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CALCULATION NOTE COVER SHEET

SECTION TO BE COMPLETED BY AUTHOR(S):

Calc-Note Number: FAI/09-44R

Revision Number: 0

Title: Post-Test Analysis of the FAI Millstone 3 RWST ¼ Scale Gas Entrainment Test

Project: Assess the transport of non-condensable gas in the Millstone 3 ECCS suction lines.

Project Number Or Shop Order:

Purpose: The purpose of this report is to assess the ability of RELAP5 to predict the entrainment and transport of gas in the FAI Millstone 3 RWST ¼ scale test facility.

Results Summary: The comparisons of RELAP5 model results to test data shows that RELAP5 hydrodynamic models predict entrainment conservatively and reasonably.

References of Resulting Reports, Letters, or Memoranda (Optional)

Author(s): Name (Print or Type)	Signature:	Completion Date:
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SECTION TO BE COMPLETED BY VERIFIER(S):

Verifier(s): Name (Print or Type)	Signature:	Completion Date:
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Method of Verification: Design Review ___ Independent Review or Alternate Calculations X Testing ___

Other (specify):

SECTION TO BE COMPLETED BY MANAGER:

Responsible Manager: Name (Print or Type)	Signature:	Approval Date:
Robert E. Henry	Robert E. Henry	3/13/09

CALC NOTE NUMBER FAI/09-44R **PAGE** 2

CALCULATION NOTE METHODOLOGY CHECKLIST

CHECKLIST TO BE COMPLETED BY AUTHOR(S) **(CIRCLE APPROPRIATE RESPONSE)**

1.	Is the subject and/or the purpose of the design analysis clearly stated?	[✓ YES]	NO	
2.	Are the required inputs and their sources provided?	[✓ YES]	NO	N/A
3.	Are the assumptions clearly identified and justified?	[✓ YES]	NO	N/A
4.	Are the methods and units clearly identified?	[✓ YES]	NO	N/A
5.	Have the limits of applicability been identified? (Is the analysis for a 3 or 4 loop plant or for a single application.)	[✓ YES]	NO	N/A
6.	Are the results of literature searches, if conducted, or other background data provided?	YES	NO	[✓ N/A]
7.	Are all the pages sequentially numbered and identified by the calculation note number?	[✓ YES]	NO	
8.	Is the project or shop order clearly identified?	[✓ YES]	NO	
9.	Has the required computer calculation information been provided?	[✓ YES]	NO	N/A
10.	Were the computer codes used under configuration control?	[✓ YES]	NO	N/A
11.	Was the computer code(s) used applicable for modeling the physical and/or computational problems identified? (i.e., Is the correct computer code being used for the intended purpose.)	[✓ YES]	NO	N/A
12.	Are the results and conclusions clearly stated?	[✓ YES]	NO	
13.	Are Open Items properly identified	YES	NO	[✓ N/A]
14.	Were approved Design Control practices followed without exception? (Approved Design Control practices refers to guidance documents within Nuclear Services that state how the work is to be performed, such as how to perform a LOCA analysis.)	YES	NO	[✓ N/A]
15.	Have all related contract requirements been met?	[✓ YES]	NO	N/A

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Report No.: FAI/09-44R

Post-Test Analysis of the FAI Millstone 3 RWST ¼ Scale Gas Entrainment Test

Submitted to:

Dominion

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ABSTRACT

A gas volume detected in the Millstone Unit 3 RWST suction line led to installation of additional piping vents and required that an understanding of the transport of that gas in postulated ECCS initiation events be developed. The utility performed detailed RELAP5 modeling of the ECCS suction piping as part of their assessment. In addition, a ¼ scale test of the RWST suction piping was built at FAI and exercised to experimentally investigate the fluid dynamic response and serve as a test for the analytical predictions. As part of this testing effort, a RELAP5 model was developed and used to analyze the scale model results. This report documents the results of that effort.

This report evaluates the RELAP5 model of the ¼ scale test loop and compares the gas entrainment predictions to the test data. It also shows that the test loop gas separators introduce a velocity oscillation on pump start in the test facility. The results of the comparison demonstrate that RELAP5 gas entrainment models conservatively over-predict the gas transport observed.

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1.0 INTRODUCTION

Recently, a gas void was identified in the Millstone 3 ECCS suction piping adjacent to the RWST. The gas void was conservatively estimated at 8% in a section of 24 inch piping upstream of the RHR, SIH, and Charging pumps. Analytical predictions of the void transport were prepared by utility personnel using the RELAP5 Mod 3.3 computer code as part of their assessment of the safety significance of this event. A ¼ scale test was also performed at FAI to provide additional understanding of the gas transport phenomena in this condition. The RELAP5 code was also used to perform post-test analysis of the ¼ scale testing. This report documents the results obtained and insights gained in this analysis work.

The objective for this report is to demonstrate the capability of RELAP5 Mod 3.3 to predict the major phenomena observed in the scale tests. One result of this work was the development of insights with respect to the key phenomena observed in the test as well as the application of the code to properly capture them.

It should be noted that both the utility personnel as well as FAI applied the RELAP5 Mod 3.3gl (patch 03) configuration in performing this work. This is significant due to the changes implemented in the horizontal stratification vapor pull through models with this release.

2.0 DESCRIPTION OF TEST FACILITY/RESULTS

The Millstone 3 ECCS suction test facility is described in detail in (FAI, 2009). In summary, the facility consisted of a main 6" loop with prototypic connections for the RH, SIH, and Charging systems. The RH suction connection is a 4 inch diameter 45 degree downward tee connection. The SIH suction is a 2 inch pipe that connects to the bottom of the 6 inch main header, just upstream of the RH connection. The charging line is a horizontal connection downstream of the RH suction tee.

The RH piping continues after the 45 degree downward tee to a horizontal header that leads to a gas water separator. The test RH pump takes suction on a line from the side of the separator. Test RH flow measurement is taken between the pump and the separator outlet. It should be noted with respect to the much larger flow rate for the scaled RH system compared to the SIH and charging systems, the gas volume in the RH separator was comparable to the gas volumes used in the SIH and charging separators during the testing.

The SIH piping drops vertically 9 inches and then is routed horizontally to a gas water separator. In the test SIH pump takes suction on a line from the side of the separator. The test SIH flow measurement is taken between the pump and the separator outlet. A fairly large gas volume was applied in the SIH and Charging separators during testing.

The Charging line drops vertically approximately 39 inches from the elbow connecting it to the header downstream of the RH suction takeoff. There is a short horizontal run of approximately 12 inches before the line enters the separator. The test Charging pump takes suction on a line from the side of the separator. The test flow measurement is taken between the pump and the separator outlet. The charging separator and SIH separator were constructed nearly identically and were operated comparably.

The test matrix and observed results is shown on the next page.

Table 2-1 Test Matrix (Experimental Planning)

Test Number	Flow Rate For the RHS (gpm)	Flow Rate For the SIH (gpm)	Flow Rate For the Charging System (gpm)	Initial Gas Void Fraction (%)	Purpose of the Test	Gas Volumes Collected (in^3)	
						SIH	Charging
1	315	23	22	8	Represent the max ESF case.	0	8.6
2	310	23	22	8	Repeat of Test #1.	0	0
3	315	24	21	8	Repeat of Test #1.	0	4.3
4	310	38	34	8	Increase the Froude numbers for the SIH and charging flows by 50% as recommended by the Hydraulics Institute.	0	17.2
5	310	38	34	8	Repeat Test #4.	0	17.2
6	310	38	34	8	Repeat Test #4.	0	17.2
7	0	40	34	8	Investigate small break LOCA response.	0	159.8
8	0	40	34	8	Repeat Test #7.	0	137.6
9	170	24	21	8	Investigate a single train response for the RHS.	0	30.1
10	97	24	21	8	Benchmark case for RELAP5.	0	98.9
11	0	27	22	5	Investigate smaller average void for small break LOCA conditions.	0	0
12	0	27	22	8	Investigate small break LOCA without a 50% increase in the Froude number.	0	30.1
13	0	27	22	8	Repeat Test #12.	0	34.4
14	172	26	22	8	Repeat Test #9.	0	51.6
15	172	25	22	8	Repeat Test #9.	0	47.3
16	175	25	22	5	Investigate single RHS train behavior with a smaller average void.	0	6.5
17	175	25	22	5	Repeat Test #16.	0	4.3

Cases selected for post test analysis comparison were:

1) Case 1
2) Case 9
3) Case 10
4) Case 11
5) Case 12

The pump flow transient data was reviewed to develop approximations of the flow transient imposed by the pump start. Two observations were significant in the review of the data and photographic results for the various cases:

a. The test loop tended to accumulate more gas in the charging line separator than would have originally been expected, based on the RELAP5 calculations for the Millstone 3 plant.

b. The gas transport in the charging line was related to the initial pump start transient. Once steady conditions were achieved, a stable gas bubble would be formed at the charging line elbow with water flowing underneath it. Very little gas stripping occurred in this condition, which is consistent with the relatively low flows present.

3.0 RELAP5 Calculations for the Experiment

Pretest predictions were made for Case 1 with a simplified model. (Appendix A) The pretest model reasonably predicted the results for Case 1, namely that the gas would primarily be transported down the RH line with little or no gas transported to the SI and charging pumps. Further application of this model to other cases quickly demonstrated that the simplified model was not adequately capturing the startup transient deposition of gas to the charging line in the experiment. The steady state behavior of the model was consistent with the test data. The model was revised to include the following:

1) Gas Separators were added for all three suction lines. Initial air volumes were modeled for the charging and SI. The RH accumulator was assumed full of water, due to the smaller ratio of the gas volume the the RH flow rate in the scaled tests. (Initially, the separators applied the stacked volume level option, but this was dropped when non-physical temperature oscillation was observed in volumes experiencing void boundaries crossing the junction)

2) Actual pump start times were developed from the test data to provide more accurate simulation of the start transient. For the purposes of this comparison, the pumps were assumed to start simultaneously. In the tests, the electrical knife switches were activated with a single bar to make the pump initiation as simultaneous as practical.

3) Void volumes of 5 and 8% were applied in the main header.

4) Actual piping runs to the gas separators were added, with pump suction taken from the side of the separator.

5) A control system and TDJ were added to maintain the supply tank at constant elevation, consistent with the tests.

Model development calculations are provided in Appendix B. A diagram of the model is provided in Figure 3-1.

The model is exercised for a 100 second null transient prior to the pump start to enable stable pressures and void fractions to be attained. The pumps are started and run for times comparable to the test. The model is exercised for 10 seconds beyond the pump stop to enable a rest condition to be achieved in the gas separators comparable to what was measured shortly after each test.

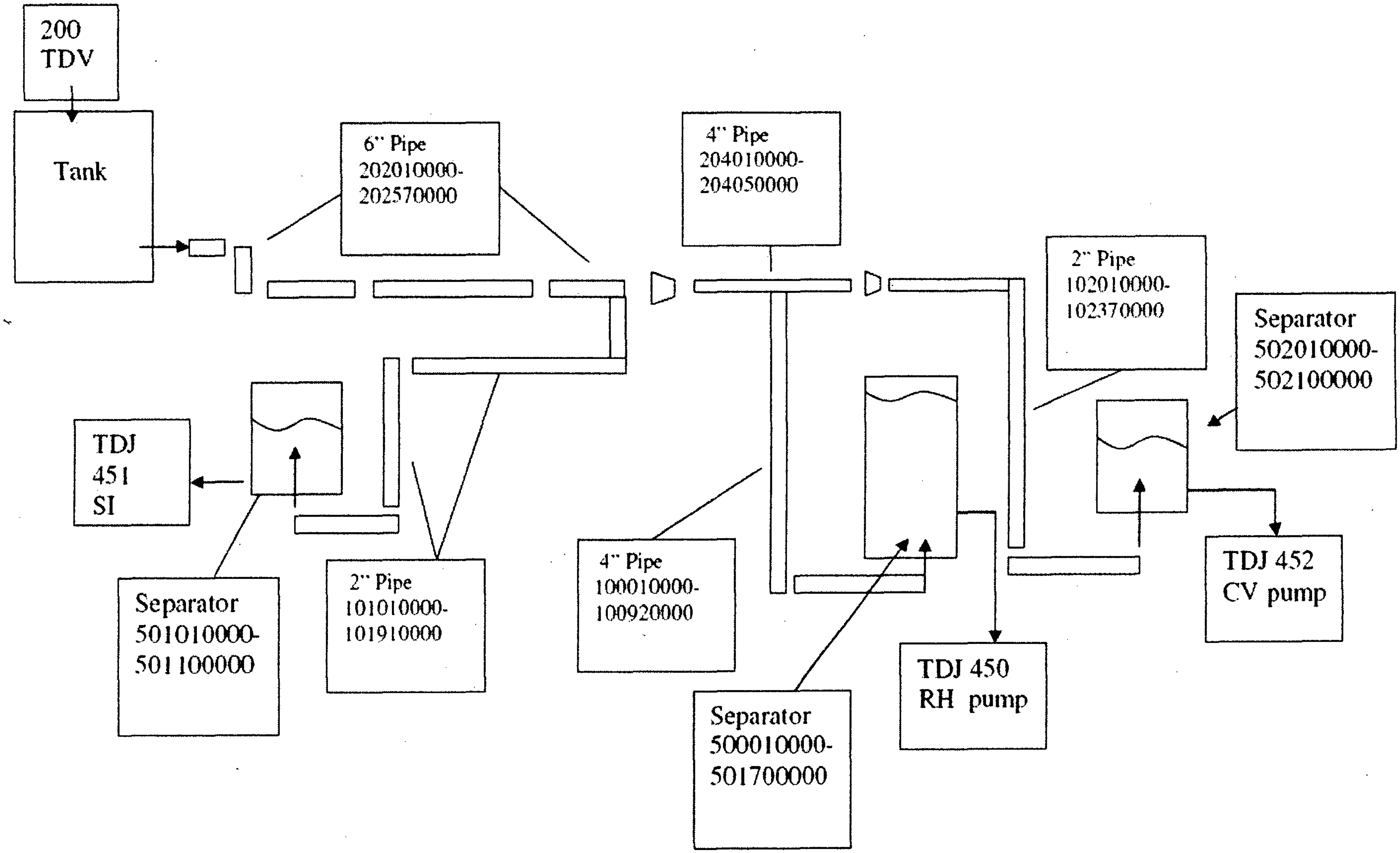

Figure 3-1 Test facility RELAP5 model diagram.

Cases 1, 9, 10, 11, and 12 were simulated with the RELAP5 model. As noted previously, the pre-test model was upgraded to add more detail, particularly with respect to physically modeling the gas separators and their non-condensable gas volumes. The effect of doing this is shown in Figure 3-2, which provides the flow velocity part way down the vertical drop from the main header and compares it to the measured flow on the line between the separator and the pump suction (note that velfj452 is the measured velocity, applied at a time dependent junction). The presence of a gas volume in the system clearly induces a dynamic response in the piping. The velocity oscillation resulting from the start transient can result in differences in the computed entrainment, and are the most likely reason we observed gas entrainment in the charging line that exceeded our expectations. In addition, it provides an explanation of the sinusoidal early oscillatory behavior we observed in the videos taken of this line, as well as the visual observation that virtually any gas entering the charging line did so very early in the test. The initial negative flow shown in Figure 3-2 is due to the dominance of the RH flow transient.

The predicted air transport as measured in the separators is compared to the actual measurements in Table 3-1. The RH gas separator proved to experience too much carryunder to provide a reliable measurement of gas transport to that loop so RH gas transport was calculated separately using a command file with APTPLOT. The RELAP model predicted this behavior as well. The pattern that emerges is that the code correctly predicts no SI entrainment, and tends to send all the gas down the RH 45 degree inclined pipe. In the absence of RH flow claiming the air (Tests 11 and 12), the entrainment in the charging line is predicted quite well and slightly on the conservative side. The RH gas transport for Cases 1, 9, and 10 are shown in Figure 3-3, Figure 3-4 and Figure 3-5. In case 1, virtually all the gas in the system is transported and fully expelled from the RH suction piping. In case 9, most of the gas in the system is transported into the RH suction piping, but a large percentage is held up in the suction line and returns to the system after pump trip. In case 10, a significant fraction of the gas in the system is pulled into the RH line and held up, but very little actually is entrained and transported through the system.

Figure 3-6 provides the charging line flow velocity for Case 12, the case with no RH pump running. As can be seen, a velocity oscillation occurs due to the effects of the gas separator. There is no initial negative flow, which confirms the hypothesis that the RH start transient causes an initial reverse flow in the charging piping. As noted above, RELAP5 does a very good job at predicting the entrainment and transport of gas for this case. Figure 3-7 shows the gas void fractions at the down-turning elbow in the charging suction line. The plot clearly shows that gas is being held up in the elbow. Figure 3-8 shows the liquid velocities for the same volumes. This shows that the liquid is running at higher speeds under the gas void at the elbow, supplying the flow required by the pump. This feature, sometimes referred to as a kinematic shock, was clearly seen in the test.

3.1 Supplemental Test Comparison

Based on the results obtained in the test comparison and the observed impact of the gas-separator dynamic contributions, a decision was made to repeat some of the tests with the intent of more closely observing the transient level response of the gas separators. The base conditions present in Test 12 were selected (RH=0, Chg=21gpm, SIH=25gpm with an 8% initial header void). Three additional tests were run at these flows and the gas separator level behavior was confirmed to exhibit sinusoidal oscillation during pump start. The measured gas transport to the charging separator was very consistent with that observed in Test 12. Four additional tests were performed to allow additional data points at increased charging pump flow rates. Test 21 was run at a charging flow of 55 gpm (SIH at 25 gpm). At this flow rate, some gas bubbles were observed to entrain in the charging gas separator and be transported towards the pump. The next test point selected was with a charging flow rate of 35 gpm (SIH=25gpm). This flow proved to remain within the capability of the gas separator to fully retain the gas entering the separator. This test condition was repeated twice more to establish repeatability. (Tests 22-24). The tests run and observed gas transport are provided in Table 3-2.

The model was configured to reflect the flows of Test 21 and Test 24 and cases were run for comparison. The gas transport to the charging line separator comparison is provided in Table 3-3. For Test 21, the RELAP model predicted a small amount of carryunder from the gas separator, which was consistent with the behavior observed. The results from this case need to be treated with some circumspection, since there is no way to accurately compare the carryunder gas flows. There was no carryunder observed in the Test 24 case. The gas transport predicted compared very favorably with the test measured values.

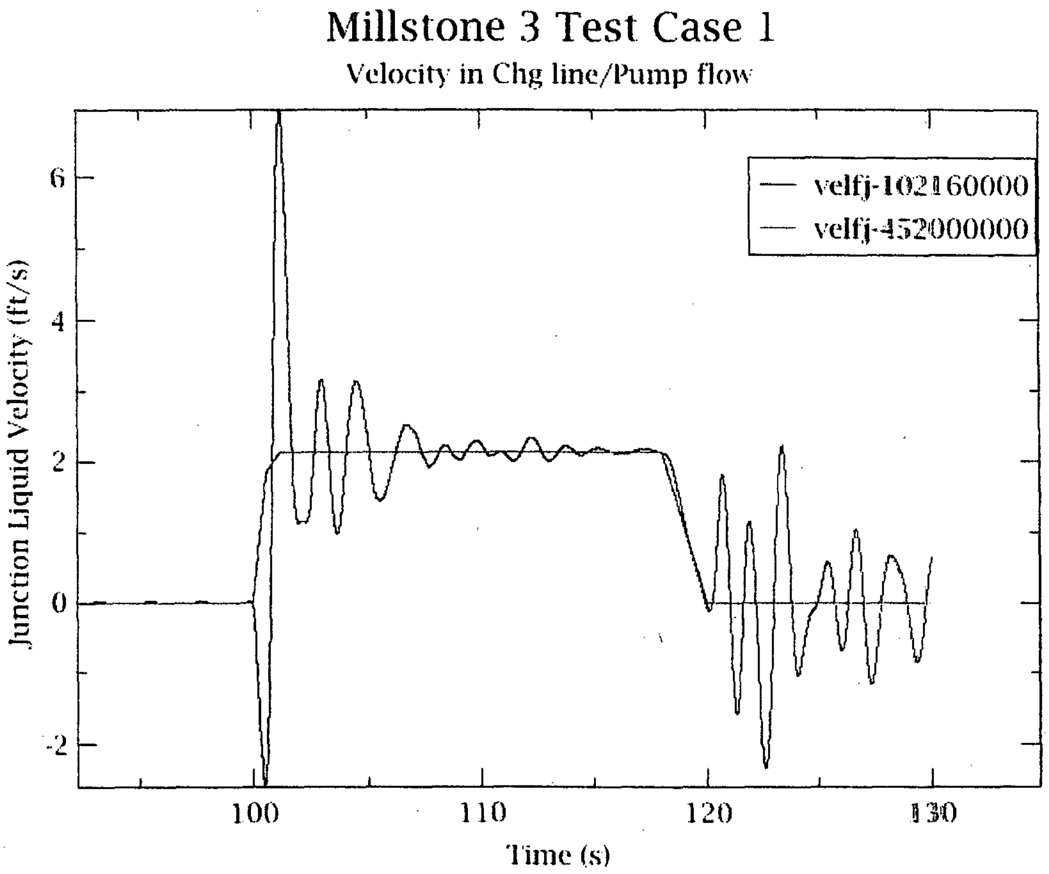

Figure 3-2 Case 1 charging flow velocity.

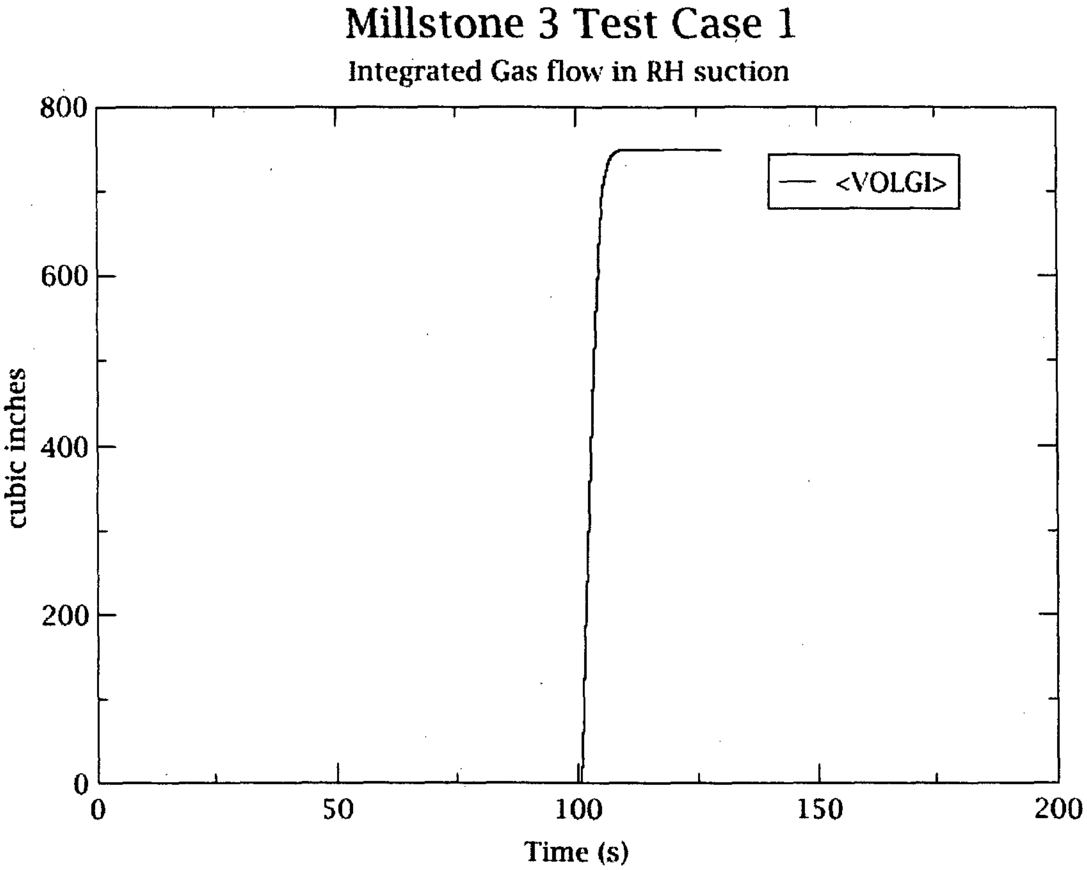

Figure 3-3 Case 1 RH line gas transport.

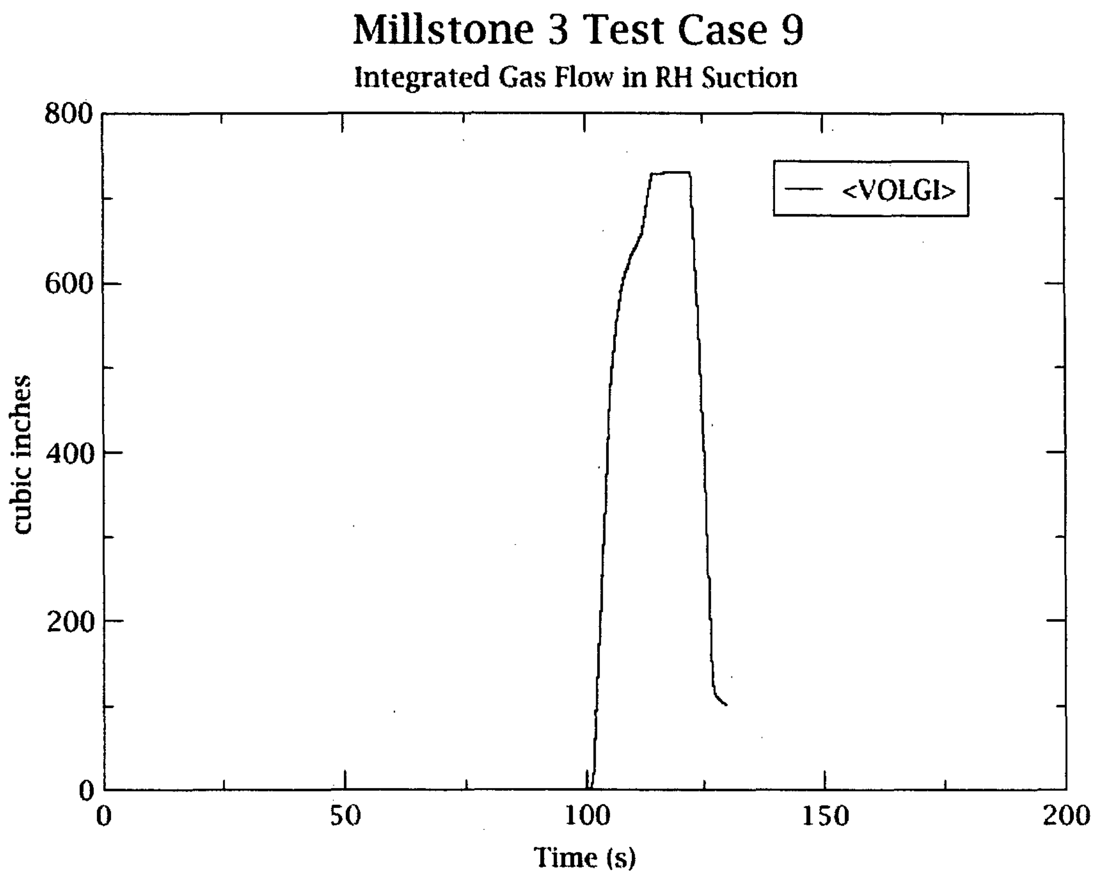

Figure 3-4 Case 9 RH line gas transport.

Note: The downturn and decay to approximately 100 cu in reflects the return of gas to the 4 and 6 inch headers following pump trip.

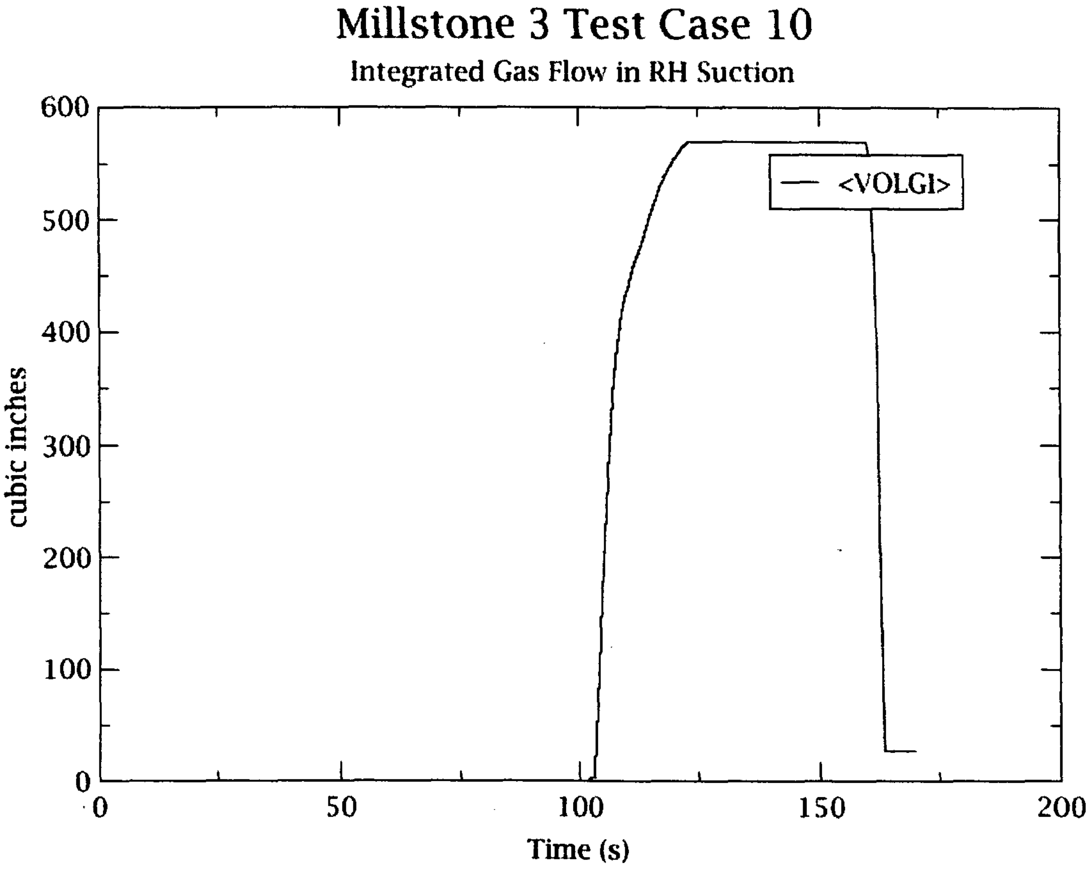

Figure 3-5 **Case 10 RH line gas transport.**

Note: The downturn and decay to approximately 30 cu in reflects the return of gas to the 4 and 6 inch headers following pump trip.

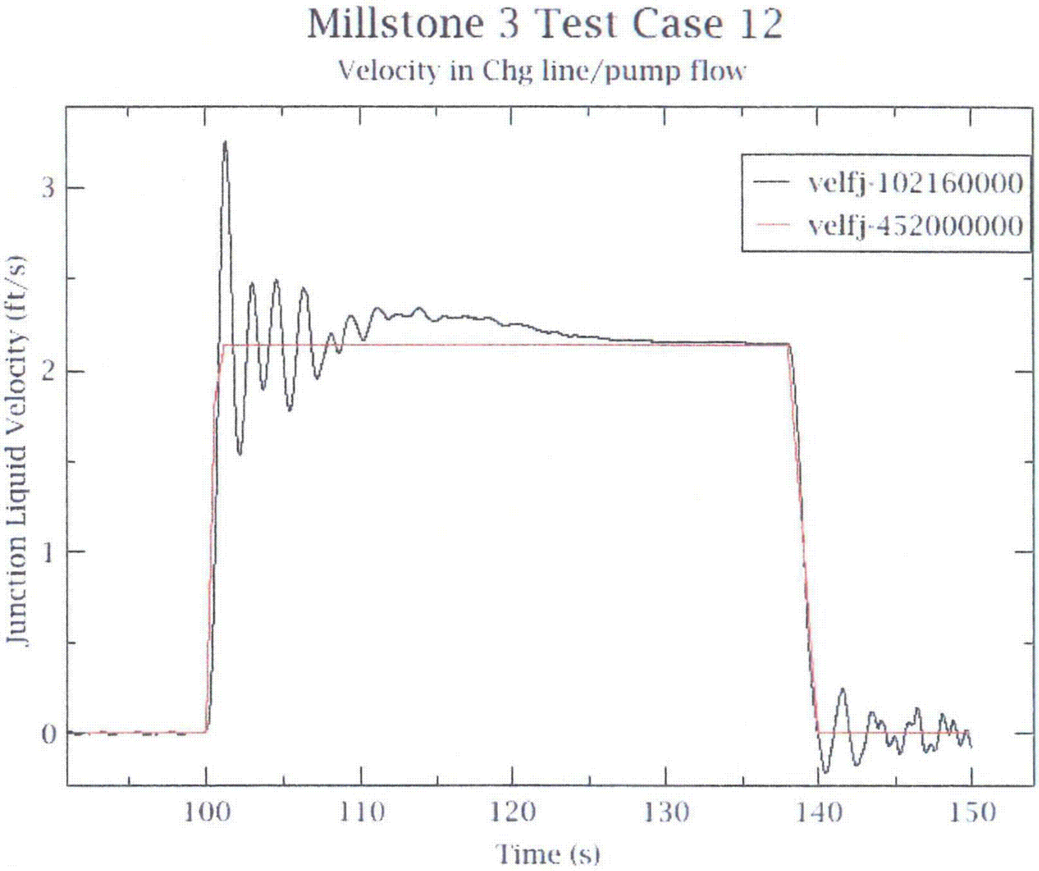

Figure 3-6 Test Case 12 charging line velocity.

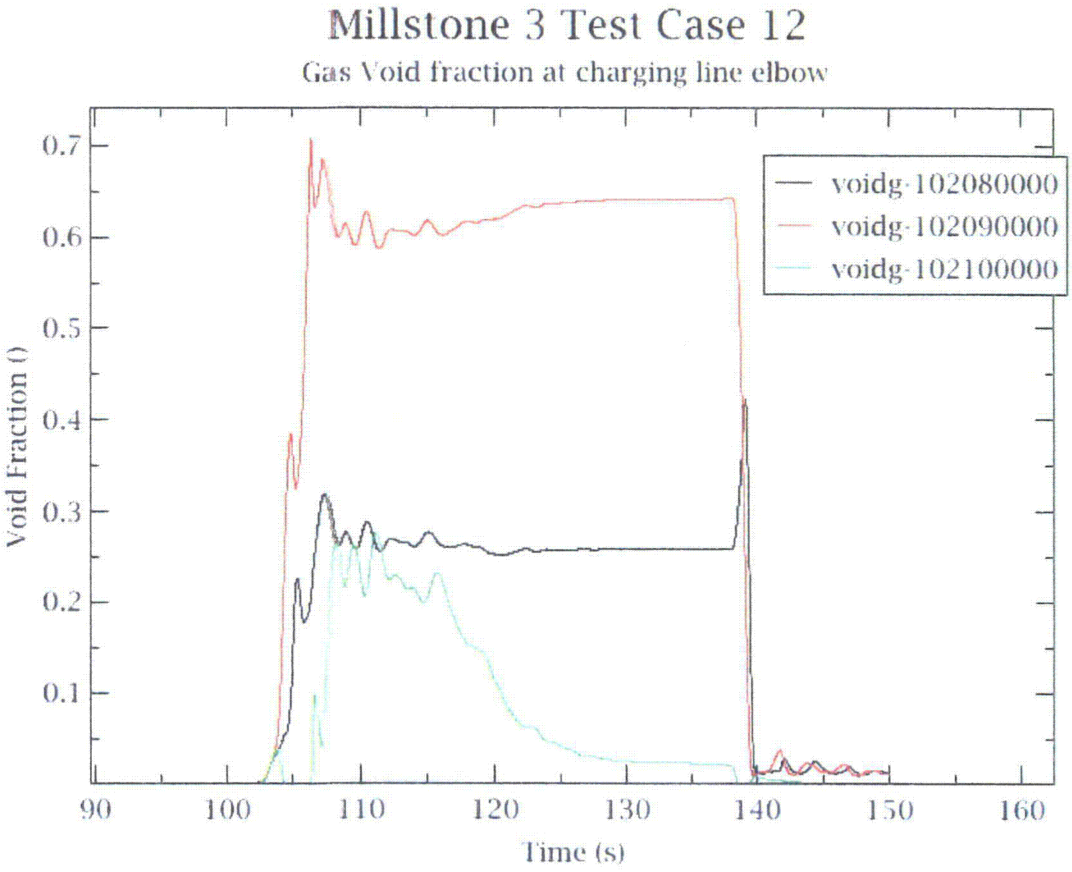

Figure 3-7 Test Case 12 gas void fraction near charging line elbow.

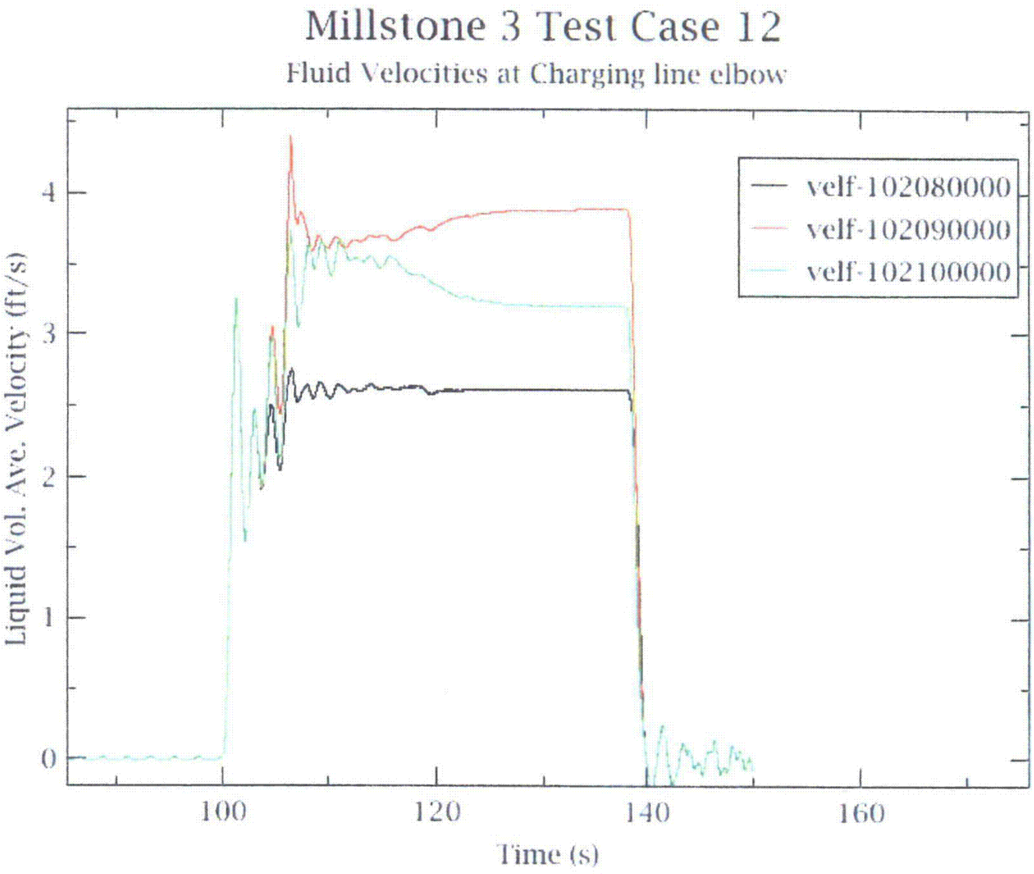

Figure 3-8 Test Case 12 fluid velocity near charging line elbow.

Table 3-1 Air Transport Result Comparison

Case	Chg (Meas./Pred) cu-in	SIH cu-in	Flows Modeled RH/SI/CHG
1	0-9/0	0/0	315/23/22
9	30-50/0	0/0	170/25/22
10	98.9/18.3	0/0	100/25/22
11	0/12.4	0/0	0/25/22
12	30-35/42	0/0	0/25/22

Table 3-2 Supplemental Tests

Case	Chg (Measured gas accumulation cu-in)	SIH cu-in	Flows Modeled RH/SI/CHG
18	29	0/0	025/21
19	34.6	0/0	0/25/21
20	29	0/0	0/25/21
21	393	0/0	0/25/55
22	185	0/0	0/25/35
23	231	0/0	0/25/35
24	185	0/0	0/25/35

Table 3-3 Supplemental Test Comparison

Case	Chg (Measured gas accumulation cu-in)/Predicted	SIH cu-in	Flows Modeled RH/SI/CHG
21	393/371	0/0	0/25/55
24	185/167	0/0	0/25/35

4.0 CONCLUSIONS

A detailed model of the ¼ scale Millstone 3 RWST suction piping test was prepared and exercised using the measured pump flow rates and known initial void conditions. The following observations are salient:

1) The model does a good job of predicting the entrainment in the Charging line in the absence of RH flows, and for a range of charging flows, demonstrating that RELAP correctly handles entrainment at downward elbows in pipe models.
2) The horizontal stratification vapor pull through model on the downward pointing SI takeoff matches the test observations of no gas entrainment in any of the test cases.
3) The horizontal stratification vapor pull through model on the 45 degree RH takeoff works well, and may be somewhat over-conservative in its prediction of gas pull through. The results match the test data in that RH was observed to entrain virtually all the gas available.
4) The additional dynamic behavior produced by the presence of the gas separators highlights the importance of capturing any such effects when performing analysis of gas transport in piping systems.
5) The results obtained in these comparisons support a conclusion that RELAP5 Mod 3.3gl (patch 03) demonstrates the ability to predict gas transport for this configuration with reasonable fidelity.

5.0 REFERENCES

FAI/09 (2009). *"Test Results for the Millstone 3 Gas/Water Transport Tests"*. FAI/09-22: Fauske & Associates, LLC.

APPENDIX A: Pretest Predictions for Case 1

Pretest Predictions of the Millstone 3 FAI ¼ Scale Test Using RELAP5

Introduction

A RELAP5 model was prepared to simulate the gas void transient in the FAI ¼ scale experiment. The model was based on as built measurements of the test apparatus. Two cases with different initial void content in the 6 inch piping were run for the same pump flow combinations. The results obtained provide insight into what may be expected to occur in the test assembly.

Model Description

A diagram of the RELAP5 model is attached. Generally, the piping was subdivided into node lengths such that the L/D ratio was approximately 1, in keeping with code developer guidelines. The horizontal stratified flow pull through model was applied for a 45 degree outtake condition for the RH line, and for a 90 degree outtake condition for the SI line. The CV line did not specifically apply the horizontal stratified pull through model. Time steps of 2 milliseconds were applied for both cases. The pump outflows were modeled as time dependent junctions with specified velocity condition vs time.

Case Description

Two cases were performed: 5% initial void present in the 6 inch header, and 10% initial void present in the 6 inch header. The pump flows were computed based on 25 gpm each through the SI and Charging headers, and 310 gpm flow through the RHR line.

Results

The model was initialized with the desired void fraction present in the 6 inch header. A linear ramp of pump flow was initiated at 1 second with the pumps reaching steady condition in one second. The runs were continued until the void was transported through the system. Figure A-1 shows the void fraction at two locations in the 6 inch header for the 5% initial void case. Figure A-2 shows the void fractions exiting the TDJ's representing the pump outtakes. As can be readily seen, the RHR line carries virtually all of the gas. A very minute amount of gas is transported in the charging header, on the order of 0.05%.

Figure A-3 provides the void fraction at two locations in the 6 inch header for the 10% initial void case. Figure A-4 shows the void fractions exiting the TDJ's representing the pump outtakes. The model predicts virtually all the void entering the RHR header, with a small amount (less than 1% void fraction) entering the charging line.

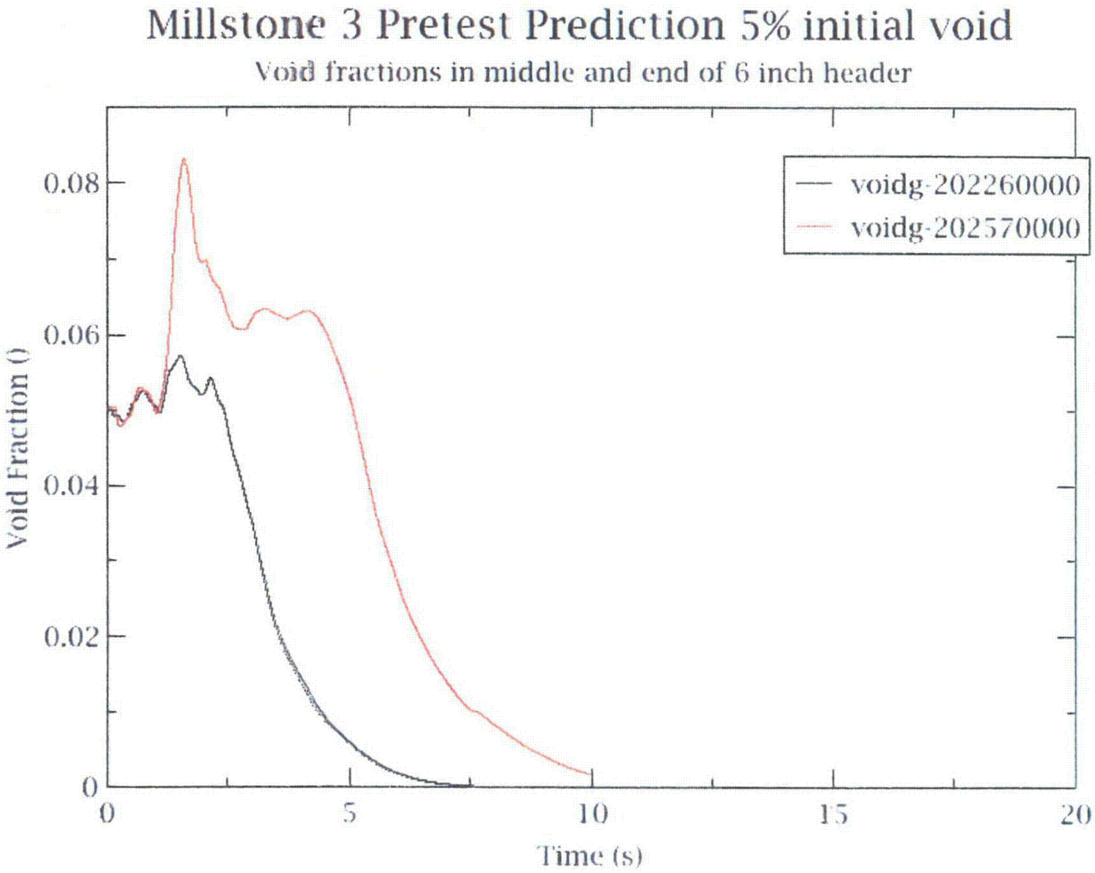

Figure A-1 Void fractions in 6 inch header 5% void case.

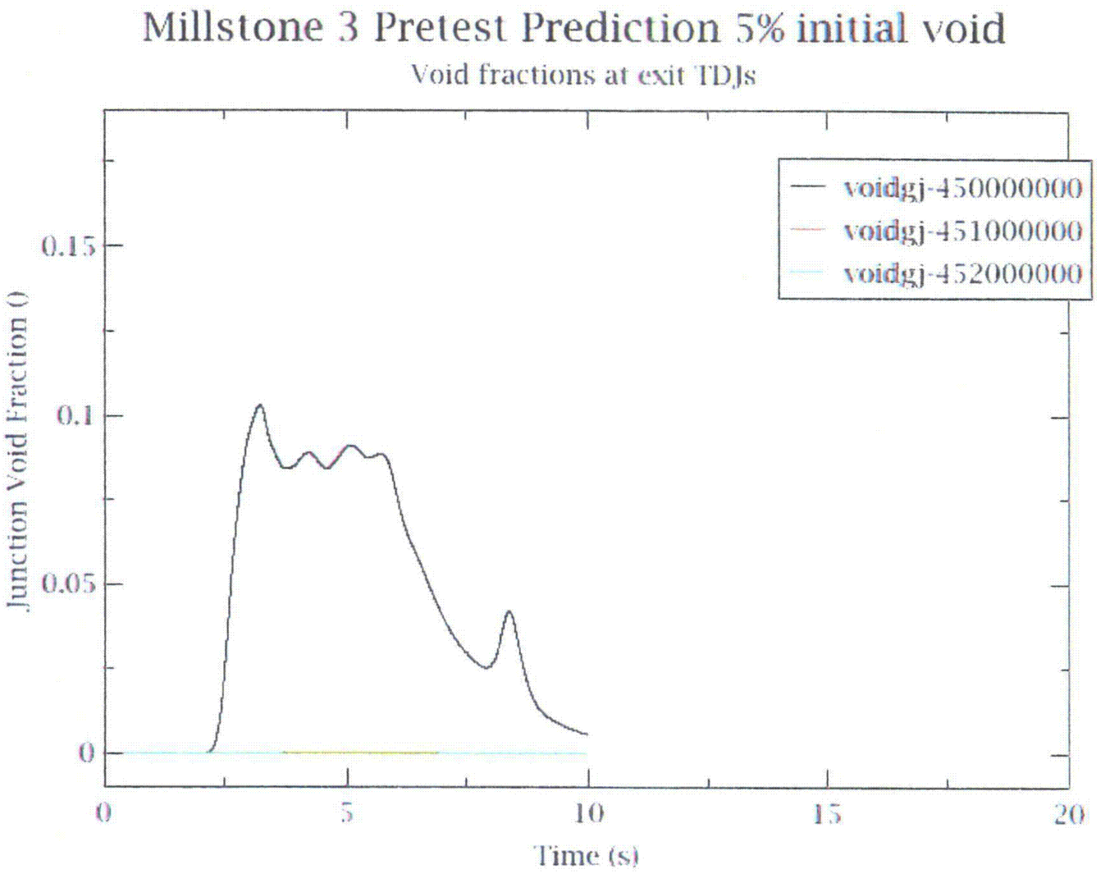

Figure A-2 Void fractions exiting the time dependent junctions – 5% initial void case.

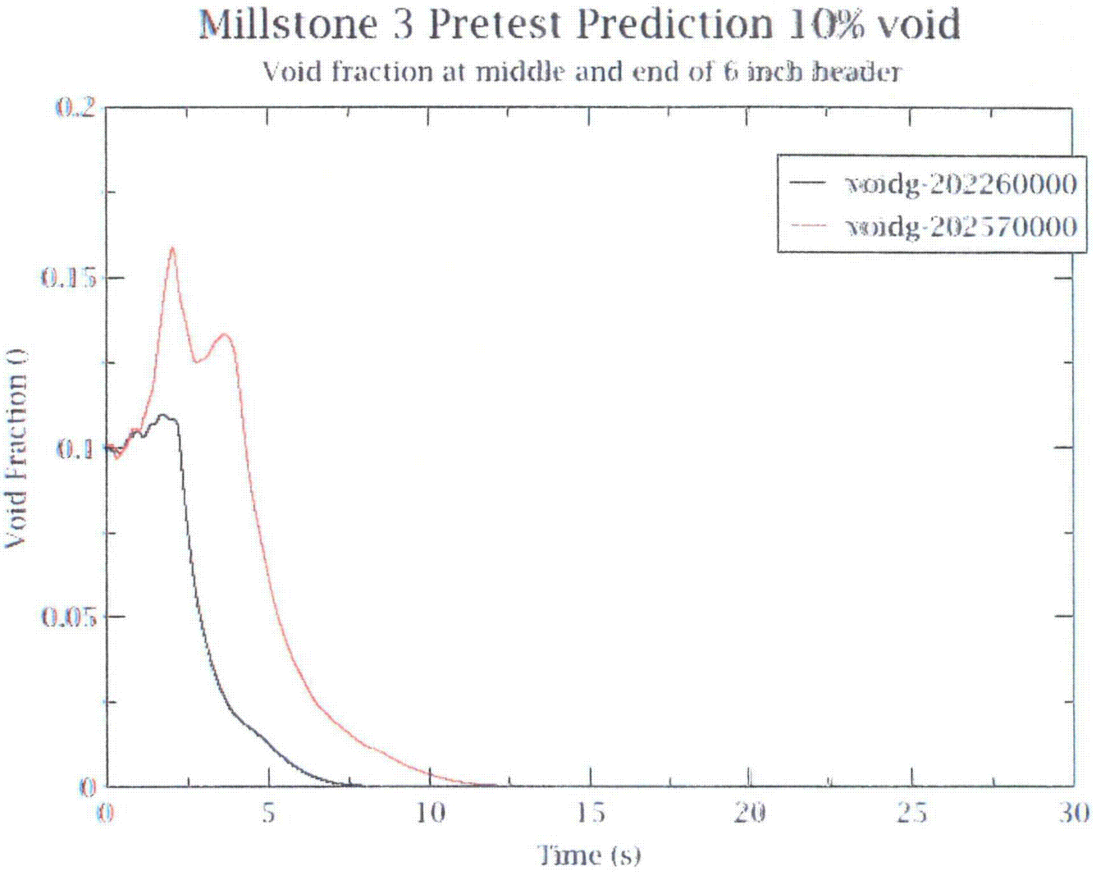

Figure A-3 Void fractions in 6 inch header 10% void case.

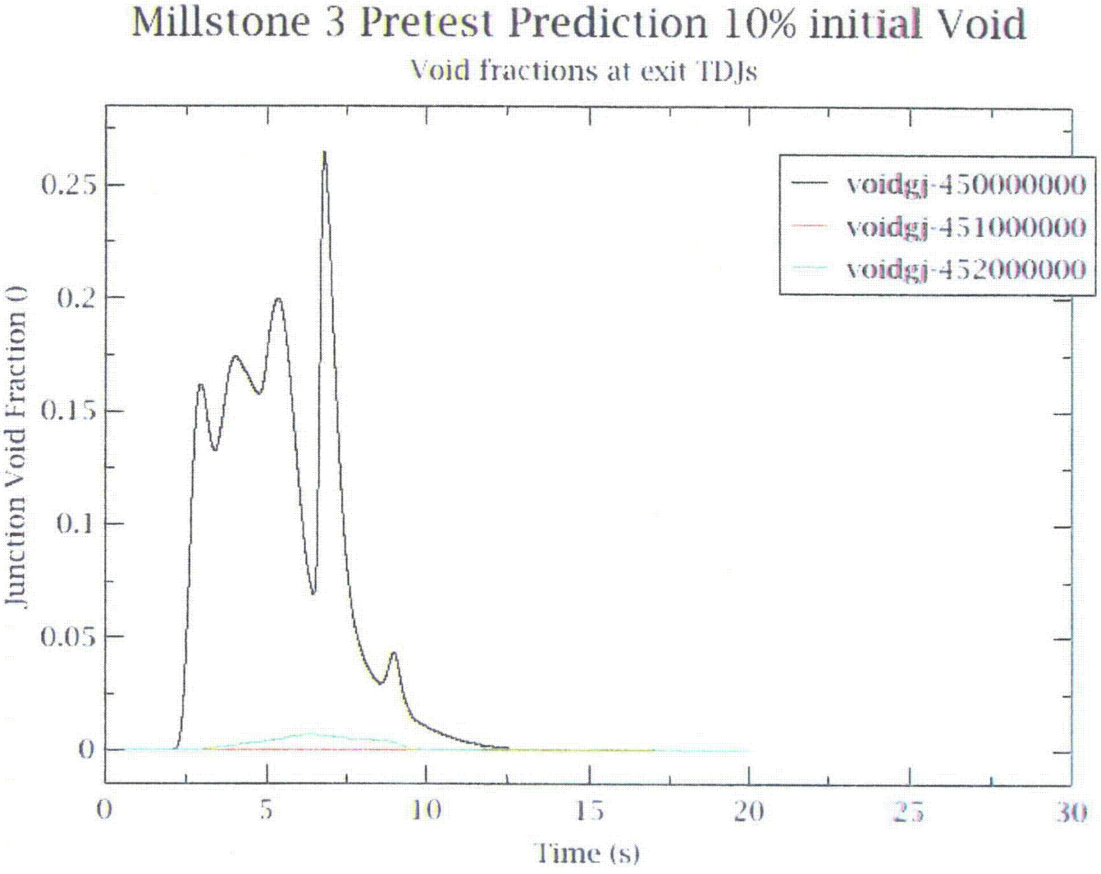

Figure A-4 **Void fractions exiting the time dependent junctions – 10% initial void case.**

APPENDIX B: Model Development Calculations

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APPENDIX C: RELAP5 Model Input Deck

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