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Post-Processing V&V Level II ASC Milestone (2843) Results

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Abstract

The 9/30/2008 ASC Level 2 Post-Processing V&V Milestone (Milestone 2843) contains functionality required by the user community for certain verification and validation tasks. These capabilities include fragment detection from CTH simulation data, fragment characterization and analysis, and fragment sorting and display operations. The capabilities were tested extensively both on sample and actual simulations. In addition, a number of stretch criteria were met including a comparison between simulated and test data, and the ability to output each fragment as an individual geometric file.

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1. EXECUTIVE SUMMARY

Sandia has met the requirements of the 9/30/2008 ASC Level 2 Post-Processing V&V Milestone (Milestone 2843). All functionality required by the user community is present and has been tested extensively. Capabilities provided and/or tested by the user community for this milestone include fragment detection, characterization, display, and output while running in parallel. Also, the ability to calculate fragment plane intersections was added. In addition, a number of stretch criteria were met, including the ability to save fragment geometry and a comparison with actual test data. All SNL tasks are documented in the *VandV08 Post-Processing DOE Success Stretch Criteria* (WFS762662) document. All results are documented in this document (WFS762658).

2. MILESTONE OBJECTIVE SUCCESS CRITERIA

The Completion Criteria specified in the Milestone were to provide scalable analysis capabilities to support validation of large data with particular emphasis on comparison of simulation and test data. The project expects to deliver capability supporting specific aspects of large data analysis that will be of use to a range of customers.

From the completion criteria specified above, the following objective success criteria were developed early in the calendar year by the milestone team, consisting of David Karelitz, Dino Pavlakos, David Rogers, Ken Moreland, Tom Otahal, Lisa Ice, Jason Wilke, and Stephen Attaway. To successfully complete the milestone, the following baseline capabilities were developed and tested against example and actual datasets to the satisfaction of the customers, Stephen Attaway and Jason Wilke.

1. Fragment Operations
    a. Fragment detection
        i. Successful detection of all fragments from a single timestep in a simulation results file using a parallel invocation of the visualization tool
    b. Fragment characterization
        i. Successful calculation of the following quantities for each fragment
            1. Mass
            2. Longest Dimension
            3. Shortest Dimension
            4. X, Y, Z Position
            5. Other variables present in the input file
    c. Fragment organization and display
        i. Successful thresholding of fragments by quantities calculated in 1b.
        ii. Successful binning of fragments by quantities computed in 1b. The bin quantity will be referred to as the primary variable in the following items.
        iii. Successful plotting of primary variable versus count
        iv. Successful computation of the average value of the non-primary variables for each bin
        v. Successful plotting of primary variable versus non-primary variable.
        vi. Successful output of primary and secondary variables as well as bin count to a text file
2. Geometry Intersection Operations
    a. Successful calculation of all material intersecting a given plane at a single timestep
        i. Colored by velocity
        ii. Colored by mass
    b. Successful calculation of time and place of intersection of all fragments and a plane

i. Display Types
   1. Mark indicating fragment position on the plane at time of intersection
   2. Mark colored by any of the quantities listed in 1b above.

3. MILESTONE OBJECTIVE STRETCH GOALS

1. Compare fragment results from a simulation to experimental data – The ability to do comparative analysis to support validation is a fundamental driver for the work associated with this milestone. Demonstrating such ability is viewed as a high priority. The milestone team intends to do everything it can to complete such a demonstration – however, due to the uncertainty associated with completion of an associated experiment in the time frame needed to meet the milestone schedule, that demonstration is included as a stretch goal, rather than part of the baseline success criteria.
2. Saving Fragment Geometry - Provide the ability to save each fragment as an STL file

4. ALGORITHM

Overview

The fragment detection filter takes as input an SPCTH dataset and produces three outputs. The first is an isosurface of each selected material at the specified material volume fraction. The second is a single point either at the center of mass of each fragment, or the center of the bounding box, where each point contains all the characteristics of that fragment (mass, volume, velocity, etc.). The third output is either an axis-aligned or oriented bounding box per fragment, whichever is smaller. Due to the nature of the oriented bounding box calculation, it is only an approximation, not the absolute smallest bounding box.

Fragment identification

The vtkCTHFragmentConnectFilter works by traversing the input data set's blocks, block by block and cell by cell, within each block, searching for cells which have a material fraction that is greater than a user supplied threshold value. As cells are visited, they are marked as outside the search space, so that the search space is successively reduced with each cell visited. When a cell having material fraction greater or equal to the threshold value is found, it is used as a seed for the fragment generator. The fragment generator searches the seed cell's neighbors for cells which also have a material fraction that is greater or equal to the threshold value. If any are found, they are treated as seed cells and the process continues until no more seeds can be found. The resulting set of seed cells belong to a single fragment.

Collection phase

During the output phase, fragments, which may have geometry split across processes and within a process, are examined to determine which pieces belong to the same fragment. This is called fragment resolution. During resolution, the controlling process gathers fragment ids and computed attributes. The resolution process is based on internally generated equivalence sets that describe fragment connectivity across processes. For fragment pieces which are identified as being split across processes, attribute contributions are accumulated, and the calculations are finalized. Once the controlling process has resolved the fragments' attributes, the resolved attribute arrays are broadcast to all other processes for output dataset generation.

5. RESULTS

5.1 Milestone Objective Success Criteria

1a. Successful detection of all fragments from a single timestep in a simulation results file using a parallel invocation of the visualization tool

Two sets of test data were generated for this milestone. The first consisted of 4 fragments moving at a known constant velocity and was used to verify the calculation ParaView performed on each fragment. The second was generated from the CTH amr-3d-oblique example input deck and was used to test fragment detection at a larger scale. This dataset shows a hemisphere hitting a block and consists of 256 files and 182 million cells. Figure 1 below shows the results of running the fragment detection filter on the large dataset at the last timestep using 16 nodes from blackrose. The visualization is colored by fragment ID; however, due to color resolution issues, only 256 different colors are shown.

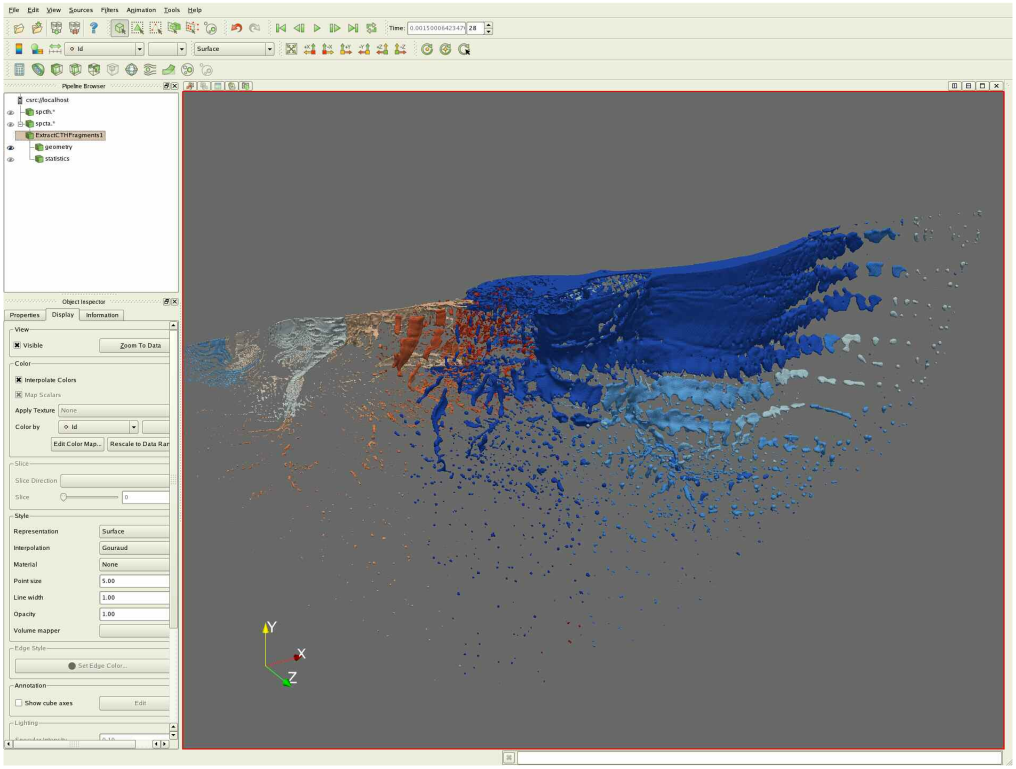


Figure 1: Fragments colored by fragment ID

1b. Fragment characterization

Successful calculation of the following quantities for each fragment:

1. Mass
2. Longest Dimension
3. Shortest Dimension
4. X, Y, Z Position
5. Other variables present in the input file

Figure 2 shows the Mass, Volume, longest, middle, and shortest dimensions (OBB Dimensions), and fragment center of mass location (Point Coordinates) for a set of fragments from the large dataset. Velocity was the only other variable present in the input file, and the volume-weighted average of this variable was computed for each fragment.

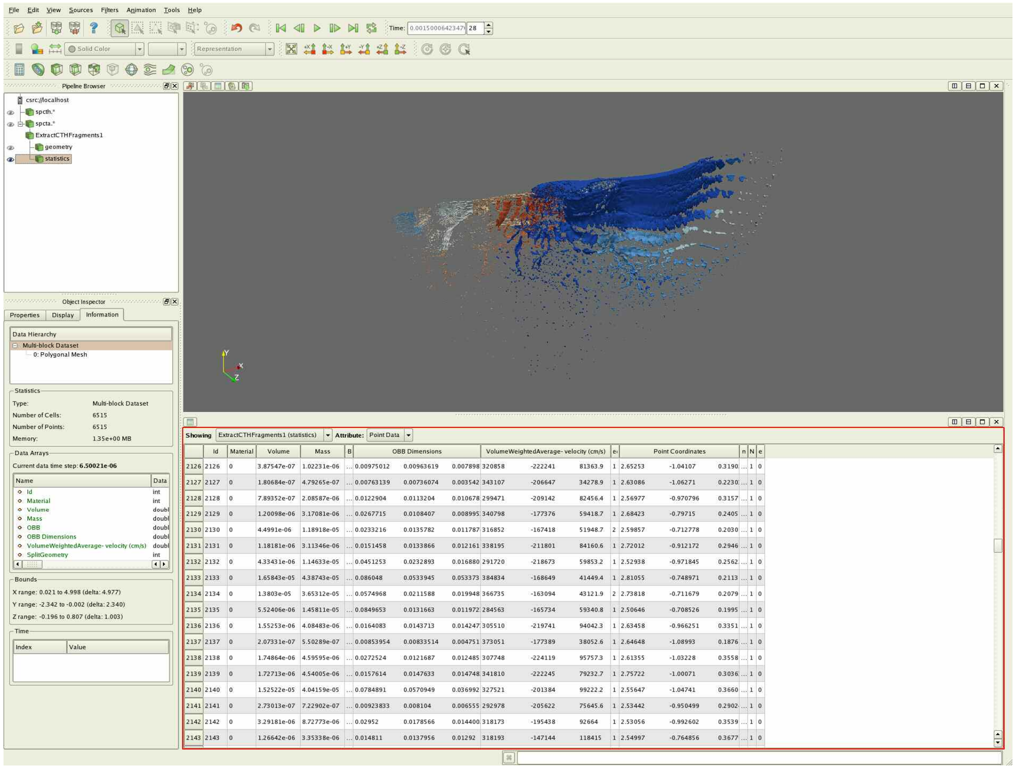


Figure 2: Numerical display of Mass, Velocity, Position and Size of each fragment

1c. Fragment organization and display

1. Successful thresholding of fragments by quantities calculated in 1b.
2. Successful binning of fragments by quantities computed in 1b. The bin quantity will be referred to as the primary variable in the following items.
3. Successful plotting of primary variable versus count
4. Successful computation of the average value of the non-primary variables for each bin
5. Successful plotting of primary variable versus non-primary variable.
6. Successful output of primary and secondary variables as well as bin count to a text file

Figure 3 shows the fragments thresholded by mass such that only the 3 heaviest fragments remain, demonstrating item one above. Figure 4 shows a mass histogram of all the smaller fragments (between 1e-8 and 1e-6 grams) demonstrating items two and three above. Figure 5 shows a plot of mass versus the average temperature of fragments with that mass, demonstrating items four and five. The text file containing the data from Figure 5 is shown as Appendix B: Histogram output.

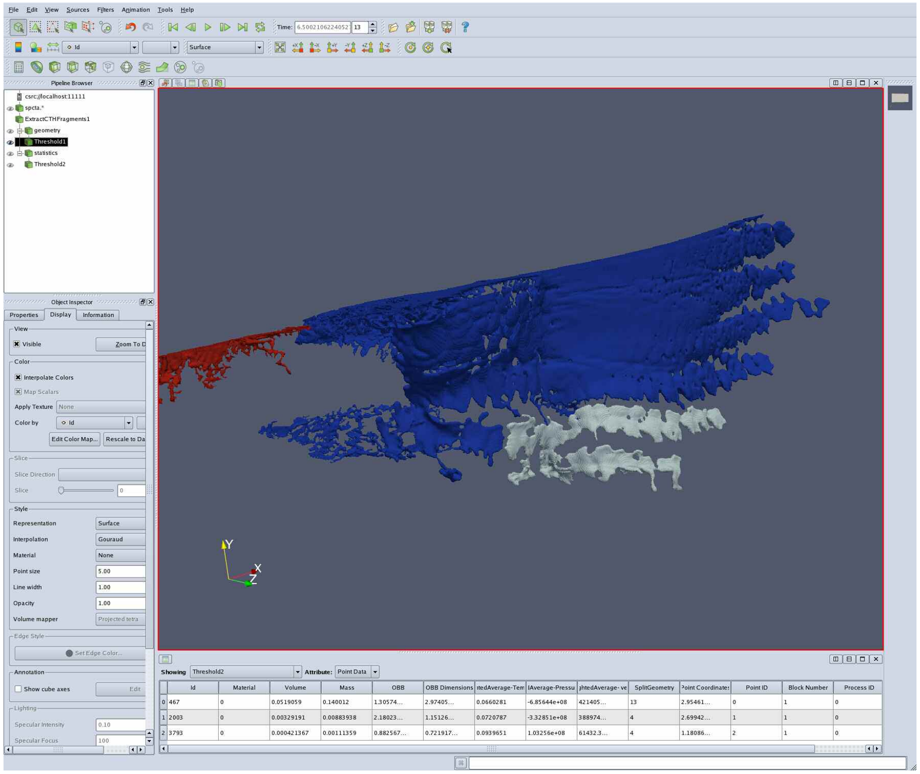


Figure 3: Three heaviest fragments

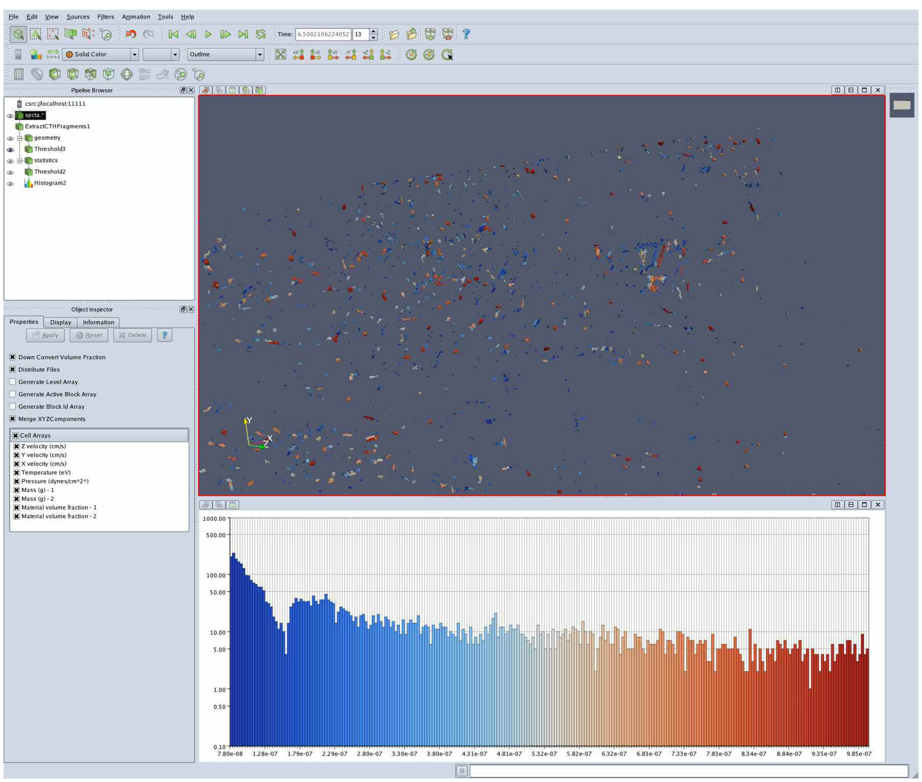


Figure 4: Histogram of smaller fragments

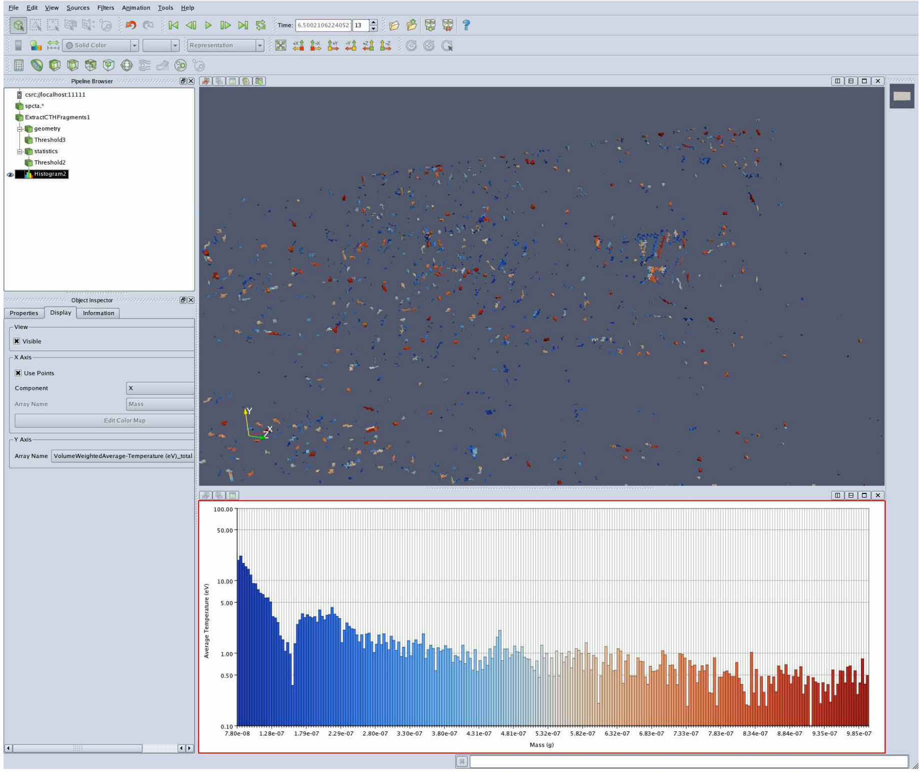


Figure 5: Plot of mass vs. average temperature

2a. Successful calculation of all material intersecting a given plane at a single timestep

1. Colored by velocity
2. Colored by mass

Figure 6 shows the intersection of a plane and all the fragments. The top view shows the outline of each fragment while the bottom view shows all the fragments and the plane used for intersection. The fragments in the bottom view and their outlines in the top view are colored by the average velocity of the fragment. Figure 7 shows a similar figure, but using mass instead of velocity.

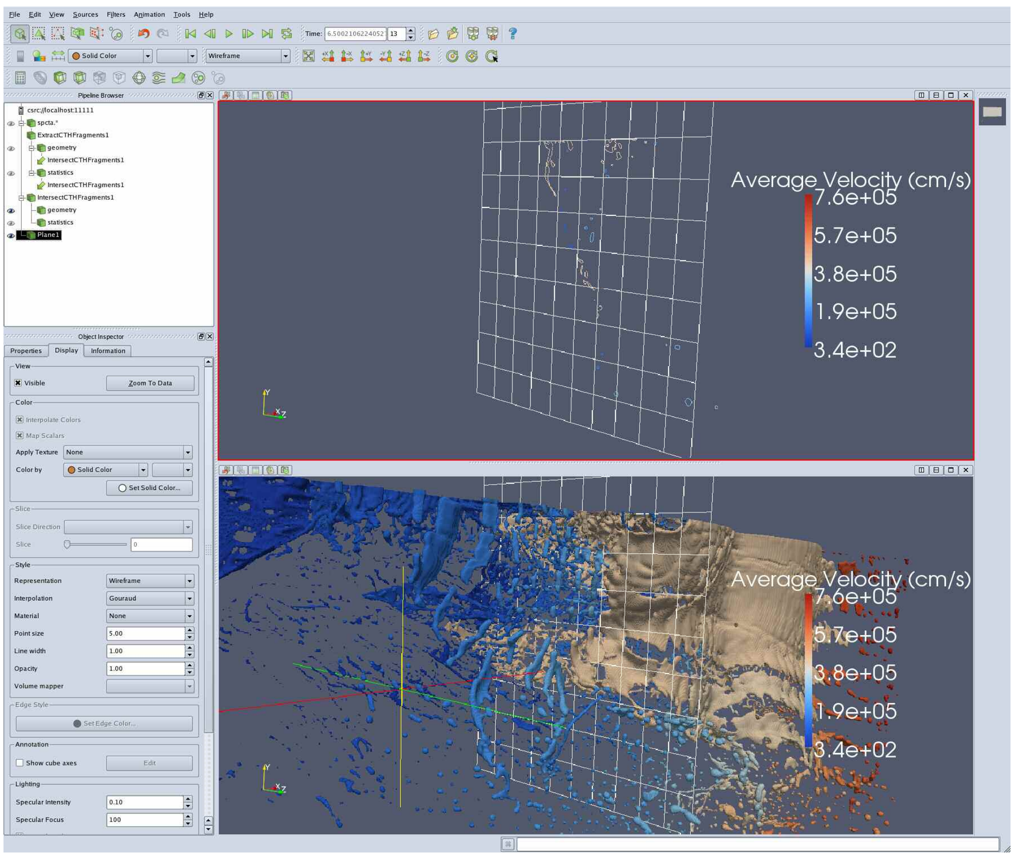


Figure 6: The fragment/plane intersection outlines, colored by velocity, are visible in the top. The bottom shows the fragment field and the plane

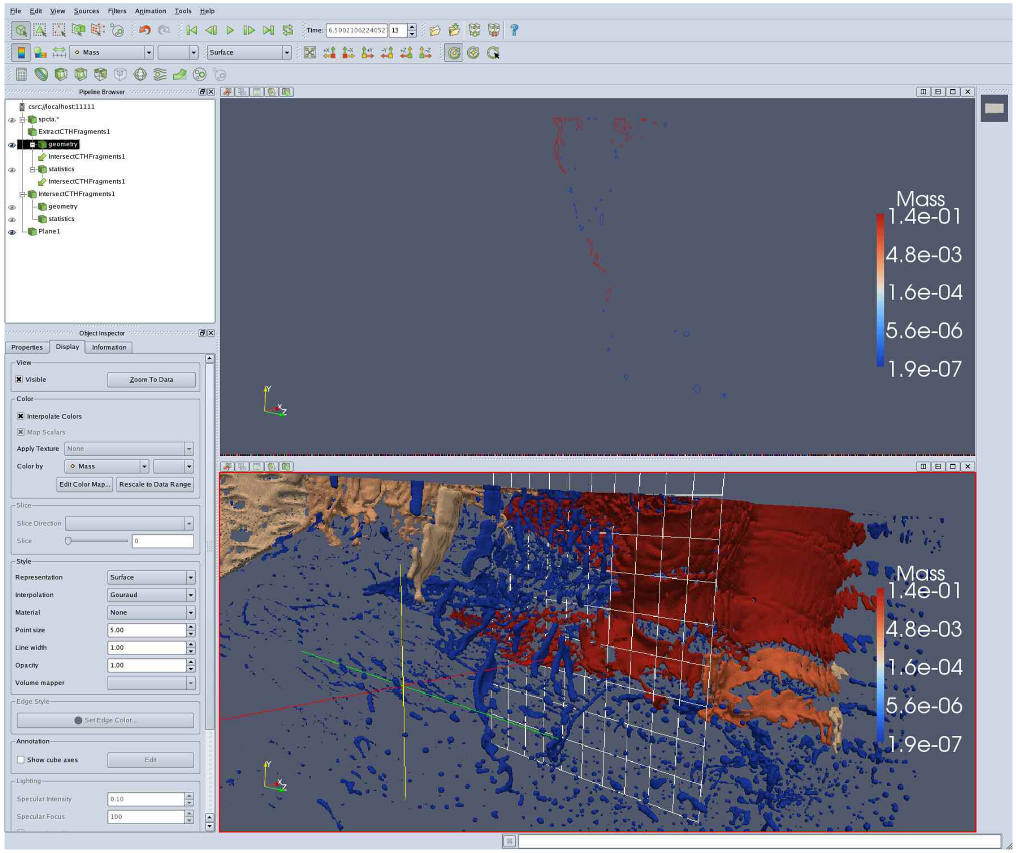


Figure 7: The fragment/plane intersection outlines, colored by mass, are visible in the top. The bottom shows the fragment field and the plane

2b. Successful calculation of time and place of intersection of all fragments and a plane

   1. Mark indicating fragment position on the plane at time of intersection

Figure 8 below shows one mark per fragment with the marks colored by the fragment ID. The top and bottom views are correlated. In addition to the visual display, a csv file containing the fragment attributes (mass, volume, velocity, etc.), similar to that produced for 1c above, can be output either for the current timestep or for all timesteps. A short sample of these files is available as Appendix

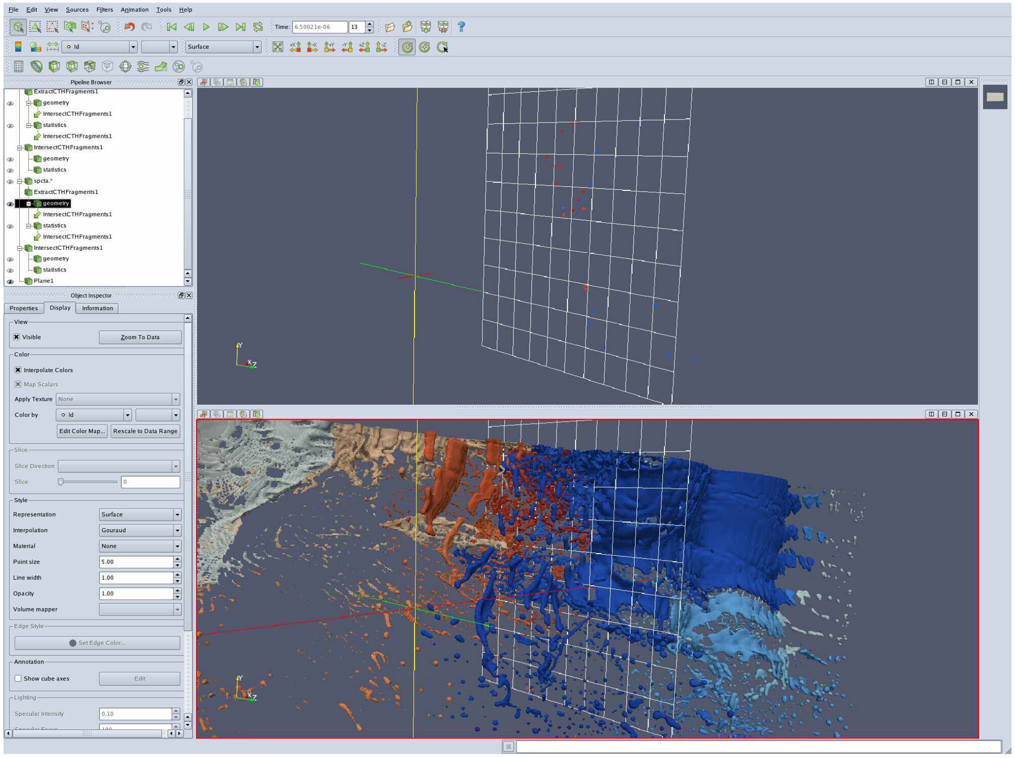
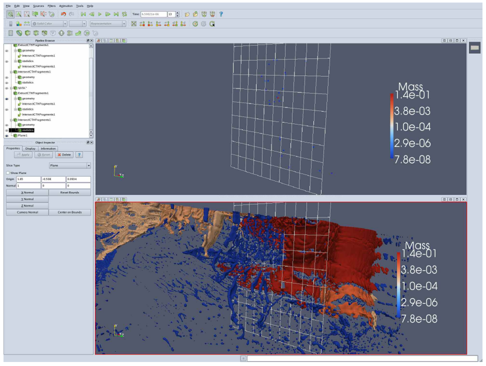


Figure 8: One mark per fragment intersecting the plane, colored by fragment ID

2. Mark colored by any of the quantities listed in 1b above.

Figures, 9, 10, 11, and 12 below show a similar image to Figure 8 above, but the marks are colored by Mass, Velocity, Shortest Dimension, and Longest Dimension respectively.



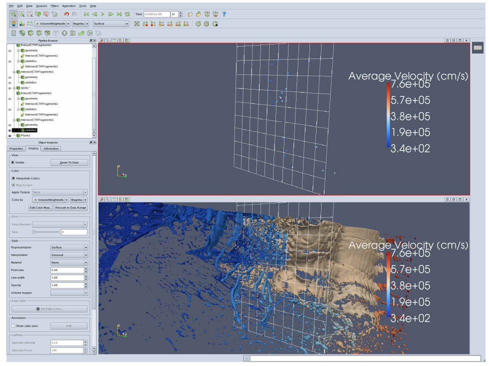
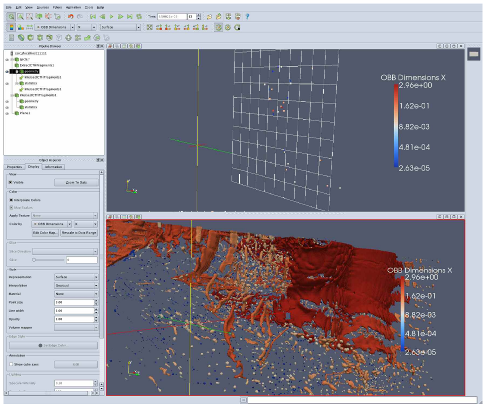


Figure 9: Mass

Figure 10: Velocity



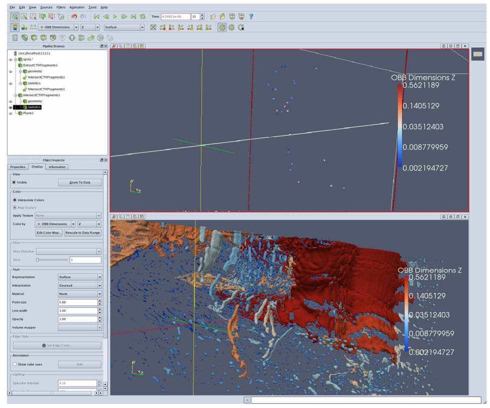


Figure 11: Longest Dimension

Figure 12: Shortest Dimension

5.2 Milestone Objective Stretch Goals

1. Compare fragment results from a simulation to experimental data.

A test article (Figure 13) designed to produce fragments of a given size was constructed and detonated. A one-quarter symmetry version was modeled and simulated using CTH. A comparison between the simulation and representative fragments is shown in Figure 15, Figure 17, and Figure 17.

The initial simulations using the actual test-article model showed that the cylinder fragments would follow the scores in the vertical direction, but would not fracture as desired in the horizontal direction (Figure 15). An additional simulation was run using deeper grooves, which did fracture as desired (Figure 18). The actual test data supported the first simulation as the fragments produced were vertical strips of the original cylinder.

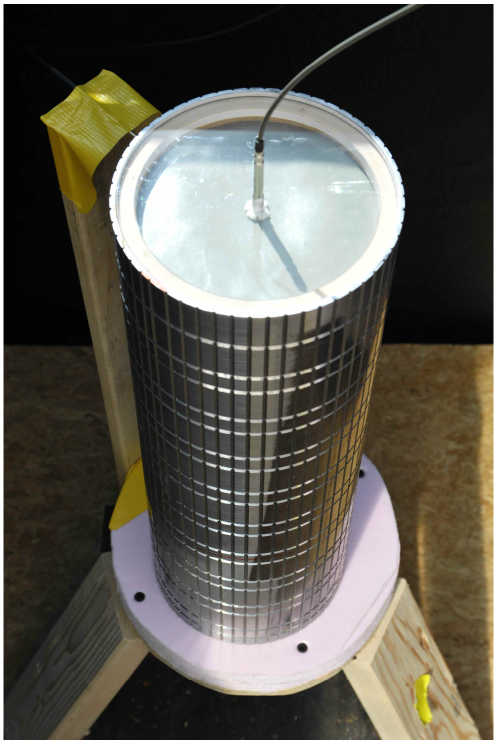


Figure 13: Test article

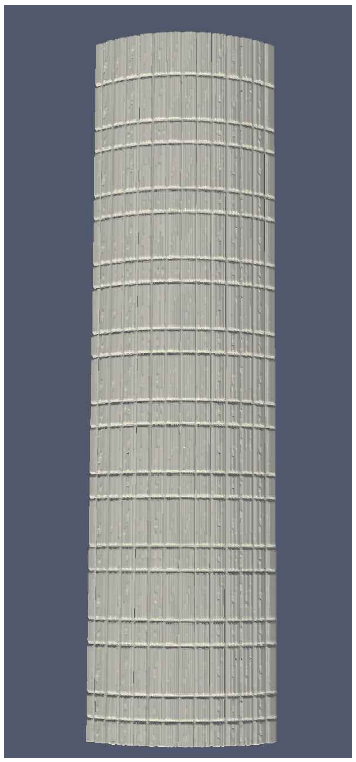


Figure 14: Quarter-symmetry CTH model of outer case

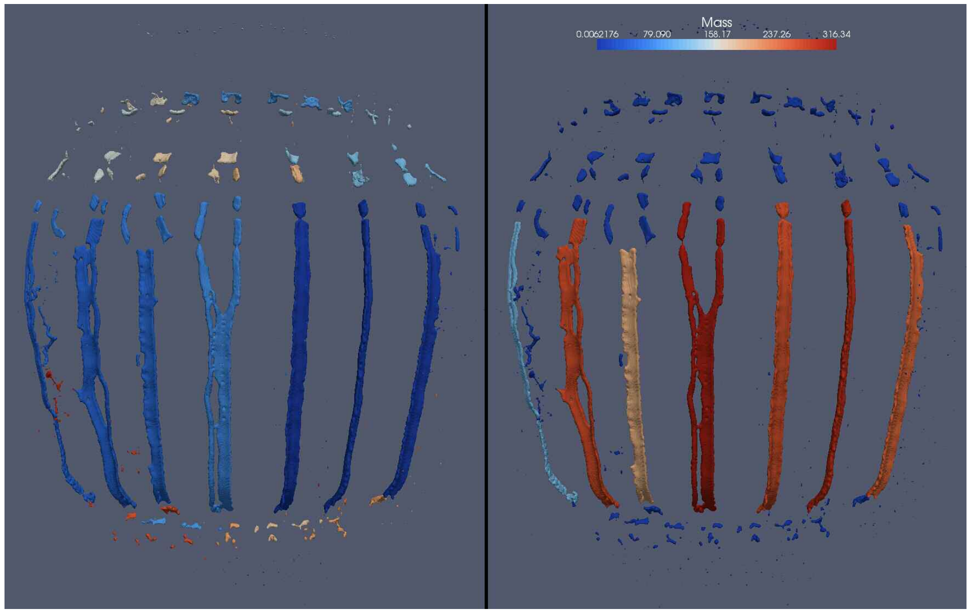


Figure 15: Quarter-symmetry CTH simulation at 2.00e-04 seconds. The left image is colored by fragment ID. The right image is colored by fragment mass.

Figure 16: Witness plate from the test article. Notice the fragment strip indentations highlighted in yellow.

Figure 17: Representative fragments from the test article

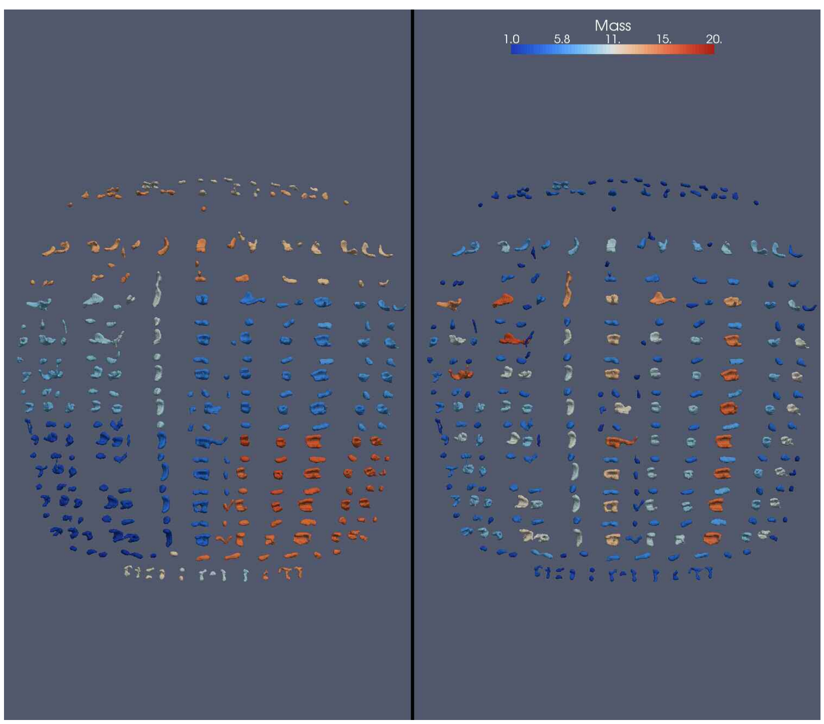


Figure 18: Quarter-symmetry simulation at 2.0e-04 seconds. The grooves in this simulation were deeper than the actual test article and those used in Figure 15 resulting in fragmentation along those grooves. The left image is colored by fragment ID. The right image is colored by fragment mass.

2. Provide the ability to save each fragment as an STL file

ParaView provides the ability to save all the fragments from a simulation to an STL file, one per fragment. Figure 19 shows a comparison between one of the saved fragments (top) with the same fragment from the simulation (bottom). The saved fragments are not guaranteed to be watertight manifolds and therefore present problems to downstream processes. There is ongoing work to ensure that the fragment geometry is a watertight manifold to alleviate these concerns.

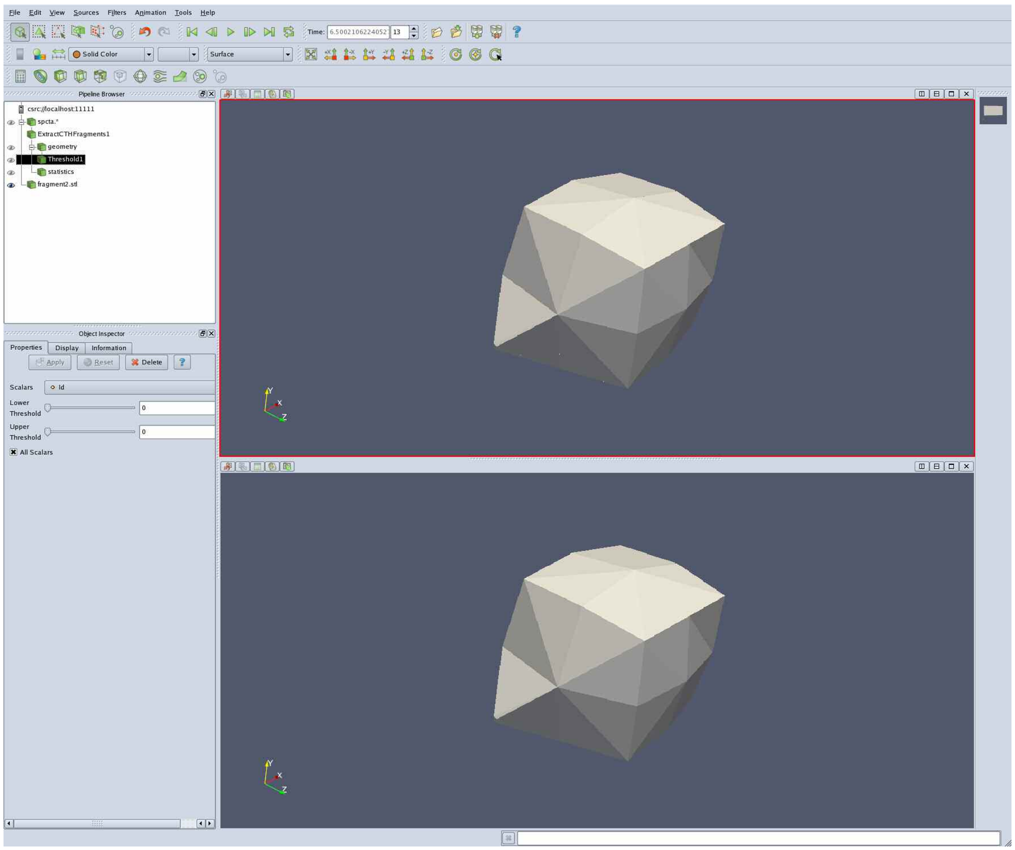


Figure 19: STL file (top) and original fragment (bottom)

6. CALCULATION VERIFICATION

One of the data sets generated for this milestone consisted of 4 fragments of known mass and volume moving at a known velocity. This dataset was used to verify that the fragment calculations were being performed correctly.

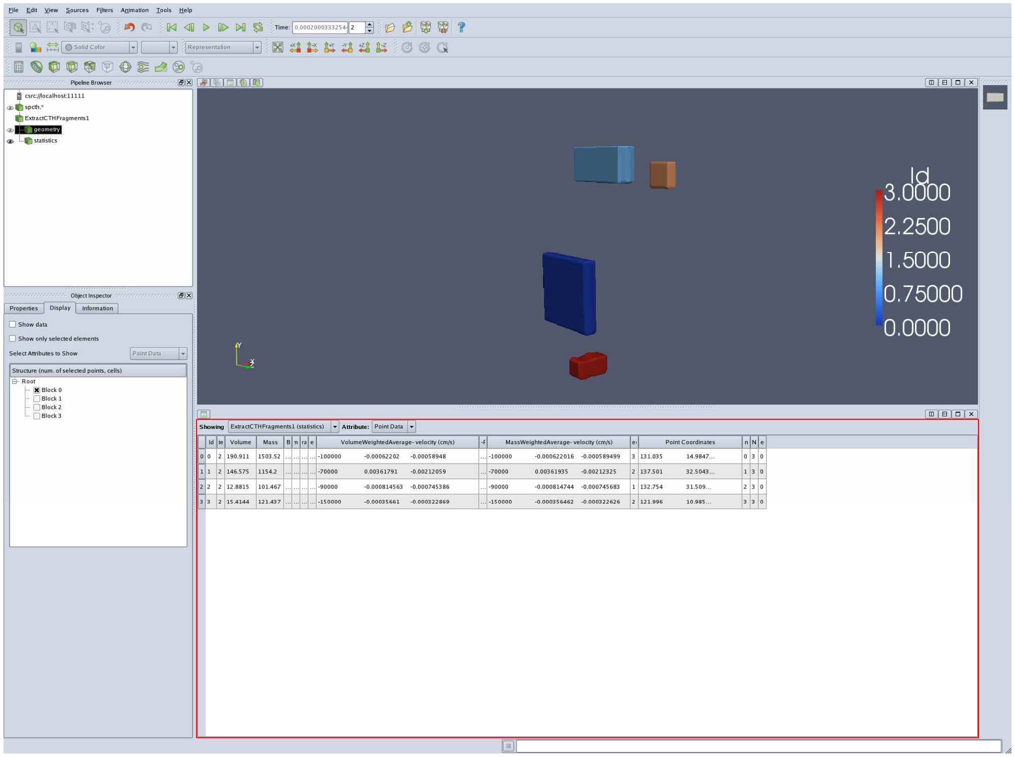


Figure 20: Verification dataset containing four fragments with known attributes

Appendix A: Customer Signoff Memo

Sandia National Laboratories

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Sandia Corporation

Albuquerque, New Mexico 87185-

date: September 3, 2008

to: John D. Zepper (Senior Manager 9320); Constantine Pavlakos (Manager 9326); David Rogers (Manager 1424);

cc: David Karelitz (9326); Lisa Ice (9326); Ken Moreland (1424); Thomas Otahal (1424); Steven Heffelfinger (Manager 6454); David Swahlan (Manager 6475);

from: Jason Wilke (6475); Stephen Attaway (1534)

subject: Organization 9326 Fragment Characterization Milestone Successfully Completed

The Level II Fragment Characterization Post-Processing V&V Milestone Team, which consisted of David Karelitz (9326), Lisa Ice (9326), Ken Moreland (1424) and Thomas Otahal (1424), has successfully demonstrated to Center 6400 the fragment characterization tool they have developed. The team has shown that the fragment characterization tool meets the required goals of the milestone which include; detecting and counting fragments from a single simulation timestep, characterizing the fragment masses, determining the fragment velocity vectors and magnitudes, locating the fragments' x, y, and z positions, and tracking the fragments as they intersect a given plane. Additionally, the tool meets the stretch goal of outputting .STL files containing the fragment data that can be exported to other simulations or CAD software.

The tool has already been used effectively to harvest and sort data from applied large scale parallel computations. This data is currently being evaluated and is being used to make real-world design and operations decisions.

Appendix B: Histogram output

bin value (mass(g))	Bin Count	Volume	velocity (cm/s):0	velocity (cm/s):1	velocity (cm/s):2	Pressure (dynes/cm^2^)	Temperature (eV)
7.97548E-08	204	3.03E-08	44021.2	-10630.6	7787.22	2.58E+07	0.093103
8.33544E-08	235	3.15E-08	33358.7	-7767.26	4436.05	5.75E+07	0.0924275
8.6954E-08	186	3.28E-08	36532.1	-10833.9	5319.93	76733.6	0.0927703
9.05537E-08	166	3.42E-08	54535.9	-17280.2	9271.83	9.90E+07	0.0935561
9.41533E-08	153	3.56E-08	41273.6	-8634.39	5857.25	3.03E+07	0.0935982
9.77529E-08	127	3.69E-08	61014.7	-13432.8	8591.62	-2.39E+06	0.0939813
1.01352E-07	96	3.83E-08	45910.1	-12693.4	4805.29	5.57E+06	0.0948002
1.04952E-07	95	3.97E-08	47169.2	-13850.6	7089.8	1.15E+08	0.0951473
1.08552E-07	79	4.10E-08	47978.9	-10857	5855.54	3.41E+07	0.0947577
1.12152E-07	71	4.24E-08	50756.2	-15815	8990.59	7.86E+07	0.0940351
1.15751E-07	67	4.39E-08	75343.1	-18385.5	7014.22	1.10E+08	0.0959247
1.19351E-07	60	4.52E-08	50731	-7516.97	4040.61	5.61E+07	0.0957721
1.22951E-07	60	4.66E-08	68905.1	-21431.4	10276.4	1.74E+07	0.0961824
1.2655E-07	52	4.80E-08	98022.2	-26741.9	11453.9	9.61E+07	0.0974709
1.3015E-07	33	4.94E-08	62921.4	-11994.6	11931.4	1.79E+07	0.096677
1.33749E-07	31	5.07E-08	63977.6	-14907.3	11001.7	2.28E+06	0.0983256
1.37349E-07	27	5.21E-08	52222.2	-21723.8	3160.11	2.48E+08	0.0981106
1.40949E-07	18	5.35E-08	83259.1	-33216.5	19910.7	8.89E+07	0.0962909
1.44548E-07	15	5.48E-08	59858.3	-17686.7	4682.54	-8.31E+06	0.101812
1.48148E-07	11	5.61E-08	170068	-67151.7	39800.5	-9.49E+07	0.0968538
1.51748E-07	14	5.75E-08	215128	-76010.8	31364.5	2.13E+06	0.0998988
1.55347E-07	10	5.90E-08	115349	-48814.6	20327.6	1.22E+07	0.0970702
1.58947E-07	4	5.97E-08	55086.8	-39811.7	17883	1.16E+08	0.0898395
1.62547E-07	14	6.15E-08	12864.6	-2580.06	-1536.95	-2.40E+06	0.096667
1.66146E-07	27	6.29E-08	27926.8	-9245.13	3330.56	-3.81E+07	0.0922498
1.69746E-07	31	6.42E-08	41689.9	-7210.76	11569.2	-1.11E+07	0.0925795
1.73345E-07	38	6.55E-08	27424.5	-8169.03	6049.2	1.55E+07	0.0915645
1.76945E-07	33	6.71E-08	27421.6	-3391.19	2952.81	-976484	0.0937588
1.80545E-07	37	6.82E-08	23506.7	-5254.04	8859.08	2.73E+06	0.0910878
1.84144E-07	34	6.95E-08	22549.6	-5980.08	6049.5	2.06E+07	0.0932821
1.87744E-07	33	7.09E-08	42853	-8965.23	10478.6	9.30E+06	0.0929913
1.91344E-07	34	7.24E-08	42161.3	-15342	7766.86	-3.39E+06	0.0936755
1.94943E-07	28	7.38E-08	72567.9	-15315.2	7952.21	198275	0.095492
1.98543E-07	42	7.50E-08	62857.3	-19107.7	8593.35	3.50E+07	0.0937008
2.02142E-07	34	7.65E-08	48215.5	-10527.1	7325.17	9.34E+07	0.0947604
2.05742E-07	30	7.80E-08	68350.1	-21062.1	7247.58	2.62E+07	0.0957515
2.09342E-07	36	7.92E-08	30239.1	-16023.8	9836.64	-6.24E+06	0.0924217
2.12941E-07	36	8.06E-08	46560.3	-9063.59	7140.93	5.90E+07	0.0944508
2.16541E-07	45	8.19E-08	34323	-8349.54	5813.45	6.06E+06	0.0947561
2.20141E-07	36	8.34E-08	93644.1	-26388.2	17523.1	4.60E+07	0.0958641
2.2374E-07	33	8.49E-08	76152.1	-24492.3	16665.1	2.03E+07	0.0974321
2.2734E-07	31	8.63E-08	68964.9	-26831.1	13927.1	3.28E+07	0.096894
2.3094E-07	14	8.77E-08	106194	-48363.4	8878.6	2.62E+07	0.0997171
2.34539E-07	22	8.87E-08	135272	-57611.4	19239.9	-7.32E+06	0.0945151
2.38139E-07	27	9.02E-08	104899	-38743.7	14805.6	8.40E+07	0.0965525
2.41738E-07	25	9.14E-08	85740.4	-35984.3	12122.5	855432	0.093599
2.45338E-07	23	9.29E-08	100915	-46341.7	15261.8	2.17E+07	0.0943724

2.48938E-07	22	9.44E-08	95817	-47804	22684	3.36E+07	0.0965732
2.52537E-07	19	9.55E-08	107945	-35202.3	16785.3	-161025	0.0941308
2.56137E-07	15	9.70E-08	37722.5	-13146.4	5149.16	2.27E+07	0.0952433
2.59737E-07	18	9.86E-08	89934.7	-40396.3	10023	-1.77E+07	0.0996874
2.63336E-07	12	9.99E-08	55146	-33814.1	12725.6	9.71E+07	0.0957017
2.66936E-07	19	1.01E-07	93208.9	-30660.8	18251.5	-6.44E+06	0.0964575
2.70536E-07	20	1.02E-07	64473.7	-31168.6	16587.8	1.67E+07	0.0942945
2.74135E-07	15	1.04E-07	40138	-27939.5	10026.9	-2.93E+06	0.0955182
2.77735E-07	11	1.05E-07	76237.5	-27160.1	11815.7	1.04E+08	0.0928825
2.81334E-07	13	1.07E-07	140226	-43115.5	22883.6	1.95E+08	0.101992
2.84934E-07	19	1.08E-07	56004.9	-25913.2	8115.25	-1.86E+07	0.0935599
2.88534E-07	14	1.09E-07	54777.4	-27053.2	18446.4	2.22E+07	0.0938046
2.92133E-07	20	1.11E-07	61643.9	-25920.1	11737.6	7.97E+06	0.0924555
2.95733E-07	15	1.12E-07	113647	-59773.2	24259.2	3.94E+06	0.0931957
2.99333E-07	12	1.13E-07	56648.7	-28938	9087.85	3.83E+07	0.09292
3.02932E-07	18	1.15E-07	52787.6	-23577.8	14090.5	5.77E+06	0.0950144
3.06532E-07	16	1.16E-07	93543.2	-23353.3	11245.7	1.38E+07	0.0935956
3.10132E-07	12	1.17E-07	25790.9	-9420.48	2514.64	3.41E+07	0.0912679
3.13731E-07	15	1.19E-07	77376.7	-19572.5	13483.2	-4.16E+06	0.0951622
3.17331E-07	10	1.20E-07	34495.1	-37873.7	27016.5	-1.07E+07	0.0899002
3.2093E-07	13	1.22E-07	87166.3	-15382.2	17823.2	-5.27E+06	0.0927897
3.2453E-07	9	1.23E-07	109954	-21150.4	18887	-2.30E+07	0.0964889
3.2813E-07	16	1.24E-07	61512.2	-32131.9	20526.1	3.15E+07	0.0927349
3.31729E-07	9	1.26E-07	103973	-18066.3	6319.37	-1.96E+07	0.10227
3.35329E-07	14	1.27E-07	32236.3	-31537.7	12458.3	233400	0.0979091
3.38929E-07	16	1.28E-07	69804.2	-28660.9	14929.2	-1.31E+06	0.0953097
3.42528E-07	14	1.30E-07	55925.5	-15561	14147.9	-1.35E+07	0.0938602
3.46128E-07	14	1.31E-07	118748	-52369.2	18928.7	6.12E+06	0.0953243
3.49728E-07	19	1.33E-07	81010.6	-42735.7	23939.6	3.54E+07	0.0968009
3.53327E-07	9	1.34E-07	13161.2	-2671.58	387.923	-1.02E+06	0.0942346
3.56927E-07	12	1.35E-07	135752	-60901.6	25960.3	8.66E+06	0.093078
3.60526E-07	13	1.37E-07	140362	-42408	27880.4	-1.79E+07	0.098734
3.64126E-07	12	1.38E-07	77894.2	-16208.7	10528.1	3.10E+06	0.0966719
3.67726E-07	6	1.39E-07	80342	-49565.4	16355.2	5.63E+07	0.0955479
3.71325E-07	13	1.40E-07	39879.1	-33499.8	17007.6	4.79E+06	0.0912702
3.74925E-07	11	1.42E-07	148155	-65456.9	17722.5	-5.04E+06	0.0964109
3.78525E-07	11	1.44E-07	129561	-29153	16433.5	8.13E+06	0.10032
3.82124E-07	14	1.44E-07	113297	-27134.6	19227.1	8.58E+06	0.0903348
3.85724E-07	12	1.46E-07	114085	-46293.3	6508.19	-1.48E+08	0.0947392
3.89324E-07	12	1.48E-07	123704	-30111.5	13508.1	-5.80E+07	0.0959111
3.92923E-07	8	1.49E-07	35790.1	-13907.3	7750.39	4.66E+06	0.0931839
3.96523E-07	10	1.50E-07	37154.5	-16129.6	9427.51	1.34E+08	0.0924859
4.00122E-07	9	1.52E-07	157606	-63915.4	18886	-711470	0.098791
4.03722E-07	8	1.53E-07	78639.8	-9768.58	25938.7	-2.65E+07	0.097085
4.07322E-07	14	1.54E-07	31163.9	-9621.67	10451.5	-5.61E+06	0.0917435
4.10921E-07	7	1.56E-07	237204	-38497	25625.6	-1.87E+07	0.10218
4.14521E-07	11	1.57E-07	111217	-21727.7	12187	1.36E+06	0.0945095
4.18121E-07	9	1.58E-07	97047.9	-41959.4	3705.01	-1.68E+07	0.0944452
4.2172E-07	6	1.60E-07	41055.4	-22579.3	4888.5	9.93E+06	0.097068
4.2532E-07	12	1.61E-07	89723.3	-17097.3	8733.01	-1.72E+06	0.0931107

4.28919E-07	6	1.62E-07	79527.4	-59015.3	49494.8	4.13E+07	0.0929023
4.32519E-07	8	1.64E-07	155775	-32686.6	23871.7	1.62E+08	0.0986811
4.36119E-07	6	1.65E-07	172646	-47607	53595.4	2.25E+06	0.0988156
4.39718E-07	9	1.67E-07	160821	-65101.4	31657.2	-3.15E+07	0.0983925
4.43318E-07	7	1.68E-07	134500	-66850.9	11003.5	1.15E+07	0.0968208
4.46918E-07	12	1.69E-07	143880	-65211.4	22774.4	1.63E+06	0.0952933
4.50517E-07	9	1.71E-07	116337	-77001.5	34197	-728748	0.0947419
4.54117E-07	13	1.72E-07	95711.8	-25758	18395.5	-1.27E+07	0.0947018
4.57717E-07	17	1.74E-07	67593.1	-39767.1	7076.15	3.40E+07	0.0975731
4.61316E-07	21	1.75E-07	107124	-16491.2	15957	-1.10E+07	0.0975585
4.64916E-07	8	1.76E-07	140084	-54718.7	53676.9	2.72E+06	0.0986314
4.68515E-07	12	1.77E-07	137834	-56108.3	23633.8	-3.15E+06	0.0949368
4.72115E-07	12	1.79E-07	83990.9	-32408.7	11970.2	-1.70E+07	0.0951619
4.75715E-07	9	1.80E-07	199549	-72221.6	20464.7	9.87E+07	0.0954893
4.79314E-07	10	1.81E-07	162075	-76837.8	17488.6	-4.73E+06	0.0952474
4.82914E-07	13	1.83E-07	132514	-40345.2	16297.1	-1.03E+07	0.0964083
4.86514E-07	11	1.84E-07	156132	-72350.6	13893.3	1.30E+06	0.0948243
4.90113E-07	11	1.85E-07	160518	-65278.4	9847.28	6.10E+06	0.0933444
4.93713E-07	13	1.87E-07	59437.3	-33001.4	5722.17	4.79E+07	0.0940744
4.97313E-07	9	1.89E-07	141057	-62722.2	26976.5	-3.35E+06	0.0974358
5.00912E-07	9	1.89E-07	70993.1	-38804.3	17667.7	1.23E+07	0.0929614
5.04512E-07	8	1.92E-07	231690	-86440.2	29150.5	-9.56E+07	0.103164
5.08111E-07	7	1.92E-07	82291	-38303.5	8754.12	4.48E+06	0.0928035
5.11711E-07	6	1.94E-07	175485	-86003.7	35674.9	-1.13E+06	0.0960564
5.15311E-07	8	1.96E-07	107724	-33332.6	17510.4	2.65E+06	0.0977272
5.1891E-07	5	1.96E-07	43919.6	-21754.3	23562.1	1.82E+07	0.0930163
5.2251E-07	13	1.98E-07	163085	-48450.3	14251.9	-3.32E+06	0.0988622
5.2611E-07	9	1.99E-07	76389.2	-35806.2	3373.74	-7.54E+06	0.0950621
5.29709E-07	10	2.01E-07	73064.1	-37721.5	11377.7	-1.48E+07	0.0989558
5.33309E-07	5	2.02E-07	200073	-60863.4	29022.6	-3.39E+06	0.0972439
5.36909E-07	9	2.03E-07	95931.7	-35139.1	24439.4	2.53E+07	0.0955731
5.40508E-07	5	2.04E-07	115582	-48964.7	10745.9	8.64E+07	0.0952883
5.44108E-07	11	2.06E-07	140208	-37486.2	12435.1	-2.29E+07	0.0972516
5.47707E-07	5	2.08E-07	138476	-97687.9	8740.23	1.74E+07	0.0969181
5.51307E-07	10	2.10E-07	104482	-32537.3	12293.5	-1.67E+06	0.0993394
5.54907E-07	8	2.10E-07	86224.6	-33988.4	20559.7	9.56E+06	0.0941171
5.58506E-07	9	2.12E-07	130351	-49584	31415	6.15E+07	0.0993162
5.62106E-07	11	2.13E-07	140692	-49322.5	26240.4	4.18E+07	0.0955237
5.65706E-07	7	2.13E-07	111594	-52469.3	46650.1	-4.16E+06	0.0893849
5.69305E-07	9	2.15E-07	39656.5	-3377.97	5685.9	7.87E+06	0.0942924
5.72905E-07	12	2.17E-07	63601.4	-54688.6	18428.3	4.14E+06	0.0957058
5.76505E-07	11	2.19E-07	158660	-77095.6	22203.5	1.19E+07	0.099357
5.80104E-07	10	2.20E-07	137187	-53603	23114.2	2.81E+06	0.0985264
5.83704E-07	6	2.21E-07	135806	-73297.7	30222.7	3.35E+06	0.0956355
5.87303E-07	15	2.22E-07	158657	-69257.9	37688.7	-185832	0.0925004
5.90903E-07	10	2.25E-07	92063.7	-57720.8	21315.4	-1.19E+07	0.0992252
5.94503E-07	6	2.26E-07	134711	-35168.7	15940.5	4.90E+07	0.0983414
5.98102E-07	10	2.26E-07	143529	-61000.1	26710.3	2.98E+07	0.0930884
6.01702E-07	9	2.28E-07	160119	-87537.3	24827.3	-900804	0.0955461
6.05302E-07	2	2.30E-07	65486.4	30620.9	20076.1	-1.14E+08	0.101695

6.08901E-07	5	2.31E-07	133754	-51979.6	18653	921506	0.0972949
6.12501E-07	8	2.32E-07	69241.7	-39880.2	5768.12	7.31E+06	0.0929147
6.16101E-07	13	2.33E-07	130657	-56695.1	38800.8	637276	0.0947341
6.197E-07	7	2.35E-07	89970.4	-17762.6	9531.89	1.84E+08	0.0967195
6.233E-07	10	2.36E-07	131556	-72001.6	21229.2	2.13E+07	0.096319
6.26899E-07	6	2.37E-07	207215	-153089	41100	1.50E+07	0.0955781
6.30499E-07	6	2.39E-07	109900	-81518.7	9303.8	-1.07E+07	0.0969539
6.34099E-07	12	2.40E-07	84360	-54384.6	40317.3	537665	0.0957556
6.37698E-07	11	2.42E-07	125409	-28659.8	8979.89	6.53E+06	0.0970053
6.41298E-07	4	2.43E-07	175189	-132388	61924.7	5.35E+06	0.0960446
6.44898E-07	8	2.44E-07	154355	-64381.9	19054.9	-2.29E+07	0.0972236
6.48497E-07	10	2.46E-07	112448	-34066.9	19165.2	-6.02E+06	0.0946885
6.52097E-07	5	2.47E-07	55152.7	-11333.6	8815.91	4.35E+06	0.0969833
6.55696E-07	5	2.48E-07	115403	-44024.9	23122.6	300368	0.0965327
6.59296E-07	5	2.50E-07	219363	-68213	31248.2	137529	0.0966619
6.62896E-07	9	2.51E-07	158785	-52547.6	28435.9	-3.54E+06	0.0956679
6.66495E-07	8	2.52E-07	142621	-50402.8	36010	-1.32E+07	0.0963443
6.70095E-07	8	2.54E-07	44464.6	-34833.2	14025.1	-8.63E+06	0.0959849
6.73695E-07	5	2.55E-07	235343	-99929.9	54806.2	5.68E+06	0.0940771
6.77294E-07	4	2.56E-07	47640.3	-48809.7	35881.9	2.58E+08	0.09306
6.80894E-07	7	2.58E-07	143060	-34498.4	16318.1	-4.46E+06	0.0941673
6.84494E-07	6	2.58E-07	160290	-22270.8	12003.9	4.85E+06	0.0933865
6.88093E-07	6	2.61E-07	96253	-59672.6	47577	-8.98E+06	0.09424
6.91693E-07	6	2.62E-07	160538	-13208	19479.6	914849	0.0970927
6.95292E-07	7	2.64E-07	90224.1	-49354.5	3583.33	-2.61E+06	0.0982326
6.98892E-07	11	2.65E-07	200363	-30928.5	23081.9	-4.21E+07	0.0981515
7.02492E-07	10	2.66E-07	188874	-78651.7	49757.9	3.78E+07	0.095126
7.06091E-07	4	2.67E-07	218511	-44947.8	48987.6	2.72E+07	0.0911262
7.09691E-07	7	2.69E-07	191888	-90706.9	41655	-5.37E+06	0.0967609
7.13291E-07	7	2.71E-07	76835.9	-16532	19748	1.35E+07	0.0981336
7.1689E-07	6	2.72E-07	120676	-29417	33532.7	2.85E+07	0.0990379
7.2049E-07	4	2.72E-07	89372.7	-64467.2	31366.3	-4.34E+06	0.0922435
7.2409E-07	10	2.75E-07	207049	-67182.6	28815.1	4.35E+07	0.0985252
7.27689E-07	10	2.76E-07	234694	-81168	25597.3	-340657	0.0963721
7.31289E-07	9	2.76E-07	131520	-70893.9	42184.2	-1.57E+07	0.0951376
7.34888E-07	2	2.77E-07	242598	-171521	91780.7	-56837.4	0.0925811
7.38488E-07	8	2.80E-07	130793	-85822.8	25557.2	-1.12E+07	0.0989827
7.42088E-07	7	2.81E-07	144570	-56309.6	37904.4	-8.85E+06	0.0945485
7.45687E-07	7	2.83E-07	109575	-20018.5	17762.7	562425	0.0978591
7.49287E-07	4	2.84E-07	319882	-86868.8	25451.2	-6.34E+06	0.0975957
7.52887E-07	6	2.84E-07	205980	-72862.9	32483.4	3.50E+07	0.093956
7.56486E-07	7	2.86E-07	220989	-96275.1	34984.9	1.16E+07	0.0956215
7.60086E-07	6	2.88E-07	207020	-50318.8	11650.7	-2.15E+06	0.0954618
7.63686E-07	7	2.90E-07	82101.2	-28322.7	18770.9	4.30E+06	0.0984021
7.67285E-07	3	2.91E-07	14829	8525.43	208.077	7.77E+06	0.095228
7.70885E-07	3	2.91E-07	237217	-143571	54304.1	-3.23E+06	0.0934317
7.74484E-07	9	2.93E-07	221189	-116731	41303.1	1.43E+06	0.0958867
7.78084E-07	2	2.94E-07	191164	-76160.5	20936.2	-6.47E+06	0.0937148
7.81684E-07	5	2.95E-07	41140.5	-18566.3	3591.6	9.08E+06	0.0938226
7.85283E-07	5	2.97E-07	97239.9	-62617.3	26307.6	-4.06E+06	0.0937295

7.88883E-07	6	2.98E-07	66914.5	-43846.2	36139.2	-2.95E+07	0.0919362
7.92483E-07	6	3.00E-07	146449	-85314.7	49177.3	-8.68E+06	0.0948619
7.96082E-07	5	3.03E-07	171500	-33664.9	14447.3	-6.30E+06	0.104104
7.99682E-07	5	3.02E-07	224924	-83113.9	25380.6	7.64E+06	0.0953252
8.03282E-07	5	3.04E-07	70251.5	-23099.2	10303.7	1.74E+08	0.0954512
8.06881E-07	8	3.05E-07	220872	-111095	34201.3	4.64E+07	0.0929942
8.10481E-07	5	3.06E-07	51987.8	-28551.1	20653.5	-4.08E+06	0.0902352
8.1408E-07	4	3.07E-07	212564	-103242	41421.7	-505363	0.0929452
8.1768E-07	3	3.10E-07	166523	-111325	21293.7	-1.94E+07	0.0976442
8.2128E-07	2	3.11E-07	263463	-63224.6	14594.6	3.03E+06	0.0972917
8.24879E-07	2	3.12E-07	21189	-26689.5	12175.6	-1.99E+07	0.0934863
8.28479E-07	11	3.13E-07	108755	-53544.2	26552.8	-4.54E+06	0.0933161
8.32079E-07	3	3.15E-07	316693	-147953	75449.4	-3.97E+06	0.0945274
8.35678E-07	6	3.18E-07	221068	-41975.1	26137	2.61E+06	0.0994416
8.39278E-07	2	3.17E-07	58534.3	-12305.8	-1398.42	-556515	0.0928734
8.42878E-07	5	3.19E-07	112658	-66418.5	26752.7	-1.27E+07	0.0948001
8.46477E-07	3	3.21E-07	124657	-53851.7	29698.3	-7.25E+06	0.0962326
8.50077E-07	2	3.21E-07	55777.5	-18673.1	51911.6	4.17E+06	0.0925681
8.53676E-07	5	3.24E-07	118074	-33214.5	25355.3	-4.91E+06	0.0967084
8.57276E-07	4	3.24E-07	192577	-82822.4	22089.1	3.37E+07	0.093365
8.60876E-07	5	3.26E-07	134234	-81762.4	39900.4	-1.48E+07	0.09435
8.64475E-07	3	3.28E-07	234150	-122377	43865.4	-1.22E+07	0.0980032
8.68075E-07	7	3.28E-07	132491	-48833.7	19252.8	-5.37E+06	0.0951819
8.71675E-07	6	3.30E-07	237337	-118832	69067.5	6.16E+06	0.0969448
8.75274E-07	5	3.33E-07	286591	-127425	31634.5	-2.17E+08	0.102482
8.78874E-07	7	3.34E-07	185970	-96401.1	51026	605506	0.0991728
8.82473E-07	5	3.35E-07	124457	-90080.2	43732.8	1.15E+08	0.0991413
8.86073E-07	4	3.35E-07	131280	-72346.7	35118.6	5.76E+07	0.0943338
8.89673E-07	5	3.37E-07	237720	-101164	20884.8	-3.82E+07	0.0956769
8.93272E-07	6	3.39E-07	203389	-69370	31792	1.55E+07	0.0983843
8.96872E-07	5	3.39E-07	205816	-96128.2	50401.3	-4.17E+06	0.09378
9.00472E-07	7	3.40E-07	156079	-57055.5	29674.3	-3.33E+06	0.0930733
9.04071E-07	3	3.41E-07	17151.9	-34739.3	27742.3	-1.39E+07	0.0912769
9.07671E-07	4	3.42E-07	80191.4	-97161.5	90496.3	-1.04E+06	0.091397
9.11271E-07	5	3.46E-07	111639	-38398.7	27711.3	-3.90E+06	0.0961623
9.1487E-07	1	3.47E-07	517292	-106519	-823.27	-2.10E+06	0.0999595
9.1847E-07	5	3.47E-07	68627.1	-110442	44534.7	-2.86E+06	0.0917869
9.22069E-07	4	3.50E-07	264432	-140695	50589.8	1.34E+07	0.10039
9.25669E-07	4	3.51E-07	119823	-55793.2	34886.6	9.57E+06	0.0964983
9.29269E-07	2	3.54E-07	98806	17281.8	12728.3	1.39E+07	0.101051
9.32868E-07	4	3.54E-07	121072	-61890.5	8931.36	-1.44E+07	0.0981178
9.36468E-07	3	3.55E-07	375129	-129929	39411	4.75E+07	0.0976792
9.40068E-07	4	3.55E-07	145349	-54150.6	2238.67	-2.83E+06	0.0924746
9.43667E-07	2	3.61E-07	59427.3	-63909.4	49794.9	3.87E+07	0.106002
9.47267E-07	6	3.59E-07	105857	-42366.6	24619.7	-2.72E+07	0.0978017
9.50867E-07	3	3.58E-07	60918.2	-7233.68	9416.42	1.75E+06	0.0870526
9.54466E-07	4	3.61E-07	194787	-73663.4	58221.6	-7.15E+06	0.0936081
9.58066E-07	6	3.63E-07	149601	-47229.2	16532.6	-2.05E+06	0.0954318
9.61665E-07	6	3.64E-07	305130	-149228	39009	-9.42E+06	0.0942086
9.65265E-07	4	3.66E-07	113042	-44609.9	32135.3	-7.79E+06	0.0973255

9.68865E-07	7	3.66E-07	195378	-113471	42016.2	8.51E+06	0.0920647
9.72464E-07	7	3.68E-07	301554	-68673.7	21298.7	-6.29E+06	0.0954578
9.76064E-07	4	3.70E-07	182844	-115550	22908.4	1.06E+07	0.0976666
9.79664E-07	6	3.71E-07	373757	-85865.1	32935.4	-6.27E+06	0.0956133
9.83263E-07	3	3.71E-07	103469	-75460.7	49664.9	-3.11E+07	0.0900427
9.86863E-07	4	3.74E-07	129014	-32648	25657	-7.76E+06	0.0974057
9.90463E-07	9	3.74E-07	126419	-96600.9	47600.2	-1.64E+07	0.0927632
9.94062E-07	4	3.76E-07	269098	-130199	57650.8	-5.36E+06	0.0937671
9.97662E-07	5	3.79E-07	167046	-83539.5	59315.3	2.50E+07	0.0984282

Appendix C: Fragment Intersection Results

Fragment plane Intersection over time, selected results

Timesteps 0-4 contain no intersections

Timestep 5: 2.5e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
8.54E-07	2.26E-06	693118	-191965	632.406
1.33E-07	3.50E-07	607738	-192087	149.247
0.066925	0.185852	453023	-40322	-29745
7.37E-06	1.96E-05	707069	-108504	58394.2
1.23E-05	3.28E-05	706267	-129776	55670.6

Timestep 6: 3.00e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
5.41E-07	1.43E-06	593020	-294016	-507.015
0.065986	0.18274	441155	-41832.2	-10276.3
3.57E-07	9.40E-07	546599	-218299	601.901

Timestep 7: 3.50e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
2.41E-06	6.40E-06	512461	-328606	322.022
0.065265	0.179268	428484	-42194.6	8568.07
9.30E-05	0.000248	499015	-232187	18825.1
7.26E-07	1.93E-06	492639	-264756	30512.5
7.11E-07	1.90E-06	494652	-250114	59779.1
1.62E-06	4.28E-06	440195	-253696	78307.5
5.09E-06	1.34E-05	460944	-253155	50962.5
4.14E-06	1.10E-05	469993	-243594	100239
1.00E-05	2.69E-05	503667	-190117	138004
3.72E-06	9.78E-06	431077	-256348	37136.9
4.17E-07	1.09E-06	430592	-206727	284.521
2.69E-06	7.09E-06	444126	-223146	50565.7
2.05E-07	5.31E-07	448442	-9908.74	126305

Timestep 8: 4.0e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
0.064437	0.175675	418759	-42672.4	22533.5
2.09E-06	5.54E-06	444694	-322964	14573.7
7.06E-05	0.000189	445960	-223799	3663.6
6.95E-07	1.85E-06	398799	-252337	90842.3

Timestep 9: 4.50e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
0.063147	0.171261	413659	-42279.7	31525.5

2.27E-07	5.99E-07	246059	23842.2	23980.5
1.48E-06	3.93E-06	378451	-322881	33465.3
2.19E-05	5.85E-05	388966	-198649	49420.9
2.56E-06	6.85E-06	395568	-228071	44133.1
1.76E-07	4.67E-07	323818	-218913	-11123.8
6.47E-07	1.71E-06	341271	-209503	-21776.8
2.17E-06	5.76E-06	316388	-221074	139407
7.40E-07	1.96E-06	325295	-200030	122045

Timestep 10: 5.00e-06 seconds

Volume	Mass	Average Velocity X	Average Velocity Y	Average Velocity Z
2.41E-07	6.24E-07	279015	-192613	-508.966
1.30E-07	3.44E-07	255130	-179258	-368.583
6.20E-07	1.63E-06	251961	-253145	56953.9
1.55E-06	4.08E-06	237592	-241797	39862.5
9.73E-07	2.57E-06	279036	-170457	70603.7
7.06E-07	1.86E-06	232399	-237482	44880.2
3.03E-05	8.13E-05	349751	-140534	100953
1.52E-06	4.06E-06	350405	-167362	93422.1
2.41E-06	6.47E-06	347418	-161385	98816.2
0.059917	0.162022	417777	-41722.8	36855.7
2.65E-07	7.00E-07	93353.7	30661.9	-31001.1
1.54E-07	4.08E-07	94977.7	24959.5	-34796.4
2.38E-07	6.28E-07	79331.2	11804.6	-31563.5
5.85E-07	1.55E-06	226996	-204963	52076
3.19E-07	8.46E-07	195921	-164088	40039.6
2.80E-07	7.40E-07	91431.3	-73472.1	42543.1
3.51E-06	9.28E-06	104788	-91775.9	48215.1
6.50E-07	1.72E-06	310092	-123376	48679.8
3.34E-07	8.81E-07	182381	-110936	33346.9
4.25E-07	1.12E-06	314152	-142284	43245.2
3.99E-06	1.04E-05	237765	3098.57	42406.4
1.58E-05	4.24E-05	351301	-107098	85909.8

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