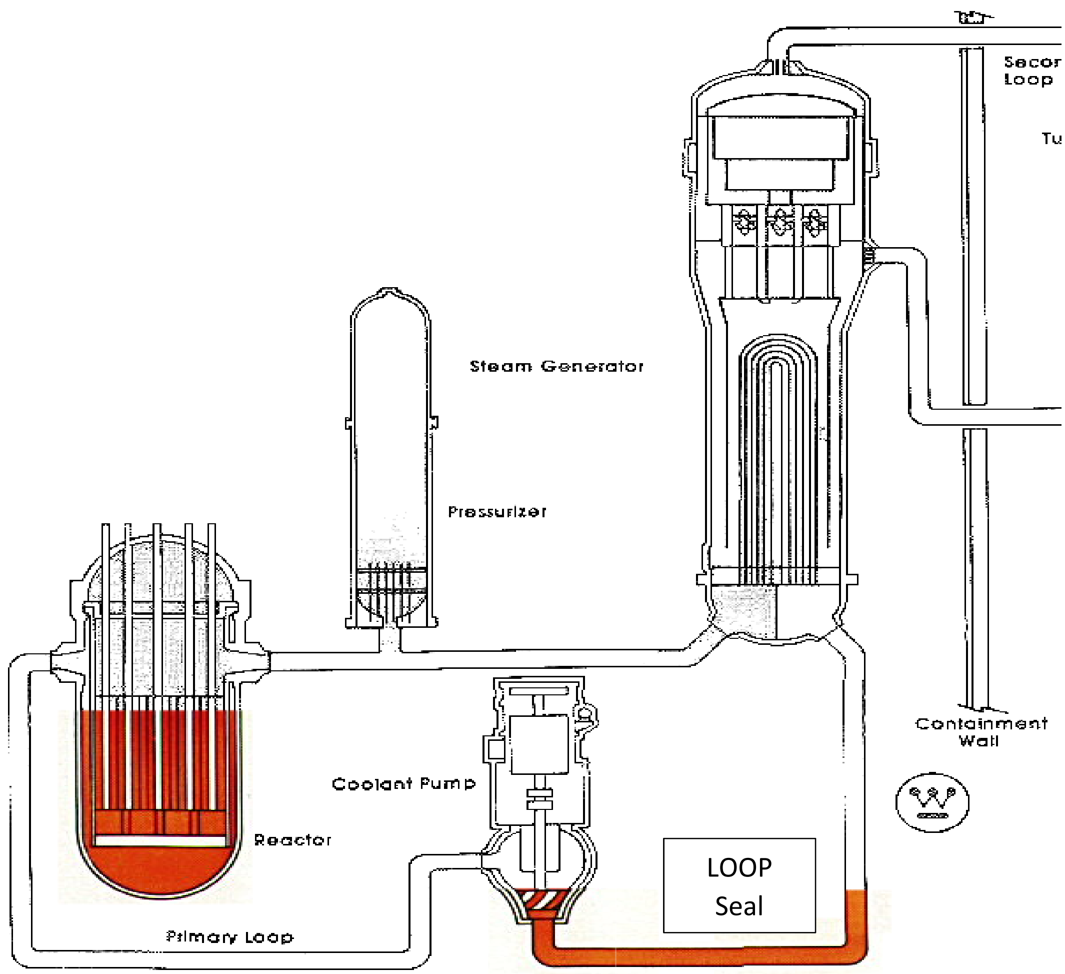


Figure C-1. LOOP Seal

With the pump loop seal filled with water, a counter-current flow field is established. This flow pattern mixes the hot gases with cooler flows returning from the SG. The thermal challenge to the tubes is reduced but not eliminated.

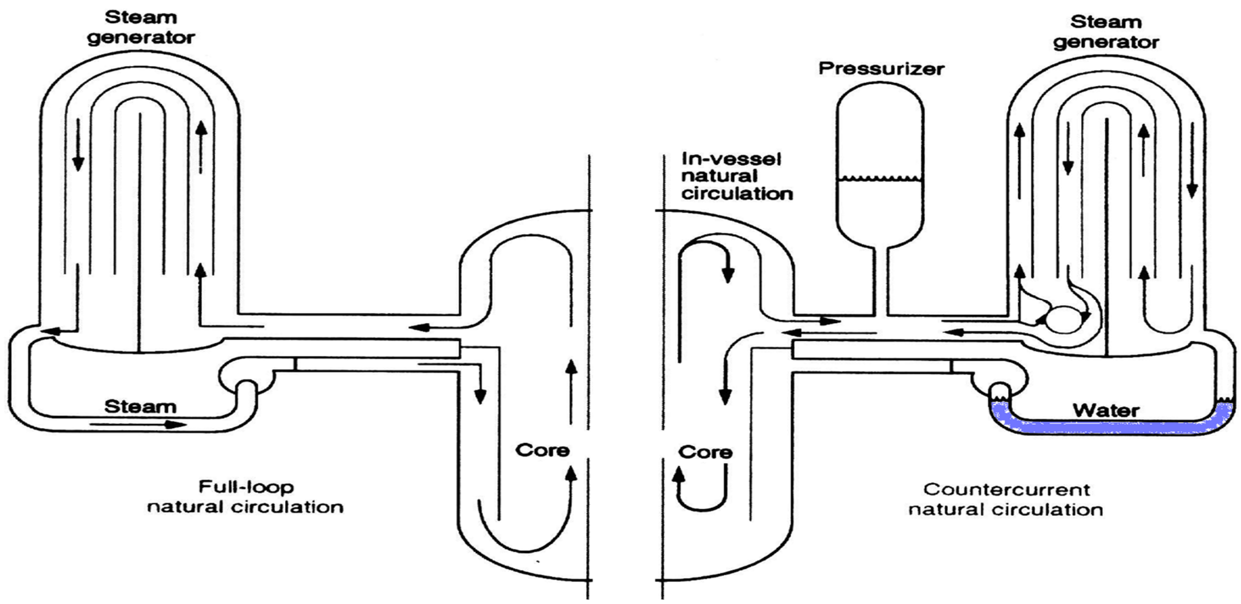


Figure C-2 Flow Patterns in PWRs with U-Tube SGs in the absence of forced flow by RCPs

In the absence of secondary cooling, loop seal clearing is important because this clearing exposes SG tubes to gases nearly as hot as those in the hot leg,

Appendix 2-D. Example Application

D-1 Overview

A SPAR model example is used to estimate LERF from C-SGTR sequences.

The example is a Westinghouse PWR with a favorable SG type. CDF sequences from the plant SPAR internal events during power operation model are collected. 38 top sequences out of a total of 711 CDF sequences are examined, as shown in Table D-3.

The total CDF is 3.07E-05/year. CDF from 38 top sequences make up 96% of the total CDF, leaving a CDF residue of 1.15E-06/year in unexamined sequences.

SSB is not modeled in this PRA. See the EXCEL workbook ML17318A001 for the CDF sequences and other calculations summarized in this appendix.

The process has 3 steps:

Step 1. Assign C-SGTR susceptibility categories to the dominant CDF sequences. Calculate CDF of these categories. Estimate additional C-SGTR CDF for those challenges that may have not been explicitly modeled in the existing PRA. Tables D-2 and D-3 illustrate this process. This step is discussed in Section D-2.

Step 2. Use conditional C-SGTR probabilities from Table 2.4-1 to calculate CDF for C-SGTR sequences. This step is discussed in Section D-3.

Step 3. Calculate LERF for C-SGTR. This step is discussed in Section D-4.

Labeling of sequence categories for C-SGTR challenge in Table D-3

For the purposes of this example, the categories assigned to sequences that are susceptible to C-SGTR challenge are simplified, compared to those categories in Tables 2.4-1 or 2.4-2.

I. Categories that would not create a C-SGTR challenge; thus are excluded from further consideration:

OK-1 No C-SGTR challenge because AFW OK; RSD OK (RHR pump operation pressure range is reached in RCS), and LOSC OK.
RSD = Rapid secondary depressurization
SSC = Cooldown (primary and secondary)
LOSC = RCP seal cooling maintained

OK-2 No C-SGTR challenge because of MLOCA or LLOCA; RCS pressure is not high

OK-3 No C-SGTR since: AFW is most likely OK (not queried in the ET); RCS likely depressurized either by break size or by operator action

OK-4 No C-SGTR since low RCS pressure due to vessel failure

SGTR CDF sequence from an IEV-SGTR event (random SGTR)

II. The following simplified categories that will create a C-SGTR challenge are considered:

	Table D-1 C-SGTR Challenge Categories
	Sequence Category
cat-1	HDL CDF - no RCP loop seal clearing
cat-2	HDL CDF - with RCP loop seal clearing
cat-3	Non-HDL CDF sequences with potentially subsumed FSG and isolated AFW
cat-4	ATWS CDF + Pressure relief fails and C-SGTR and CDF
cat-5	IE-Large SSB and C-SGTR and CDF

III. Summary of Results

	Table D-2 Summary of Results						
	Category	**In 38 CDF sequences**	**in Residue (seqs. 39-711)**	**f_i (Total CDF subject to csgtr challenge)**	**P (csgtr)**	**CDF (csgtr)**	**LERF (csgtr)**
	Plant CDF =	2.95E-05	1.15E-06	3.07E-05			
1	HDL with no RCP loop seal clearing	4.90E-06	1.90E-07	5.09E-06	0.024	1.2E-07	1.2E-07
2	HDL with RCP loop seal clearing	2.09E-07	8.13E-09	1.00E-08**	1	1.0E-08	1.0E-08
3	Non HDL CDF with subsumed FSG				0.05	3.3E-08*	3.3E-08
4	ATWS with failure of pressure relief	3.79E-07	1.47E-08	3.94E-07	0.05	2.0E-08	2.0E-08
5	Large SSB				0.02	3.0E-09*	3.0E-09
			Totals =	**5.49E-06**		**1.9E-07**	**1.9E-07**
			% of plant CDF	17.9%		0.6%	

* C-SGTR CDFs for cat-3 and cat-5 cannot be observed in PRA model; they are estimated.

** No cat-2 sequences were in the top 38 sequences. An examination of lower CDF sequences indicated that cat-2 frequency is expected to be at the order of 1E-08, which is used in this table. A more rigorous calculation can be done by examining the cutsets containing B1 and B2 seal failures coincident with AFW failures.

D-2 Step 1: CDF Sequence Categorization

In this PRA model, it is possible to identify CDF sequences for C-SGTR categories cat-1, cat-2, and cat-4 in the set of significant CDF sequences comprised of the top 38 CDF sequences out of 711. Cat-5 C-SGTR CDF is estimated separately as discussed below, since large SSB is not modeled in this PRA. Cat-3 C-SGTR CDF is also estimated separately due to the fact that these sequences are subsumed in non-HDL sequences. An estimate is provided in this section.

Estimation of cat-1, cat-2 and cat-4 CDF susceptible to C-SGTR challenge:

A set of simplified C-SGTR susceptibility categories for this example are defined in Table D-1. Table D-3 shows the assignment of C-SGTR susceptibility categories to the first 38 sequences. Cat-1, cat-2, and cat-4 CDFs values for sequences susceptible to C-SGTR challenge are summed over as shown in Table D-2.

f_1 = 5.09E-06
f_2 = 1.0E-08
f_4 = 3.94E-07

Sum = 5.49E-06 (18% of the total plant CDF).

Since the top 38 CDF sequences make up 96% of the total plant CDF, and since they include sequences for cat-1, cat-2, and cat-4, it is not necessary to account for the CDF residue in the remaining CDF sequences (#39 thru #711). However, in this example, a method for accounting for them is provided.

Treatment of the Residue

It is assumed that the C-SGTR susceptible contribution for each cat-n in the residue has the same percentage as in the ones identified in sequences #1 thru #38. This percentage of CDF is individually added to each cat-n (n=1, 2 and 4) CDF already calculated, as shown in Table D-2.

Incidentally, for cat-4 (ATWS) all 711 sequences are examined. 6 sequences where ATWS occurred and pressure release failed (pressure spike in the RCS) are identified, as a sanity check. The total CDF of these 6 sequences is 4.6E-07/year: this compares well with the cat-4 CDF already estimated in Table D-2 as 3.9E-07/year.

Estimation of cat-3 C-SGTR CDF:

Table 2.4-1 gives p(csgtr) value of 0.0013 for a non-HDL CDF sequence in which a FSG occurs; AFW is isolated; and C-SGTR occurs, followed by core damage due to additional failures. In this example, a bounding assumption is made that all CDF sequences can have FSG followed by the conditions described above. Thus, the CDF of cat-3 is estimated as:

CDF(cat-3) = 3.07E-05 * 1.3E-04 = 3.3E-08/year.

This value is placed in Table D-2. Note that this CDF already includes the fraction p(csgtr), whereas the above CDF estimates for cat-1, cat-2, and cat-3 do not include it yet: see step 2.

Estimation of cat-5 C-SGTR CDF:

Since large SSB initiating event is not modeled in this PRA, its contribution to CDF of C-SGTR is estimated as follow.

IEV-SGTR (random SGTR) is already modeled in the PRA: refer to Table D-6 for information about the CDF of this event.

To estimate the CDF of a large SBB with C-SGTR, the following assumptions are made:

1. Large SSB success criteria will be the same or very similar to IEV-SGTR event tree model in this PRA (faulted SG in both events).

2. Some initial HFEs may have higher HEPs, higher due to existence of large SSB and C-SGTR concurrently. An examination of IEV-SGTR CDF cutsets indicates that HEP contributions are not dominant.

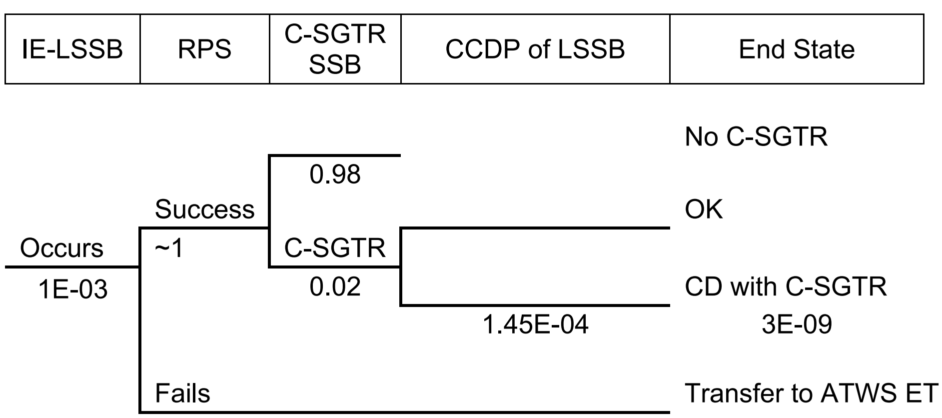
3. It is assumed that a large SSB event is a rare event, not expected to occur during the lifetime of the plant; assign an initiating event frequency of 1E-03/year to large SSB.

4. P(csgtr) is taken from Table 2.4-1 as 0.02.

5. CCDP of large SSB and C-SGTR event is taken as 2 times the CCDP of IEV-SGTR due to a potential HEP disadvantage in early sequence development.

Using the above assumptions, the CDF(large SSB and C-SGTR) is calculated as 3E-09/year, as shown below. This value is placed in Table D-2. Note that this CDF already includes the fraction p(csgtr).

C-SGTR in Large SSB Event Tree Model



	SGTR	LSSB and C-SGTR	Comment on LSSB
IEV frequency	2.07E-03	1.0E-03	Rare event, not expected to occur during plant life.
CCDP	7.23E-05	1.45E-04	2 times the CCDP of SGTR due to less favorable HEPs.
p(csgtr)		0.02	From Table 2.4-1
CDF	1.50E-07	3E-09	

The CDF calculated in this example for large SSB and C-SGTR is small enough that the potential impact of uncertainty in the 2 key values used in the model (SSB initiating event frequency and CCDP) is minimal in the total final LERF; for example, even with an order of magnitude increase, this contribution will not affect the total C-SGTR LERF significantly.

D-3. Step 2: Calculation of C-SGTR Frequency

In this section, the CDF f_i of each category of sequences susceptible to C-SGTR, as calculated in Section D-2, and the conditional C-SGTR probabilities given in Table 2.4-1 are used to estimate the C-SGTR CDF.

CDF(csgtr) = $f_1 * p_1$(csgtr) + $f_2 * p_2$(csgtr) + $f_4 * p_4$(csgtr) + CDF(cat-3) + CDF(cat-5).

CDF(Cat-3) and CDF(cat-5) already include the fractions p_3(csgtr) and p_5(csgtr).

This calculation is shown in Table D-2, resulting in

CDF(csgtr) = 1.9E-07.

An approximation to calculation of C-SGTR frequency:

If the ratio of ($f_1+f_2+f_4$) to the total plant CDF from the PRA is ~20%, then estimation of CDF(cat-3) and CDF(cat-5) may be skipped. The rationale behind this approximation is that sufficient C-SGTR candidate CDF sequences are already collected, thus the expected small contribution from cat-3 and cat-4 can be left out as a first approximation:

CDF(csgtr) ≈ $f_1 * p_1$(csgtr) + $f_2 * p_2$(csgtr) + $f_4 * p_4$(csgtr).

D-4. Step 3: Calculation of LERF

The simple LERF model used in this report states that if C-SGTR and core damage occurs, it would be classified as LERF: p(lerf) = 1.0.

The total CDF for all C-SGTR sequences is calculated as 1.9E-07/year in Table D-2. This CDF value is 0.6% of the total plant CDF for internal events during power operation. For this example, LERF(csgtr) is

LERF(csgtr) = 1.9E-07/year.

Table D-3 Assigning C-SGTR susceptibility categories to dominant CDF sequences

	Event Tree	Sequence	CDF	Description	AFW	LOOP	EDG	RCS Pressure (/RSD or LPI)	RCP SLOCA, or LOCA	Sequence Category
1	LONSW	04-02-10	1.67E-05	IEFT-LONSCW, /RPS, /AFW, /PORV, LOSC-NSW, REC-NSW, /RCPT, /RSD, /BP1, BP2, HPI, SSC1				low	182 gpm	OK-1
2	LOACA	20	2.50E-06	/RPS, AFW, MFW, FAB	Fails			high		cat-1
3	LOACA	02-02-03	2.23E-06	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, /HPI, /SSC, RHR, LPR				low	182 gpm	OK-1
4	LOACA	02-02-09	1.91E-06	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, HPI, /SSC1, LPI				low	182 gpm	OK-1
5	LONSW	04-03-10	8.36E-07	IEFT-LONSCW, /RPS, /AFW, /PORV, LOSC-NSW, REC-NSW, /RCPT, /RSD, BP1, /BP2, HPI, SSC1				high	76 gpm	OK-1
6	LOACA	19	5.74E-07	/RPS, AFW, MFW, /FAB, SSCR, HPR	Fails			high		cat-1
7	ISL-RHR	3	3.89E-07	ISL-RPT-RHR, /ISL-DIAG, ISL-REC-RHR				ISL low		OK-3
8	TRANS	21-16	3.79E-07	RPS, RCSPRESS				ATWS high		cat-4
9	MLOCA	03	3.49E-07	/RPS, /HPI-ML, /AFW-ATWS, /SSC, HPR, LPR				low	MLOCA	OK-2
10	TRANS	20	3.15E-07	/RPS, AFW, MFW, FAB	Fails			high		cat-1
11	LOOPWR	16-03-10	2.61E-07	/RPS-L, EPS, /AFW-B, /PORV, /RSD-B, /BP1, /BP2, OPR-04H, DGR-04H, AFW-MAN, SG-DEP-LT	Fails	Loop	Fails	high	21 gpm	cat-1
12	LOOPWR	16-06	2.18E-07	/RPS-L, EPS, /AFW-B, /PORV, /RSD-B, /BP1, BP2, OPR-04H, DGR-04H	Late fails	Loop	Fails	high	182 gpm	cat-1
13	LONSW	04-04-10	2.09E-07	IEFT-LONSCW, /RPS, /AFW, /PORV, LOSC-NSW, REC-NSW, /RCPT, /RSD, BP1, BP2, HPI-ML, /ACC, /AFW-ATWS, /SSC, LPI				LSC	480 gpm	OK-1
14	LOOPGR	15	2.08E-07	/RPS-L, /EPS, AFW-L, FAB-L	Fails	Loop		high		cat-1
15	LOOPGR	16-03-10	1.73E-07	/RPS-L, EPS, /AFW-B, /PORV, /RSD-B, /BP1, /BP2, OPR-04H, DGR-04H, AFW-MAN, SG-DEP-LT	Fails	Loop	Fails	high	21 gpm	cat-1
16	LOOPWR	16-45	1.64E-07	/RPS-L, EPS, AFW-B, OPR-04H, DGR-04H	Fails	Loop	Fails	high		cat-1
17	ISL-RHR	4	1.50E-07	ISL-RPT-RHR, ISL-DIAG				ISL low		OK-3

	Event Tree	Sequence	CDF	Description	AFW	LOOP	EDG	RCS Pressure (/RSD or LPI)	RCP SLOCA, or LOCA	Sequence Category
18	LOOPGR	16-06	1.44E-07	/RPS-L, EPS, /AFW-B, /PORV, /RSD-B, /BP1, BP2, OPR-04H, DGR-04H	Late fails	Loop	Fails	high	182 gpm	cat-1
19	LODCA	02-02-03	1.21E-07	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, /HPI, /SSC, RHR, LPR				low	182 gpm	OK-1
20	TRANS	02-02-09	1.19E-07	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, HPI, /SSC1, LPI				low	182 gpm	OK-1
21	LOOPSC	15	1.13E-07	/RPS-L, /EPS, AFW-L, FAB-L	Fails	Loop				cat-1
22	LOACA	02-03-03	1.12E-07	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, BP1, /BP2, /HPI, /SSC, RHR, LPR				low	76 gpm	OK-1
23	LODCA	02-02-09	1.09E-07	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, HPI, /SSC1, LPI				low	182 gpm	OK-1
24	LOOPGR	16-45	1.08E-07	/RPS-L, EPS, AFW-B, OPR-04H, DGR-04H	Fails	Loop	Fails			cat-1
25	LODCB	02-02-09	1.06E-07	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, HPI, /SSC1, LPI				low	182 gpm	OK-1
26	RXVRUPT	2	1.00E-07	RXVESSEL						OK-4
27	MLOCA	10	9.74E-08	/RPS, HPI-ML, /ACC, /AFW-ATWS, /SSC, LPI				low	MLOCA	OK-2
28	LOACA	02-03-09	9.54E-08	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, BP1, /BP2, HPI, /SSC1, LPI				low	76 gpm	OK-1
29	LONSW	04-14-10	8.46E-08	IEFT-LONSCW, /RPS, /AFW, /PORV, LOSC-NSW, REC-NSW, RCPT, HPI-ML, /ACC, /AFW-ATWS, /SSC, LPI				low		OK-1
30	LOOPGR	02-02-09	8.46E-08	/RPS-L, /EPS, /AFW-L, /PORV-L, LOSC-L, /RSD-L, /BP1, BP2, /OPR-02H, /RPS, /AFW, HPI, /SSC1, LPI		Loop		low	76 gpm	OK-1
31	SLOCA	03	8.38E-08	/RPS, /AFW, /HPI, /SSC, RHR, LPR				low	SLOCA	OK-1
32	SGTR	12	8.23E-08	/RPS, /AFW, /HPI, SGI, REFILL1, ECA						SGTR
33	TRANS	02-02-03	7.91E-08	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, /HPI, /SSC, RHR, LPR				low	76 gpm	OK-1
34	LOOPSC	02-02-09	7.21E-08	/RPS-L, /EPS, /AFW-L, /PORV-L, LOSC-L, /RSD-L, /BP1, BP2, /OPR-02H, /RPS, /AFW, HPI, /SSC1, LPI		Loop			182 gpm	OK-1
35	LOOPWR	15	6.64E-08	/RPS-L, /EPS, AFW-L, FAB-L	Fails	Loop				cat-1

	Event Tree	Sequence	CDF	Description	AFW	LOOP	EDG	RCS Pressure (/RSD or LPI)	RCP SLOCA, or LOCA	Sequence Category
36	TRANS	21-14	6.24E-08	RPS, /RCSPRESS, MFW, /AFW-ATWS, BORATION						ATWS
37	LODCB	02-02-03	5.57E-08	/RPS, /AFW, /PORV, LOSC, /RCPT, /RSD, /BP1, BP2, /HPI, /SSC, RHR, LPR				low		OK-1
38	LOMFW	20	5.44E-08	/RPS, AFW, MFW, FAB	Fails					cat-1

Table D-4 provides event tree node descriptions for the symbols used in Table D-3.
Table D-5 provides the initiating event categories modeled in this PRA.
In sequence descriptions, / indicates success: /AFW = AFW successful; AFW = AFW failed.

Sequence Categories

OK-1	No C-SGTR challenge because AFW OK; RSD OK (RHR pump operation pressure range is reached in RCS).
OK-2	No C-SGTR challenge because of MLOCA or LLOCA; RCS pressure is not high.
OK-3	No C-SGTR since: AFW is most likely OK (not queried in the ET); RCS likely depressurized either by break size or by operator action.
OK-4	No C-SGTR since low RCS pressure due to vessel failure
cat-1	HDL CDF - no RCP loop seal clearing
cat-2	HDL CDF - with RCP loop seal clearing
cat-4	ATWS CDF + Pressure relief fails and C-SGTR and CDF

RSD	Rapid secondary depressurization.
SSC	Cooldown (primary and secondary)
LOSC	RCP seal cooling maintained

Table D-4. Event Tree Node Descriptions

In Table D-3, success of an event tree node is shown with a / placed in front of the node symbol.

	Event Tree Node (Fault Tree)	**Description**
1	ACC	ACCUMULATOR 3-OF-3
2	AFW	AUXILIARY FEEDWATER
3	AFW-ATWS	AUXILIARY FEEDWATER
4	AFW-B	AUXILIARY FEEDWATER (BLACKOUT)
5	AFW-L	VOGTLE AFW USING LOOP-FTF FAULT TREE FLAGS FAULT TREE
6	AFW-MAN	MANUAL CONTROL AFW
7	BORATION	EMERGENCY BORATION
8	BP1	RCP SEAL STAGE 1 INTEGRITY (BINDING/POPPING)
9	BP2	RCP SEAL STAGE 2 INTEGRITY (BINDING/POPPING)
10	CSI	TERMINATE OR CONTROL SAFETY INJECTION
11	CST-REFILL	CONDENSATE STORAGE TANK REFILL
12	CST-REFILL-LT	CONDENSATE STORAGE TANK REFILL LONG-TERM
13	CST-REFILL-LT1	CONDENSATE STORAGE TANK REFILL LONG-TERM
14	DGR-01H	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 1 HOUR
15	DGR-02H	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 2 HOURS
16	DGR-03H	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 3 HOURS
17	DGR-04H	DIESEL GENERATOR RECOVERY (IN 4 HR)
18	DGR-06H	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 6 HOURS
19	DGR-08H	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 8 HOURS
20	DGR-30M	OPERATOR FAILS TO RECOVER EMERGENCY DIESEL IN 30 MINUTES
21	ECA	DECAY HEAT REMOVAL /RECOVERY (ECA-3.1/3.2)
22	EPS	EMERGENCY POWER
23	FAB	FEED AND BLEED
24	FAB-L	VOGTLE FEED AND BLEED IS UNAVAILABLE using LOOP-FTF
25	FAB-NSW	FEED AND BLEED IS UNAVAILABLE USING LONSW-FTF
26	FAB2	FEED AND BLEED (1 PORV REQUIRED)
27	HPI	HIGH PRESSURE INJECTION
28	HPI-L	HIGH PRESSURE INJECTION
29	HPI-ML	HIGH PRESSURE INJECTION
30	HPR	HIGH PRESSURE RECIRC
31	HPR-L	HIGH PRESSURE RECIRC
32	HPR-ML	HIGH PRESSURE RECIRCULATION
33	HPR1	HIGH PRESSURE RECIRCULATION
34	IE-ISL-HPI	ISLOCA IE 2-CKV HPI interface
35	IE-ISL-LPI	ISLOCA IE 2-CKV LPI interface
36	IE-ISL-RHR	RHR pipe ruptures
37	IE-LOACCW	LOSS OF AUXILIARY COMPONENT COOLING WATER
38	IE-LONSW	LOSS OF NUCLEAR SERVICE COOLING WATER
39	IE-LOOP	LOSS OF OFFSITE POWER
40	IE-SGTR	SG TUBE RUPTURE
41	IE-SLBIC	STEAMLINE BREAK INSIDE CONTAINMENT INITIATOR
42	IEFT-LOACW	AUXILIARY COMPONENT COOLING WATER (IE FT)
43	IEFT-LONSCW	NUCLEAR SERVICE COOLING WATER (IE FAULT TREE)
44	ISL-DIAG	Operators fail to diagnose ISLOCA
45	ISL-REC-HPI	Operators fail to recover (isolate) ISLOCA
46	ISL-REC-LPI	Operators fail to recover (isolate) ISLOCA
47	ISL-REC-RHR	Operators fail to recover (isolate) ISLOCA
48	ISL-RPT-HPI	HPI pipe ruptures
49	ISL-RPT-LPI	LPI pipe ruptures
50	ISL-RPT-RHR	RHR/SDC pipe ruptures
51	LOSC	RCP SEAL COOLING MAINTAINED
52	LOSC-ACCW	LOSS OF SEAL COOLING

	Event Tree Node (Fault Tree)	Description
53	LOSC-L	VOGTLE RCPSL USING LOOP-FTF FAULT TREE FLAGS
54	LOSC-NSW	LOSS OF SEAL COOLING
55	LOSC-TT	LOSS OF SEAL COOLING (TURBINE TRIP)
56	LPI	LOW PRESSURE INJECTION
57	LPI-NSW	LOW PRESSURE INJECTION - LONSW
58	LPR	LOW PRESSURE RECIRC
59	LPR-LL	LOW PRESSURE RECIRCULATION
60	LPR-NSW	LOW PRESSURE RECIRCULATION - LONSW
61	MFW	MAIN FEEDWATER
62	O1	RCP SEAL STAGE 1 INTEGRITY (O-RING EXTRUSION)
63	O2	RCP SEAL STAGE 2 INTEGRITY (O-RING EXTRUSION)
64	OPR	OFFSITE POWER RECOVERY
65	OPR-01H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 1 HOUR
66	OPR-02H	OFFSITE POWER RECOVERY IN 2 HRS
67	OPR-03H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 3 HOURS
68	OPR-04H	OFFSITE POWER RECOVERY (IN 4 HR)
69	OPR-06H	OFFSITE POWER RECOVERY IN 6 HRS
70	OPR-08H	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 8 HOURS
71	OPR-30M	OPERATOR FAILS TO RECOVER OFFSITE POWER IN 30 MINUTES
72	PORV	PORVs ARE CLOSED
73	PORV-B	VOGTLE PORVs/SRVs OPEN DURING STATION BLACKOUT
74	PORV-L	VOGTLE PORVs/SRVs OPEN DURING LOOP
75	PORV1	VOGTLE PORVS/SRVS OPEN DURING TRANSIENTS (AFW FAILED)
76	PORV2	PORVs ARE CLOSED
77	PWR-REC	LATE POWER RECOVERY
78	PWR-REC-06H	LATE POWER RECOVERY (6 HR)
79	PWR-REC-07H	LATE POWER RECOVERY (7 HR)
80	PWR-REC-09H	LATE POWER RECOVERY (9 HR)
81	PWR-REC-15H	LATE POWER RECOVERY (15 HR)
82	PWR-REC-24H	LATE POWER RECOVERY (24 HR)
83	RCPT	REACTOR COOLANT PUMPS TRIPPED
84	RCSPRESS	RCS PRESSURE LIMITED
85	REC-NSW	NSCW RECOVERY
86	REFILL	RWST REFILL
87	REFILL1	RWST REFILL
88	RHR	RESIDUAL HEAT REMOVAL
89	RPS	REACTOR TRIP
90	RPS-L	REACTOR SHUTDOWN
91	RSD	RAPID SECONDARY DEPRESSURIZATION (<1710 PSI IN 2 HR)
92	RSD-B	RAPID SECONDARY DEPRESS
93	RSD-L	RAPID SECONDARY DEPRESS
94	RXVESSEL	REACTOR VESSEL RUPTURES
95	SG-DEP-LT	DEPRESSURIZE SGs
96	SGI	FAULTED STEAM GENERATOR ISOLATION
97	SSC	COOLDOWN (PRIMARY & SECONDARY)
98	SSC1	COOLDOWN (PRIMARY & SECONDARY)
99	SSCR	SECONDARY SIDE COOLING RECOVERED

Table D-5. Initiating Event (event tree) Descriptions

	Event Tree	Initiator	Description
1	ISL-HPI	IE-ISL-HPI	SI cold leg discharge ISLOCA
2	ISL-LPI	IE-ISL-LPI	RHR discharge ISLOCA
3	ISL-RHR	IE-ISL-RHR	RHR suction ISLOCA
4	LLOCA	IE-LLOCA	large loss-of-coolant accident
5	LOACA	IE-LOACA	loss of vital ac 1AA02 bus
6	LOACCW	IE-LOACCW	loss of auxiliary component cooling water
7	LOCHS	IE-LOCHS	loss of condenser heat sink
8	LODCA	IE-LODCA	loss of vital dc 1AD1 bus
9	LODCB	IE-LODCB	loss of vital dc 1BD1 bus
10	LOMFW	IE-LOMFW	loss of main feedwater
11	LONSW	IE-LONSW	loss of nuclear service cooling water
12	LOOPGR	IE-LOOPGR	loss of offsite power (Grid related)
13	LOOPPC	IE-LOOPPC	loss of offsite power (Plant Centered)
14	LOOPSC	IE-LOOPSC	loss of offsite power (Switchyard centered)
15	LOOPWR	IE-LOOPWR	loss of offsite power (Weather related)
16	MLOCA	IE-MLOCA	medium loss-of-coolant accident
17	RXVRUPT	IE-XLOCA	reactor vessel rupture
18	SGTR	IE-SGTR	steam generator tube rupture
19	SLOCA	IE-SLOCA	small loss-of-coolant accident
20	TRANS	IE-TRANS	general transient

Table D-6. IE-SGTR Core Damage Sequences

	IE-SGTR CDF						
	Event Tree	**Sequence**	**CDF**	**Description**	**AFW**	**HPI**	**Dry SG**
32	SGTR	12	8.23E-08	/RPS, /AFW, /HPI, SGI, REFILL1, ECA			Yes
49	SGTR	19	2.84E-08	/RPS, AFW, /HPI, /SGI, FAB	fails		Yes
58	SGTR	9	1.72E-08	/RPS, /AFW, /HPI, /SGI, SSC, REFILL1, ECA			Yes
74	SGTR	22	8.88E-09	RPS			Yes
83	SGTR	20	6.84E-09	/RPS, AFW, /HPI, SGI	fails		?
106	SGTR	14	2.70E-09	/RPS, /AFW, HPI, /SGI, /SSC1, RHR		fails	Yes
123	SGTR	18	1.97E-09	/RPS, AFW, /HPI, /SGI, /FAB, HPR	fails		Yes
167	SGTR	6	9.95E-10	/RPS, /AFW, /HPI, /SGI, /SSC, CSI, REFILL, ECA			Yes
238	SGTR	15	1.90E-10	/RPS, /AFW, HPI, /SGI, SSC1		fails	Yes
254	SGTR	21	1.44E-10	/RPS, AFW, HPI	fails	fails	Yes
287	SGTR	16	9.29E-11	/RPS, /AFW, HPI, SGI		fails	?
391	SGTR	3	1.76E-11	/RPS, /AFW, /HPI, /SGI, /SSC, /CSI, RHR, CST-REFILL			Yes
		Total=	**1.50E-07**				
				IEV-SGTR =	2.07E-03		
				CCDP(SGTR) =	7.23E-05		
				CDF IEV-SGTR =	1.50E-07		

	ECA	DECAY HEAT REMOVAL /RECOVERY (ECA-3.1/3.2)
REFILL	REFILL1	RWST REFILL
SSC	SSC1	COOLDOWN (PRIMARY & SECONDARY)
	CSI	TERMINATE OR CONTROL SAFETY INJECTION
	SGI	ISOLATION OF THE FAULTED SG (FSG)

Appendix 2-E. SG flaw distributions and large flaws

This appendix contains information about SG flaw distribution, flaw distributions by depth and length, as well as an example calculation that includes the effect of EFPY of the SG.

E-1 Number of SG tube flaws generated

The number of SG tube flaws present at the end of K number of Effective Full Power Years (EFPY) of operation can be calculated for each material type (Alloy 600 or Alloy 690) as given in Section 6 of Reference 1. The same section also provides the equation for calculating the flaws generated during the last cycle. Example calculations are given in Tables E-2 and E-3 for 600TT and 690TT SG materials for a specified number of SG tubes. Reference 5 is the EXCEL workbook, C-SGTR for RASP Handbook Worksheet estimate C-SGTR due to SG ages (ML17318A002), that can be used for other calculations.

Note that for TT600, axial and circumferential flaws do not occur till after the end of EFPY 15.

No axial or circumferential flaws are observed for the limited sample of TT690 material, and they are not postulated for K>15. However, such flaws could potentially occur for K>15. This subject is not pursued in the current work leading to Table E-3.

Table E-2 Flaw Estimates - 600TT

# of tubes	13200					mu =	6.42E-05	0	0	
						sigma =	1.32E-03	2.0E-04	1.0E-03	
	Flaws generated since last EFPY[6]						**TOTAL # of flaws detected at EFPY (1)**			
K EFPY	**Volumetric**	**Axial**	**Circumf.**	**Total**		**K EFPY**	**Volumetric**	**Axial**	**Circumf.**	**Total (1)**
15	30	0	0	30		15	357	0	0	357
16	31	3	13	47		16	388	3	13	403
17	32	3	13	48		17	419	5	26	451
18	33	3	13	49		18	451	8	40	499
19	34	3	13	49		19	484	11	53	547
20	34	3	13	50		20	518	13	66	597
21	35	3	13	51		21	552	16	79	647
22	36	3	13	52		22	588	18	92	699
23	37	3	13	53		23	624	21	106	751
24	38	3	13	54		24	661	24	119	804
25	39	3	13	54		25	699	26	132	857
26	39	3	13	55		26	737	29	145	912
27	40	3	13	56		27	777	32	158	967
28	41	3	13	57		28	817	34	172	1023
29	42	3	13	58		29	858	37	185	1080
30	43	3	13	59		30	900	40	198	1137
31	44	3	13	60		31	942	42	211	1196
32	45	3	13	60		32	986	45	224	1255
33	45	3	13	61		33	1030	48	238	1315
34	46	3	13	62		34	1075	50	251	1376
35	47	3	13	63		35	1120	53	264	1437

[6] No axial or circumferential flaws are generated through operation by the end of K=15 EFPY.

Table E-3 Flaw Estimates - 690TT

# of tubes =13200						mu =	5.58E-05	0.00E+00	0.00E+00	
						sigma =	6.86E-04	0.00E+00	0.00E+00	
	Flaws generated since last EFPY						**TOTAL # of flaws detected at EFPY**			
K EFPY	**Volumetric**	**Axial**	**Circumf.**	**Total**		**K EFPY**	**Volumetric**	**Axial**	**Circumf.**	**Total**[7]
15	20	0	0	20		15	219	0	0	219
16	21	0	0	21		16	239	0	0	239
17	22	0	0	22		17	260	0	0	260
18	22	0	0	22		18	282	0	0	282
19	23	0	0	23		19	304	0	0	304
20	24	0	0	24		20	328	0	0	328
21	25	0	0	25		21	352	0	0	352
22	25	0	0	25		22	376	0	0	376
23	26	0	0	26		23	402	0	0	402
24	27	0	0	27		24	428	0	0	428
25	27	0	0	27		25	455	0	0	455
26	28	0	0	28		26	482	0	0	482
27	29	0	0	29		27	510	0	0	510
28	30	0	0	30		28	539	0	0	539
29	30	0	0	30		29	569	0	0	569
30	31	0	0	31		30	599	0	0	599
31	32	0	0	32		31	630	0	0	630
32	33	0	0	33		32	662	0	0	662
33	33	0	0	33		33	694	0	0	694
34	34	0	0	34		34	727	0	0	727
35	35	0	0	35		35	761	0	0	761

[7] Total is not adjusted for # of flaws that are already plugged.

E-2 Flaw distributions by depth and length

The flaw distribution for SG tube flaws detected during an inspection is given as Table 7-5 in Reference 1. This table is repeated below as Table E-1.

Flaw lengths and depths are sorted into a set of bins. These distributions are applicable to both thermally treated Inconel 600 and 690, and do not differentiate between the W and CE plants, or the age of the tubes. These probabilities are multiplied by the number of flaws estimated earlier to determine the average numbers of flaws for each flaw bin. The bins consisting of large flaws are estimated by considering the expected number of flaws only in the last cycle. All flaws deeper than approximately 30% of tube thickness (bin with a depth between 0.3 and 0.4) discovered in the previous cycles are assumed to have been plugged.

Table E-1 Probability that a Flaw Belongs to a Bin Size

		Flaw Length						Row Total
		0 to 1 cm	1 to 2 cm	2 to 3 cm	3 to 4 cm	4 to 5 cm	5 to 6 cm	
Flaw Depth Fraction of Total Thickness	0 to 0.1	2.74E-03	4.62E-02	2.23E-02	5.38E-03	1.04E-03	1.80E-04	7.78E-02
	0.1 to 0.2	1.86E-02	3.14E-01	1.52E-01	3.66E-02	7.08E-03	1.23E-03	5.30E-01
	0.2 to 0.3	9.59E-03	1.62E-01	7.81E-02	1.89E-02	3.64E-03	6.31E-04	2.73E-01
	0.3 to 0.4	3.09E-03	5.21E-02	2.52E-02	6.07E-03	1.17E-03	2.03E-04	8.78E-02
	0.4 to 0.5	8.47E-04	1.43E-02	6.90E-03	1.66E-03	3.22E-04	5.57E-05	2.41E-02
	0.5 to 0.6	2.14E-04	3.61E-03	1.74E-03	4.21E-04	8.13E-05	1.41E-05	6.08E-03
	0.6 to 0.7	5.14E-05	8.67E-04	4.19E-04	1.01E-04	1.95E-05	3.38E-06	1.46E-03
	0.7 to 0.8	1.19E-05	2.01E-04	9.73E-05	2.35E-05	4.54E-06	7.86E-07	3.39E-04
	0.8 to 0.9	2.71E-06	4.57E-05	2.21E-05	5.32E-06	1.03E-06	1.78E-07	7.70E-05
	0.9 to 1.0	small						
Column Total		3.51E-02	5.93E-01	2.87E-01	6.92E-02	1.34E-02	2.32E-03	1.00E+00

Table notes:

1. The blue area consists of the “large” tube flaws which are unlikely to occur. Such a flaw or combination of such flaws could cause C-SGTR in both favorable and unfavorable SG types.
2. The yellow plus blue area consists of flaws subject to plugging when detected. Flaws or combination of flaws in the yellow area could cause C-SGTR in unfavorable SGs.

6.98E-04	(blue)	total probability of blue area
1.20E-01		total probability of yellow + blue areas
1.19E-01	(yellow)	total probability of yellow area
1.00E+00		total probability of table bins

E-3 An example calculation (including effect of EFPY)

An example calculation is provided in this section, using information from Tables E-1, E-2, and E-3. The example calculation is outlined in Table E-4.

Consider an NPP equipped with four SGs, each with about 3,300 tubes. There are, therefore, 13,200 tubes for NPP. The tube material is 600TT. The plant is going into a refueling outage at EFPY = 23. The previous outage was at EFPY = 21.7.

Table 2.3-4 shows the calculations for:

1. Total # of flaws created from K 21.7 to 23 = 68 (53 + 0.3*52)
2. # of large flaws expected in K 21.7 to K 23 = 0.05 (68 * 6.98E-04)
3. # of pluggable flaws expected in K 21.7 to K 23 = 8 (68 * 0.12)[8]

A quick estimate of conditional C-SGTR probability (p(csgtr)) can be made by assuming that

- all large flaws lead to C-SGTR, given a C-SGTR challenge (driven mostly by thermal challenges after a core damage sequence)
- the accident sequence will occur in the middle of the time period of interest; thus only ~34 new flaws will be created by that time.

This estimate gives p(csgtr) = 0.025 (=0.05/2). Tables 2.4-1 and 2.4-2 provide recommended p(csgtr) values for different types of accident sequences.

P(csgtr) must be multiplied by the related sequence frequency (f_i) to estimate the C-SGTR frequency. See Section 2.4 for further discussion.

Reference 5 is an EXCEL workbook named "C-SGTR for RASP Handbook Worksheet estimate C-SGTR due to SG ages" (ML17318A002 containing the example calculations and the related tables. Additional calculations can be made by using this workbook and changing the number of SG tubes.

The number of flaws at 23 EFPY is 988 (see Table E-2). This is the cumulative number of flaws that would have accumulated in the past 23 EFPY. However it is known that some of these flaws are plugged. The fractions of flaws that are plugged is 9.5% (refer to discussion in page 7-12 of the NUREG). Note that some flaws are plugged when they are at smaller depth than 40%, which is the plugging criteria that limits the maximum depth allowed to proceed with power operation.

Note: Although the EXCEL workbook can also be used to calculate p(CSGTR) for different number of SG tubes, it is recommended that the p(SGTR) values given in Tables 2.4-1 and 2.4-2 be used as is for LERF estimates, regardless of the number of tubes or loops in a plant of interest.

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[8] The fraction, 0.12 of tubes expected to be plugged is taken from Table E-1 as the probability of flaws that are 0.30 deep or deeper, as represented by the yellow and blue areas in the table. This estimate is deemed to be pessimistic.

Table E-4 An Example Calculation

input	# of SGs	4	
input	# of tubes/SG	3300	
input	Total # of SG tubes	13200	
input	Tube material	600TT	
input	Nth outage at EFPY	23	
input	N-1th outage at EFPY	21.7	
Table 2.3-2	# of flaws created from K 21 to K 22	52	
Table 2.3-2	# of flaws created from K 22 to K 23	53	
Calc-1	Total # of flaws created from K 21.7 to 23	68	= 53 + 0.3*52
Calc-2	# of large flaws expected in K 21.7 to K 23	0.05	= 68 * 6.98E-04 (1)
Calc-3	# of pluggable flaws expected in K 21.7 to K 23	8	= 68 * 0.12 (2)
Calc-4	A quick estimate of conditional C-SGTR probability	0.025	assume all large flaws lead to C-SGTR and accident occurs in the middle of the time period (=0.05/2)

(1) The probability of a large flaw is 6.98E-04 as defined in Table E-1 by the flaws in the blue area.

(2) The fraction, 0.12 of tubes expected to be plugged is taken from Table E-1 as the probability of flaws that are 0.30 deep or deeper, as represented by the yellow and blue areas in the table. This estimate is deemed to be pessimistic.

Appendix 2-F. A Simplified Method to Estimate C-SGTR LERF

This appendix provides a simplified method to estimate C-SGTR LERF. The method is applied to some SPAR models and the resulting LERF values are summarized in Table 2-F-1. Versions 8.50 of SPAR models are used. Since SPAR models are routinely updated, the resulting values could be affected. Therefore, these values should be treated as examples only.

A more detailed examination of the sequences, and estimation of all C-SGTR categories (CAT-1 through CAT-5) are illustrated by an example in Appendix 2-D.

2-F.1 Simplified method to estimate C-SGTR-LERF

1. Run SPAR model.
2. Record plant CDF = X1 = ____________________
3. Record CDF of top 20 sequences (or top 20 cut sets) = X2 = ___________________
4. For the recorded sequences (or cuts sets), keep only those where AFW (or EFW, or MFW or FW and similar secondary cooling functions) has failed.

   Sum their CDFs as X3 = _____________________

5a. Estimate LERF due to C-SGTR for a Westinghouse plant as

   LERF(C-SGTR) = 0.02 * X3 * X1 / X2 Equation 1w.

5b. Estimate LERF due to C-SGTR for a CE plant as

   LERF(C-SGTR) = 0.2 * X3 * X1 / X2 Equation 1ce.

The END.

Example:

X1 = 1E-05

X2 = 6E-06

X3 = 1E-06

LERF(C-SGTR) = 0.02 * 1E-06 * 1E-05 / 6E-06 = 3E-08/yr for a Westinghouse plant.

or

LERF(C-SGTR) = 0.2 * 1E-06 * 1E-05 / 6E-06) = 3E-07/yr for a CE plant.

A Check:

Experience indicates that the C-SGTR LERF is in the range of 10-20% of (CDF * 0.02) for Westinghouse plants; or 10-20% of (CDF * 0.2) for CE plants.

Thus, for the above example, with CDF = X3 = 1E-05, and a 15% factor,

LERF(C-SGTR) = 0.02 * 0.15 * 1E-05 = 3E-08/yr. for a Westinghouse plant,

or

LERF(C-SGTR) = 0.2 * 0.15 * 1E-05 = 3E-07/yr. for a CE plant.

- *If a SPAR-AHZ model is used, use minimal cut sets to avoid introducing further conservatism.*
- *You can replace "top 20" with any "top N" you want (for example top 30); whatever N makes you comfortable for the SPAR model in question.*

2.F.2 Background and Assumptions

1. C-SGTR LERF is driven by temperature-induced challenges; pressure-induced challenges are a secondary effect.
2. HDL (high RCS pressure; dry SGs; low secondary side pressure) CDF sequences dominate the C-SGTR challenge.
3. If CDF occurs, and AFW fails, secondary side is very likely de-pressured before C-SGTR occurs.
4. The following conditional C-SGTR fractions for HDL sequences are a good approximation for estimating C-SGTR frequency: 0.02 for Westinghouse plants; 0.2 for CE plants.

   (Watch out for RCP seal leakage scenarios with >350gpm per pump, in which loop seal is assumed to be cleared and the conditional C-SGTR fraction is 1.0. These sequences are not considered to be frequency-wise significant in general. This will be especially true, if new generation of seals are installed.)

   (For plants with SG tubes older than 20 EFPYs, the conditional C-SGTR probabilities quoted above may be increased - up to by a factor of 2 at 35 EFPYs. See tables in ML17318A002.)
5. If C-SGTR occurs, and CDF occurs, LERF occurs.

(Items 1, 2, 3, 4, 5 above are either from NUREG-2195, or are implied by it.)

6. Estimating CDF of HDL sequences by counting a SPAR model dominant sequences in which AFW failed is a good approximation.
7. Residual CDF sequences not examined in item 5 above have the same HDL CDF to total CDF ratio as the sequences examined in item 5 above.
8. The calculational process given in this document estimates C-SGTR LERF from HDL (already CDF) sequences only (CAT-1 in Reference 2. CAT-2 through CAT-5 sequences are not included – see item 6 above.)

9. If additional issues involving CAT-2 through CAT-5 type sequences occur, refer to the RASP Handbook Section – Reference 2.
10. The calculational process given here can be applied at plant-level, or at an event tree level, or for a set of CDF sequences.
11. Number of tubes in a SG and their dimensions is not a factor in the LERF estimate. Conditional C-SGTR probability used for Westinghouse plants is for a total leak rate of 6 cm^2, from all SGs and all tubes in the plant.
12. The LERF estimate is for both thermally-treated 600 and 690 alloy tube materials. For Westinghouse plants, this model may be considered slightly conservative for 690 compared to 600.

(See also the example in Appendix D of the RASP Handbook C-SGTR Section.)

Insights:

C-SGTR is a LERF issue, mainly driven by HDL sequences where CDF has already occurred.

LERF contribution to CDF for Westinghouse plants is about 1% of the plant CDF. If one postulates that a plant LERF is in the range of 8-12% of plant CDF, then inclusion of C-SGTR LERF may increase the total LERF percentage by another percent (percentage increase in LERF is about 10%).

For example, for a plant with 1E-05 CDF and 1E-06 LERF, inclusion of C-SGTR LERF may result in a total plant LERF of 1.1E-06, without affecting plant CDF.

Table 2-F- 1 Estimation of C-SGTR LERF from SPAR Models

	Type	X1	X2	X3	Cond Prob	LERF	% of CDF	
1	W	2.28E-05	2.28E-05	1.52E-05	0.02	3.E-07	1.3%	
2	CE	6.15E-06	6.15E-06	2.20E-06	0.2	4.E-07	7.1%	
3	W	5.62E-05	5.62E-05	4.93E-07	0.02	1.E-08	0.02%	Note 1
4	CE	9.93E-06	9.93E-06	2.66E-06	0.2	5.E-07	5.4%	
5	CE	1.30E-05	1.30E-05	1.77E-06	0.2	4.E-07	2.7%	
6	CE	2.47E-05	2.47E-05	2.22E-05	0.2	4.E-06	18%	
7	W	2.37E-05	2.37E-05	6.34E-06	0.02	1.E-07	0.5%	
8	W	4.47E-06	4.47E-06	7.57E-07	0.02	2.E-08	0.3%	
9	W	4.71E-06	4.71E-06	1.02E-06	0.02	2.E-08	0.4%	
10	CE	9.47E-06	9.47E-06	9.75E-07	0.2	2.E-07	2.1%	
11	CE	1.78E-05	1.78E-05	1.24E-06	0.2	2.E-07	1.4%	
12	W	9.86E-06	9.86E-06	1.92E-06	0.02	4.E-08	0.4%	
13	W	1.66E-05	1.66E-05	1.11E-05	0.02	2.E-07	1.3%	
14	W	3.38E-06	3.38E-06	1.18E-06	0.02	2.E-08	0.7%	
15	W	4.30E-06	4.30E-06	1.51E-06	0.02	3.E-08	0.7%	
16	W	1.71E-05	1.71E-05	7.52E-06	0.02	2.E-07	0.9%	
18	W	6.68E-05	6.68E-05	1.29E-05	0.02	3.E-07	0.4%	
18	W	2.01E-05	2.01E-05	5.22E-06	0.02	1.E-07	0.5%	
19	W	4.48E-05	4.48E-05	1.99E-05	0.02	4.E-07	0.9%	
20	W	9.01E-05	9.01E-05	1.12E-07	0.02	2.E-09	0.0%	Note 2
All internal events CDF sequences from the SPAR model are used. Thus X1 = X2.								
LERF = (Cond Prob) * X3 * X1 / X2 Equations 1w and 1ce above.								Note 3

Note 1 When LERF % is this small, all one can conclude is that the LERF contribution is very mall, without referring to a value. In such cases, CAT-2 through CAT-5 SGTR categories may contribute enough to change this percentage, but not enough to change the conclusion that C-SGTR LERF contribution is small. For Plant 3, 94% of CDF is from LORW initiating event.

Note 2 For Plant 20, 75% of CDF is from loss of SW to both units initiating event.

Note 3 For SPAR models with internal events only, there is no necessity to work with only the dominant CDF sequences. So, the LERF equation simplifies to LERF = (Cond Prob) * X3

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