-DRAFT-

BWROG Paper on Application of 40% Reduction in Debris Damage Pressures to BWRs Revision 1

BWROG Position

It is the position of the BWROG that the NRC Staff's recommended 40% reduction in debris damage pressures, as described in the NRC SE on the PWR Guidance Report NEI 04-07, from those determined in the BWROG Air Jet Impact Tests (AJIT), as documented in the Utility Resolution Guide (URG), should not be applied to BWRs.

Background

The staff's evaluation (SE) of NEI 04-07 Guidance Report section 3.4.2.2 (page 28) states, "The NRC was concerned about potential differences between air surrogates and two-phase jets, and therefore initiated a joint test program with Ontario Power Generation (OPG)." [1,2] These tests are documented in Reference 1. The evaluation of the OPG tests results relative to the AJIT test results was performed by Los Alamos National Laboratory and is documented in Section 3 of Reference 2.

The BWROG understands the NRC's concern, given the substantially different base thermodynamic conditions that exist in PWRs relative to BWRs, and the generally accepted results from the Marviken test program that conclusively demonstrated that jet impact forces (and stagnation pressures) are at least twice as high for subcooled liquid jets than for saturated liquid jets. The Marviken tests also demonstrated that saturated vapor ("steam") jets yield slightly higher impact forces than saturated liquid jets. (See Figure 1)

---

[1] It is worth noting, that it is completely impossible to address the stated test objective with the OPG Tests as performed. The OPG tests were performed with saturated (not subcooled) liquid jets. Only the pressures are different from those in the Marviken experiments, and the OPG tests clearly do not simulate PWR blowdown conditions. See Appendix A for a discussion of the OPG test thermodynamic conditions.

[2] One assumes that the concern expressed by the staff with regard to "2-phase" jets is with regard to the differences between PWR and BWR blowdown conditions. The Marviken experiments conclusively demonstrated that steam jets bound saturated liquid jets, and the NRC accepted this position when they reviewed the URG.

In the BWROG URG it was demonstrated that the stagnation pressures of air jets are conservative relative to steam jets, which in turn are conservative relative to two-phase jets from saturated water piping.

Thus, the argument

$$P_{stag(air)} > P_{stag(sat-vapor)} > P_{stag(sat-liquid)} \tag{1}$$

demonstrates that air testing is conservative for BWR conditions. The NRC staff concurred that air jet tests conservatively bounded BWR conditions during their review of the URG.

Publically available information on the OPG tests is limited. The only OPG test report in the NRC data base is listed as "preliminary" and the SE (page 28) states, "Testing of low-density fiberglass ended prematurely after only one test, and the concerns were not fully resolved...". The only available information on the results of this test is in the discussion provided in Reference 2, page 17, where it is stated, "The single OPG fiberglass test available to the parametric evaluation was conducted at a distance of 10D with the seam at 45° and with banded aluminum cladding... This indicates that the fiberglass destruction pressure was significantly less than 6 psig."

Using the data from Reference 1, the AJIT test report in the URG, and the unpublished data cited above, Reference 2 concluded that there are differences in the destruction pressure results between the OPG and AJIT tests, with the AJIT results being non-conservative. The staff SE (bottom of page 28) concludes, "...it is prudent to attribute the observed effect to the difference in the jet medium (i.e., the difference between air used in the BWROG tests and the steam/water mixture used by OPG)." The BWROG disagrees with this conclusion. While it certainly may be "prudent" - particularly for a PWR jet having highly subcooled blowdown characteristics – to have different debris damage ZOIs for highly-subcooled liquid jets, the two-phase tests performed at OPG are not useful in determining these conditions. Additionally, the significant differences between the OPG and AJIT test article geometries effectively preclude any meaningful comparison of the results of the two tests.

Discussion

The BWROG recognizes that there are differences in the results obtained from the OPG and AJIT tests; however the differences in the test parameters and target geometry make it impossible to compare the test results in any meaningful way. The OPG tests included fifteen tests with jacketed calcium-silicate targets and one test with jacketed low-density fiberglass (LDFG). The OPG test report, as obtained from the NRC website, is marked as "preliminary" and there is no evidence of a completed verification or approval. The single LDFG test is not included in this test report. It has been reported that the single LDFG test was terminated early because of "test issues", but information on the specifics of these test issues is not provided, only that the issues were not resolved, and that testing was terminated.[3] The size, jacket and banding design characteristics of the test articles for the two tests were completely different. The AJIT used several prototype insulation segments provided by various BWROG member utilities, while the OPG used a single insulation jacketing design "per the specifications for large scale piping used in OPG's nuclear plants". Finally, the defined failure mechanism was different in the test programs.

Based on the preliminary OPG test report, LANL concluded in Reference 2, and the NRC staff concurred in the SE to NEI 04-07, that the difference in the test results between the AJIT and OPG tests is due to the blowdown medium. Identification of the difference in blowdown medium between the OPG and AJIT tests as cause of perceived differences in the pressure required to damage metal jacketed insulation has absolutely no technical basis, and is inconsistent with all previous analytical and test results. Also, if the medium is the source of a new debris damage mechanism, it is not logical to use a revised criteria (40 % reduction in pressure) only related to damage pressure and not related to medium properties such as quality or void fraction at the jet impact location.

[3] The BWROG finds the comment in the last paragraph on page 14 of Reference 2, "In addition the AJIT testing was not comprehensive." to be inaccurate, especially when compared to the OPG tests. The AJIT consisted of 77 tests using mostly prototype insulation configurations, and are meticulously documented, with appropriate quality assurance documentation. The OPG tests have one-fifth the number of tests, at one quarter the size, and no approved or signed documentation.

Test Configurations and Results

The conclusions of Section 3 of Reference 2 are substantially based on comparison of OPG tests 12-15 with AJIT tests 15-1 through 15-4. (The AJIT test results are from pages 154-159 of Reference 3). The commonality between these tests is that they all used "aluminum jacketed calcium silicate" insulation material. However, that is about the only commonality. Table 1 provides a comparison of the tested insulation geometries

Table 1
Insulation Target Geometry – Cal-sil Insulation

Characteristic	OPG	AJIT
Length (inch)	48	36
Diameter (inch)	4.375	18.75
Jacket	0.016 inch aluminum sheet	Aluminized cardboard cassettes
Bands	8 – 0.020 inch thick	4 – 0.75 inch wide
Band material	Stainless Steel	Stainless steel
Band spacing at jet centerline (inch)	8	Approx 10
Seam Orientation[4]	45°	90° and 270°
Circumferential seams	2 – 9 inch from center and 12 in from center	None
Prototype	"OPG specifications"	Grand Gulf

In the AJIT tests, the results showed essentially no damage for tests 15-1 through 15-3. Test 15-4 had minimal damage with more than 95% of the insulation remaining intact on the target pipe. The jacket was deformed, but remained on the target pipe. The primary damage was at one end of the 36-inch long segment. (See Figure 2) The stagnation pressure at the target surface was calculated to be approximately 160 psig. The NRC SE on the URG accepted a value of 150 psig as the debris failure pressure for this type of insulation.

[4] The two reports use different nomenclature – for consistency, 0 degrees is defined as facing directly into the jet, i.e. the top is 90 degrees, and 180 degrees is the back side of the insulation target

All four (4) of the OPG tests showed damage to the insulation, with 60 to 80% of the insulation remaining on the target pipe. In all cases the failure was, (see page 6 of Reference1) "due to the cladding being "unwrapped" by the jet from the exposed edge to the back side". The OPG tests did not measure jet pressures, only distances (jet source diameters) from the jet source to the target surface . The test 15 distance was 20D. LANL calculated the stagnation pressure at the target surface to be approximately 24 psid.[5]

As discussed previously, there is also the single fiberglass test performed at OPG. With regard to this test, Reference 2 (page 17) makes the statement, "The ANSI/ANS 58.2 model pressure at 10D is 6.4 psid.[6] As shown in Table 3-1, this pressure is significantly less than the BWROG recommended pressure and probably less than the NRC recommendation. "

The AJIT performed 15 tests on jacketed and unjacketed NUKON® fiberglass insulation (See Reference 3 pages 186-187), and the results are dependent on the jacketing construction/orientation and installation of the fiberglass blankets. In all cases, the failure of the jacket (or closure devices) is the governing failure mechanism. The 10-psi damage pressure was selected as the appropriate damage pressure because this is the pressure at which significant transportable debris was generated. From Page 187 of Reference 3:

- "...in Test 6-1, or approximately 2.5 psig, the blanket remained intact on the target pipe.
- ...in Test 6-2, or approximately 6 psig, the cloth covering of the insulation blanket was completely removed, leaving the inner fiberglass wool panels and the supporting scrim material wholly

[5] LANL calculated the stagnation pressures using the ANSI/ANS 58.2 (1988) jet model. There has been considerable discussion of the adequacy of this method for prediction of jet pressures and the SE even states, on page 27 of the SE, "The NRC reviewed the BWROG calculations and found the NPARC code to be a more capable method of modeling steam jets than the ANSI model." To the knowledge of the BWROG, no model/data comparisons exist to validate this methodology. However, the accuracy of the pressures is not critical to the BWROG case, and for simplicity we will stipulate that the pressures as calculated are representative.

[6] The calculated 6.4 psid value cited here for 10 D from the jet source is inconsistent with calculated pressure of 24 psid at 20 D. Assuming that the LDFG test was started from the same blowdown vessel conditions, the pressure should be higher closer to the jet source, not the other way around. By comparison with the Cal-sil tests, the 6.4 psid cited is in error by a factor of at least 5. If this supposition is correct, then the entire LANL conclusion on damage for LDFG is in error.

intact but exposed. This insulation debris would not be considered transportable.

- ...in Test 5-5, or approximately 10 psig, generation of debris from the fiberglass insulation resulting in approximately 3.6% (by weight) of fiberglass fines and 63.4% large pieces."

AJIT Tests 5 and 6 used unjacketed NUKON® fiberglass insulation. Table 2 provides a comparison of the tested insulation geometries. (See Figures 3 & 4)

Table 2
Insulation Target Geometry – Fiberglass insulation

Characteristic	OPG[7]	AJIT
Length (inch)	Not stated	Not stated – approx 24" from pictures
Diameter (inch)	Not stated – 4.375" assumed	Not stated – approx 20" from pictures
Jacket	0.016 inch aluminum	Fiberglass fabric
Bands	8 – 0.050 inch thick	None – 3 Velcro® fasteners
Band material	Stainless Steel	n/a
Band spacing at jet centerline (inch)	Not stated	n/a
Seam Orientation	45°	180°
Circumferential seams	Not stated	None
Prototype	Not stated	Multiple

Consequently, the differences in the tested configurations and failure criteria (~ 30% debris removal in OPG test vs. significant transportable debris in AJIT test) result in different damage pressures between the two tests. The BWROG does not dispute this conclusion. The issue is the conclusion, first stated in the LANL report (Reference 2) that the difference is due to the blowdown medium, and the subsequent NRC endorsement of this position.

[7] There is very little information provided in any source as to the actual test geometry.

Issues

If there is a single conclusion that can be drawn from both the OPG and AJIT tests, it is that "the devil is in the details". A good example is the results of the AJIT reflective metal insulation (RMI) tests, which showed an order of magnitude difference in destruction pressure for different RMI manufacturers. In all cases, in both tests, the primary destruction mechanism was failure of the closure and/or jacketing material. Failure occurs after the jacket or closure mechanism fails, and it is jacket and/or closure mechanism geometry that should be the primary test independent variable, not the insulation material.

Much is made in Reference 2 about the 45° seam alignment used in the OPG tests relative to the seam alignment used in the AJIT tests. On page 17 it is stated, "Further, it appears that the optimum seam angle for maximum destruction is 45°, an angle not tested by the BWROG." This statement is incorrect for two reasons. First, the OPG tests only used orientations of 0, 45, and 180 degrees (and only a single test at that location). No tests were run with the seam at 90 degrees, where potential flow fluid mechanics would indicate occurrence of the maximum fluid velocity, and therefore the maximum dynamic pressure occurs.

Second is the detail of the seam itself. Neither test report provided specific details of the jacket seam design. A "bump" in the OPG rolled seam (as would be expected for a sheet-metal aluminum jacket - and appears to be the case from the picture Figure D-10 of Reference 1) will have a much different failure mode (opening of the seam and unrolling of the jacket) than a (relatively) smooth aluminum foil cardboard jacket cassette secured by bands, where failure of the band securing crimp may be the key failure mechanism (See Figure 4). Yet these two configurations are precisely what have been compared by LANL in Reference 2. The only valid technical conclusion that can be drawn from the seam orientation in the OPG tests is that for the seam design tested, a 45° degree orientation is worse than a zero or 180° orientation. Different (and probably worse) results could be expected for a 90° degree seam orientation in the OPG configuration. The conclusion on page 19 of Reference 2 that, "It is likely that the 45° of the OPG tests is more severe than the AJIT orientation." has no physical basis, and is at best highly speculative.

The diameter of the target assemblies is another matter that requires discussion, and is absent in Reference 2. All of the AJIT tests utilized targets that were between a factor of 4 and 5 larger than OPG tests and are more representative of a BWR plant LOCA debris source that could produce a significant quantity of debris material. Neither report discusses the relationship between target size and initial jet diameter (both tests used jets of the same initial diameter). Even more important, however is the size effect of the jacket seam and closure method geometry relative to the pipe diameter. The size of the perturbation of the flow field caused by the seam in the jacket would not scale directly with pipe diameter size (the cassettes tested by the BWROG would be expected to have a relatively constant seam size). Therefore, the flow field perturbation and the associated pressures due to a specific size seam would have a smaller effect on a larger diameter pipe than for a smaller pipe.

Finally, all the OPG tested configurations have a radial seam in addition to the longitudinal seam in the aluminum sheet jacketing. The details of the radial seam are not given in the report, but a reasonable assumption (given the sketch of page B-1 of Reference 1) is that this seam is a simple overlap with a band encircling both the central and outboard section. This seam does not occur in any of the AJIT test articles. There is insufficient discussion of the exact failure mechanism in the OPG report text, but the figures in Appendix D (specifically D-3, -4, -13, and –14) strongly suggest simple mechanical displacement of the radial seam has a major effect on the test results. Once the longitudinal seam starts to "unwrap", the entire jacket segment simply pulls out of the "end" band, effectively opening up the insulation inside to the jet. This single effect is a likely reason for the differences in damage pressures in the OPG test compared to the AJIT results. This failure mechanism is not applicable to the BWR-prototype insulation types as tested in the AJIT. **The AJIT and OPG experiments are not in any way comparable.**

In addition to the above issues, there is a fundamental disagreement between the conclusions in Reference 2 that the fluid medium contributes to debris damage with those of the industry-accepted

Marviken blowdown experiments, (consistent with the staff's own conclusion in accepting the AJIT methodology during the URG review).

Finally, the staff conclusions in the first paragraph of page 29 of the SE bear comment. The SE states, "Several plausible physical mechanisms may contribute to enhanced debris generation in 2-phase jets, including penetration and erosion from entrained droplets, increased shear forces within the jet caused by radial components of the expanding fluid, and higher local velocities because of the lower density of water vapor compared to air. To judge the potential contributions of these effects without more extensive data would be speculative, as would any counter arguments offered to refute their importance."

What is speculative is the argument is that there is a new important debris damage phenomena that has been previously overlooked, which is independent of stagnation pressure, but is fluid medium dependent.

Penetration and erosion by liquid droplets may have a very small effect on the amount of insulation material generated (after the failure of the jacketing) and the composition (size) of such debris. However, this speculation is fundamentally incompatible with the observed primary failure mechanism (in both experiments) being the jacketing seam and/or connection mechanisms. This failure mode can only be due to physical force, proportional to the dynamic pressure on the target. Additionally, basic thermodynamic and two-phase flow equations indicate that at the target, the jet has a quality on the order of 40% and a void fraction (far more important than quality) on the order of 96%. Under BWR blowdown conditions the void fraction may approach 99%. Thus, even if erosion is occurring in the OPG test configuration, the jet's liquid volume fraction (~4%) is about 4 times larger than would be the case for BWRs (~1%) and the erosion effect would be proportional (i.e. 4 times higher in the OPG than in a BWR).

There may be some merit in the supposition that there are radial velocity components in the jets (both air and two-phase), however every jet model shows that the radial components will be small compared to the axial components. As discussed in their writings on debris damage (References 4 and 5), Dr's Wallis and Ransom note that the jet expansion is dominated by oblique shocks, resulting in supersonic axial velocities, with only relatively small radial velocities.

Finally, there is the discussion relative to the different densities of water vapor and air. (One assumes that the staff means the 2-phase mixture here, since the saturated water component on the 2-phase mixture dominates the density.) Any density effect on damage pressures is included in the "rho" and "v" (density and velocity) terms included in the calculated dynamic pressure, and thus accounted for in the analysis.

Conclusions

The BWROG continues to consider the AJIT test results to be appropriate for evaluating insulation damage in BWRs. The test results were included in the URG document submitted to the NRC for review. The NRC SE on the URG accepted the damage pressures, with some minor reductions for certain materials.

The OPG two-phase jet test results cannot be compared to the AJIT test results because of differences in test parameters, geometries, and failure modes. The OPG tests may demonstrate that the features of the jacket design should be properly considered in determining debris damage ZOIs. However, the OPG tests do not contradict or invalidate the results of the AJIT tests. The OPG tests represent a small set of two-phase jet test data that is only applicable to plants with similar insulation jacket features and LOCA conditions. Therefore, a generic 40% reduction to all AJIT debris damage pressures should not be applied to BWRs.

Figure 1
Marviken Stagnation Pressures

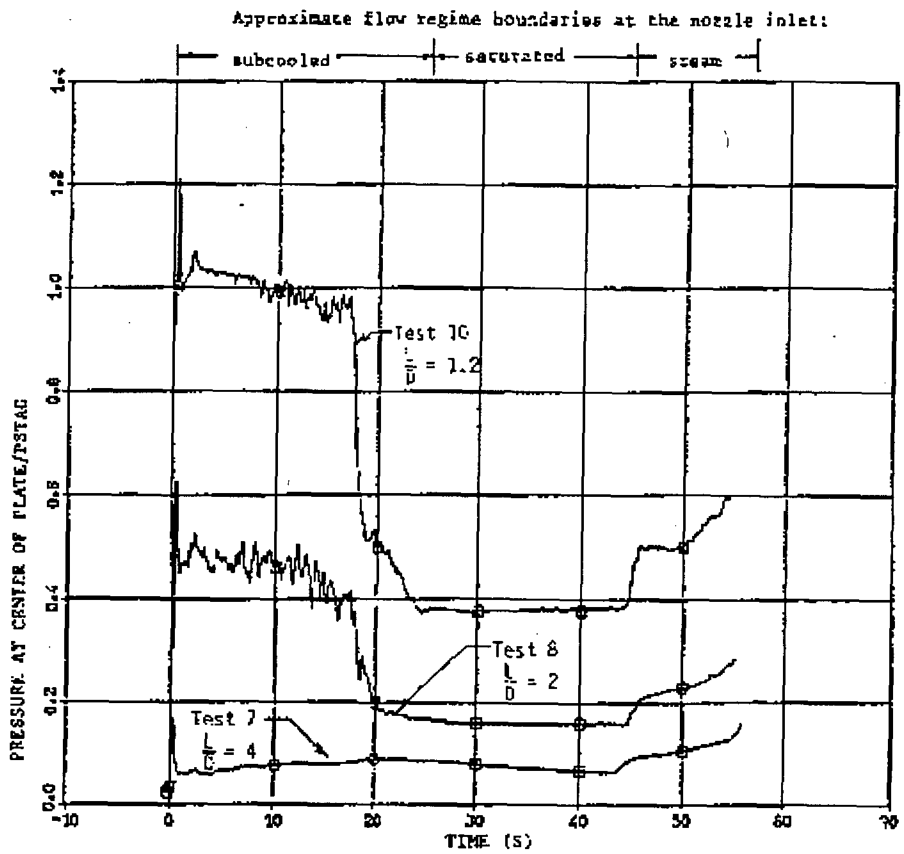
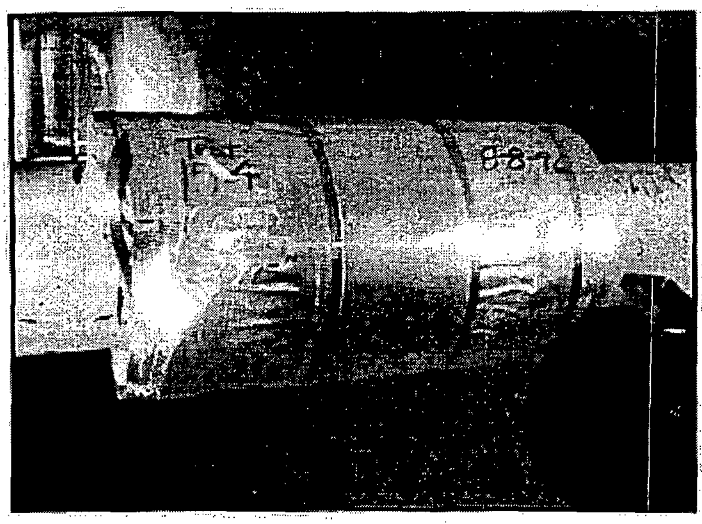
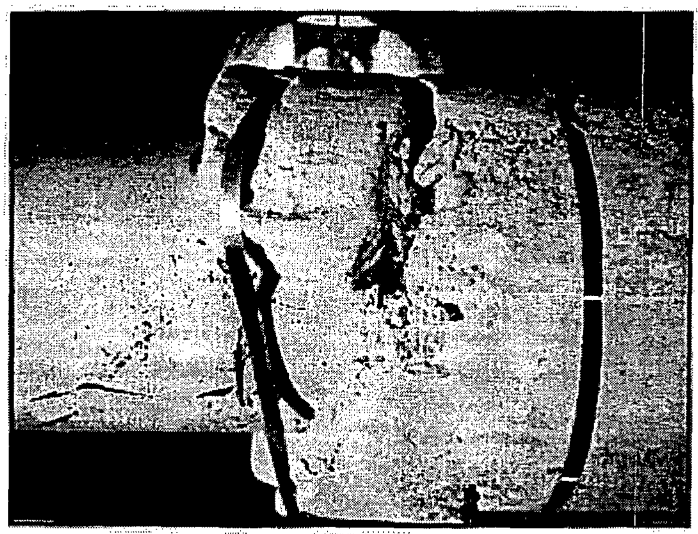


FIG. 2 Stagnation Pressure at Impingement Plate Center for Tests 7, 8 and 10

Figure 2
AJIT Test 15-4 Post-Test Conditions

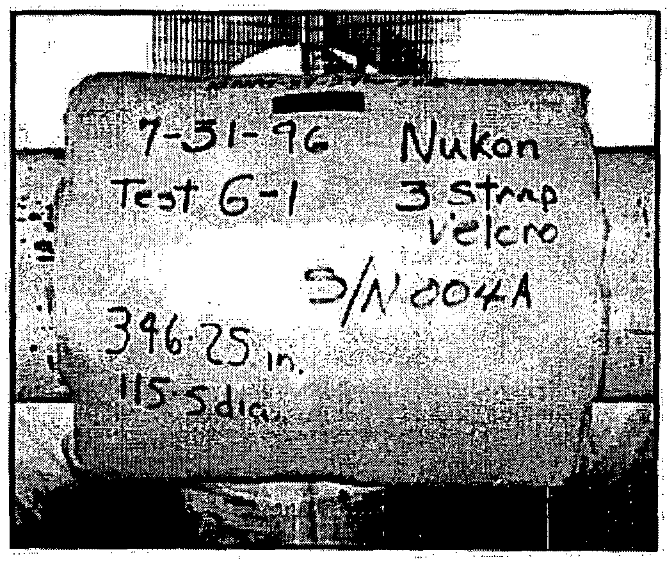


Picture 4-159
Test 15-4 (Post-test)

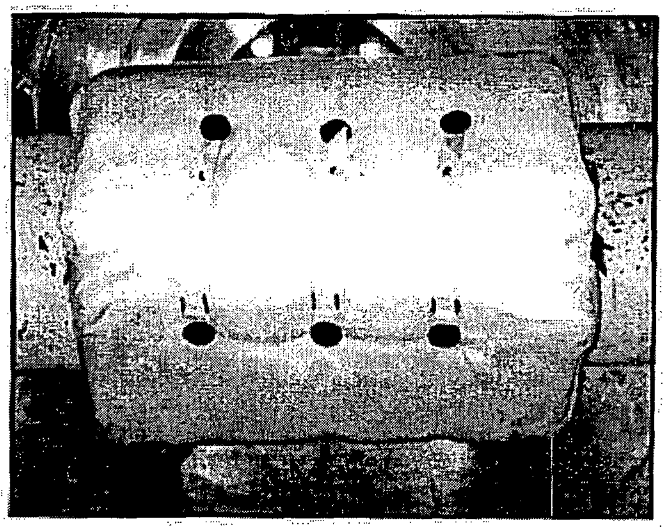


Picture 4-160
Test 15-4 (Post-test)

Figure 3
AJIT LDFG Insulation Target Configuration



Picture 4-88
Test 6-1 (Pretest)

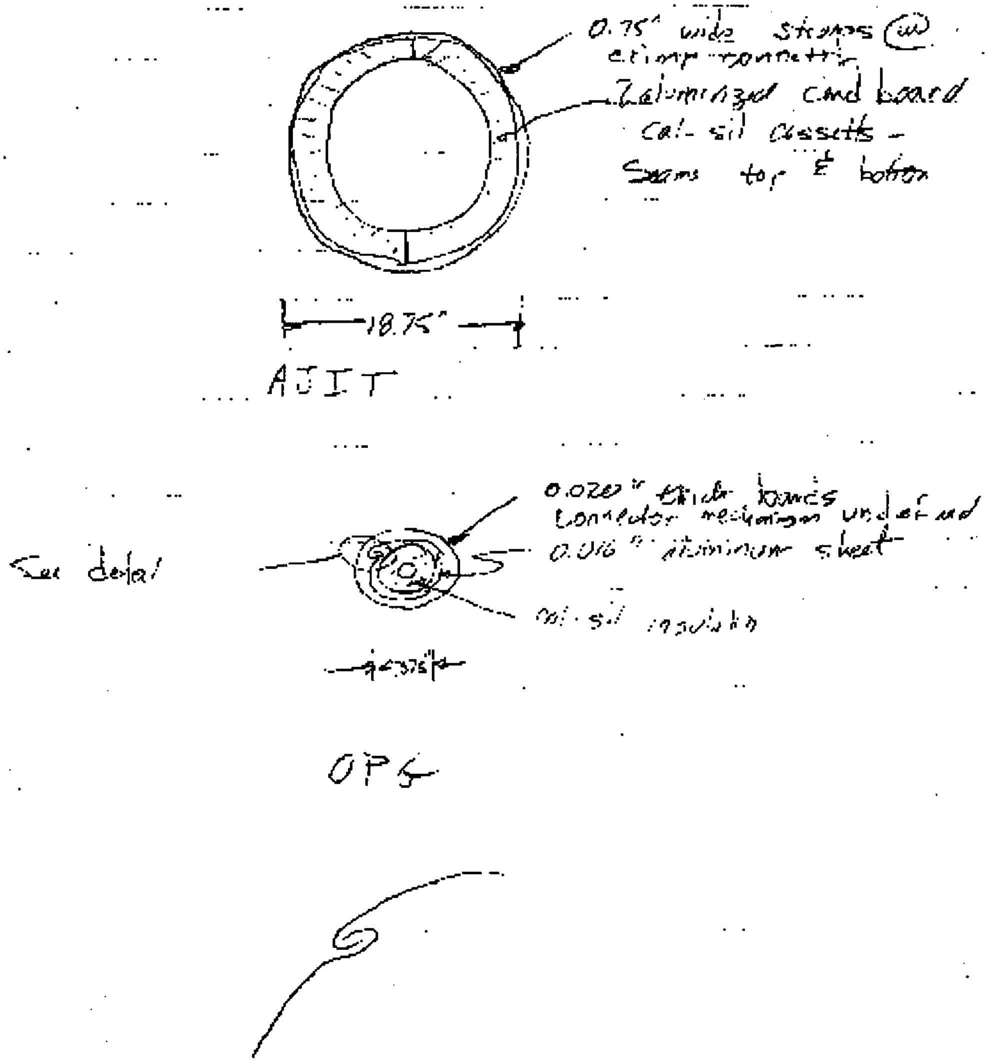


Picture 4-89
Test 6-1 (Pretest)

Figure 4
Jacket/Insulation Target Comparison

Figure 4

Target Configuration (Assumed)
Cal-Sil Tests



Typical rolled seam detail

References

1. "Jet Impact Tests – Preliminary Results and their Application" Ontario Power Generation Engineering Report N-REP-334320-10000, April 2001.
2. "GSI-191 Technical Assessment: Development of Debris Generation Quantities in Support of the Parametric Evaluation", NUREG/CR-6762, Volume 3 (LA-UR-01-6640)
3. "Air Jet Impact Testing of Fibrous and Reflective Metallic Insulation", Continuum Dynamics Report (96-06), RG Technical Support Information Volume II Tab, November 1996.
4. Graham Wallis, "The ANSI/ANS Standard 58.2-1988. Two Phase Jet Model," September 15, 2004.
5. Victor Ransom, "Comments on GSI-191 Models for Debris Generation," September 14, 2004.

Appendix A

Discussion of OPG Test Thermodynamic Conditions

The thermodynamic conditions of the blowdown system used in the OPG tests needs some clarification. Sometimes these tests are referred to as "saturated liquid tests" sometimes "two-phase", and in one case (erroneously) "sub cooled liquid". This latter case is from NUREG/CR-6808, the "knowledge base" for PWR strainer evaluations, which cites a temperature of 324° F and a pressure of 1417 psig as the blowdown vessel temperature and pressure prior to the start of the test. This set of thermodynamic conditions would result in a highly subcooled thermodynamic state, however this is incorrect. Throughout the OPG test report, temperatures are given in degrees C and pressures are given in psi. Appendix A of the test report (the test procedure), makes it very clear that the blowdown vessel fluid is saturated liquid. Step 13, for example, states, "Drain the cold water from the bottom of pressure vessel until temperature T5 reaches 280° C." This step removes any subcooled water from the pressure vessel.

Figure 1 of the test report also shows the heater arrangement in the blowdown vessel to heat the water near the bottom – as would be done to yield saturated water. Finally, the blowdown pressure history shown in Figure 2 of the OPG test report is typical of a saturated liquid blowdown – the rupture disc is broken at ~ 27 seconds, and saturated liquid flows from the vessel until 37 seconds, at which time the flow changes to saturated steam when the liquid inventory in the vessel has been depleted.

- **The OPG blowdown conditions are saturated liquid for the first 10 seconds (starting at a vessel pressure of approximately 1400 psi) followed by approximately 5 seconds of saturated steam (when the pressure is approximately 900 psi).**

However, it is very important to realize that the vessel conditions are not the same as the jet conditions at the point of impact on the insulation target. As the jet pressure drops, the thermodynamic state conditions will change. Table A-1 provides the jet conditions at an absolute pressure of 20 psia – somewhat typical of the OPG test conditions at the target.

Table A-1
Jet Thermodynamic conditions at 20 psia

Vessel Conditions	Expanded Quality
Sat Liquid – 1400 psia	0.42
Sat Liquid – 900 psia	0.35
Sat Vapor – 900 psia	1.04

From Table A-1 it may be seen that the jet conditions at 20 psia are two-phase for the saturated liquid duration of the blowdown, with the quality decreasing from 42% to 35% over the 10 second "test duration". Once the liquid inventory is depleted, the jet will yield superheated steam conditions for approximately 5 seconds

- **The OPG jet conditions at the target start as a two 2-phase mixture of saturated water and vapor and later become superheated steam near the end of the test.**

Since the test was not terminated prior to the depletion of liquid in the vessel, both 2-phase and superheated steam conditions will have occurred at the target location. In fact, since the Marviken experiments conclusively demonstrated that for a given set of thermodynamic conditions steam jets yield higher pressures than two-phase jets, and pressures were not measured at the target locations in the OPG test, <u>there is no assurance that the damage occurred during the two-phase portion of the blowdown test.</u> The dynamic pressure at the target location certainly increased when the jet conditions transition from two-phase to superheated steam at 900 psi. The OPG test report does not address the pressure differences at the target between the initial two-phase conditions at a blowdown pressure of 1400 psig and the superheated conditions at 900 psi.