COMMENTS ON GSI-191 MODELS FOR DEBRIS GENERATION

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INTRODUCTION

A review of NUREG/CR-6808, and the NEI documentation has revealed, in my opinion, some serious omissions/inadequacies about the treatment of blast waves, supersonic jets, and the parameters that are important for debris generation. The situation appears to be sufficiently confused that it is impossible to determine if the recommended methods would produce a conservative or a non-conservative result for the quantity of debris that would be generated during a LOCA. For example, the primary parameter used to gauge the extent of debris generation is referred to as "damage pressure", "destruction pressure", stagnation pressure, and "jet pressure" which are used more or less interchangeably without definition. The correct parameter is dynamic pressure which is a function of the velocity. Further, except for one set of tests, the experiments that have been performed were performed at less than PWR initial system pressure and the debris models that have been developed are not in terms of parameters that would account for variation in the initial jet stagnation pressure or variations of the target position relative to the jet. In addition, the ANSI/ANS Standard Jet Plume model does not, in my opinion, adequately account for the properties of a supersonic jet plume that are important for assessment of damage to insulation and structure of an LWR system. I will expand on these statements in the discussion to follow.

The overall process leading to sump blockage will consist of a pipe opening or rupture which will release a high pressure steam-water mixture through a blow-down process that will continue until the system pressure and the containment pressures are essentially equilibrated. The initial system depressurization and containment atmosphere pressurization will produce a spherical shock or blast wave that will propagate out radially from the pipe opening. This initial transient will be followed by formation of a supersonic jet plume that will impinge on the surrounding equipment and structure. Both of these processes have the potential to produce debris. I will present some information from the literature and use some simple analysis to shed light on the character of these processes.

THE INITIAL BLAST WAVE

As the discharged fluid expands it will do work on the containment atmosphere and produce compression waves that will coalesce into a spherical shock wave or blast wave. This wave will travel radially at supersonic speeds until it is reflected from structure or the containment wall. The spherical shock will initially have a significant overpressure that will decrease as the shock expands radially. The possible existence of such phenomena is acknowledged in NUREG/CR-6808 and it is stated that substantial damage may result in the vicinity of the break. However, it is subsequently stated that the shock wave decays rapidly as it expands radially, which is true, but no analysis is presented to substantiate this or to define a region in which damage may occur. Further, it is surmised that the break opening will occur over a finite period of time and that this would reduce blast effects. With this reasoning, blast wave effects are not considered further in the debris generation modeling proposed in NUREG/CR-6808 nor in the NEI guidance.

The initial blast wave for a sudden opening break will have the same strength as a normal shock with a stagnation pressure equal to 2250 psia and a downstream static pressure equal to 14.7 psia. The overpressure produced by this shock will be as high as 241 psi (upstream static pressue minus the downstream static pressure). This overpressure is sufficient to cause extensive damage to insulation and structure on which it impinges. Even if the break does not open instantaneously, the pressurization process produces compression waves that travel successively faster and will coalesce into a spherical shock wave. The weakening of this shock as it expands should be determined in order to define a zone of influence for destruction associated with the blast wave. There are no exact and general solutions for this type of shock wave propagation and a numerical solution for the transient viscous flow is required. However, there are approximate methods for estimating the shock behavior that may be sufficient. One approximate method, based on similarity considerations, is described in Holt, "Basic Developments in Fluid Dynamics, Volume 1", Academic Press 1965. In summary, the initial blast wave should not be dismissed without a more substantial basis.

THE JET MODEL

The ANSI/ANS Standard model for the jet appears to be an overly simplistic and perhaps incorrect model for an under expanded supersonic jet. The transient nature of the jet plume that will result as the system depressurizes is ignored and it does not include the expansion process that occurs after an under expanded jet leaves the break opening. Further, the parameters that are used to define the jet, isobars of pressure, are not an appropriate choice for estimating fluid forces on structures. The two parameters that are normally used in estimating forces on structures are overpressure, associated with blast waves and traveling shocks, and the dynamic pressure, associated with the velocity field. The overpressure due to a shock wave is the sudden change in static pressure across the shock. Whereas, the surface forces due to flow over a body, i.e. the lift and drag forces, are expressed in terms of the dynamic pressure of the surrounding flow by defining lift and drag coefficients as functions of the Reynolds number. Clearly the forces that cause damage to structures are the transient local static pressures and shear forces that cause dynamic stress in the structure from fluid structure interaction, such as flutter due to the classic Kelvin-Helmholtz type of instability. These periodic forces then produce fragmentation by shearing and fatigue. Prediction of these local instantaneous forces requires a level of detailed transient simulation far beyond what is possible or needed for the sump clogging issue. Consequently, empirical models for the forces on objects submerged in the jet plume from a break and the resulting damage are needed for this purpose. These models require determination of the local jet plume properties, e.g. the dynamic pressure, in the vicinity of the submerged object. There will be interaction effects when there are several objects within the plume. Such interaction effects are beyond the scope of what is needed since the details of the jet size, orientation, and object location are not known a priori. The empirical models for damage in terms of local undisturbed jet plume parameters should provide a conservative estimate of damage since shadowing effects are ignored.

The jet plume that will emanate from a break in the primary system of an LWR will consist of a steam-water two phase jet. Modeling such flows is beyond the present state of the art except for homogeneous-equilibrium (HEM) models. Presumably multi-dimensional two fluid models could be used, but I do not know of any that have been developed for supersonic flow. The entire flow, including the normal shocks that form along the axis of the jet as well as the turbulent mixing process at the jet boundary can be modeled by finite difference methods using sufficiently fine grids and shock capturing difference methods. Examples of such calculations for an ideal gas are reported in NASA Technical Paper 3596,"Numerical Simulation of Jet Aerodynamics Using the Three-Dimensional Navier-Stokes Code PAB3D", September 1996. A PDF file of this report will be attached to the email transmitting this discussion. Some figures from the NASA report also will be included later in this discussion. Calculations similar to the NASA calculations could be made based on the HEM thermodynamic model using either FLUENT or the PAB3 code.

To help provide insight to the character of supersonic jet plumes, two sketches are shown in Figure 1 for jet plumes that are representative of (1)conditions at high initial system stagnation pressure and (2)for the conditions that would exist near the end of blowdown. Both plumes are for under expanded flows. I have attempted to illustrate the key features of the plume. The Prandtl-Meyer angle is the angle between the tangent to the jet boundary and the axis of the jet as it emanates from the break (Assuming that the jet exits at a Mach number of 1.0 parallel to the axis). This angle is usually expressed in terms of the Mach number which in turn depends on the jet pressure ratio (The ratio of the jet stagnation pressure to the ambient static pressure). The jet boundary curves toward the axis of the jet due to multi-dimensional effects and this produces compression waves that coalesce into a curved oblique shock. This shock terminates at a so called Mach stem or disk that is a strong shock that extends through the axis of the jet and produces regions of subsonic flow at high pressure that subsequently reexpand. The oblique shock from the plume boundary is reflected at the Mach stem and will intercept the plume boundary further downstream and be reflected as an expansion. This process will be repeated until the jet becomes more or less uniform in size and velocity. The shocks cause entropy increase in the jet and are part of the dissipation of the kinetic energy of the jet to thermal energy.

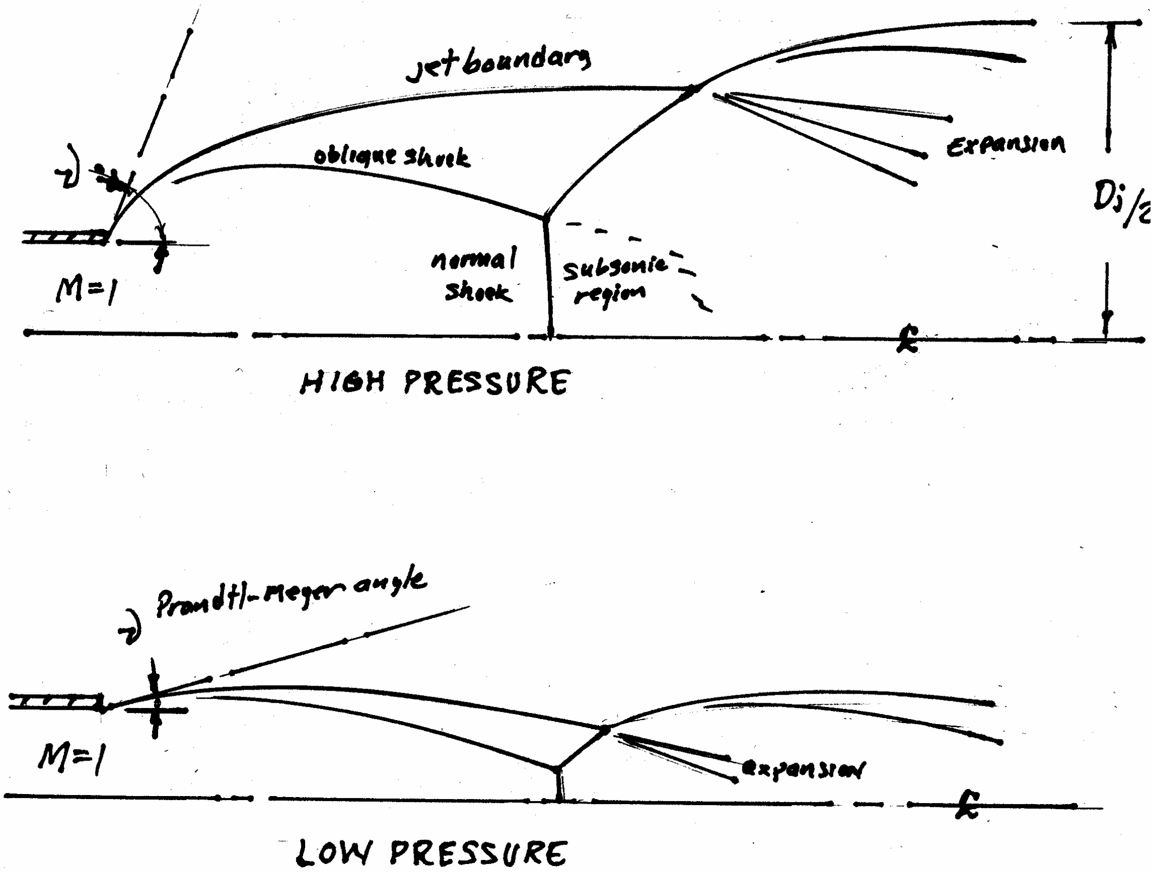


Fig 1. Schematics of expanding supersonic jet plumes showing key features

Not illustrated in Figure 1 is the mixing region that forms along the boundary of the jet as momentum and mass are exchanged with the containment atmosphere. This viscous outer layer results in diffusion of momentum to the containment atmosphere which increases mass flow in the jet and reduces the velocity.

Even though the under expanded supersonic jet has multi-dimensional features, insight to the character of a supersonic jet plume can be obtained by using simple one-dimensional ideal gas models. I have included some parametric calculations based on the one-dimensional ideal gas model for the relevant plume parameters in Appendix A. These calculations could also be made using the HEM model for the steam-water mixture. This is left as an exercise.

Appendix A contains the details of the parametric calculations for key parameters of an isentropic expansion of an ideal gas jet plume to a fixed containment pressure. The parametric variable in the calculations is the system stagnation pressure that the jet is issuing from. The range is from an initial pressure of 2250 psia to 30 psia, i.e. approximately to the limit for choked discharge to a containment pressure of 14.7 psia. This covers the entire range of jet plumes that would occur during a LOCA in a PWR. MATHCAD is used to make these parametric calculations and to produce plots of the key parameters. The parameters calculated include the jet Mach number for isentropic expansion to the containment pressure, the diameter ratio between the jet plume diameter and the diameter of the break, the dynamic pressure, and the Prandtl-Meyer angle.

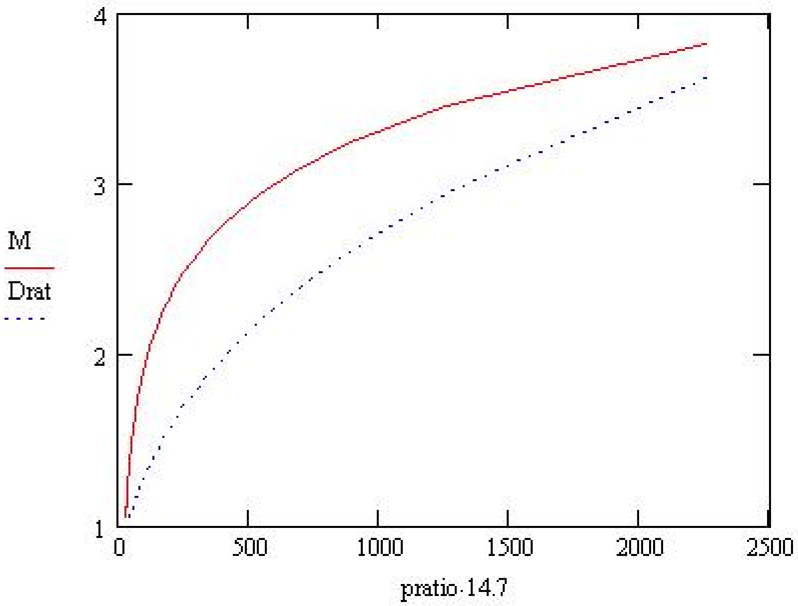


Figure 2. Mach number and diameter ratio of the plume as functions of the system stagnation pressure (psia).

The Mach number of the fully expanded jet and the resulting diameter ratio are plotted in Figure 2 (copied from Appendix A). These calculations are for a specific heat ratio of 1.3, approximately that of steam. Note that a maximum Mach number of 3.75 results and that the maximum plume diameter ratio is about 3.6. The jet is underexpanded until the system pressure drops to about 30 psia, only then would the jet emanate from the break with a diameter approximately equal to the break diameter.

The dynamic pressure and Prandtl-Meyer angle are plotted on Figure 3 , also from Appendix A. The dynamic pressure in the fully expanded jet is approximately 140 psi and the flow cross sectional area is approximately a factor of 10 bigger than the break cross sectional area. The initial jet angle relative to its axis, the Prandtl-Meyer angle gradually reduces from the maximum of approximately 70 deg as the system stagnation pressure reduces. It becomes near zero as the so called jet design pressure ratio is approached and the jet Mach number approaches 1.0.

Clearly, neither the geometry of the jet plume nor the relevant flow parameters are constant throughout the blowdown period.

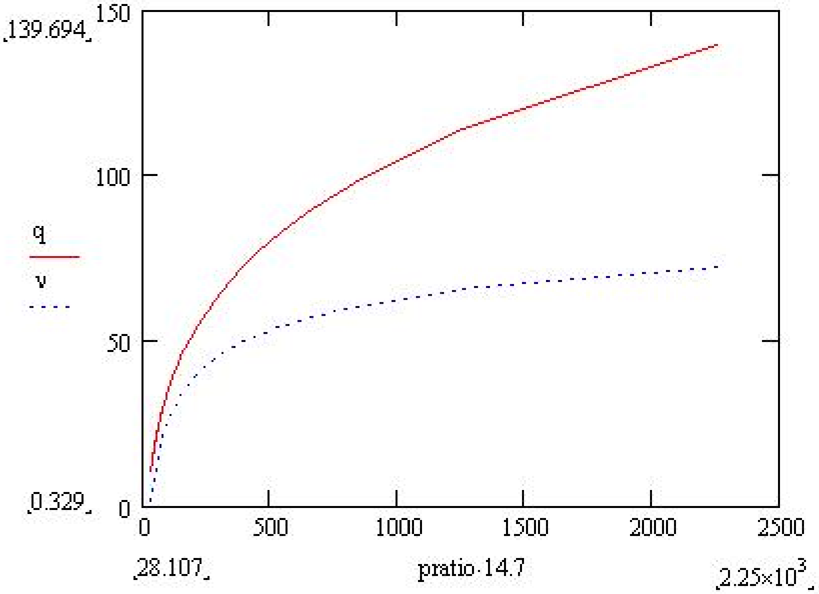


Figure 3. Jet plume Mach number and Prandtl-Meyer angle as a function of the system stagnation pressure (psia).

The static pressure of the jet plume in all cases is assumed equal to the containment pressure. However, the dynamic pressure ranges from approximately 150 psi at the maximum system pressure down to approximately 20 psi at the end of blowdown. During most of the blowdown the dynamic pressure remains greater than 50 psi. A blunt object has a drag coefficient approximately 1.0 so that the force exerted on such an object can be estimated from dynamic pressure multiplied by the frontal area in square inches.

Insight as to the multi-dimensional nature of the jet plume is provided by the results from NASA Technical Paper 3596. I will show several figures from this paper and will also append the entire report in PDF format to the transmittal email for this note. Figure 4 (the figure numbers and captions from the NASA report have also been left on the figures) is a calculated result for the density isobars in an under-expanded jet. Note the successive cells formed, this figure is included only to illustrate the nature of an under expanded supersonic jet The jet exit Mach number is 1.5 and the ratio of static pressure at the exit to the ambient pressure is 1.445. These conditions would be intermediate to the high pressure phase of a LOCA blowdown and the end of blowdown. However, these results are not directly comparable to the LOCA jet because the nozzle exit Mach number is 1.5 compared to 1.0 for the LOCA which does not have a diverging nozzle.

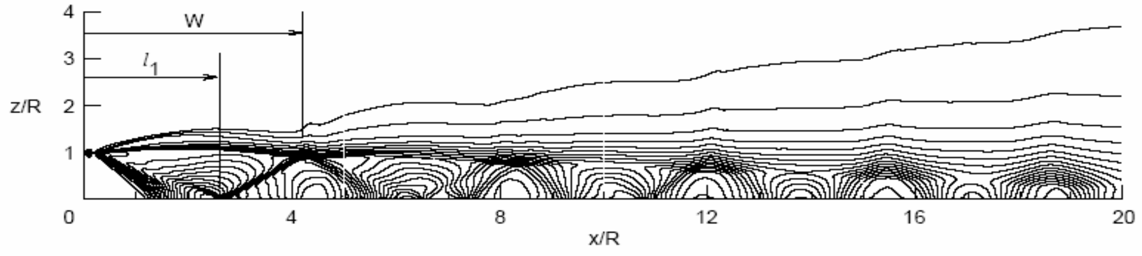


Figure 10. Typical density contours and first shock-cell length definitions for circular underexpanded supersonic jet. Jet exit Mach number = 1.50; $p_e/p_o = 1.445$.

Figure 4. Illustration of under expanded jet plume.

Figure 5 shows calculations compared to data for a jet having a Mach number of 2.0 and a jet pressure ratio of 1.445. Here again these results are not directly applicable to the LOCA blowdown because a diverging nozzle is used to achieve a Mach number of 2.0 prior to further free expansion outside the nozzle exit. These calculations model the mixing process with the surrounding stagnant atmosphere and illustrate the pressure oscillations that occur in an under expanded jet. These oscillations persist far downstream before mixing is complete. Note the relative agreement between the calculations and data.

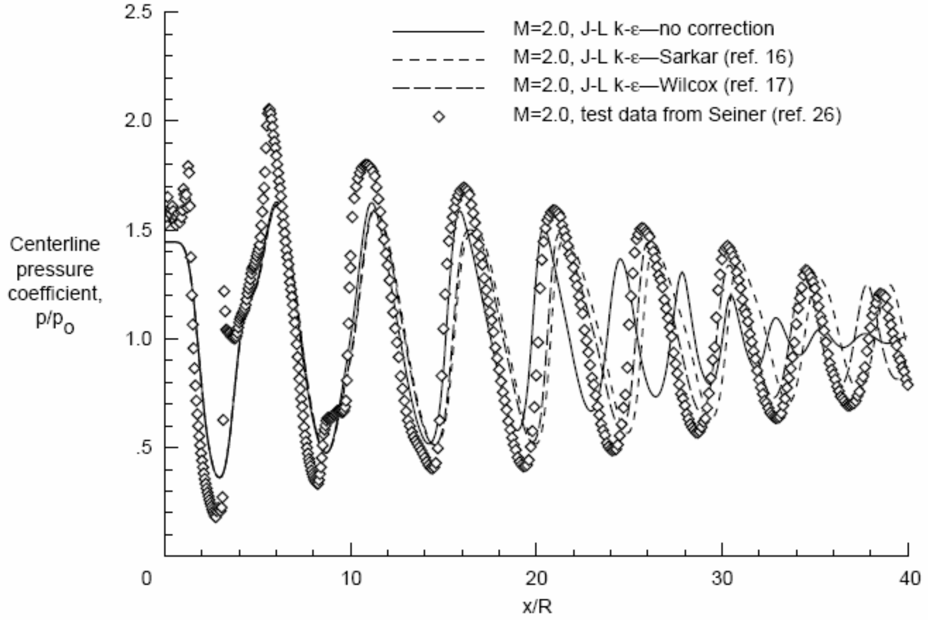


Figure 13. Centerline pressure distribution computed with Jones-Launder *k*-ε model with different compressibility corrections for $p_e/p_o = 1.445$.

Figure 5. Pressure oscillations along the jet plume axis.

The decay in axial velocity due to mixing for a Mach number 2.22 jet at design pressure ratio is shown in Figure 6 compared to measured data. The core of the jet is relatively undiminished out to a distance of about 30 nozzle exit radii. Since this data is for a Mach number 2.22 flow which has an area ratio about 2.15, the length to radius ratio should be multiplied by at least 1.47 to be comparable to a Mach number 1.0 outflow.

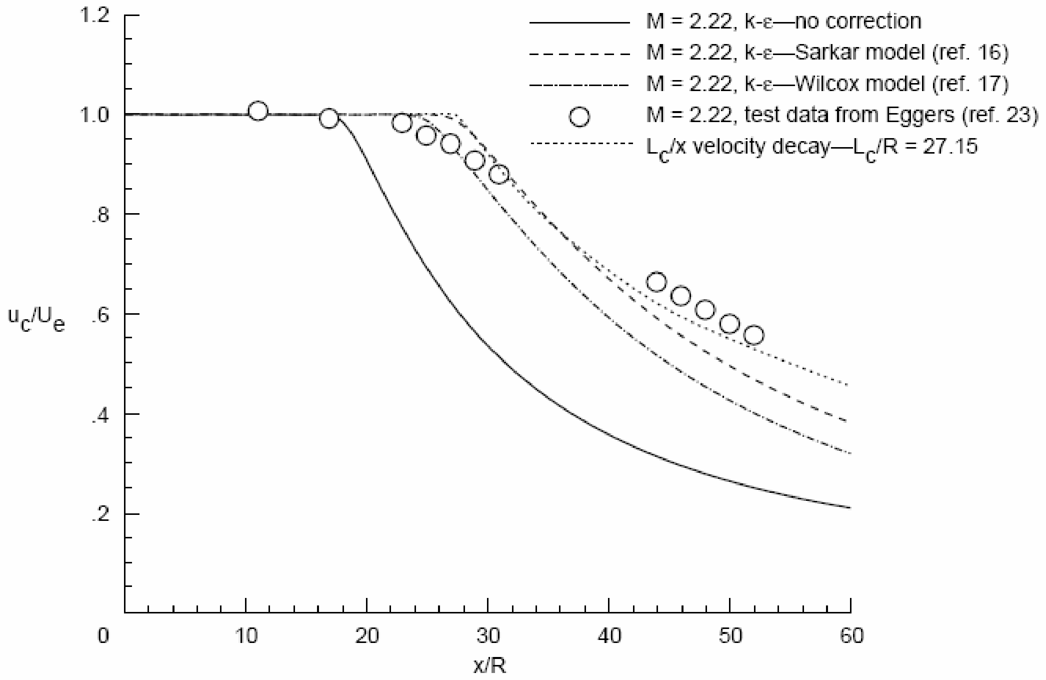
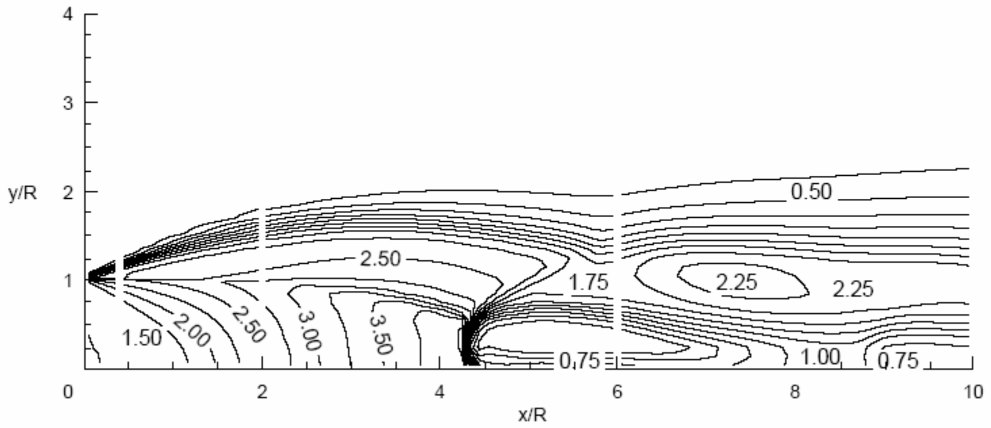


Figure 5. Centerline velocity distribution for supersonic jet using *k*-ε turbulence model with different compressibility corrections.

Figure 6. Ratio of axial velocity to jet exit velocity as a function of axial distance for a jet exit Mach number of 2.22 and a jet pressure equal to the ambient pressure.

The calculated Mach number contours for an under expanded jet plume from a nozzle having and exit Mach number of 1.5 are shown on Figure 7. This figure clearly shows the shock structure within the plume as was illustrated earlier. However, these results are again for a jet Mach number greater than 1.0 and for a jet pressure ratio of 3.15. In comparison, the LOCA jet for the maximum stagnation pressure will have an exit Mach number of 1.0 and a pressure ratio 83. Thus the plume diameter and Mach number will be much greater than this example.



(b) One-half density grid Mach number contours; Interval = 0.25.

Figure 18. Grid study for underexpanded circular jet containing multiple Mach disks. Jet exit Mach number = 1.50; $p_e/p_o = 3.15$.

Figure 7. Mach number contours for an under expanded jet having Mach number 1.5 jet and a pressure ratio of 3.15.

The NASA Technical paper also gives a correlation for the length of the plume core in terms of jet Mach number. This is the length of the jet before the velocity begins to decrease due to turbulent mixing. The correlation is as follows:

$$L_c/R = 8.4 + 2.2M^2$$

For a LWR LOCA the maximum exit Mach number is 3.75 and the radius of the plume at this Mach number is 3.5. For this case the correlation would predict a length to break diameter of 68.8, i.e. for a break diameter of 1m this would mean that the undiminished jet would persist out to about 70 m.

SUMMARY

The results presented here in must be qualified, i.e. the two-phase jet may differ significantly from the characteristics presented based on gas flows and further work would be required to quantify such effects.

The calculations and data shown here indicate that the models used for estimating the zone of influence for a supersonic jet may under predict the extent of the zone.

The reasons for this are:

1. Neglect of blast wave effects.
2. Use of the ANSI/ANS model for the jet plume which appears to be overly simplistic if not wrong.
3. Extent of damage model based on a "pressure" of some sort which seems intuitively incorrect.
4. Test data used for verification of the damage models does not appear to be based on any scale considerations that could be used for generalization of the data and most of the data is for stagnation pressures about half the maximum that would exist for an LWR LOCA.

RECOMMENDATIONS

I think that the aerospace literature needs to be searched for information on blast wave effects, the character of under expanded jet plumes, and models for flutter and other damage mechanisms associated with high speed fluid flow over structures.

To collect sufficient data to put the modeling of debris generation on firm ground is a formidable task. I personally think that more effort should go into design of simple modifications to the containment that would effect hold up of debris such as fences, screens, etc., so that debris does not reach the sump. Alternatively, reduce the sources of debris.

Since the zone of influence model will depend more or less directly on the cube of the break diameter, the volume of the zone will reduce as break diameter is reduced. Thus if risk informed methods can be used to justify consideration of a break smaller than the maximum cooling pipe break then the volume of debris that has to be accommodated by pump sump screens is reduced.

Appendix A Isentropic Jet Plume Analysis

Calculations for a compressible jet of ideal gas having specific heat ratio 1.3

$$j := 0 .. 100$$

range variable for calculation of pressure ratio
Initial stagnation pressure = 2250 paia
Containment pressure = 14.7 psia
Jet is assumed to issue from a DEGB at Mach =1.0 (choked)

$$\gamma := 1.3$$

increment of pressure ratio change from 0.523 to 14.7/2250

$$\Delta := \frac{0.523 - \frac{14.7}{2250}}{100}$$

Incremented ratio of containment pressure to
jet stagnation pressure

$$pr_j := \frac{14.7}{2250} + j \cdot \Delta$$

jet Mach number

$$M_j := \sqrt{\left(\frac{2}{\gamma - 1}\right) \cdot \left[\left(pr_j\right)^{\frac{1-\gamma}{\gamma}} - 1\right]}$$

Prandtl-Meyer angle of expanding jet (degrees)

$$\nu_j := \frac{360}{2 \cdot \pi} \cdot \left[\sqrt{\frac{\gamma + 1}{\gamma - 1}} \cdot \operatorname{atan}\left[\sqrt{\left(\frac{\gamma - 1}{\gamma + 1}\right)} \cdot \left[\left[\left(M_j\right)^2\right] - 1\right]\right] - \operatorname{atan}\left[\sqrt{\left(M_j\right)^2 - 1}\right]\right]$$

Ratio of crossectional area of jet to pipe exit area

$$AR_j := \frac{1}{M_j} \cdot \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \cdot \left[1 + \frac{\gamma - 1}{2} \cdot \left(M_j\right)^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}$$

Diameter ratio of jet to pipe diameter at break

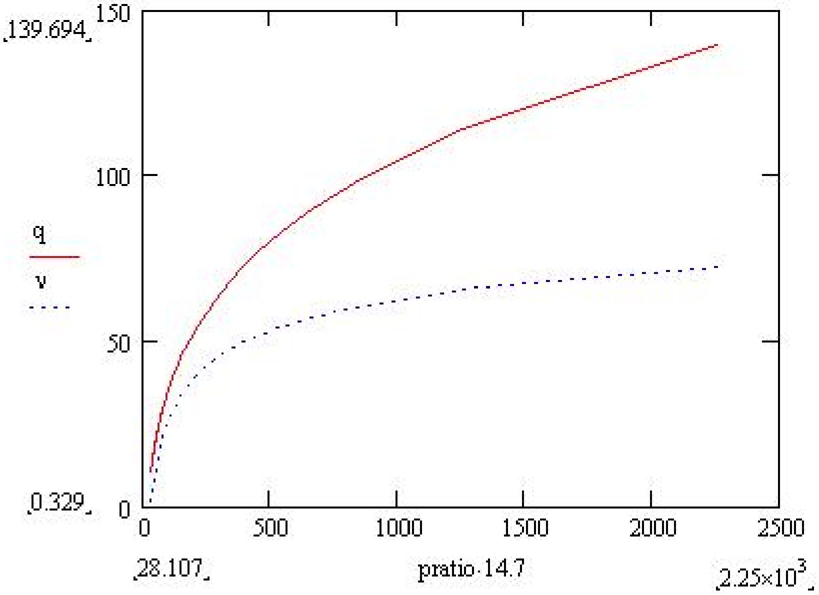
$$Drat_j := \sqrt{AR_j}$$

$$q_j := \frac{\gamma}{2} \cdot \left(M_j\right)^2 \cdot \left[1 + \frac{\gamma - 1}{2} \cdot \left(M_j\right)^2\right]^{\frac{-\gamma}{\gamma-1}} \cdot \frac{14.7}{pr_j}$$

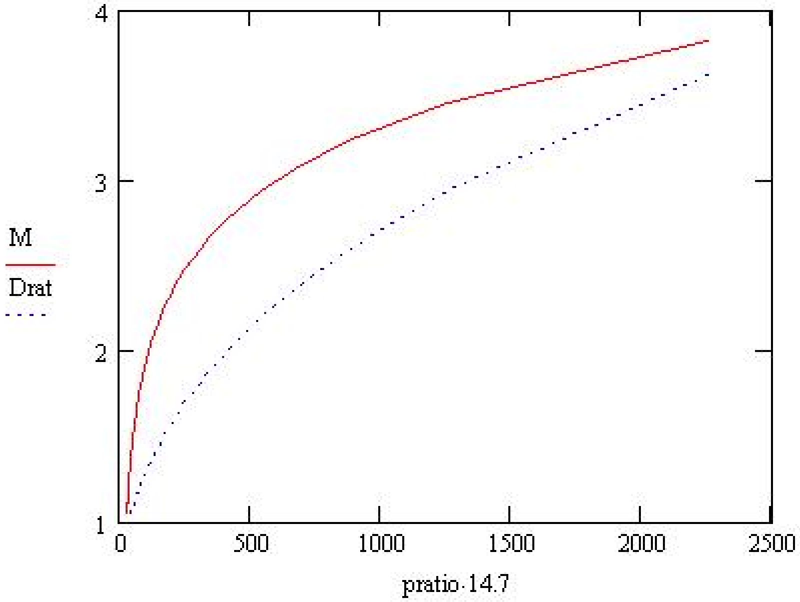
Dynamic pressure of jet

$$pratio_j := \frac{1}{pr_j}$$

Ratio of upstream stagnation pressure to containment pressure
Plot of dynamic pressure (psi) and Prandtl-Meyer angle (deg) vs jet stagnation pressure



(jet stagnation pressure)
Plot of jet Mach number and diameter ratio vs jet stagnation pressure



(jet stagnation pressure)
Static pressure ratio across a normal shock at beginning of blowdown
Jet Mach number at begining of
blowdown

$$Mi := \sqrt{\left(\frac{2}{\gamma - 1}\right) \cdot \left[\left(\frac{14.7}{2250}\right)^{\frac{1-\gamma}{\gamma}} - 1\right]}$$

Ratio of static pressure across a normal shock
with upstream Mach number = Mi

$$Ptratio := \frac{2 \cdot \gamma \cdot Mi^2 - (\gamma - 1)}{\gamma + 1}$$

Ptratio = 16.397

Static pressure upstream of blast wave at begining of blowdown

Pblast := Ptratio·14.7

Pblast = 241.029

psi