Meeting with NRC on Jet Impingement for the U.S. EPR (RAI 354 Questions 03.06.02-33 through 40)

AREVA NP
Rockville, MD
November 1, 2010

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Agenda

Subject	Presenter	Proprietary?
▶ Introductions	R. Wells	No
▶ Regulatory Background	R. Wells	No
▶ Objectives of the Meeting	R. Wells	No
▶ Jet Impingement Background ◇ Regulatory Guidance ◇ Key Issues	C. McGaughy	No
▶ AREVA NP Methodology	C. McGaughy	Yes
▶ Conclusions	C. McGaughy	No
▶ Closure Plan	R. Wells	No

Regulatory Background and Objectives of the Meeting

Russ Wells
Advisory Engineer
New Plants Licensing

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Regulatory Background

- SRP 3.6.2 Rev. 2 issued March 2007 identified concerns with the modeling of jet impingement forces in ANSI 58.2-1998 which had been accepted by NRC. As noted in the SRP:
  - "However, based on recent comments from the Advisory Committee on Reactor Safeguards (ACRS) (V. Ransom and G. Wallis), it appears that some assumptions related to jet expansion modeling in the ANSI/ANS 58.2 standard may lead to nonconservative assessments of the jet impingement loads of postulated pipe breaks on neighboring SSCs. The NRC staff is currently assessing the technical adequacy of the information pertaining to dynamic analyses models for jet thrust force and jet impingement load that are included in this SRP Section and ANSI/ANS 58.2. Pending completion of this effort, the NRC staff will review analyses of the jet impingement forces on a case by case basis. These analyses should show that jet impingement loadings on nearby safety related SSCs will not impair or preclude their essential functions."

Regulatory Background

- U.S. EPR FSAR RAIs related to jet impingement:

RAI No.	No. of Questions	Date of AREVA NP responses
107	8	12/1/2008 2/20/2009 (Suppl. 1)
222	8	7/6/2009 9/11/2009 (Suppl. 1)
354	7	4/15/2010 5/20/10 (Draft Suppl. 1)

Regulatory Background

- **Interfaces with NRC on this subject:**
  - **10/29/08 – Telecon with NRC on RAI 107**
  - **5/29/09 – Telecon with NRC on RAI 222**
  - **1/26/10 – Telecon with NRC on RAI 354**
    - AREVA NP recommends an audit to address the NRC concerns.
    - NRC states that AREVA NP needs to perform oscillatory jet loads before they will agree to an audit.
  - **6/1/10 - Telecon with NRC on the Draft Response to RAI 354 Supplement 1.**
    - NRC agrees that AREVA NP acknowledged that dynamic oscillatory loads must be considered.
    - NRC states that AREVA must do a confirmatory analysis to prove the results of our hand calculations.
    - NRC states that AREVA NP should do a CFD approach.
  - **7/21/10 – Follow-up telecon with NRC on the Draft Response to RAI 354 Supplement 1.**
    - NRC agrees to a public meeting on this issue to define a closure plan.

Objectives of the Meeting

- Explain the AREVA NP methodology jet impingement and supporting data
- Provide supporting information from an independent expert
- Demonstrate how the AREVA NP methodology satisfies the ACRS concerns
- Agree upon a closure plan path forward to resolve NRC questions

Jet Impingement Background

Chris McGaughy
Advisory Engineer

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Jet Impingement Background

▶ Break Locations

◇ Determination of Break Locations established by BTP 3-4

- Provides criteria to determine break locations and types of breaks (circumferential, longitudinal, leakage crack)

◇ Locations Not Requiring Break Postulation

- Lines qualified by Leak-Before-Break Methodology (LBB) via SRP 3.6.3
  - RCS Loop Piping (Hot Leg, Cold Leg, Crossover Leg)
  - PRZR Surge Line
  - Main Steam Lines Inside Containment

- Systems displaying *Adequate Separation from Essential Systems and Components*
  - Outside containment, separation is achieved through four Safeguard Buildings for U.S. EPR
  - Inside containment, separation must be evaluated for each Essential SSC per BTP 3-3

Jet Impingement Background

▶ Break Locations

◇ Breaks postulated at following locations:

- Terminal ends (only circumferential breaks)
- High Stress Locations – Class 1 Piping
  - ASME Eqn 10 and 12 or 10 and 13 stress range exceeds 2.4 S_m (i.e., 0.8 x ASME allowable) or
  - Cumulative Usage Factor exceeds 0.1 (i.e., 0.1 x ASME allowable)
- High Stress Locations – Class 2/3 Piping
  - Sum of ASME Eqn 9 and 10 stress range exceeds $0.8(1.8S_h+S_A)$ (i.e., 0.8 x ASME allowable)

Jet Impingement Background

▶ Break Types

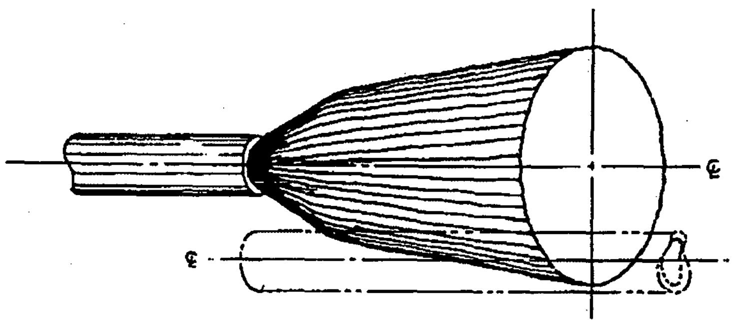
◇ Determination of Break Types established by BTP 3-4

- Circumferential Breaks
  - Caused by Longitudinal Stress
  - Loading Constituents: Bending Moment, Axial Pressure Stress
  - Locations where Longitudinal Stress > 1.5 x Circumferential Stress

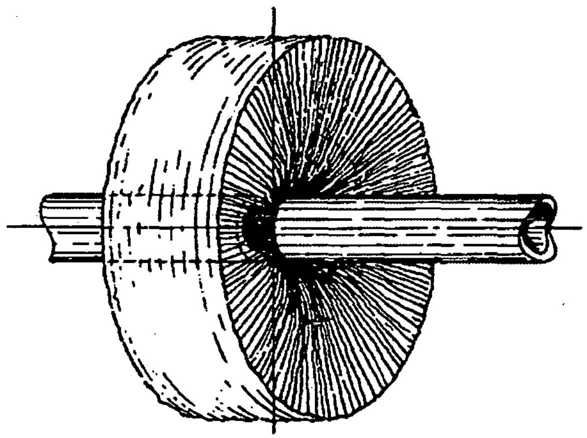
- Longitudinal Breaks
  - Caused by Circumferential Stress
  - Loading Constituents: Circumferential Pressure Stress (a.k.a Hoop Stress)
  - Locations where Longitudinal Stress < 1.5 x Circumferential Stress

Jet Impingement Background

- **Circumferential Breaks – Restrained and Unrestrained**
  - ◇ **The jet direction is <u>well defined</u> and whip restraints can be designed to restrain the break.**



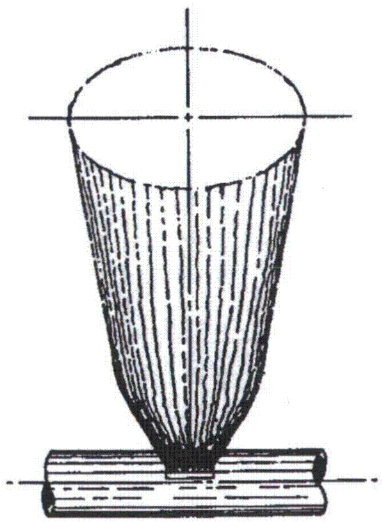
(A) Jet From Circumferential Break with Unrestrained Ends



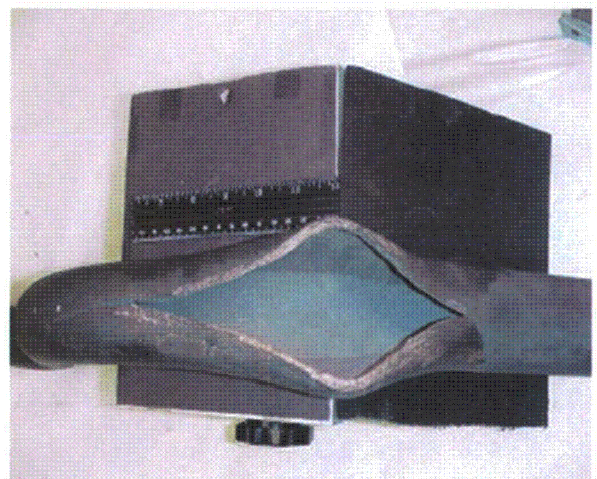
(B) Jet From Circumferential Break with Ends Restrained

Jet Impingement Background

- **Longitudinal Breaks**
  - **The jet direction is <u>undefined</u> and whip restraints cannot be designed to restrain the break.**



(C) Jet From Longitudinal Break



Jet Impingement Background

- **Jet Impingement**
  - **Jet impingement methodology described in SRP 3.6.2**
  - **Previous revisions of SRP 3.6.2 (used by operating plants)**
    - Methodology was based on ANS 58.2
      - Considered steady jets
      - Jet area, expansion angle and loading was defined
  - **Current revision of SRP 3.6.2 (Rev. 2 - 2007)**
    - Acceptable methodology is not defined
    - Indicates that ACRS considers some assumptions in ANS 58.2 as nonconservative, based on Ransom/Wallis papers

Jet Impingement Background

- **Jet Impingement**
  - **Ransom/Wallis papers (2004)**
    - Identified Possible Nonconservatisms in ANS 58.2
      - Consideration of steady jets
      - Jet area calculation
      - Jet pressure distribution across target area
      - Jet expansion angle and propagation distance

- **Blast Effects**
  - **Blast loading is currently not discussed in SRP 3.6.2**
    - Current operating plants do not consider blast loading due to pipe rupture
  - **Ransom paper identified blast loading as a possible concern**
    - Indicated that approximate analytical methods may be appropriate but there should be some basis

NRC Key Issues from RAIs

- **Jet Impingement**
  - **Jet Geometry**
    - ANS 58.2 jet geometry was not based on basic thermodynamics
    - Asymptotic plane not understood
    - Jet expansion angle was independent of jet properties
    - Jet deflection was not considered
  - **Unsteady Jet Behavior**
    - Supersonic and high speed subsonic jets (M = 0.5 – 1.0) are known to exhibit unsteady behavior
      - Resonance may exist in some cases (i.e., the jet flow structures may exhibit specific frequencies)
      - Random unsteadiness (i.e., broadband noise or turbulence) in the jet should be considered

NRC Key Issues from RAIs

- **Blast Effects**
  - **Blast Effects**
    - The possibility of additional loadings due to blast effects was never considered
    - In considering blast effects, the interaction of blast waves with nearby SSC must be considered

AREVA NP Methodology

Chris McGaughy
Advisory Engineer
RCS & Class 1 Piping & Supports

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AREVA NP Methodology

▶ AREVA Jet Impingement Methodology

◇ Goal

- Develop conservative engineering solutions that may be easily replicated and meet regulatory requirements

◇ Break Locations and Types

- Break locations and types are determined based on BTP 3-4

◇ Jet Geometry

- Effective length based on NUREG/CR-2913 (Two Phase Jets) or NEA/CSNI/R(95)11 (Steam Jets)

- Jet area based on continuity equation

AREVA NP Methodology

▶ AREVA Jet Impingement Methodology

◇ Unsteady Jet Behavior

- Evaluate possibility of jet resonance based on:
  - Nozzle pressure ratio (NPR)
  - Nondimensional target distance (Target Length (L) / Nozzle Diameter (D))
  - Steadiness of source conditions (i.e., pressure and flow)

- Evaluate impact of random unsteadiness on essential SSC

◇ Jet Deflection

- Consider all targets as primary if jet is capable of striking as a secondary target

AREVA NP Methodology

- **AREVA Jet Impingement Methodology**
  - **Target SSC Structural Evaluation**
    - In cases where jet resonance is possible, use sinusoidal loading consistent with the jet minimum frequency and dynamic pressure
    - Structural evaluations performed using applicable codes and standards (ASME, AISC, ACI)
    - JI loads combined with loads due to pressure, weight, seismic and other pipe rupture loading constituents, if applicable

AREVA NP Methodology: Break Locations

▶ Breaks postulated at following locations:

◇ Terminal Ends (only Circumferential Breaks)

◇ High Stress Locations – Class 1 Piping

- ASME Eqn 10 and 12 or 10 and 13 stress range exceeds 2.4 S_m (i.e., 0.8 x ASME allowable) or
- Cumulative Usage Factor exceeds 0.1 (i.e., 0.1 x ASME allowable)

◇ High Stress Locations – Class 2/3 Piping

- Sum of ASME Eqn 9 and 10 stress range exceeds $0.8(1.8S_h+S_A)$ (i.e., 0.8 x ASME allowable)

AREVA NP Methodology: Break Types

- **Determination of Break Types established by BTP 3-4**
  - **Circumferential Breaks**
    - Caused by longitudinal stress
    - Loading constituents: Bending Moment, Axial Pressure Stress
    - Locations where Longitudinal Stress > 1.5 x Circumferential Stress
  - **Longitudinal Breaks**
    - Caused by circumferential stress
    - Loading Constituents: Circumferential Pressure Stress
    - Locations where Longitudinal Stress < 1.5 x Circumferential Stress

Note: Circumferential stress consists of pressure only, which is held to ~1.0 S_m by ASME design requirements (i.e., minimum required wall thickness calculation). If stress exceeds 2.4 S_m, it must be longitudinal stress and, therefore causes a circumferential break

Conclusion: Longitudinal breaks are not a credible failure mode for the U.S. EPR piping

AREVA NP Methodology:
Jet Geometry

▶ Jet Geometry

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AREVA NP Methodology: Jet Geometry

▶ **Jet Geometry**

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AREVA NP Methodology: Unsteady Jet Behavior

▶ Unsteady Jet Behavior - Resonance

◇ Feedback Loop

- Various studies have considered the possible mechanisms for the feedback loop, inside the jet, in the shear layer and outside the jet (Nosseir and Ho, Tam, etc.)

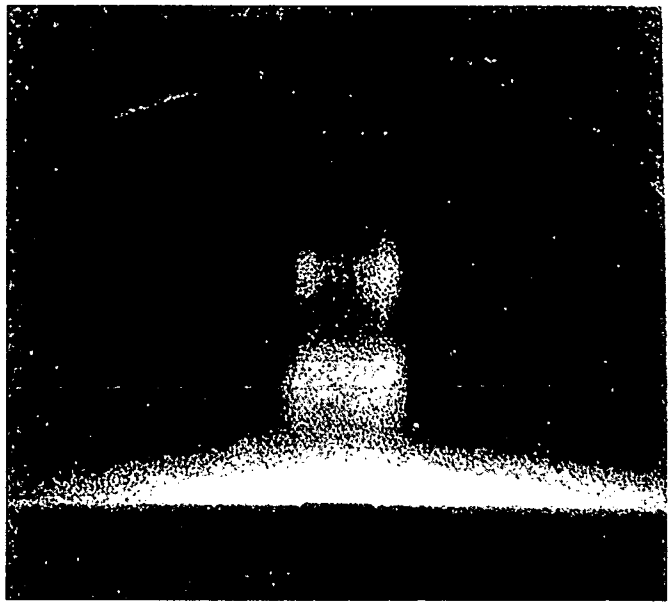
- Two types of jet resonance
  - Impinging tones – Significant impact on jet pressure/force variations
  - Screech tones – High Frequency and limited impact on jet pressure/force variations

- High speed subsonic jets are capable of generating strong impingement tones in the form of axisymmetric jet modes only (Ref. Tam)
  - Mach number must be greater than 0.7 (Ref. Nosseir and Ho)
  - Strouhal number must be greater than 0.3 (Ref. Nosseir and Ho)

- Supersonic jets are capable of generating strong impingement tones in the form of axisymmetric or helical/flapping jet modes (Ref. Tam)
  - Dominant mode shapes can be axisymmetric (low L/D) or helical/flapping (high L/D)

AREVA NP Methodology: Unsteady Jet Behavior

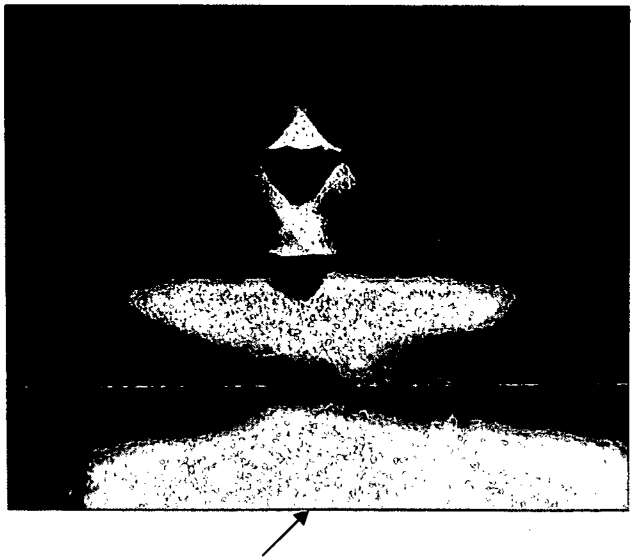
▶ **High Speed Subsonic Jets – Axisymmetric Modes**



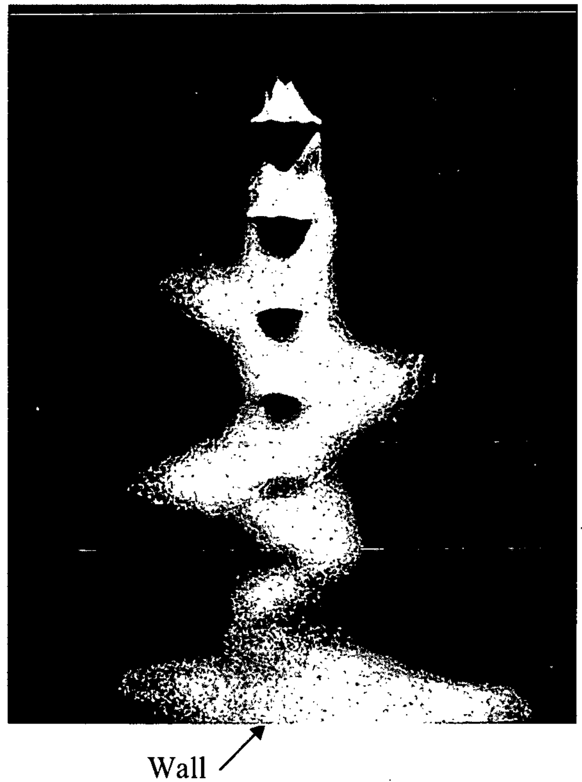
Mach 0.8 jet, L / D = 4.0

AREVA NP Methodology: Unsteady Jet Behavior

▶ **Supersonic Jets – Axisymmetric and Helical Modes**



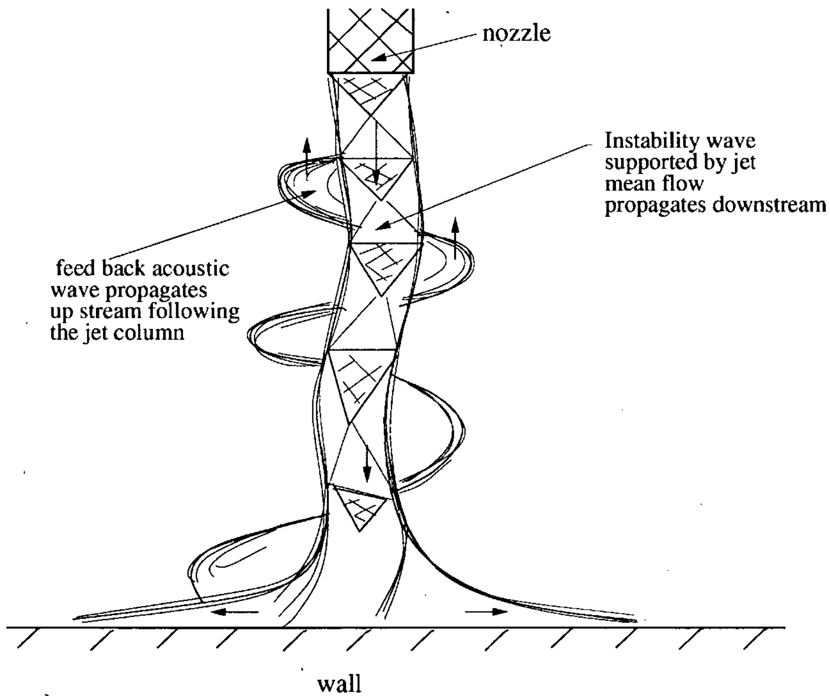
Mach number 1.4, L /D = 6.0



Mach number 1.4, L /D = 10.0

AREVA NP Methodology: Unsteady Jet Behavior

▶ Unsteady Jet Behavior – Feedback Mechanism



AREVA NP Methodology: Unsteady Jet Behavior

- **Unsteady Jet Behavior - Resonance**

AREVA NP Methodology: Source Conditions

- **Source Conditions**

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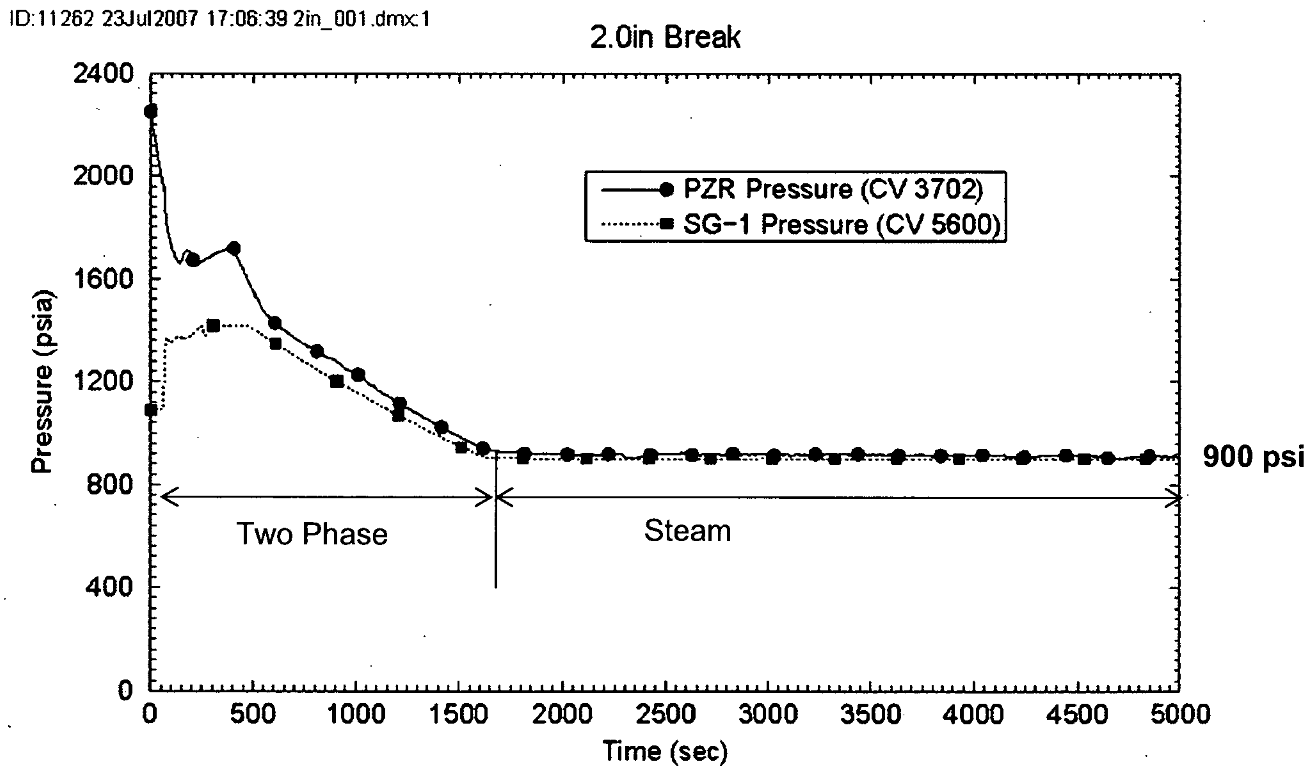
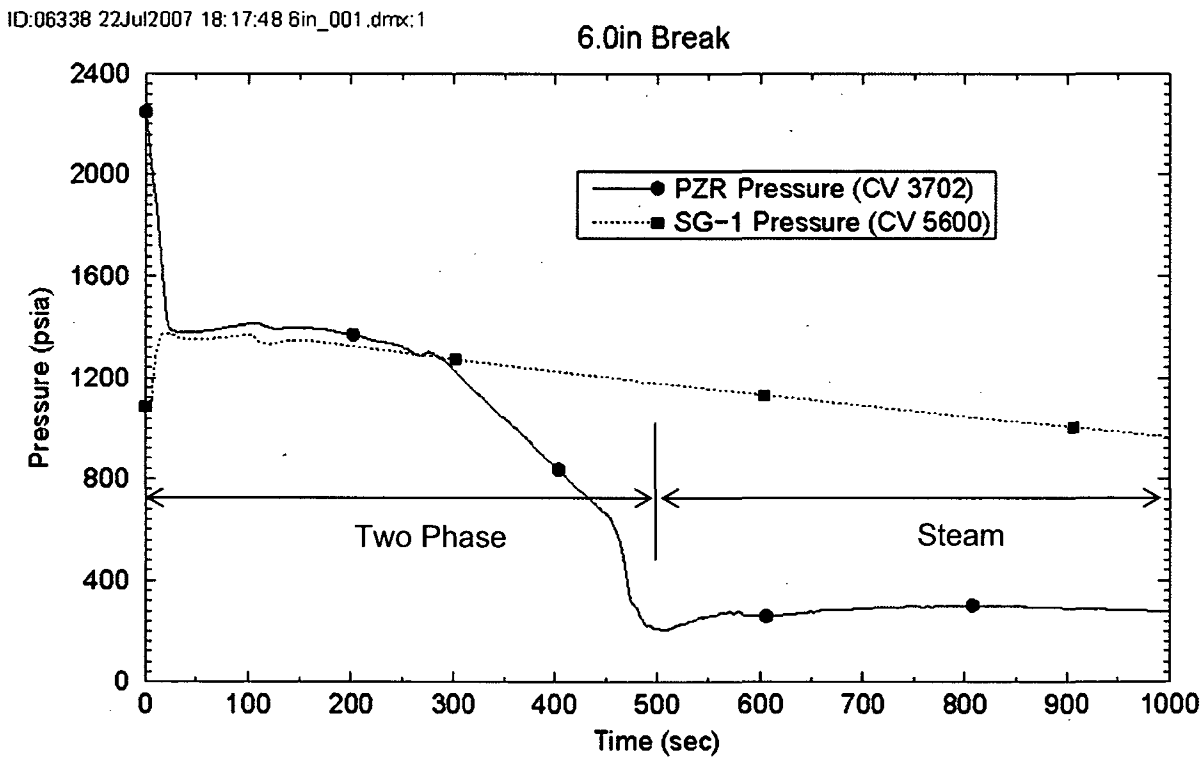
AREVA NP Methodology: Source Conditions

▶ **Source Conditions – RCS Blowdown – 2" Break**



AREVA NP Methodology: Source Conditions

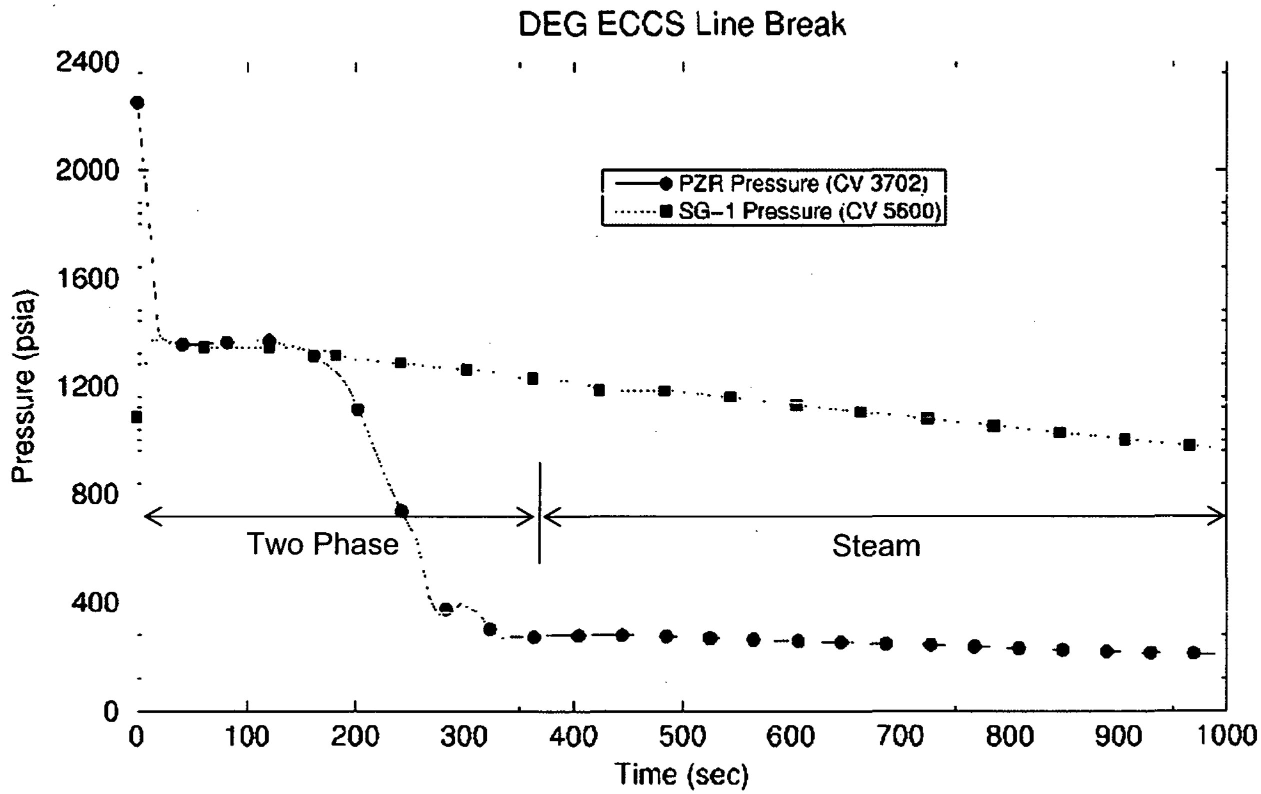
▶ Source Conditions – RCS Blowdown – 6" Break



300 psi

AREVA NP Methodology: Source Conditions

- ▶ **Source Conditions – RCS Blowdown – ECCS Break (8.5")**



200 psi

AREVA NP Methodology: Source Conditions

▶ Source Conditions

◇ RCS Primary Side Blowdown Analysis results:

- Conditions in two phase jets (initially subcooled water) change rapidly until system pressure reaches saturation

- After steam conditions are reached, the conditions remain steady

- Steady state steam pressure depends on break size and ability of ECCS to replace inventory
  - 2" Break = 900 psi
  - 6" Break = 300 psi
  - 8.5" ECCS Break = 200 psi (largest RCS break)

▶ Source Conditions

◇ Conclusions

- The only jets in the U.S. EPR that are capable of maintaining a constant source pressure and flow rate are steam jets

- While all two phase jets and steam jets must be considered for loading of target SSC, only steam jets are important, relative to studies of resonance

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AREVA NP Methodology: Unsteady Jet Behavior

Jet Resonant Frequencies

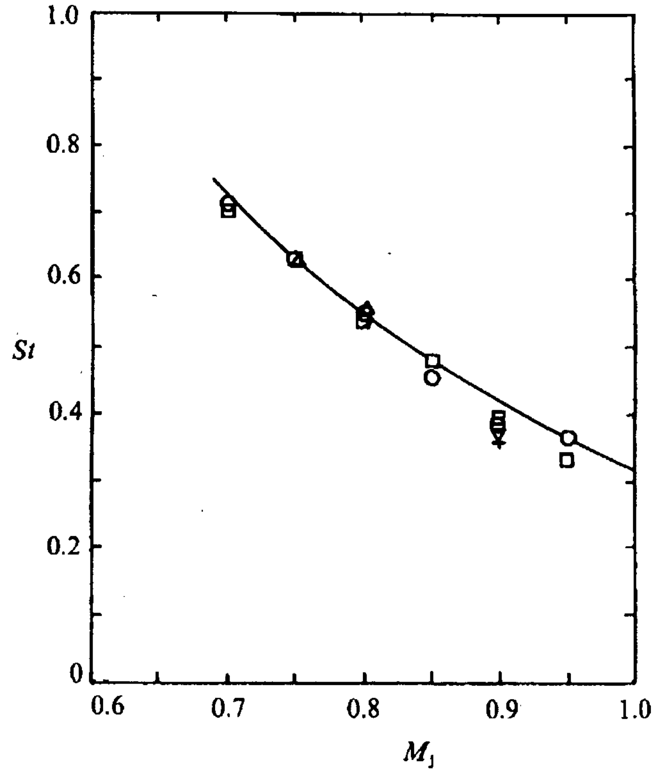
- Impingement tones are generated by a feedback loop consisting of an instability wave of the jet and a feedback acoustic jet column mode. The instability wave provides the energy that sustains the feedback loop.
  - **In subsonic jets, only axisymmetric modes can achieve resonance. Tam provides a plot of Strouhal number vs. Jet Mach number for impinging tones.**
  - **In supersonic jets, axisymmetric and helical modes can achieve resonance. Tam provides a plot of Strouhal number vs Jet Mach number for helical modes and an equation for the minimum frequency of axisymmetric impinging tones, as follows:**

$$\omega > \frac{7.66U_{jet}}{D_{jet}M_{jet}(a_{jet}/a_{ambient})(a_{ambient}/a_{jet}+M_{jet})^2+1)^{0.5}}$$

Tam & Ahuja (1990)

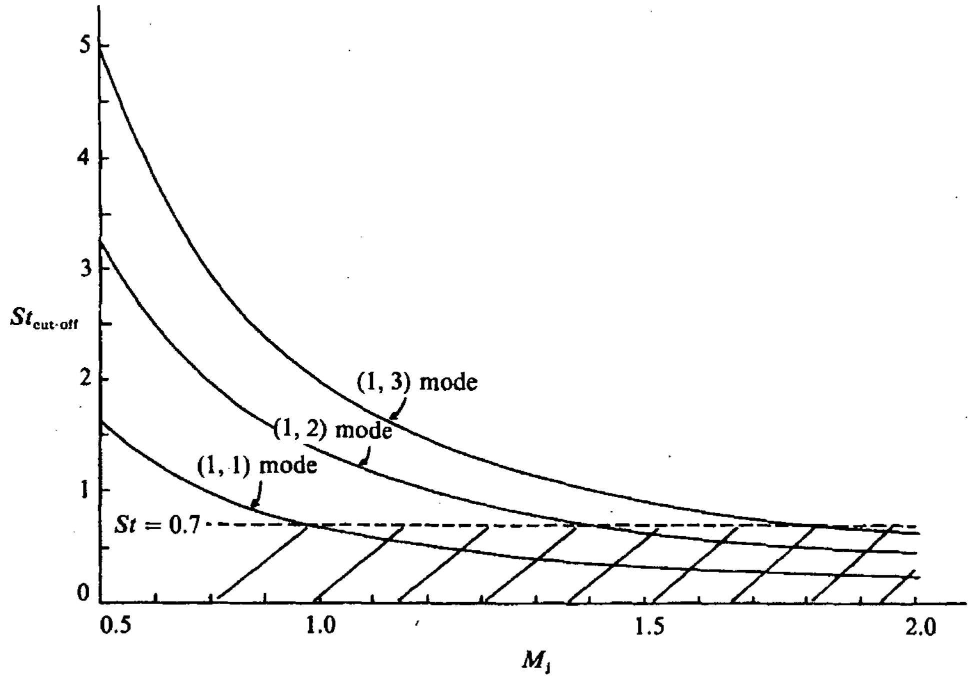
AREVA NP Methodology: Unsteady Jet Behavior

- Jet Resonant Frequencies – Subsonic Axisymmetric Modes (Ref. Tam)



AREVA NP Methodology: Unsteady Jet Behavior

- **Jet Resonant Frequencies – Supersonic Helical Modes (Ref. Tam)**



AREVA NP Methodology: Unsteady Jet Behavior

▶ Jet Resonant Frequencies

◇ **Based on this information, the following impinging tone frequencies are calculated.**

Minimum Jet Impingement Tone Frequencies

Pipe Diameter (in)	Jet Sound Speed (ft/sec)	Subsonic Jet Freq (M=0.7) (Hz)	Subsonic Jet Freq (M=0.9) (Hz)	Supersonic Jet Axisym. Freq (M=2) (Hz)	Supersonic Jet Helical Freq (M=2) (Hz)
4	1500	2205	1620	987	1286
6	1500	1470	1080	658	857
10	1500	882	648	395	514
14	1500	630	463	282	367
18	1500	490	360	219	286
24	1500	368	270	165	214

AREVA NP Methodology: Unsteady Jet Behavior

- Random Unsteadiness

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AREVA NP Methodology

Jet Impingement References

1. Tam, C. K. W. and Ahuja, K. K., "Theoretical Model of Discrete Tone Generation by Impinging Jets," 1990
2. Nosseir, N. S. and Ho, C-M., "On the Feedback Phenomenon of an Impinging Jet," 1979
3. Kim, S. I. and Park, S. O., "Oscillatory Behavior of Supersonic Impinging Jet Flows," 2005
4. Dauptain, A., Cuenot, B. and Gicquel, L.Y.M., "Large Eddy Simulation of Stable Supersonic Jet Impinging on Flat Plate," 2010

AREVA NP Methodology: Computational Fluid Dynamics (CFD) Results

AREVA NP Methodology: CFD Results

- Steam Jet: NPR < 10

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AREVA NP Methodology: CFD Results

- ▶ **Steam Jet: NPR < 10**

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AREVA NP Methodology: CFD Results

- Steam Jet: NPR > 10

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AREVA NP Methodology: CFD Results

▶ **Steam Jet: NPR > 10**

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AREVA NP Methodology

- **Unsteady Jet Behavior**
  - ◇ **Conclusions drawn from literature and analyses**

AREVA NP Methodology

▶ Jet Deflection

◇ **Deflection of a supersonic jet creates an oblique or normal shock**

- Shocks increase entropy and convert kinetic energy to thermal energy
- Loss of kinetic energy reduces dynamic pressure and momentum flux
- Oblique shocks have a minor impact on jet conditions
- Normal shocks have a major impact on jet conditions

◇ **Maximum allowable oblique shock angle can be calculated**

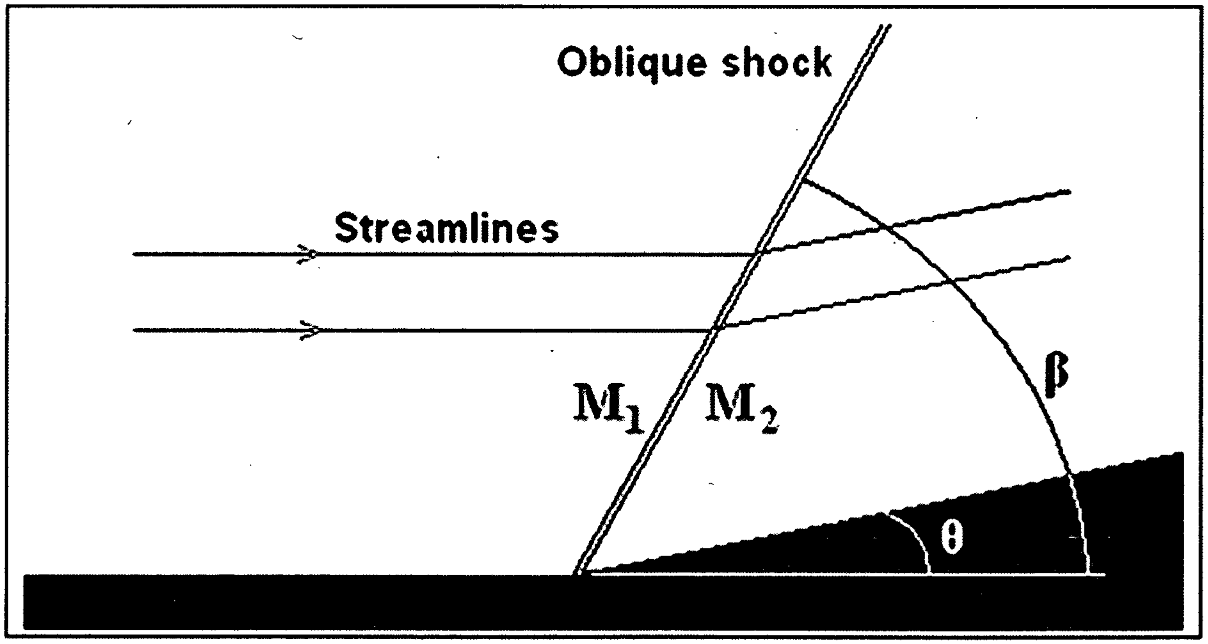
- Mach 2.5 jet can be turned about 30° without experiencing a normal shock (Ref. Shapiro)

AREVA NP Methodology

▶ Oblique Shock

◇ **Maximum turning angle depends on upstream Mach Number**

- For M=2.5, maximum angle is about 30° (Ref. Shapiro)



AREVA NP Methodology

▶ Jet Deflection

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AREVA NP Methodology

AREVA NP Methodology

▶ AREVA Blast Effects Methodology

◇ Goal

- Develop conservative engineering solutions that may be easily replicated and meet regulatory requirements

◇ Energy

- Assume isentropic expansion to the environment to determine available energy

- Compare available energy to TNT heat of detonation to determine equivalent weight of TNT

◇ Blast Loading

- Use methods from Kinney and Graham and Military Standard (TM5-1300) to determine overpressure and impulse

AREVA NP Methodology: Blast Effects

▷ Calculation of Energy – Break Opening Area

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AREVA NP Methodology: Blast Effects

- ▶ **Calculation of Energy – Fluid Mass**

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AREVA NP Methodology: Blast Effects

▶ Calculation of Energy – Exit Plane Sound Speed

[ ]

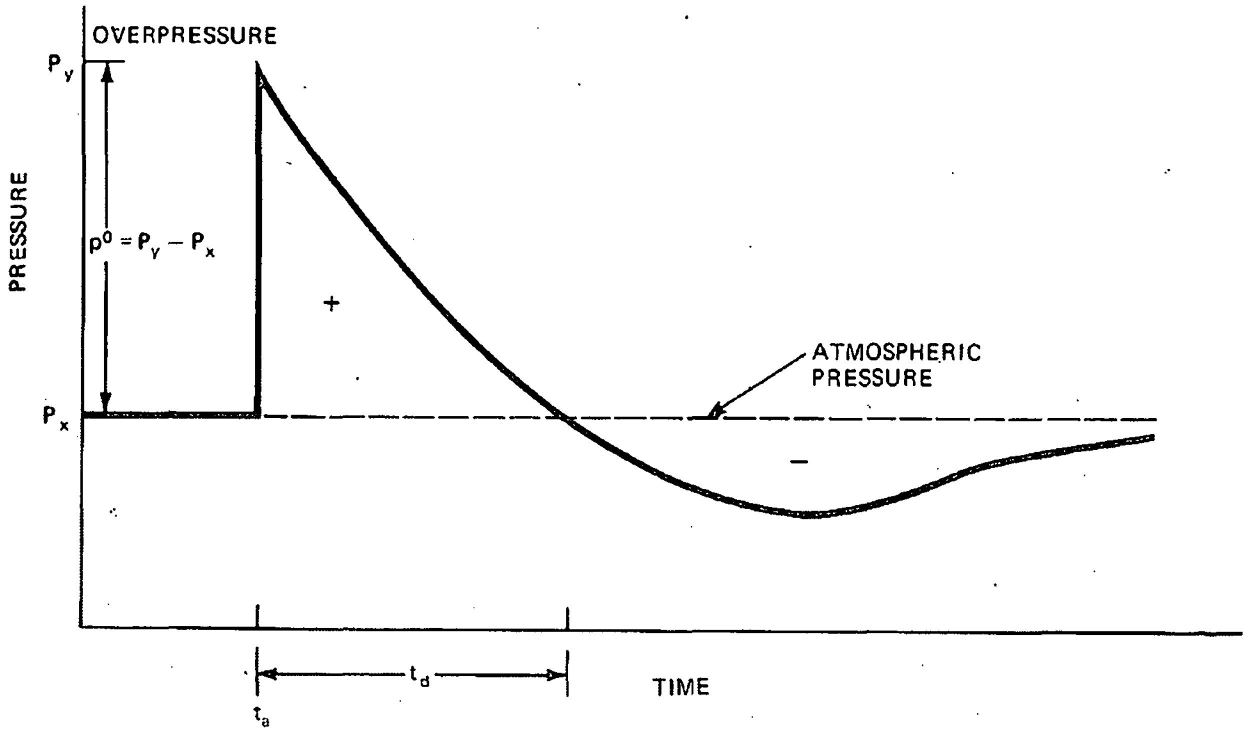
AREVA NP Methodology: Blast Effects

- **TNT Equivalence Method**
  - TNT Heat of Detonation is 2E6 ft-lbf/lbm
  - Steam (1250 psi, x = 1) Available Energy is 2E5 ft-lbf/lbm
  - Using the TNT scaling laws to determine a scaled distance, impulse and pressure can be determined

AREVA NP Methodology: Blast Effects

- Blast Effects on Target SSC

AREVA NP Methodology: Blast Effects

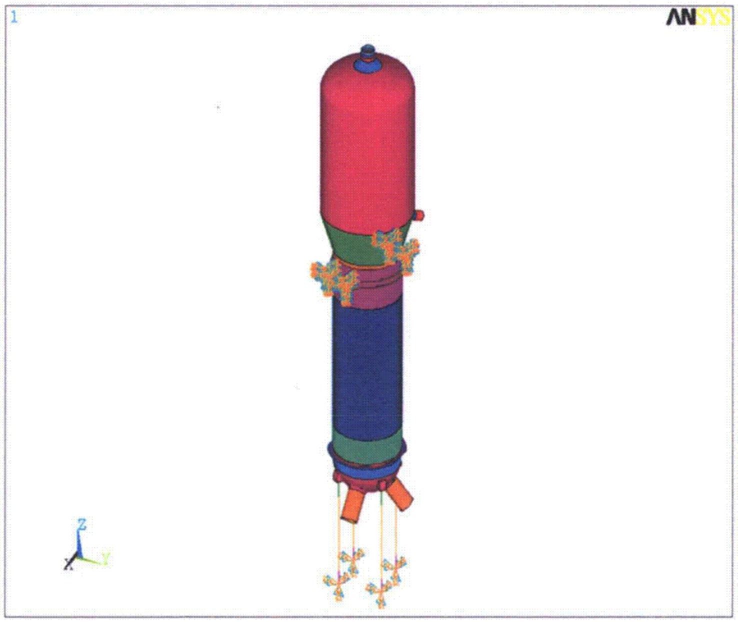


AREVA NP Methodology: Blast Effects

References

1. Army TM 5-1300/Navy NAVFAC P-397/Air Force AFR 88-22, "Joint Departments of the Army, the Navy, and the Air Force, Structures to Resist the Effects of Accidental Explosions," 1990
2. Kinney, G. and Graham, K., "Explosive Shocks in Air," 1985

AREVA NP Methodology: Dynamic Analysis of Steam Generator



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AREVA NP Methodology: Dynamic Analysis of Steam Generator

- Analytical Methodology

AREVA NP Methodology: Dynamic Analysis of Steam Generator

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Stress Intensity Trend for SG Column Supports

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Stress Intensity Trend for SG Upper Lateral Supports

Stress Intensity Trend for SG Shell

AREVA NP Methodology: Flow Chart

Issue Summary

Issue	Ransom/Wallis Papers	RAI Concerns	Issue Addressed by AREVA?
Jet Area Calculation	Yes	Yes	✓
Jet Expansion Angle	Yes	Yes	✓
Asymptotic Plane	Yes	Yes	✓
Unsteady Jet	Yes	Yes	✓
Jet Resonance	-----	Yes	✓
Jet Deflection	-----	Yes	✓
Blast Effects	Yes	Yes	✓
Blast Wave Reflection	-----	Yes	✓

Closure Plan

Russ Wells

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Closure Plan

- AREVA NP to provide Final Response to RAI 354 Questions 3.6.2-33 through 40
  - Currently due to NRC 11/18/2010 (may need to defer based on the results of the meeting)
- Need frequent and timely interaction with NRC on the final response to assure NRC concerns have been addressed.
- Suggest monthly interactions with NRC until closure ahs been achieved.

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