June 15, 2008

MEMORANDUM TO: Michael Scott, Chief
Safety Issues Resolution Branch
Division of Safety Systems

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SUBJECT: TRIP REPORT FOR IN-VESSEL TESTS AT CONTINUUM DYNAMICS INCORPORATED

Attached is the trip report prepared by the staff members who witnessed GSI-191 related in-vessel Diablo Canyon tests conducted at Continuum Dynamics, Incorporated in Trenton, New Jersey, from May 19 to 21, 2008.

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Trip Report
Diablo Canyon Bottom Nozzle Testing
Continuum Dynamics Incorporated
May 19-21, 2008

**Introduction**

NRC GSI-191 technical reviewers Paul Klein (NRR/DCI/CSGB), Ralph Landry (NRO/DSRA), John Burke (RES/DE/CIB), Steve Smith (NRR/DSS/SSIB), and Ervin Geiger (NRR/DSS/SSIB) witnessed three tests performed by Continuum Dynamics Incorporated (CDI) on behalf of Diablo Canyon Nuclear Plant. These tests were intended to evaluate the potential for significant pressure drop across a plant-specific debris bed near the reactor core bottom nozzle. This issue was raised as part of the NRC's review of topical report WCAP-16793-NP, *Evaluation of Long-Term Cooling considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid*. The three Diablo Canyon tests were conducted over a three-day period from May 19-21, 2008. In addition to the three tests observed by the staff, Diablo Canyon conducted a series of tests to evaluate repeatability of results, sensitivity to sequence of debris arrival, variations in flow resistance through the fuel assembly for hot leg or cold leg break flow rates, effect of different P-Grid geometries, and flow with a totally blocked inlet nozzle.

Overall, the NRC staff was impressed with the questioning attitude of Diablo Canyon personnel and the depth of evaluation evident in the Diablo Canyon testing. In addition, the staff appreciated the openness of Diablo Canyon in that they provided all test data to the staff for review and were available to discuss the results.

**Test Facility**

CDI has erected a test apparatus to perform licensee-sponsored tests of containment sump strainers and their effectiveness at removing loss-of-coolant accident generated debris following a postulated Loss-of-Coolant Accident (LOCA). An additional test loop was erected by CDI to study changes in fuel assembly inlet pressure drop due to buildup on the fuel assemblies of debris that has bypassed the sump strainers. The test loop developed is a simple assembly capable of using actual fuel assembly inlet nozzles and spacer grids with nylon rods replacing the Zirconium-alloy fuel rods. Debris surrogates, including chemical precipitates postulated to be present in the recirculating sump water, can be introduced into the fuel assembly simulator; and the pressure drop across the assembly can be measured as debris is captured.

The tests witnessed by the staff utilized a Diablo Canyon supplied fuel assembly inlet nozzle of the standard Westinghouse 17x17 fuel design. Two protective spacer grids (Alternate P-grid, and Standard P-grid) were used during the testing, in addition to a Westinghouse standard intermediate mixing vane grid. The fuel rods were represented by four inch long nylon rods. The nylon rods representing the control rods were physically attached to the fuel assembly inlet nozzle by screws so as to seal the holes and prevent flow. A photograph of the test article is shown in Figure 1.

The test article was supported on a plate with four flow holes the same diameter and pitch as those in the plant's core support plate.

Tests were performed using Nukon fiber material captured downstream of the sump strainers during the strainer testing or passed through a strainer segment subsequent to strainer testing. Additional debris was used based on materials and latent debris present in the Diablo Canyon

Nuclear Plant, including Marinite, Sil-Co-Sil silica sand, and Calcium Silicate. Aluminum Oxyhydroxide and Sodium Aluminum Silicate chemical precipitates were prepared using the WCAP-16530-NP instructions. One-hour precipitate settlement was measured and found to be within the acceptable limit provided in WCAP-16530-NP-A, *Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids in Support of GSI-191*.

Quantities of debris used were representative of a loop 2 crossover leg break at the steam generator (S/G) nozzle, loop 4 crossover leg break at the reactor coolant pump nozzle, hot leg break, and with various changes in the Marinite and Cal-Sil content for sensitivity studies. The debris loads are shown in Table 2. The fibrous debris load of 12.6 grams, used for most tests, is equal to about a one-third-inch theoretical fibrous bed at the core inlet.

Flow rates used during the tests are scaled from the flow rate that would be expected following a hot leg break and from a cold leg break that matches the core boiloff rate. All flow rates and debris quantities were scaled to represent that expected for one fuel assembly out of a 193 fuel assembly core.

Tests were performed using various debris addition sequences including: particulate followed by fiber followed by chemicals; fiber followed by particulate followed by chemicals; and chemicals followed by particulate followed by fiber. In general, the tests observed by the staff had the fibrous debris introduced relatively quickly following the particulate debris so that the introduction was almost homogeneous. The majority of the tests were performed using the Alternate P-grid currently used with the Westinghouse supplied fuel in the Diablo Canyon Nuclear plant. Sensitivity tests were performed using the Westinghouse Standard P-grid to determine the effect on head loss and debris capture since the licensee is considering switching to the Standard P-grid geometry.

The test procedure for the tests witnessed by the staff was to establish the specified flow rate, whether 41.1 gpm or 5 gpm, and determine the “clean” head loss. Particulates were then added to the test loop followed by fibers. Flow was maintained until the head loss stabilized, typically on the order of two to two and a half hours, and then the chemical precipitates were added to the test loop. Again flow was maintained until the pressure loss stabilized. Total test times varied from six to nine hours.

**Results**

Results for tests performed to date are given in Table 1, with several plotted in Figure 2.

Test BNT-8, performed May 19, 2008, used the hot leg scaled flow rate of 41.1 gpm, and the crossover loop 4 reactor coolant pump nozzle debris load, with the Alternate P-grid. Maximum head loss recorded was 24.5 inches of water, or approximately 0.9 psi. Post-test examination of the test assembly indicates that very little debris accumulated on the core support plate. There was also very little material in the bottom test chamber below the core support plate. The fuel assembly inlet nozzle exhibits moderate flow hole plugging as indicated in Figure 3. The spacer grids, however, trapped a considerable amount of debris.

The bottoms of the intermediate grid and the Alternate P-grid are shown in Figure 4. Material removed by the CDI technician was measured to be approximately 1/8 inch thick on the bottom of the intermediate grid.

Test assembly bypass was restricted to a 0.020 inch gap around the assembly, half of the normal fuel assembly to fuel assembly gap of 0.040 inches. To determine the pressure drop that would occur should all flow be diverted to the gap, a test was performed with the entire bottom surface of the fuel assembly inlet nozzle covered with duct tape. With the flow area restricted to only the gap, the pressure drop at 5 gpm was measured to be 9.3 inches of water, and at 36.9 gpm the pressure drop was 118.9 inches of water. Thus, in test BNT-8 flow was passing through the debris beds formed on the bottoms of both grid spacers as well as through the bypass gap. An assumption of complete flow blockage in the inlet nozzle could not account for the pressure drop measured in test BNT-8 versus that in test BNT-7.

On May 20, 2008, the test BNT-8 debris load was repeated in test BNT-9 but with lower flow representing the boiloff matching flow rate of 5 gpm. At the lower flow rate debris buildup took considerably longer and the resulting pressure drop was 11.3 inches of water, or 0.41 psi, approximately half of that of test BNT-8. At this flow rate the pressure drop was close to that of the completely blocked fuel assembly inlet nozzle test, 11.3 inches of water versus 9.3 inches of water.

Test BNT-10 performed on May 21, 2008 used the Standard P-grid with a debris load that had double the amounts of Nukon fiber, Marinite, and calcium silicate particulate used in tests BNT-8 and 9. In addition two flow rates were used, first the boiloff rate of 5 gpm, and after stable pressure drop was established, the flow rate was attempted to be increased to 41.1 gpm. However, the pressure limit of the test chamber, 120 inches of water, was exceeded at a flow rate of 30.1 gpm so the test was terminated. This pressure drop was similar to that for a completely blocked fuel assembly inlet nozzle. The pressure loss at 5 gpm with double the fiber and particulate load was found to be 74.9 inches of water, or approximately 2.7 psi.

Staff observed that during test BNT-8, with a flow rate of 41.1 gpm, flow patterns developed along the sides of the test chamber in the bypass region between the plexiglass walls and test article. Flow was observed to be in the positive direction in the center of the region and in the negative direction in the corners. Eddies were observed to spread from the corners above the test article. During test 10, at the 5 gpm flow rate, eddies were also observed although no particular pattern based on location within the assembly was identified. Conclusions relative to similar flows existing in a multiple array configuration can not be drawn since multiple arrays would not be subject to corner affects. As noted above in the comparison of the pressure drop results for the completely blocked inlet nozzle, the bypass flow contributes to the total test article. However, as also noted, the bypass gap in the test assembly is half that of an actual core configuration. Flow redistribution may be a more significant effect in cooling of a full fuel assembly configuration. Similar flow patterns were not observed in the 5 gpm test, BNT-9, that the staff witnessed.

Due to fluid opacity it was not possible to observe flow patterns within the test article.

Additional tests were performed on May 22, 2008, that were not witnessed by the staff. Results for these tests, and tests that were performed prior to the staff's visit, were provided to the staff for review. The staff concluded from review of the test results that while a "filtering bed" may form, and adhere to, the inlet surfaces of the spacer grids, it does not completely inhibit flow of cooling water to the fuel assembly.

**Key Observations**

1. Diablo Canyon has made an attempt to quantify plant-specific in-core debris head loss effects. Based on staff observations, the testing appears to be valid in quantifying prototypical head losses that could occur at the Diablo Canyon fuel inlet and spacer grids. This observation is based on use of scaled flow rates and debris quantities combined with a plant-specific fuel inlet nozzle and spacer grids.
2. The implementation of the testing at CDI was observed by the staff to be consistent and systematic. This was further illustrated by the consistency of the test results.
3. A change in the P-Grid from the Westinghouse Alternate Grid to the Westinghouse Standard Grid made a significant change in the head loss attained during testing. (Tests 7 and 8 (alternate) vs. Test 11 (standard))
4. The debris preparation for the testing was observed to result in prototypical or conservative debris characteristics based on use of fibrous debris captured during Diablo Canyon sump strainer testing combined with prototypical particulate quantities and chemical surrogates.
5. The staff observed that even under low (cold leg) break flows, fibrous and particulate debris transported upward and deposited onto various areas within the fuel assembly. At these lower flow rates some settling of particulate debris occurred. At higher flow rates (hot leg break) there was virtually no settlement of debris. Some of the particulate debris remained in suspension and circulated through the loop for the duration of the tests. Velocities in a lower reactor head may be lower than the velocities used in the test rig because the test rig inlet chamber was not scaled, and is of a relatively smaller volume than the actual reactor lower plenum, and does not contain typical instrument lines and hardware. These differences could result in more settling of particulate debris in an actual reactor vessel than was observed in the test rig. Thus the testing was likely conservative from a transport perspective.
6. Higher flow rates resulted in higher head losses.
7. Higher flow rates (higher pressure drop) resulted in the transport of more debris onto the upper grid spacer. This would be expected to result in somewhat lower head losses than if all of the debris was collected on the P-Grid.
8. For the Westinghouse Standard and Alternate P-Grids, it appears that a thin bed effect will not occur with relatively low fibrous loads. This is likely due to the many areas on which fiber can collect within the assembly. It appears that as head loss increases debris redistributes into areas higher in the assembly.

**Conclusions**

Tests performed at CDI using a Diablo Canyon fuel assembly inlet nozzle, an Alternate P-grid and a Standard P-grid, an Intermediate grid, scaled flow rates, and debris representative of that for various reactor coolant system break locations indicate that a “filtering bed” may form on, and adhere to, the inlet surfaces of the spacer grids. The bed of solid debris that forms, however, is likely not to totally impede the flow of coolant. The head loss, or pressure drop, that results from the debris bed is dependent upon the configuration of the initial grid used. When flow was halted, suspended debris settled, but that deposited on the grid spacers remained in place, including that which extended into the fuel assembly inlet nozzle.

Comparison of the pressure drop results for the completely blocked inlet nozzle with those for a nozzle with a debris bed indicates that the bypass flow contributes to the total test article flow. However, the bypass gap in the test assembly is half that of an actual core configuration. Flow redistribution may be more significant and effective in core cooling in a multiple fuel assembly configuration.

Table 1
Diablo Canyon
CDI Bottom Nozzle Tests (BNT)

| Test BNT | Flow Rate (gpm) | Debris Load (see Table 2) | P-Grid | Head Loss (in $H_2O$/psi) |
|---|---|---|---|---|
| 1a | 5 | F/P+C | Alt | 2.8/0.10 |
| 1b | 41.1 | | | 5.4/0.19 |
| 2a | 5 | F/P+C | Alt | 3.5/0.13 |
| 2b | 41.1 | | | 14.9/0.54 |
| 3a | 5 | P+C/F | Alt | 5.6/0.20 |
| 3b | 41.1 | | | 7.9/0.29 |
| 4a | 5 | F/P+C | Alt | 12.9/0.47 |
| 4b | 41.1 | | | 70.8/2.56 |
| 5 | 41.1 | 1 | Alt | 16.6/0.60 |
| 6 | 41.1 | 1 | Alt | 11.3/0.41 |
| 7 | 41.1 | 3 | Alt | 22.6/0.82 |
| 8 | 41.1 | 3 | Alt | 24.5/0.88 |
| 9 | 5 | 3 | Alt | 11.3/0.41 |
| 10a | 5 | 6 | Std | 74.9/2.70 |
| 10b | 30.1 | | | 123/4.44 |
| 11 | 41.1 | 3 | Std | 37.1/1.34 |
| 12 | 41.1 | 3 w/13.42 Nukon | Alt | 20.4/0.74 |
| Blocked nozzle-a | 5 | | Alt | 9.3/0.34 |
| Blocked nozzle-b | 36.9 | | Alt | 118.9/4.29 |

F = Fiber, P = Particulate, C = Chemicals
BNT-1-4, flow rate 5 gpm during debris/chemicals addition, raised to 41.1 gpm
BNT-5-12, flow rate constant for entire test, except BNT-10 as noted

BNT-3, chemical precipitates were added first, followed by debris
All other tests, debris was added before chemical precipitates

Table 2
Diablo Canyon
Debris Loads

| Test Material | BNT-1 thru 3 | BNT-4 | Load 1 | Load 3 | Load 6 |
|---|---|---|---|---|---|
| Nukon (grams) | 12.6 | 12.6 | 12.6 | 12.6 | 25.2 |
| PWR Dirt Mix (grams) | 204.1 | 267.7 | 220.3 | 169.8 | 169.8 |
| Marinite (grams) | 77.1 | 77.1 | 77.6 | 77.6 | 155.2 |
| Sil-Co-Sil Silica Sand (grams) | 1174.8 | 1344.9 | 1345.4 | 1326.6 | 1326.6 |
| Cal-Sil (grams) | 0.0 | 40.8 | 32.5 | 137.5 | 275.0 |
| Aluminum Oxyhydroxide (lbs) | 11.85 | 61.70 | 90.41 | 80.39 | 71.51 |
| Sodium Aluminum Silicate (lbs) | 33.45 | 45.25 | 44.27 | 45.66 | 91.3 |

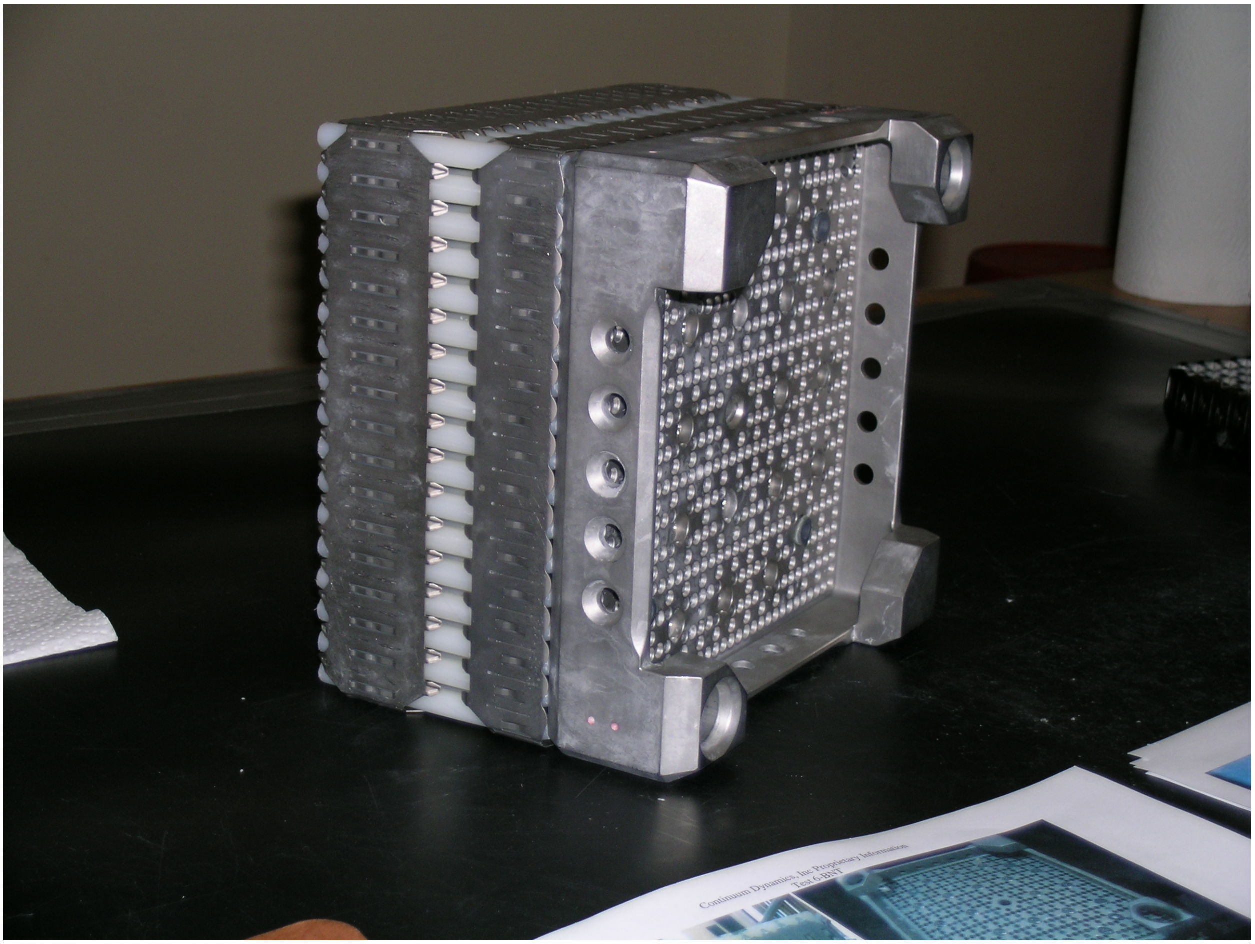


Figure 1
Diablo Canyon Test Assembly

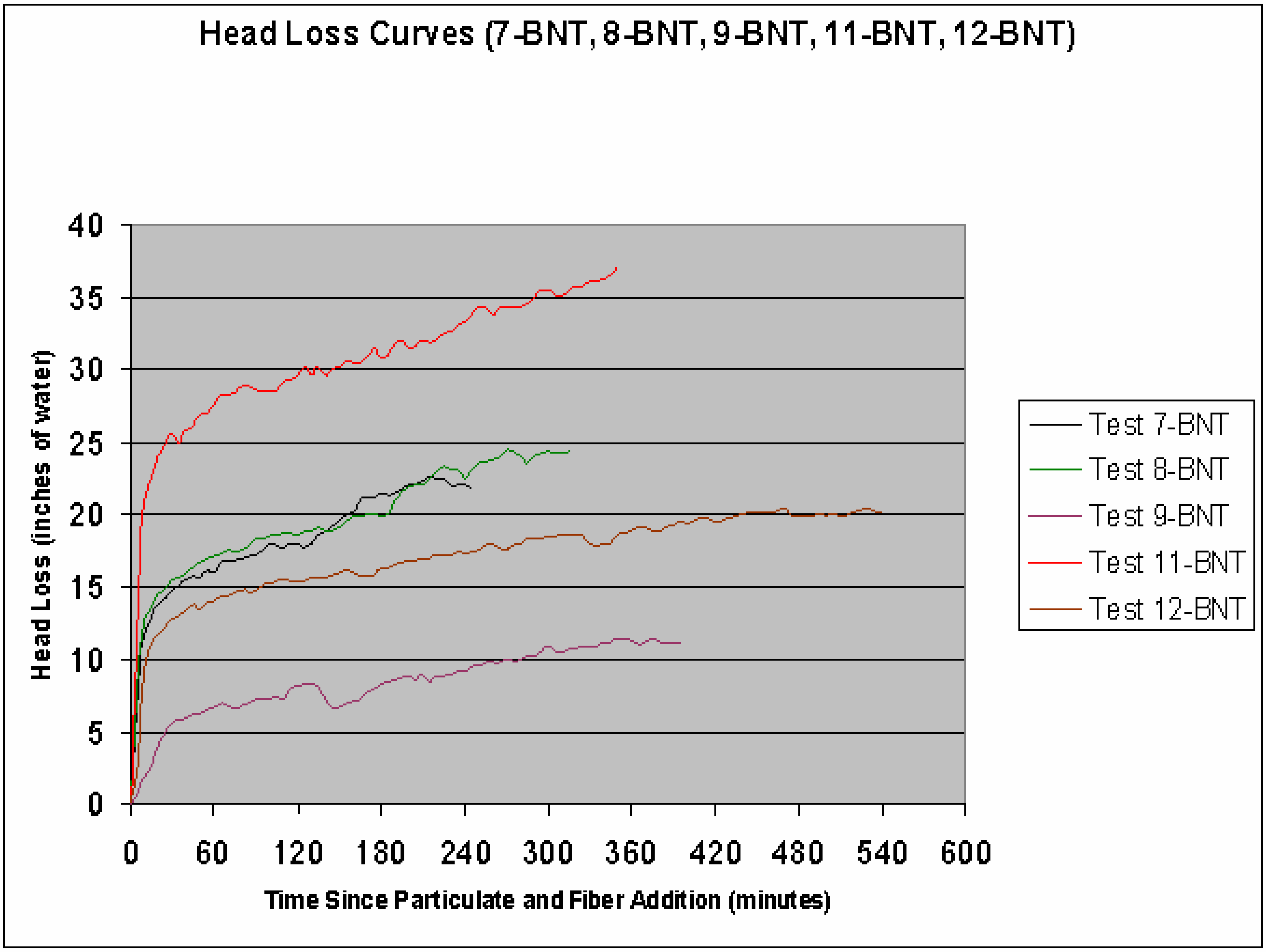


Figure 2
Diablo Canyon Head Loss Results

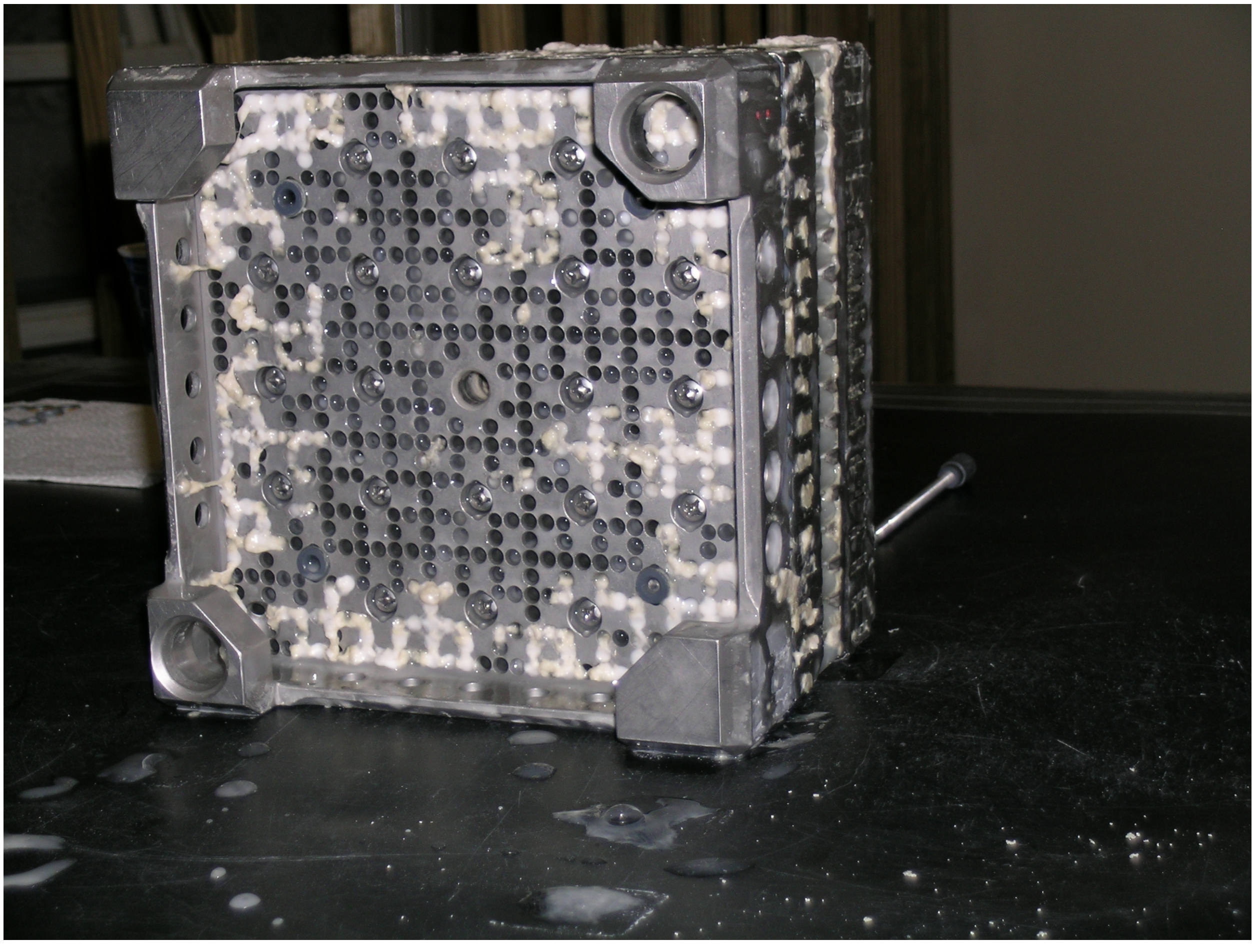

Figure 3
Diablo Canyon Fuel Inlet Nozzle after Test BNT-8

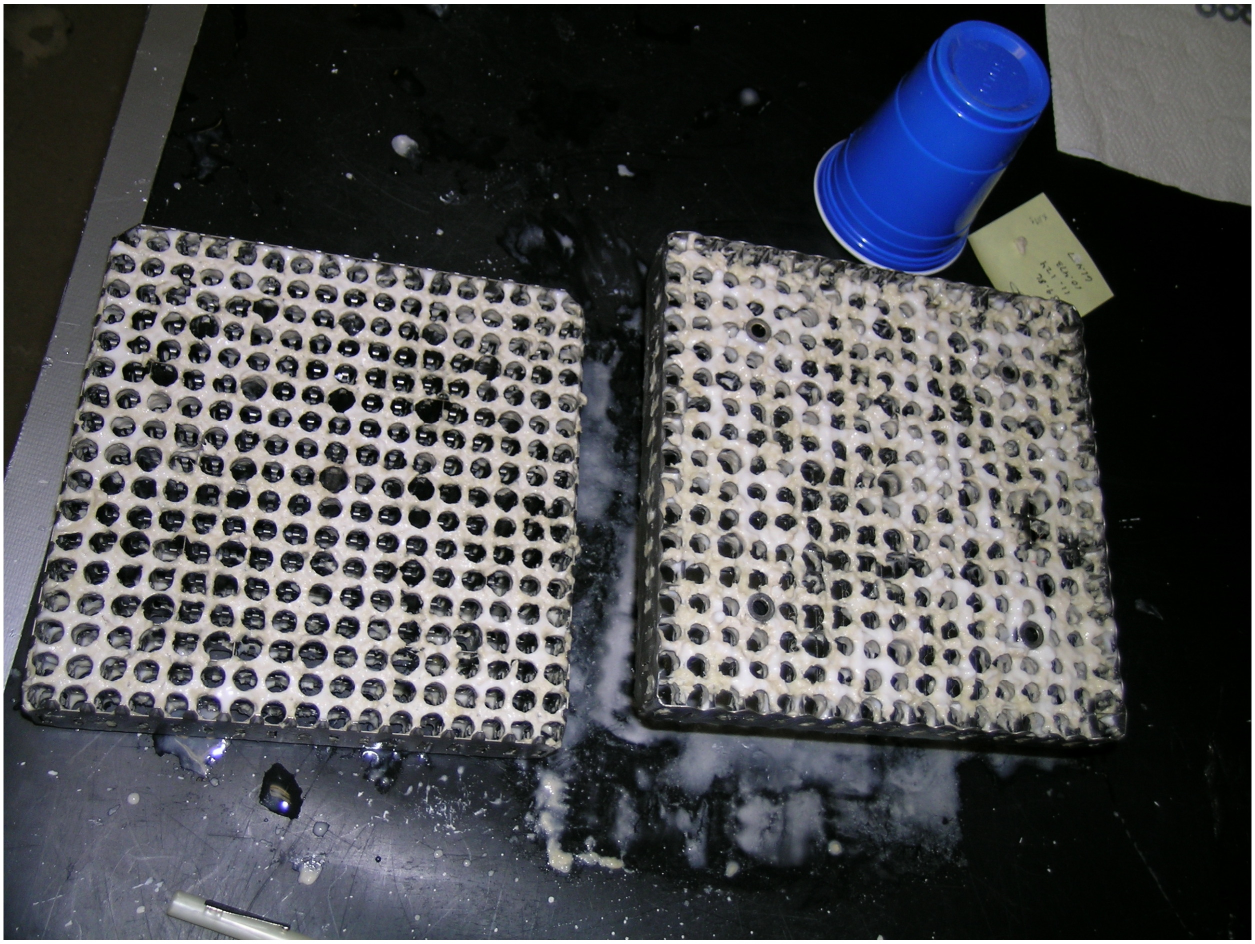

Figure 4
Diablo Canyon Grids after Test BNT-8
Left – Bottom of Intermediate Grid
Right – Bottom of Alternate P-Grid