Evaluation Methodology of Jet Impingement Loads on SSCs

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Non-Proprietary

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REVISION HISTORY

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EXECUTIVE SUMMARY

The purpose of this report is to present the design guidance that will be used to evaluate the essential Structures, Systems and Components (SSCs) for impacts from High-Energy Line Breaks (HELBs), along with a description of the analyses, studies, and experiments that provide the bases for concluding that the design guidance will conservatively bound the HELB impacts. This report addresses Nuclear Regulatory Commission (NRC) staff concerns regarding the non-conservatism in the analyses methodology of the related ANSI/ANS Standard 58.2 relative to HELB jet expansion, blast effects, and amplifications due to resonance and blast wave reflections, as expressed in the Design Specific Review Standard (DSRS) for the mPower application:

- Expansion of the jet plume in the supersonic flow cases when an expansion is assumed that can limit the penetration to a non-conservative distance from the break. Experiments have shown that the supersonic jets have potential to penetrate longer distances than evaluated in the ANS standard. The jets from the HELB are highly dependent on the surrounding medium and at a given distance from the issuing break, will spread or contract at a rate depending on the local jet conditions relative to the surrounding fluid pressure.

- The ANSI/ANS 58.2 Standard's formulas for the spatial distribution of pressure through a jet cross-section are incorrect for certain locations. The ANSI/ANS 58.2 Standard's assumes that the pressure within a jet cross section is maximum at the jet centerline; far from the break, however, the pressure variation is quite different, often peaking near the outer edges of the jet. Applying the ANSI/ANS 58.2 Standard's formulas could lead to non-conservative pressures away from the jet centerline.

- A blast wave caused by the HELB has a potential to affect SSCs that are outside of the hazard zone created by the path of the ensuing jet that forms from the break. The current ANSI/ANS 58.2 standard does not address this effect.

- There is potential for feedback and resonance from a jet impinging on an SSC which may impart a time varying oscillatory load on the SSCs in the flow path. Also, the supersonic jet can lead to backward propagating transient shock and expansion wave that can cause further unsteadiness in downstream shear layer. In some cases, synchronization of the transient waves with the shear layer vortices emanating from the jet break can lead to significant amplification of the jet pressures and forces (a form of resonance) that is not considered in the ANSI/ANS 58.2 standard. Should the dynamic response of the neighboring structure also synchronize with the jet loading time scales, further amplification of the loading can occur, including that at the source of the jet.

To the extent possible, the methodologies presented in this report are developed based on physics arguments and test data (see Section 2). A computational fluid dynamics (CFD) model is also developed, using the Star-CCM+ CFD solver platform. The CFD model is qualified for use through Verification and Validation (V&V), as per the ASME NQA-1 standard, following techniques documented in the ASME V&V 20-2009 Standard (see Appendix A). CFD results are used to confirm the design guidance that will be used to obtain bounding HELB conditions for the KHNP conditions (see Section 3). Design guidance is summarized in Section 4.

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ACRONYMS AND ABBREVIATIONS

2-D	Two-Dimensional
3-D	Three-Dimensional
AF	Amplification factor
ANS	American Nuclear Society
ANSI	American Nuclear Standards Institute
APR	Advance Pressurized Water Reactor
ASME	American Society of Mechanical Engineers
BTP	Branch Technical Position
CFD	Computational Fluid Dynamic
CV	Chemical and Volume Control System
DCD	Design Control Document
DSRS	Design Specific Requirement Document
EPRI	Electric Power Research Institute
ESBWRTM	Economic Safe Boiling Water Reactor
FW	Feed-water
HELB	High Energy Line (Pipe) Break
IBZ	Initial Blast Zone
KHNP	Korea Hydro and Nuclear Power
LBB	Leak Before Break
MBZ	Modified Blast Zone
MS	Main Steam
NRC	Nuclear Regulatory Commission
NUREG/CR	Nuclear Regulation/Contractor Prepared
PWROG	Pressurized Water Reactor Owners Group
RC	Reactor Coolant System
RCS	Reactor Coolant System
SAC	Semi-Analytical Correlation
SD	Steam Generator Blowdown
SI	Safety Injection
SSC	Structures, Systems and Components
V&V	Validation & Verification

1.0 INTRODUCTION

1.1 Purpose

The purpose of this report is to present the design guidance that will be used to evaluate the essential Structures, Systems and Components (SSCs) for impacts from High-Energy Line Breaks (HELBs), along with a description of the analyses, studies, and experiments that provide the bases for concluding that the design guidance will conservatively bound the HELB impacts.

1.2 Current Analysis Methodology

The current analyses methodology for the HELB as described in APR 1400 DCD Section 3.6.2 establishes break locations in accordance with Branch Technical Position (BTP) 3-4, calculates jet dynamic forces and evaluates effects on the essential SSCs. Both circumferential and longitudinal breaks are evaluated. Blowdown thrust force is determined by multiplication of parameters (i.e., appropriately calculated thrust coefficient considering the fluid condition, piping internal pressure, cross sectional area at the break location). This methodology is based on the simplified methods described in ANSI/ANS 58.2-1988 (Reference 14) and pipe thrust and loads (Reference 15). Additionally, leak before break (LBB) for the reactor cooling system (RCS) main loop piping, surge line, shutdown cooling and safety injection lines is applied using the guidelines of NUREG-1061 and SRP 3.6.3.

1.3 NRC Position on Jet Impingement Analysis Methodology

The NRC positions on the non-conservative analyses regarding the HELB using the ANSI/ANS standard as documented in Appendix A of the NRC mPower Design Specific Review Standard (mPower DSRS), 3.6.2, are as follows:

(1) Blast Wave

In the event of a high pressure pipe rupture, the first significant fluid load on surrounding SSCs would be induced by a blast wave. A spherically expanding blast wave is reasonably approximated to be a short duration transient and analyzed independently of any subsequent jet formation. However, the expansion of blast waves in an enclosed space is not purely spherical, and reflections and amplifications may need to also be accounted for. Blast waves are not considered in the ANSI/ANS 58.2 Standard for evaluating the dynamic effects associated with the postulated pipe rupture.

(2) Expansion of Jet Plume

In the characterization of supersonic jets given by the ANSI/ANS 58.2 Standard, some physically incorrect assumptions underlie the approximating methodology. The model of the supersonic jet itself is given in Figures C-1 and C-2 of the ANSI/ANS 58.2 Standard. The standard assumes that a jet issuing from a high pressure pipe break will always spread with a fixed 45° angle up to an asymptotic plane and subsequently spread at a constant 10° angle. The characteristics of the jet, however, are not universal. Initial jet spreading rates are highly dependent on the ratio of the total conditions of the source flow to the ambient conditions. Subsequent spreading rates depend, at a given axial position, on the ratio of the static pressure in the outermost jet flow region to the ambient static pressure.

In the ANSI/ANS 58.2 Standard, the asymptotic plane is described as the point at which the jet begins to interact with the surrounding environment. This has been interpreted to mean that the jet is subsonic downstream of the asymptotic plane. Experts have demonstrated that, supersonic or not, the jet is highly dependent on the conditions in the surrounding medium and, at a given distance from the issuing break, will spread or contract at a rate depending on the local jet conditions relative to the surrounding fluid pressure.

(3) Distribution of Pressure within Jet Plume

The ANSI/ANS 58.2 Standard’s formulas for the spatial distribution of pressure through a jet cross-section are incorrect for certain locations. The ANSI/ANS 58.2 Standard’s assumes that the pressure within a jet cross-section is maximum at the jet centerline; far from the break, however, the pressure variation is quite different, often peaking near the outer edges of the jet. Applying the ANSI/ANS 58.2 Standard’s formulas could lead to non-conservative pressures away from the jet centerline.

(4) Potential Feedback Amplification and Resonance

Furthermore, unsteadiness in free jets, especially supersonic jets, tends to propagate in the shear layer and induce time-varying oscillatory loads on obstacles in the flow path. Pressures and densities vary non-monotonically with distance along the axis of a typical supersonic jet, feeding and interacting with shear layer unsteadiness. In addition, for a typical supersonic jet, interaction with obstructions will lead to backward-propagating transient shock and expansion waves that will cause further unsteadiness in downstream shear layers. In some cases, synchronization of the transient waves with the shear layer vortices emanating from the jet break can lead to significant amplification of the jet pressures and forces (a form of resonance) that is not considered in the ANSI/ANS 58.2 standard. Should the dynamic response of the neighboring structure also synchronize with the jet loading time scales, further amplification of the loading can occur, including that at the source of the jet.

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1.4 KHNP Position for Analysis of Jet Impingement Loads due to High Energy Line Break

Blast Wave

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2.0 ANALYSIS METHODOLOGY

The analyses methodology for the HELB jet impingement and blast effects are presented in the sections below.

The detailed analyses for determining the jet zone of hazard and the magnitude of blast pressure are performed using the CFD Software STAR CCM+. This is commercially available software, and specific applications of the software for the APR 1400 HELB evaluations are supported by the validation and verification (V&V) of this software against published literature and test data. Refer to Appendix A for the V&V of the STAR CCM+ software.

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4.0 CONCLUSION

4.1 Conclusions

The analyses in the technical report provide a basis for evaluating the impact of a HELB on SSCs in the zone affected. The methodology addresses all issues listed below, which include all concerns identified by the NRC staff in the mPower DSRS:

- Effect of blast waves due to HELB
- Amplification due to blast wave reflection
- Jet pressure amplification due to feedback and resonance phenomena
- Long penetration distances of steam jets and
- Deflection of steam jets from SSCs in the hazard zone

The analyses, studies and experiments described in this report provide the bases for concluding that the design guidance presented in Section4.2 will conservatively bound the HELB impacts.

4.2 Design Guide to Evaluate SSCs

The techniques described in this design guide are intended only to discern whether an SSC can withstand the bounding jet and blast pressure loadings during a HELB. If an SSC cannot withstand the bounding jet and blast pressure loadings, additional analyses may be performed to refine the assessment.

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APPENDIX A

Validation and Verification (V&V) of Software Used in Analyses

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A.1.0 PURPOSE

STAR-CCM+ is a general purpose commercial computational fluid dynamics program developed by one of the leading CFD software companies. The capabilities of the program include steady state and transient flows, ranging from incompressible and low speed to hypersonic regime. The program can also handle single and multiphase flows involving gases, liquids, solid particulates, with phase change, heat and mass transfer. The STAR-CCM+ program has a large user base that allows for errors to be caught and fixed quickly during testing phase as well as in stable releases. It is envisaged that STAR-CCM+ capabilities should be adequate to model the jet and blast wave phenomena associated with high energy line breaks carrying superheated or high quality saturated steam at high pressures. STAR-CCM+ CFD code will be used on the project only after completion of Verification and Validation process.

The purpose of this Appendix is to document the verification and validation of the STAR-CCM+ computer program for compressible jet flows, shocks, and blast waves. The STAR-CCM+ program is intended to be used for the following processes:

1.1 Calculation of blast wave pressures associated with pipe breaks in superheated steam lines

1.2 Calculation of pressures and loads from transient developing and developed steady jets issuing out of superheated steam line pipe breaks

1.3 Document lockdown model settings that were verified and validated

1.4 Document the non-dimensional parameter ranges that are covered by the verification and validation study

A.2.0 ASSUMPTIONS

The assumptions relevant to different validation problems considered in this calculation are summarized below.

i. One-dimensional linear shock tube

   1. one dimensional shock tube with instantaneous diaphragm rupture
   2. separating high and low pressure regions filled with ideal gas

ii. Spherical shock from exploding frangible sphere

   1. instantaneous rupture of pressurized spherical vessel in a blast chamber
   2. ideal gas behavior of gas in sphere and ambient

iii. Developing jet – instantaneous pipe break in high pressure line with air at 100 atmosphere pressure creating a developing jet discharged into unconfined ambient at 1 atmosphere pressure

   1. instantaneous pipe break
   2. ideal gas behavior of gas in jet and ambient

iv. Supersonic impinging jet – supersonic jet (at Mach number of 2.95) impinging on a flat plate approximately 4 diameters downstream of the jet location.

   1. Negligible two-phase effects
   2. ideal gas behavior of jet and ambient gases

A.3.0 DEFINITIONS

Mach number – Local fluid velocity divided by the local speed of sound.

Shock Wave Mach Number – Velocity of moving shock wave divided by speed of sound in undisturbed medium into which the shock wave is propagating.

Overpressure - The excess static pressure over the ambient pressure in the undisturbed ambient associated with the passing shockwave.

Overpressure duration – Time interval over which static pressure exceeds ambient static pressure after arrival of blast wave.

Positive Impulse - Time integral of overpressure over duration of overpressure, i.e., time period when the static pressure exceeds the far field ambient level.

Underpressure - The static pressure defect relative to the ambient pressure at a given location due to passage of blast wave.

Underpressure duration – Time interval over which pressure at given location remains below ambient due to the passage of blast wave.

Negative Impulse - The time integral of underpressure over the duration of underpressure.

Verification – The process of verifying that the mathematical model equations are correctly coded and solved in the CFD code.

Validation – The process of comparing computational results to experimental data, analytical, or appropriate numerical results considering the uncertainties in numerical solution due to discretization and iterative convergence errors, comparison data uncertainty, and simulation inputs uncertainty. The validation process is performed after verification and measures the uncertainties introduced into the simulation result from all the modeling assumptions.

Simulation Result (S) – The value of a solution quantity of interest calculated from the numerical solution.

Data (D) – The value of a comparison quantity of interest (from experiment, analytical solution, or other validated and verified simulation result) that will be compared to simulation result for the same quantity.

Model Bias (E) – The difference between the solution quantity calculated from numerical simulation and the comparison data.

U_{num} and u_{num}- The uncertainty in the simulation result arising from discretization error and iterative convergence error. U_{num} and u_{num} are numerical uncertainty estimates for 95% and $1-\sigma$ confidence levels.

U_D and u_D- The uncertainty in data (from experiment, analytical solution, or other validated and verified simulation result). U_D and u_D are data uncertainty estimates for 95% and $1-\sigma$ confidence level.

U_{input} and u_{input} - The uncertainty in simulation result attributed to uncertain input conditions (from experiment, analytical solution, or other validated and verified simulation result). U_{input} and u_{input} are numerical result uncertainty estimates for 95% and $1-\sigma$ confidence level.

GCI - The 95% (or $2-\sigma$) confidence level numerical uncertainty in the simulation result arising from discretization error that is estimated based on Richardson extrapolation and a factor of safety, F_S.

Richardson Extrapolation – A generally applicable method for estimating a more accurate value of simulation result based on simulations carried out on different grid resolutions and/or different time steps. This method assumes that the simulation result being considered can be expressed in power series of grid resolution or time step size.

A.4.0 PHENOMENA IDENTIFICATION AND RANKING

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A.5.0 GOVERNING EQUATIONS

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A.6.0 DESIGN INPUTS

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A.7.0 LOCKDOWN MODEL SETTINGS

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A.8.0 VERIFICATION PROBLEMS

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A.9.0 VALIDATION PROBLEMS

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A.10.0 VALIDATION METHODOLOGY & CRITERIA

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A.11.0 VALIDATION DATASET ANALYSIS

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A.12.0 VERIFICATION RESULTS

Before completing the formal validation involving determining the validation metrics, the lockdown CFD model is verified by comparing the numerical solution profiles for verification problems 1 and 2 in section A.8.0. The numerical results from the verification problems are compared to the analytical solution for,

- Density profile
- Velocity profile
- Mach number profile
- Static pressure profile
- Total pressure profile
- Static temperature profile
- Total temperature profile

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A.13.0 VALIDATION RESULTS

The results from the validation with the four validation problems in section A.9.0 are summarized in this section.

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A.14.0 MODEL VARIANT STUDY

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A.16.0 CONCLUSIONS

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APPENDIX B

Blast Wave Pressure Semi-Analytical Correlation

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B.1.0 PURPOSE

The purpose of this appendix is to propose similarity correlations for calculating blast wave quantities for blast waves propagating in gases such as ambient air, created by explosions or ruptures in vessels or pipes containing gases at high pressure. The correlations may not be applicable if the ambient fluid and the pressure vessel/high pressure line fluid are not gas phase. The correlation will not apply if the pressure vessel/high pressure line fluid is liquid or two-phase.

Propose similarity correlation for overpressures and impulses in blast waves created by ruptures in steam lines based on experimental measurements for spherical blast waves from frangible spheres.

Confirm that proposed correlation is bounding with respect to selected numerical results for blast waves reported in literature

Confirm that the proposed correlation is bounding with respect to blast wave measurements for selected pressure vessel burst tests reported in literature.

Document the conservativeness of correlations applied to calculate blast wave quantities for steam piping High Energy Line Breaks (HELB)

Summarize the application of proposed correlations to calculating loads on objects and pressures on impingement surfaces exposed to blast wave effects from HELBs

B.2.0 INPUTS

B.2.1 Design Inputs

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B.2.2 Assumptions

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B.2.3 Definitions

Mach number – Local fluid velocity divided by local speed of sound

Shock Wave (or Blast Wave) Mach Number – Velocity of moving shock wave divided by speed of sound in undisturbed medium into which the shock wave is propagating

Overpressure - The excess static pressure over the ambient pressure in the undisturbed ambient associated with the passing shockwave

Overpressure Duration – Time interval over which static pressure exceeds ambient after arrival of blast wave

Positive Impulse - The time integral of overpressure over the duration of overpressure. (This does not include the time when the pressure drops below the far field ambient level).

Underpressure - The static pressure defect relative to the ambient pressure at a given location due to passage of blast wave

Underpressure Duration – Time interval over which pressure at given location remains below ambient due to the passage of blast wave

Negative Impulse - The time integral of underpressure over the duration of underpressure.

Under-expanded Jet – A jet with static pressure greater than the ambient pressure at the jet discharge location.

Fully-expanded Jet – A jet with static pressure equal to the ambient pressure at the jet discharge location

B.3.0 METHODOLOGY

B.3.1 Calculation of Blast Wave Quantities for Pipe Breaks

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B.3.2 Existing Solutions and Experimental Data

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B.3.3 Proposed Similarity Correlations

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B.3.4 Data Fits

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B.4.0 RESULTS

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B.4.2 Maximum Positive Impulse Correlation

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B.5.0 CONCLUSIONS

B.5.1 Proposed Correlations

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B.5.2 Comparison to Numerical Results from Literature

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B.5.3 Comparison to Test Results from Pressure Vessel Burst Tests

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B.5.4 Conservativeness of the Proposed Correlation

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B.5.5 Calculation of Loads on Objects and Impingement Surface Pressures Using the Proposed Correlations

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