Water Flow Simulation Using Smoothed Particle Hydrodynamics (SPH)

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Motivation

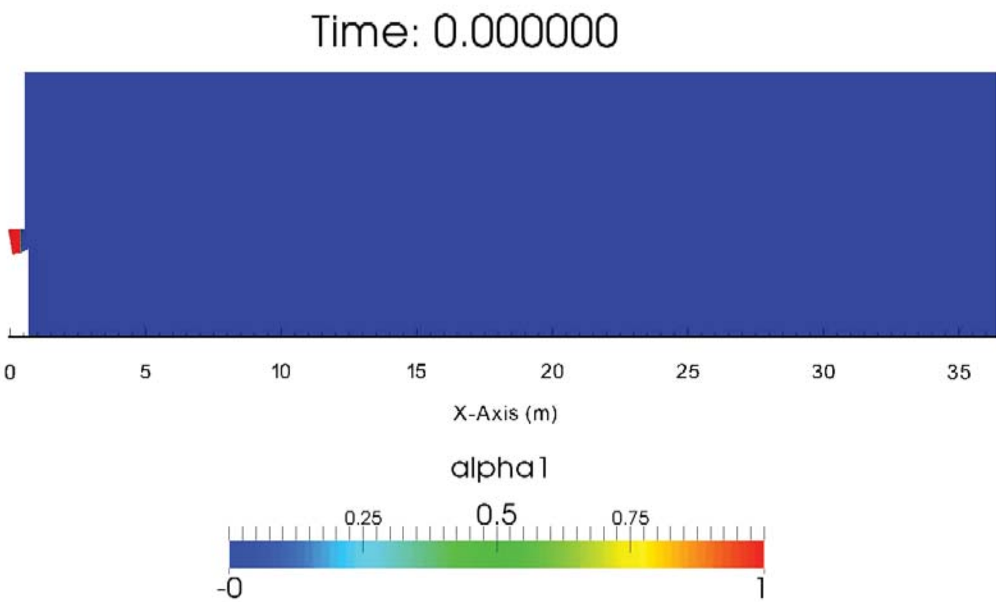
- Is rainbird water throw going to wet the vehicle?
- Answer it by smoothed particle hydrodynamics (SPH) modeling

SSS Flow Test 39A, May 2004

VOF Simulations

- 2 simulations using a 2-D structured mesh of rainbird nozzle mounted 12’ above the deck based on OpenFOAM multiphase flow solver.
- Simulation 1 - “corner rainbird” case: Water injection at 112,500 gpm.
- Simulation 2 - “center rainbird” case: Water injection at 55,250 gpm.
- Both simulations were run up to 5 seconds.

55,250 GPM



Time: 0.000000
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X-Axis (m)
alpha1
0.25
0.5
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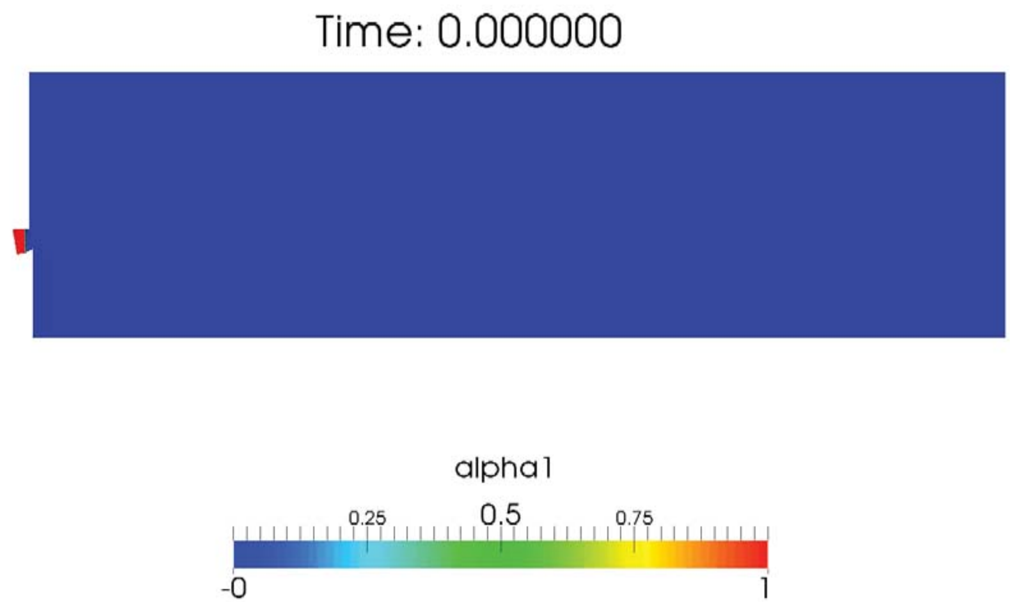

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alpha1
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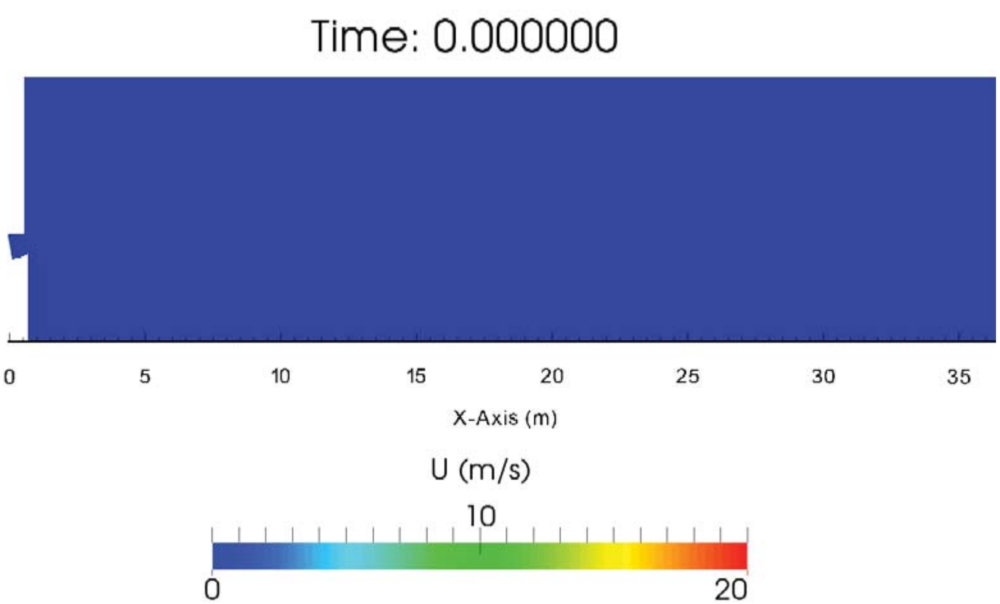
55,250 GPM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X-Axis (m)
U (m/s)
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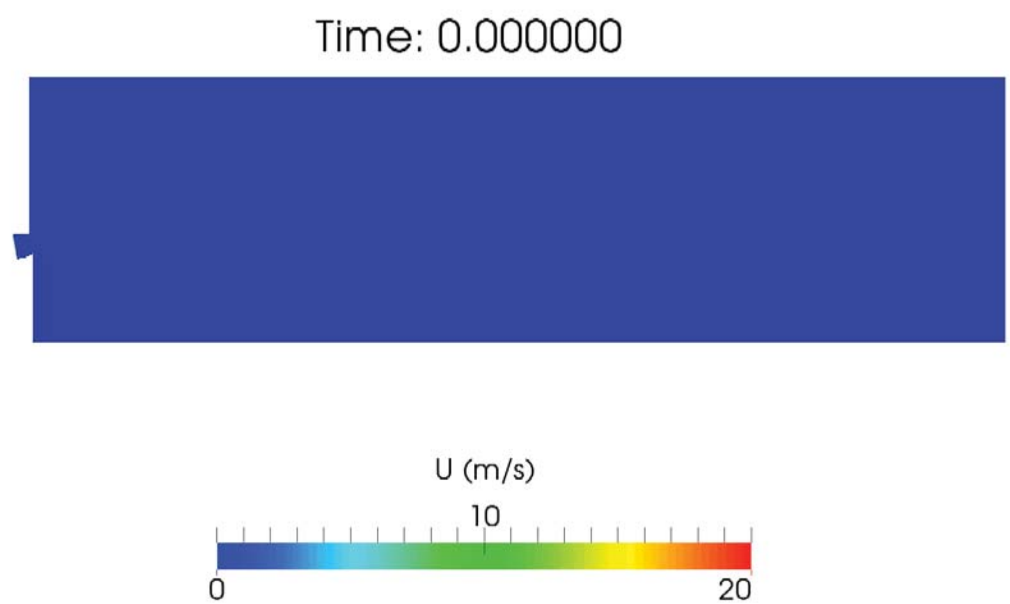
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U (m/s)
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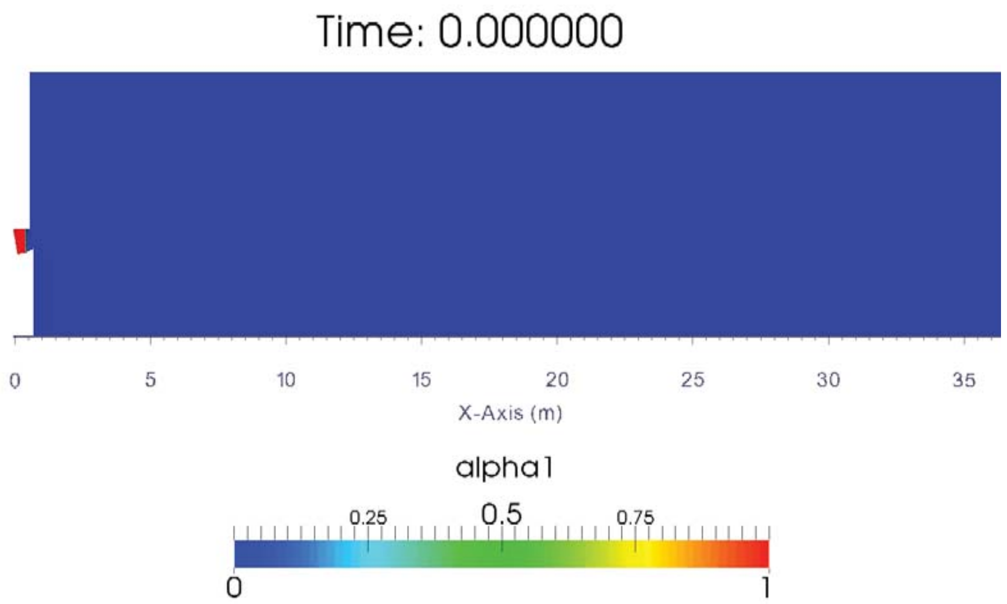
112,500 GPM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X-Axis (m)
alpha1
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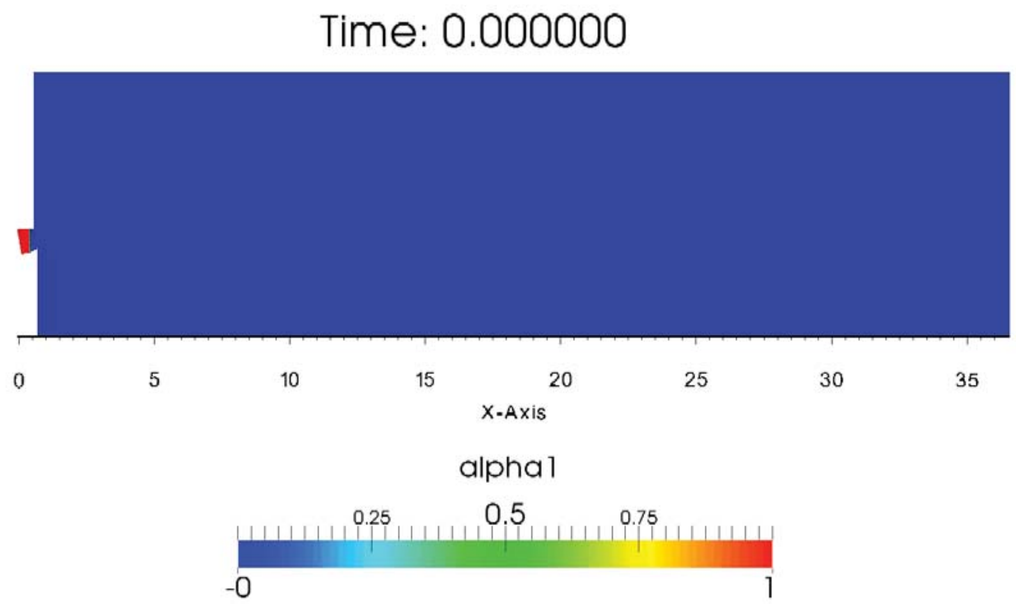
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X-Axis
alpha1
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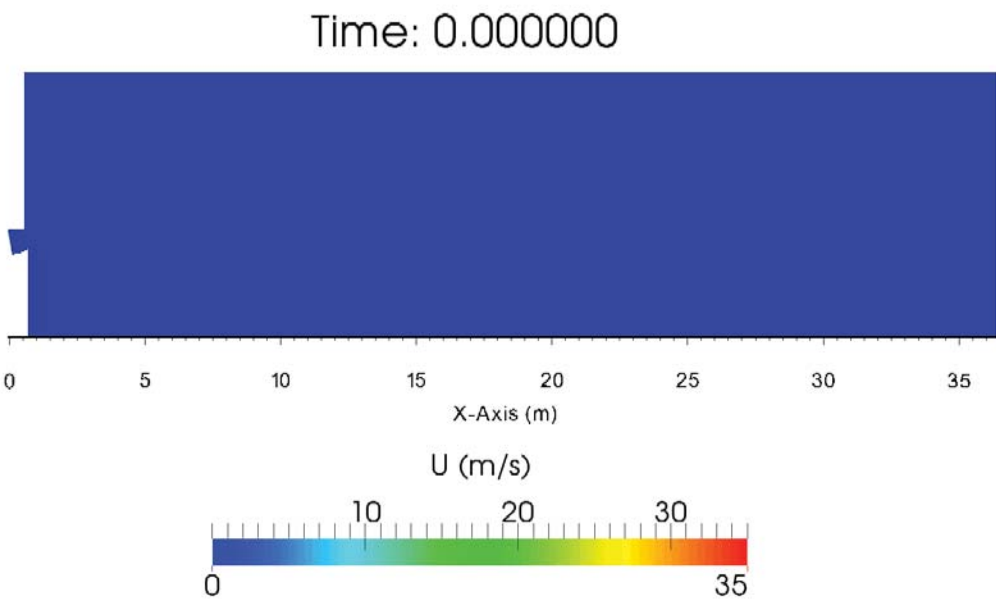
112,500 GPM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X-Axis (m)
U (m/s)
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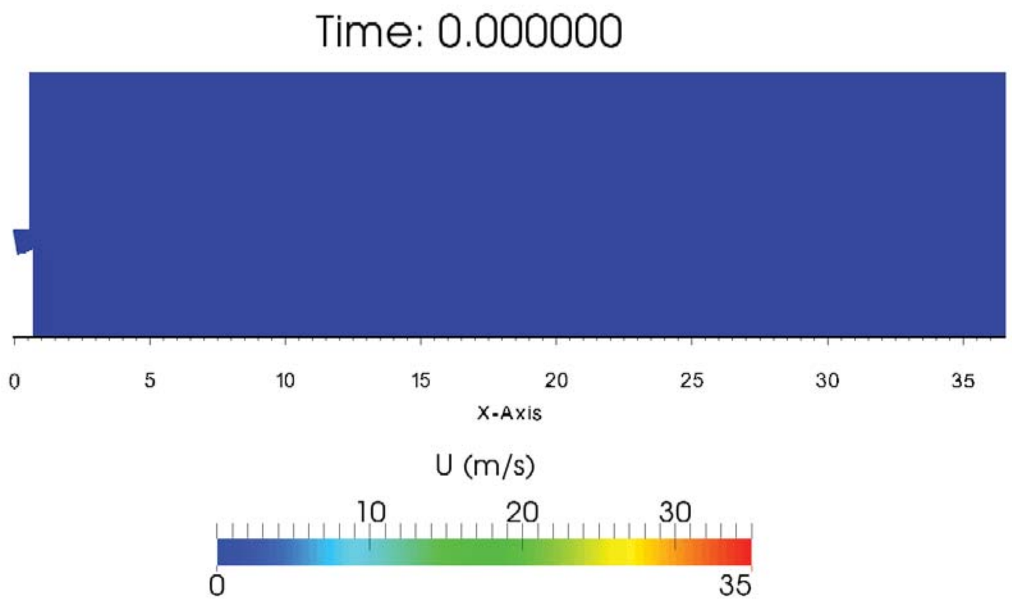
Time: 0.000000
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X-Axis
U (m/s)
10
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Recommendation

- 3-D VOF
- Smoothed Particle Hydrodynamics

SPH Formulation

- SPH is a meshfree method with nodal collocation, spatial discretization, and kernel approximation.
- Starting with the conservation equation of mass and momentum:

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\vec{v}$$

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla P + \upsilon\nabla^2\vec{v} + g$$

written in compact matrix form: $A\left(f\left(r\right)\right) = \nabla\sigma + F, \quad \forall r \in \Omega$

$$B\left(f\left(r\right)\right) = \bar{f}, \quad \forall r \in \Gamma$$

- Let $f^h(r)$ is an approximation of $f(r)$:

$$f(r) \approx f^h(r) = \sum_{i=1}^{n} N_i(r) f_i$$

where $f_i = f(r_i)$ is nodal value of $f(r)$ at specified particle r_i.
$N_i(r)$ is the shape function used to interpolate field $f(r)$ from f_i

SPH Formulation

- For any test function v in the domain Ω and boundary Γ,

$$\int_{\Omega} v^T A\big(f(r)\big)d\Omega + \int_{\Gamma} v^T B\big(f(r)\big)d\Gamma = 0$$

- Test function v can be constructed by some basis function $\bar{\Phi}_i$

$$v = \sum_{i=1}^{r} b_i \Phi_i \text{ and } \bar{v} = \sum_{i=1}^{r} b_i \bar{\Phi}_i$$

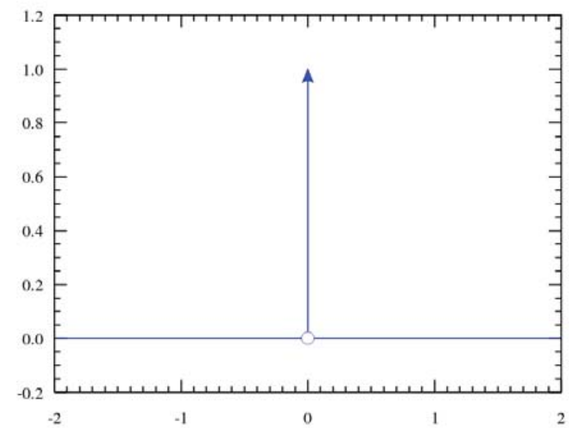
leading to the final weighted residual function

$$\int_{\Omega} \Phi^T A\big(f^h(r)\big)d\Omega + \int_{\Gamma} \bar{\Phi}^T B\big(f^h(r)\big)d\Gamma = 0$$

SPH Formulation

- Point collocation discretized the weighted residual function based on Dirac delta function

$$\delta(r) = \begin{cases} 0, & r \neq 0 \\ 1, & r = 0 \end{cases}$$



- Dirac delta function has some useful properties:

$$\int_{\Omega} \delta(r) dr = 1 \qquad \int_{-\infty}^{\infty} \delta(r - r') f(r') dr' = f(r)$$

- For a boundary value problem,

$$A(f(r)) = 0, \quad \forall r \in \Omega$$
$$B(f(r)) = 0, \quad \forall r \in \Gamma$$

- Use the delta function $\delta(r_i - r)$ as test function, we can derive a set of collocation eqs:

$$A(f^h(r_i)) = 0, \quad i = 1,2,\ldots,r_1$$
$$B(f^h(r_j)) = 0, \quad j = 1,2,\ldots,r_2$$

where r_1 and r_2 are particles in Ω and Γ, respectively

SPH Formulation

- In a Kernel approximation, the δ function can be replaced by a smoothing function $w(r\text{-}r',h)$, which is an even function and satisfies the following conditions:

$$\int_{\Omega} w(r-r',h)dr'=1 \qquad \lim_{h\to 0} w(r-r',h)=\delta(r-r') \qquad w(r-r',h)=0 \text{ when } |r-r'|>kh$$

where k defines the compact support of the smoothing function, and $f(r)$ can be approximated as

$$f^h(r)=\int_{\Omega} f(r')w(r-r',h)dr'$$

- The integral form can be discretized by particle approximation:

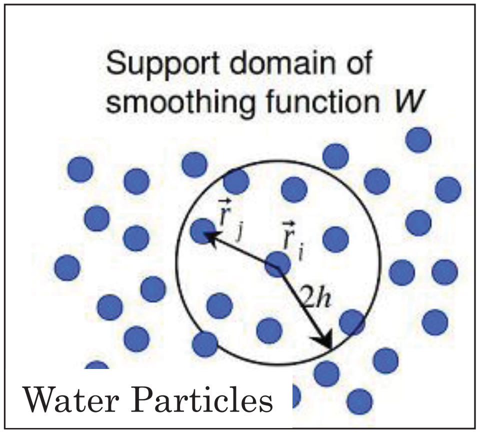
$$f^h(x)=\sum_{i=1}^{n} w_i(r)\Delta V_i f_i = \sum_{i=1}^{n} N_i(r) f_i$$

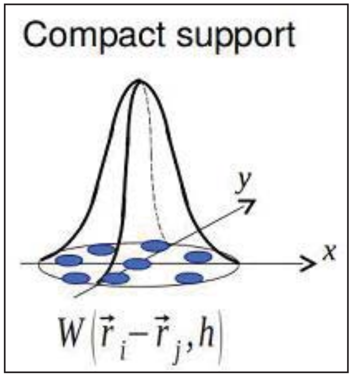
where $w_i(r)=w(r\text{-}r_i)$, and ΔV_i is the volume of particle r_i

SPH Formulation

- In SPH, finite volume of particle is related to mass of particle through density

$$m_i = \rho_i \Delta V_i$$





- The approximate function can be written as

$$f^h(r) = \sum_{i=1}^{n} w_i(r)\Delta V_i f_i = \sum_{i=1}^{n} w_i(r)\frac{m_i}{\rho_i} f_i$$

- The approximate solution of particle i is

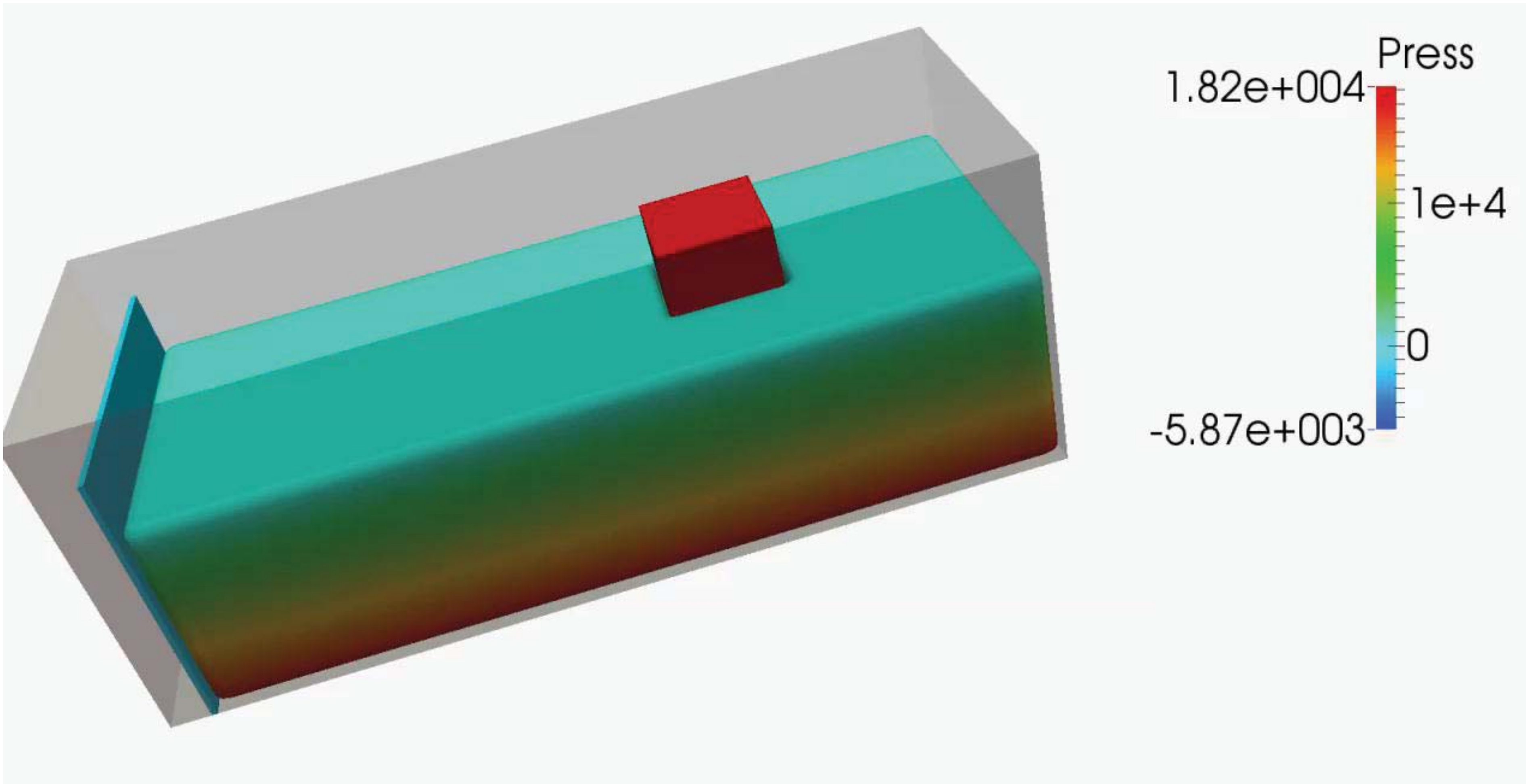
$$f^h(r_i) = \sum_{j=1}^{n} w_{ij}\frac{m_j}{\rho_j} f(r_j)$$

where $w_{ij} = w(r_i - r_j, h)$, thus the density of particle i becomes:

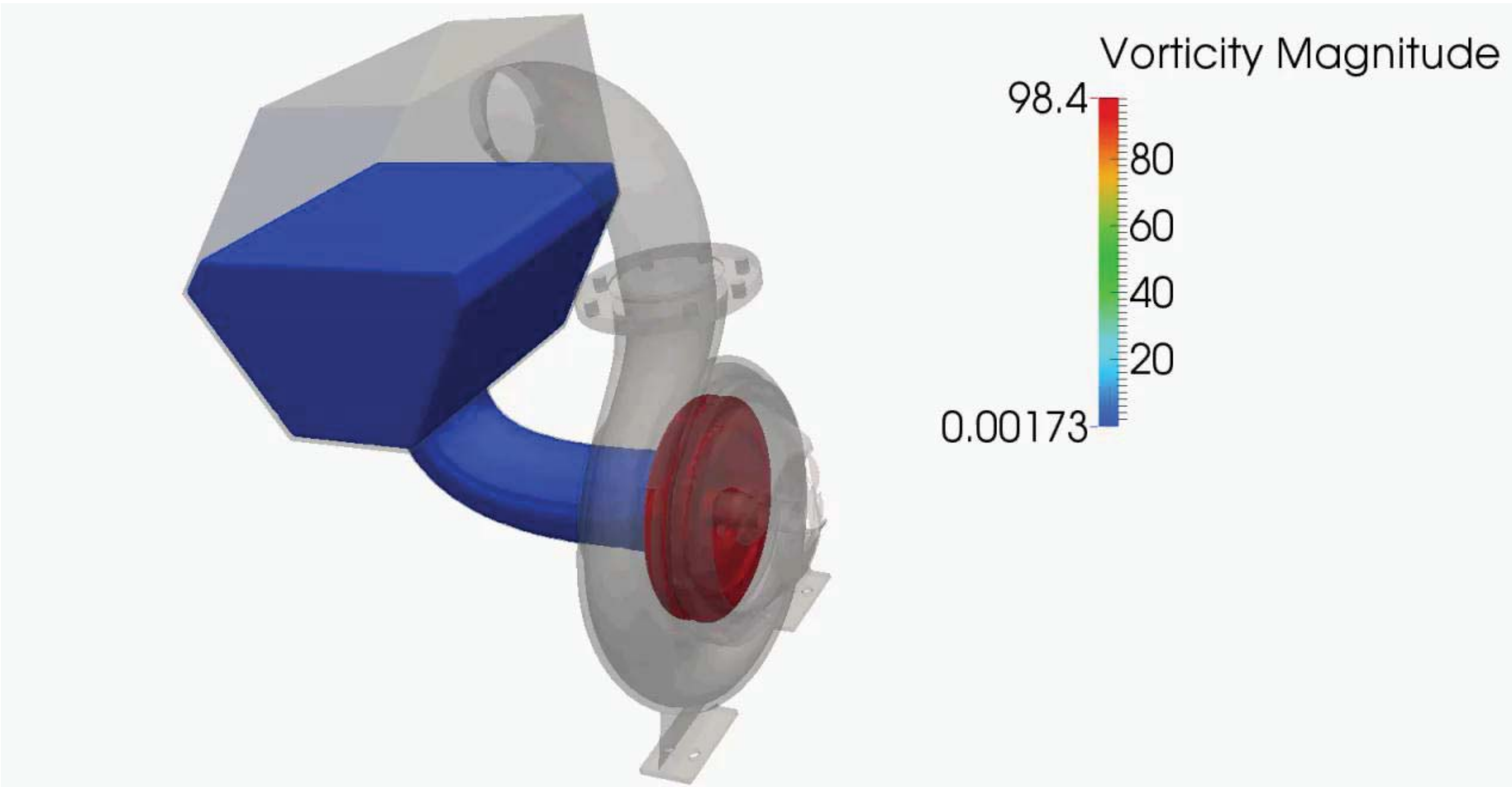
$$\rho_i = \sum_{j=1}^{n} w_{ij} m_j$$

- The above equation shows particle density is based on smoothing the surrounding particle masses, therefore the name "**smoothed particle**".

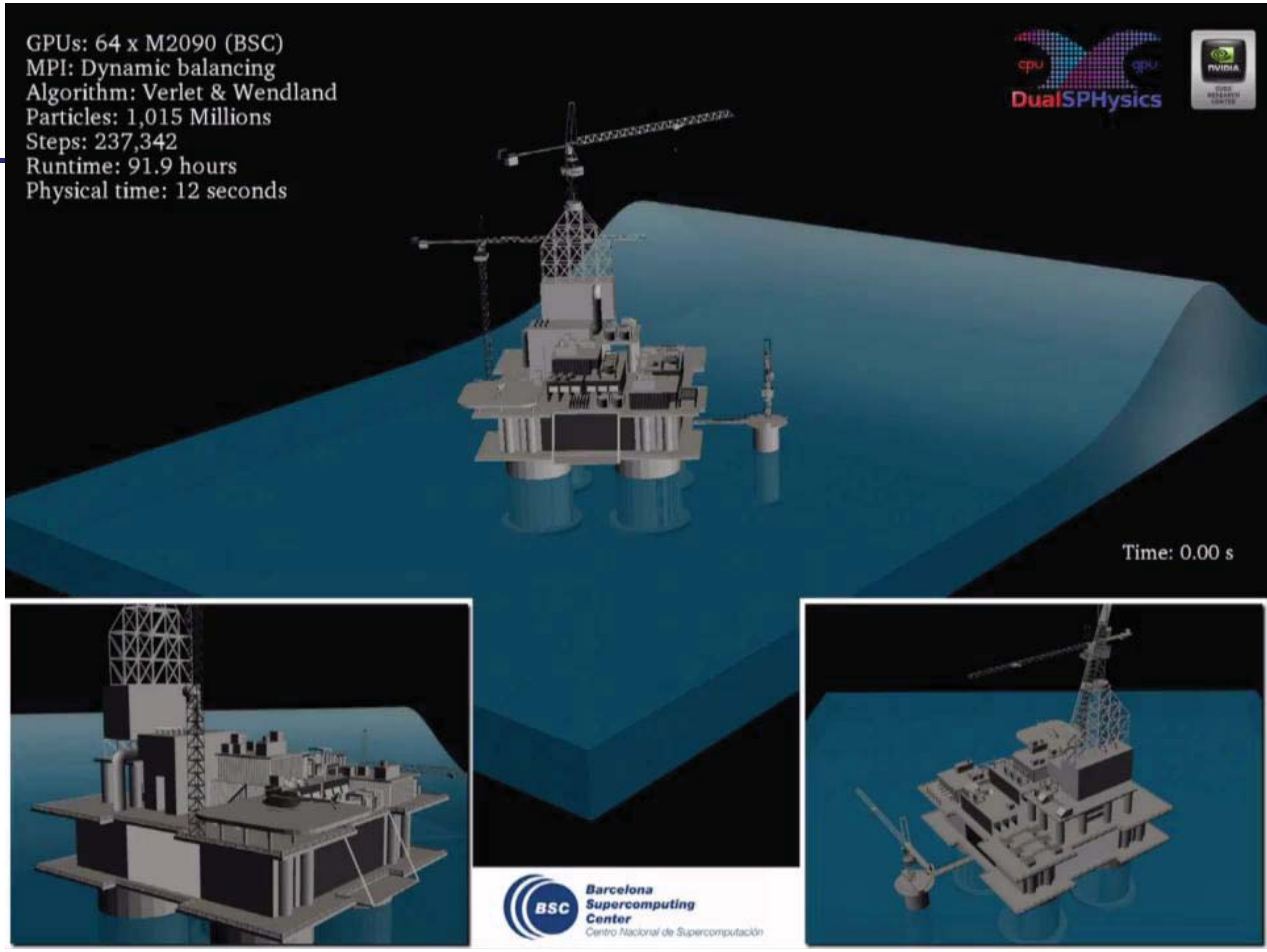
Floating



Pump



Multi-GPU SPH



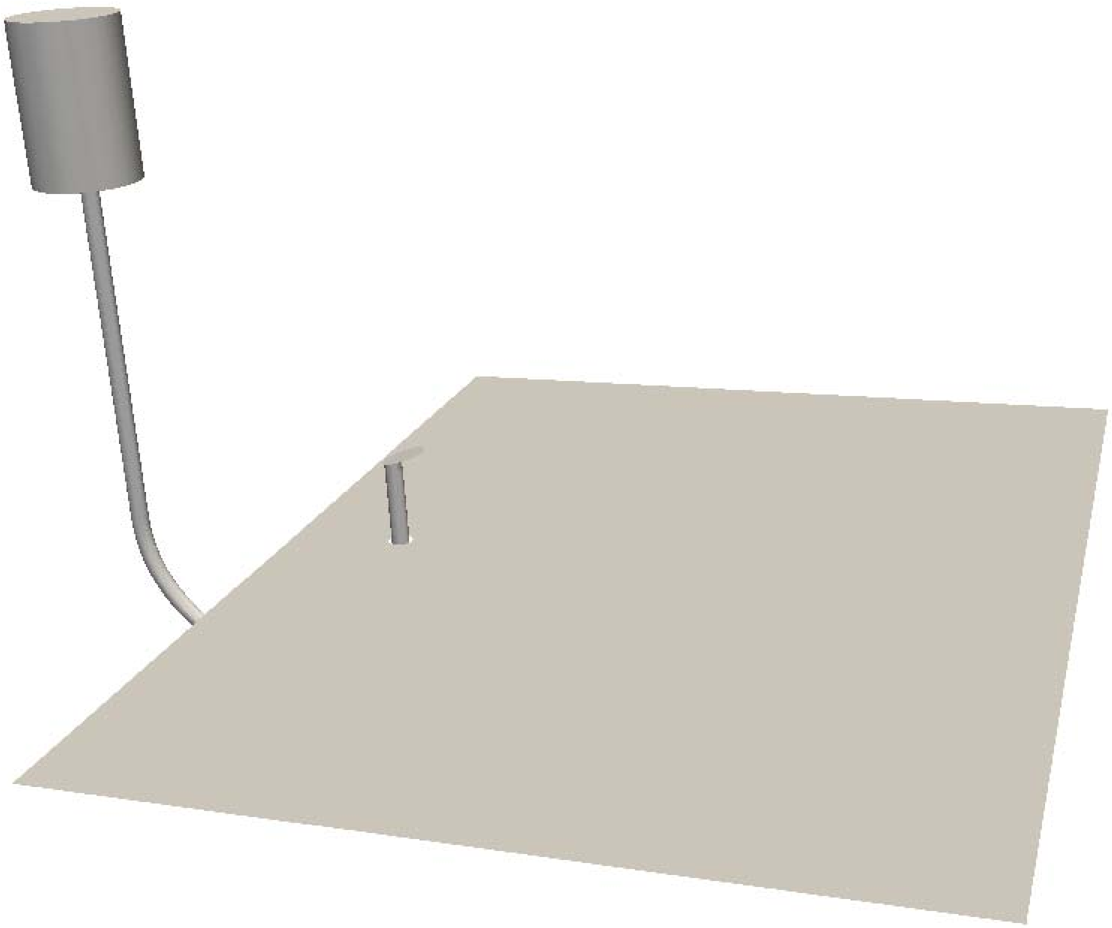
Computational Resource

- Current Beast:
  - Dual Quadro 6000, 6 GB, 448 CUDA GPU
  - 256 GB RAM
  - Dual Intel Xeon E5-2690
  - 512 GB SSD, 3 TB SATA (Win7)
  - 256 GB SSD, 2 TB SATA (Debian Linux)
- Upgrade Beast:
  - Tesla K40 (12 GB GDDR5, 2880 CUDA cores) for computations (4.29 Tflops)
  - Quadro K6000 (12 GB GDDR5, 2880 CUDA cores) for graphic rendering (2560x1600)
  - 1 TB SSD Drives

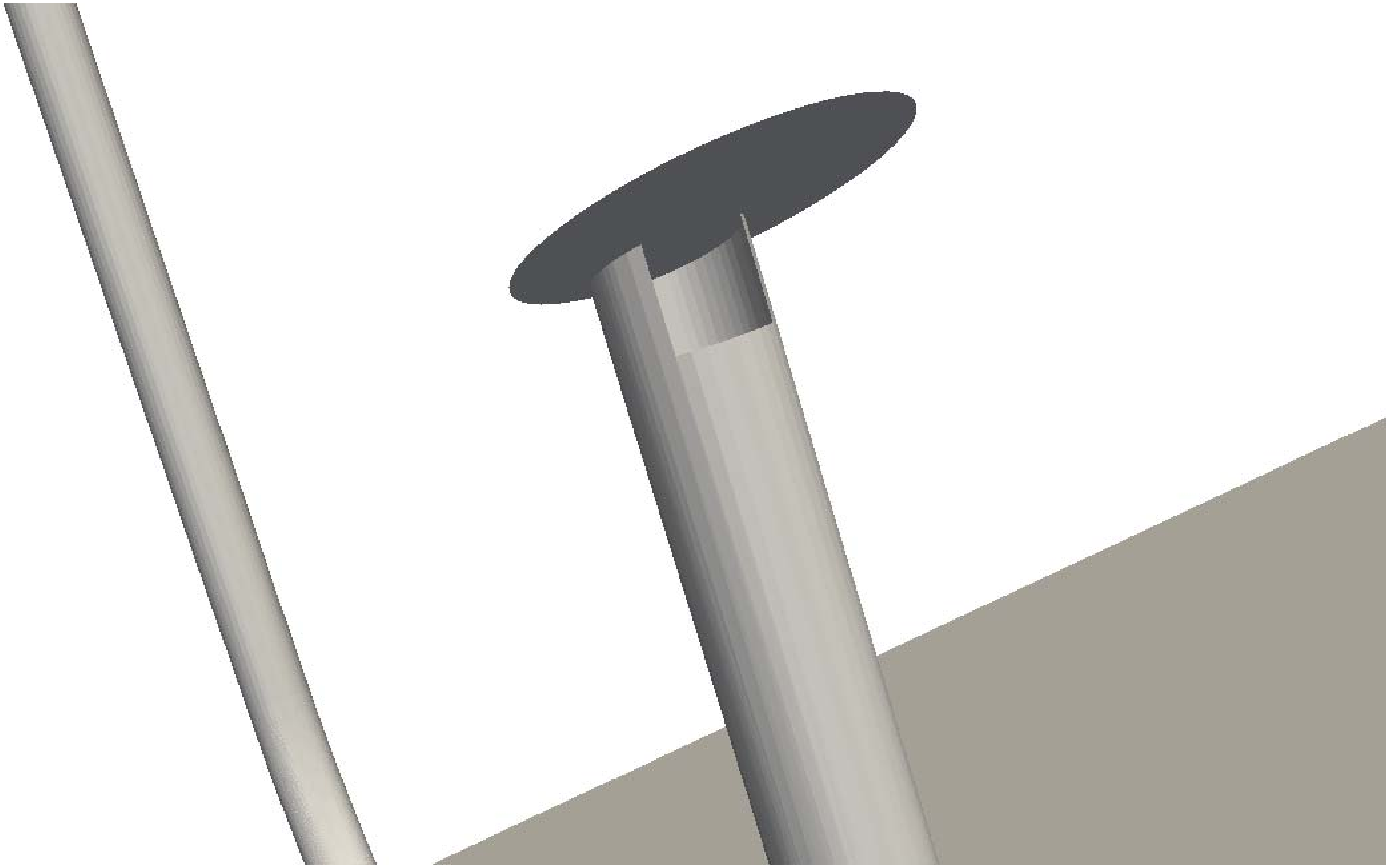
Approach

- Import full ML CAD Model
- Run multiple rainbirds with variable flowrates and timing sequence
- Activate vehicle motion with velocity/acceleration profile extracted from MSFC trajectory analysis

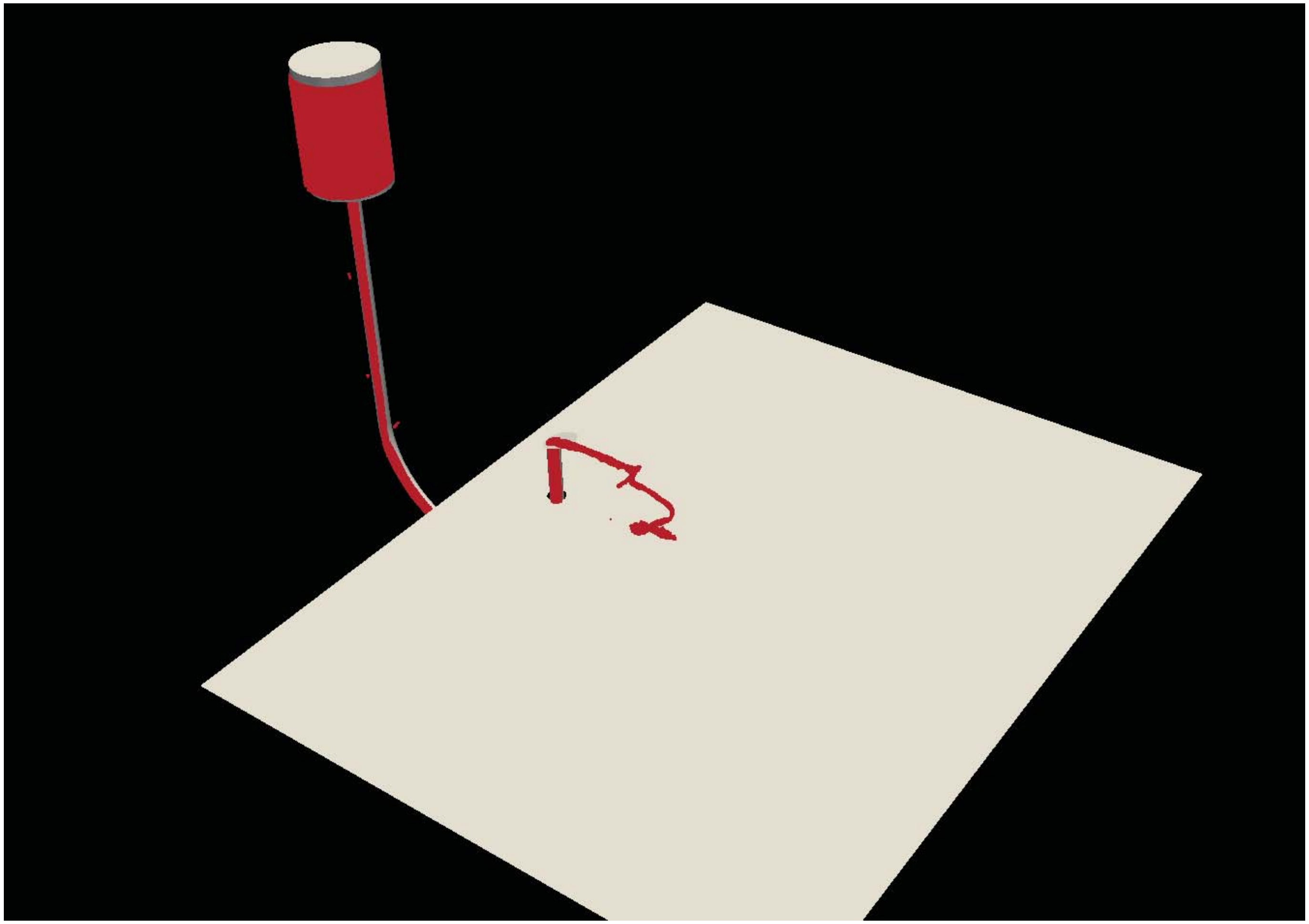
Water Tank & Rainbird



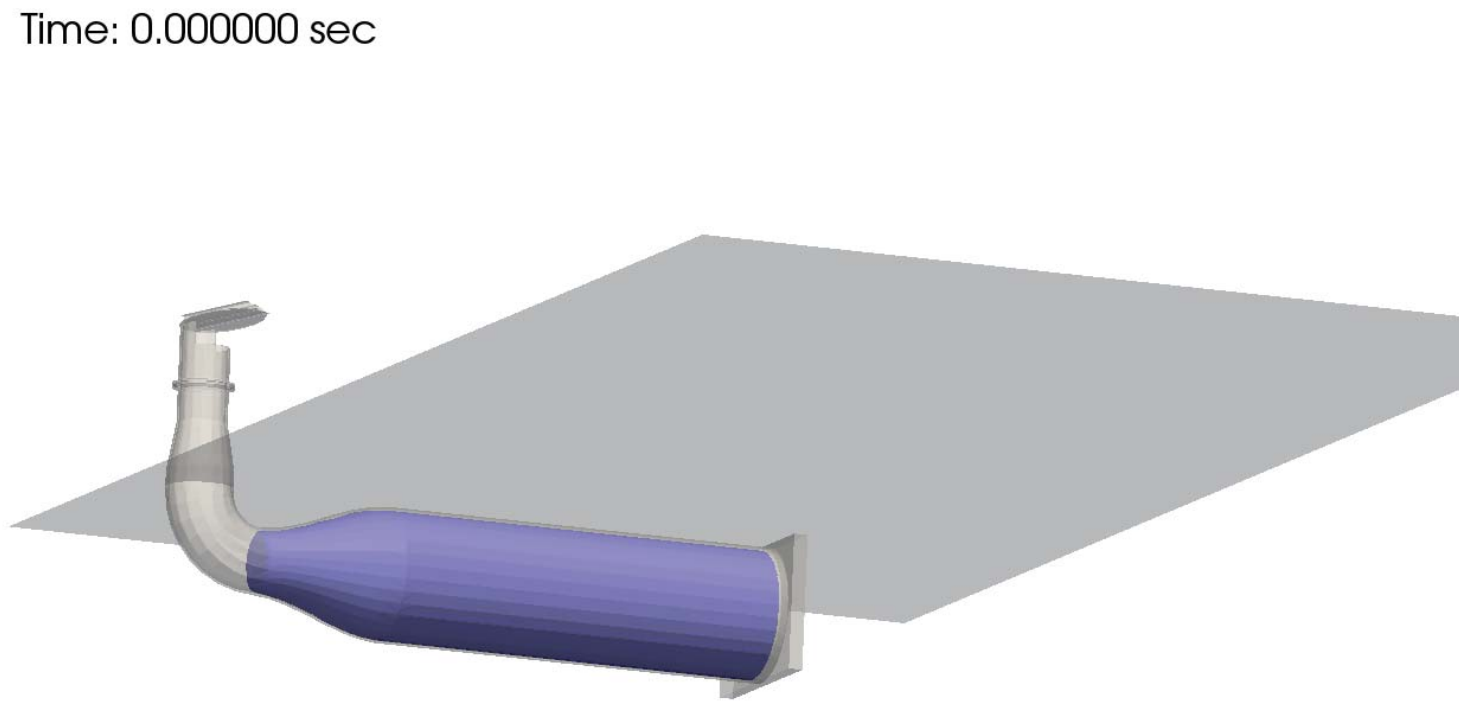
Rainbird



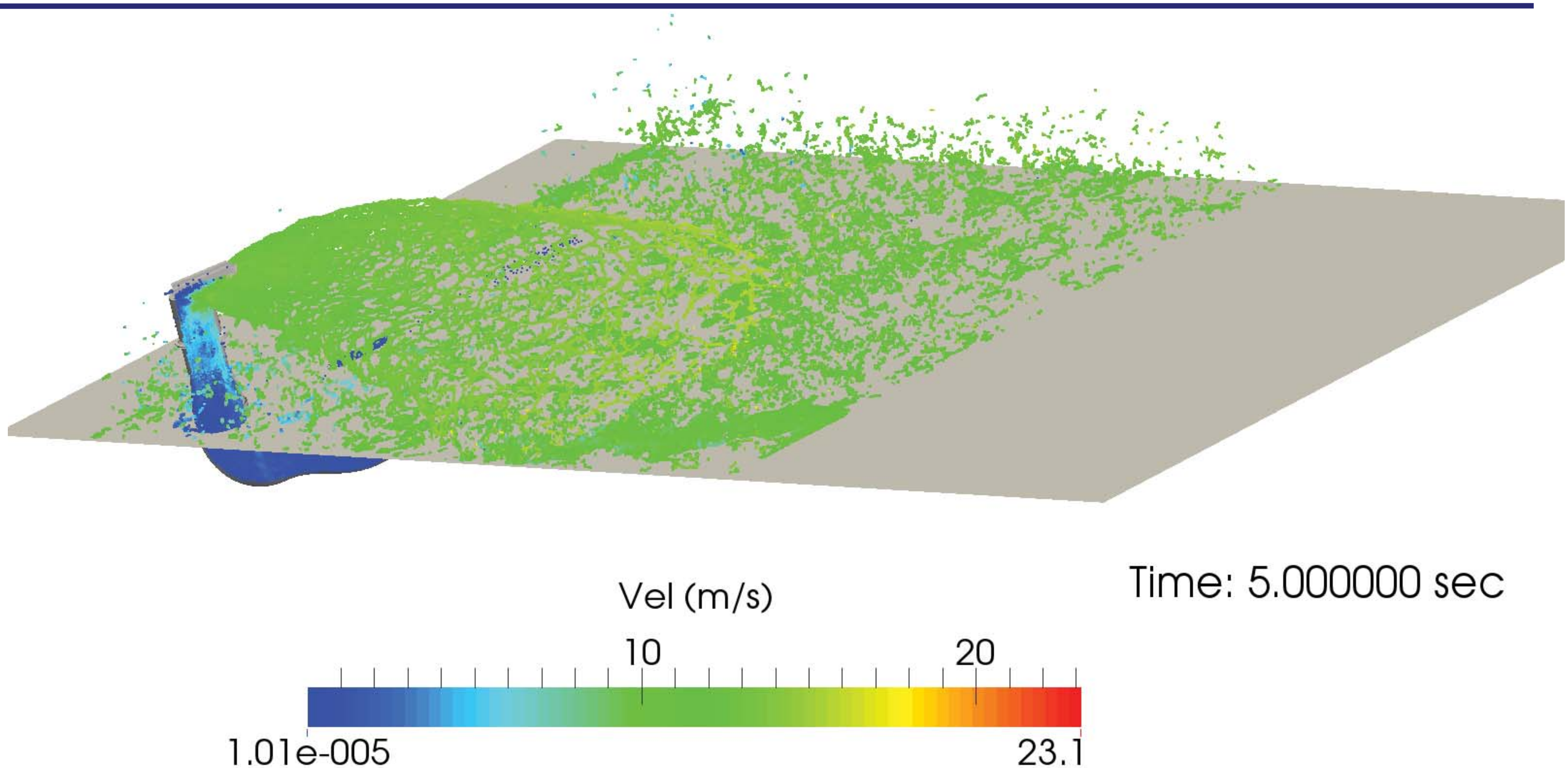
SPH Rainbird



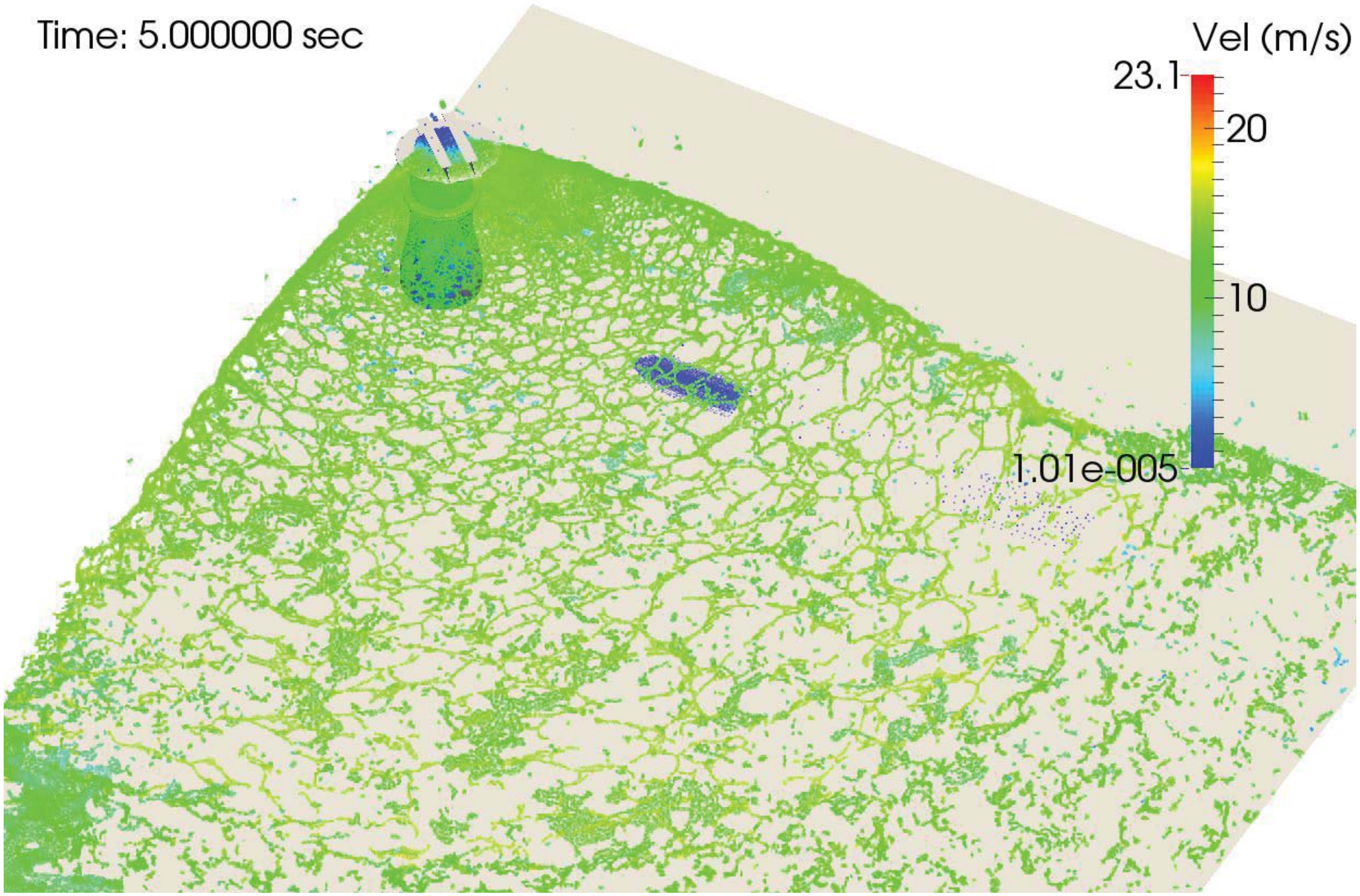
SPH Rainbird



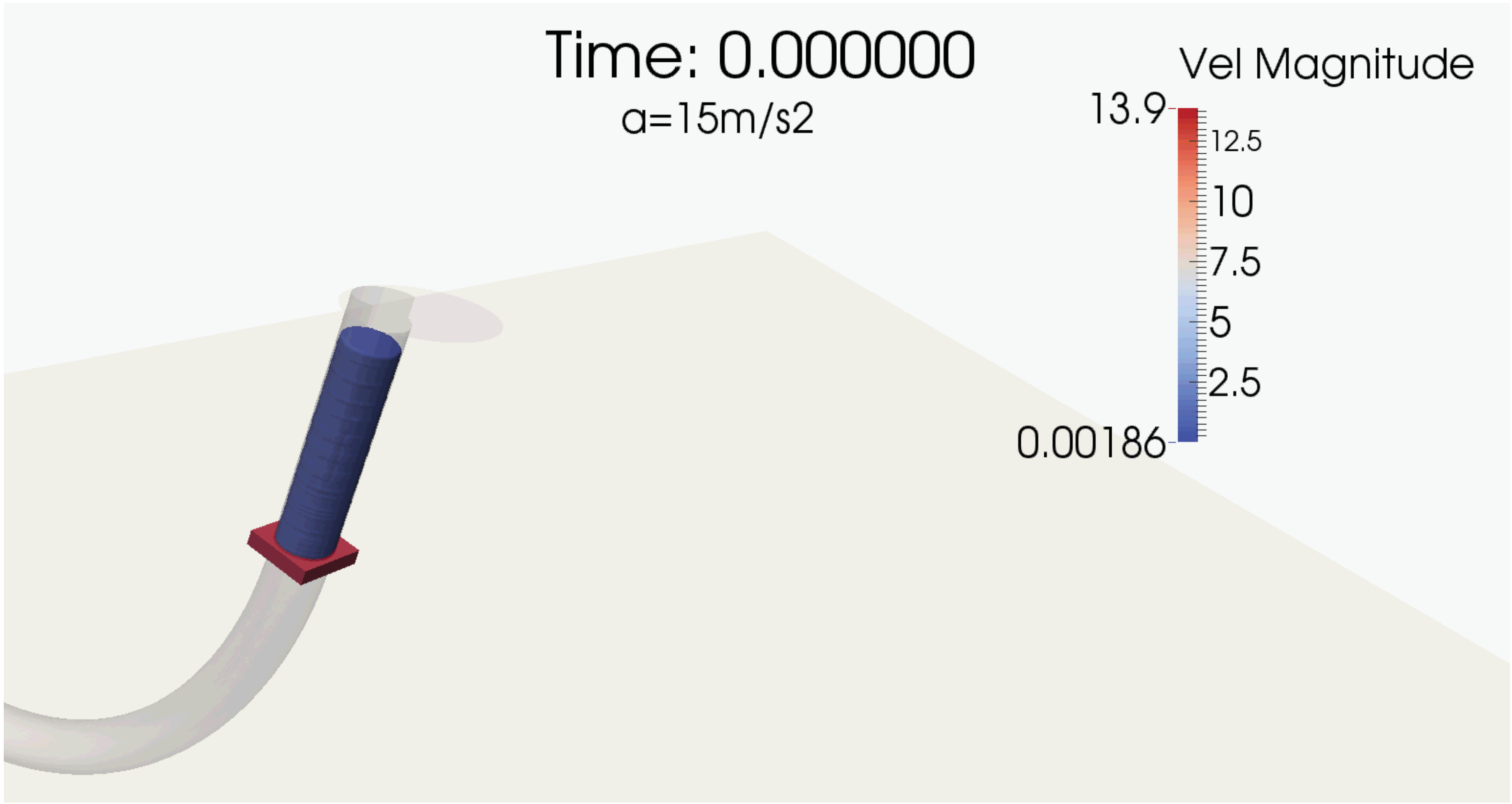
SPH Rainbird



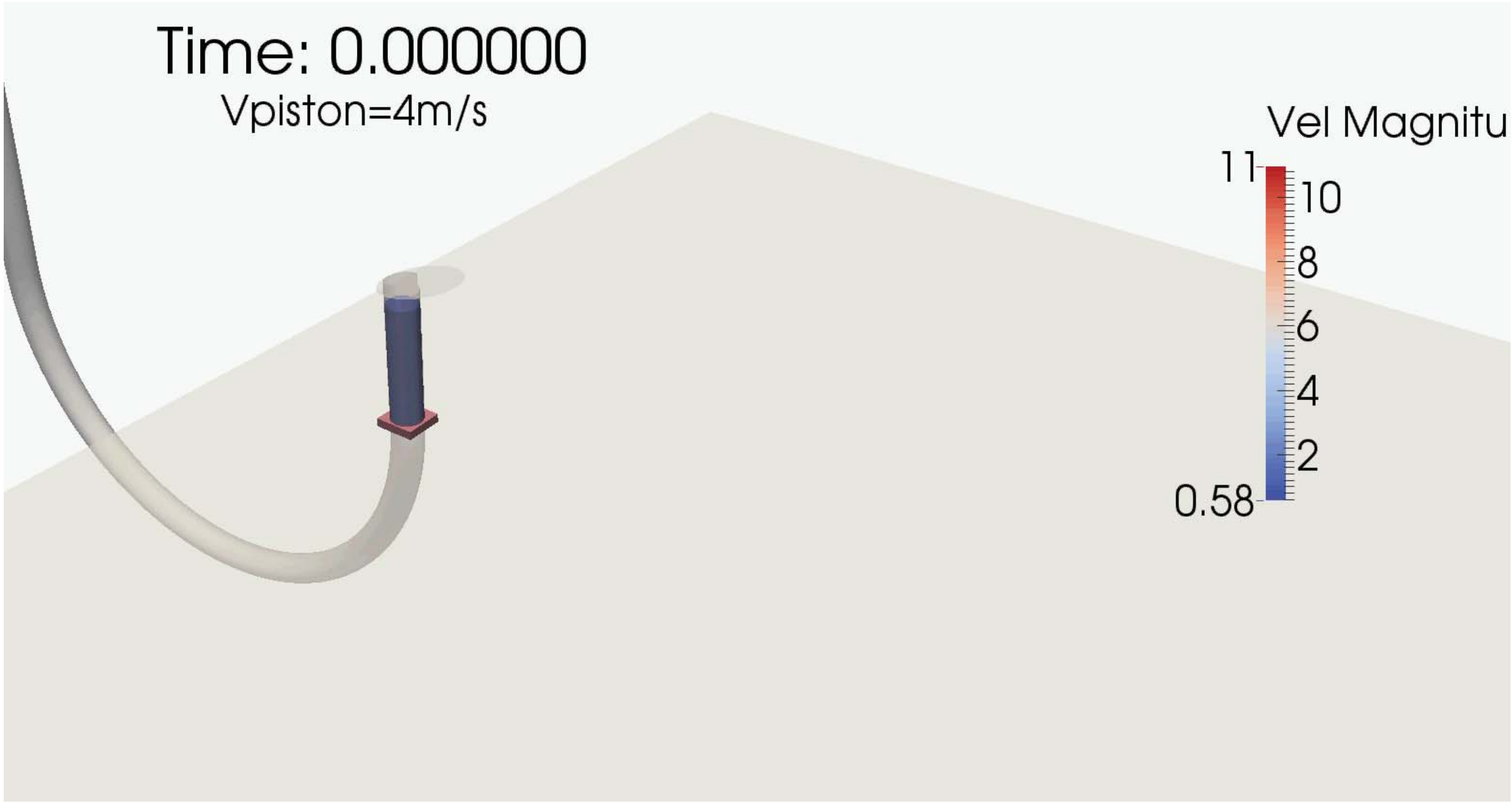
SPH Rainbird



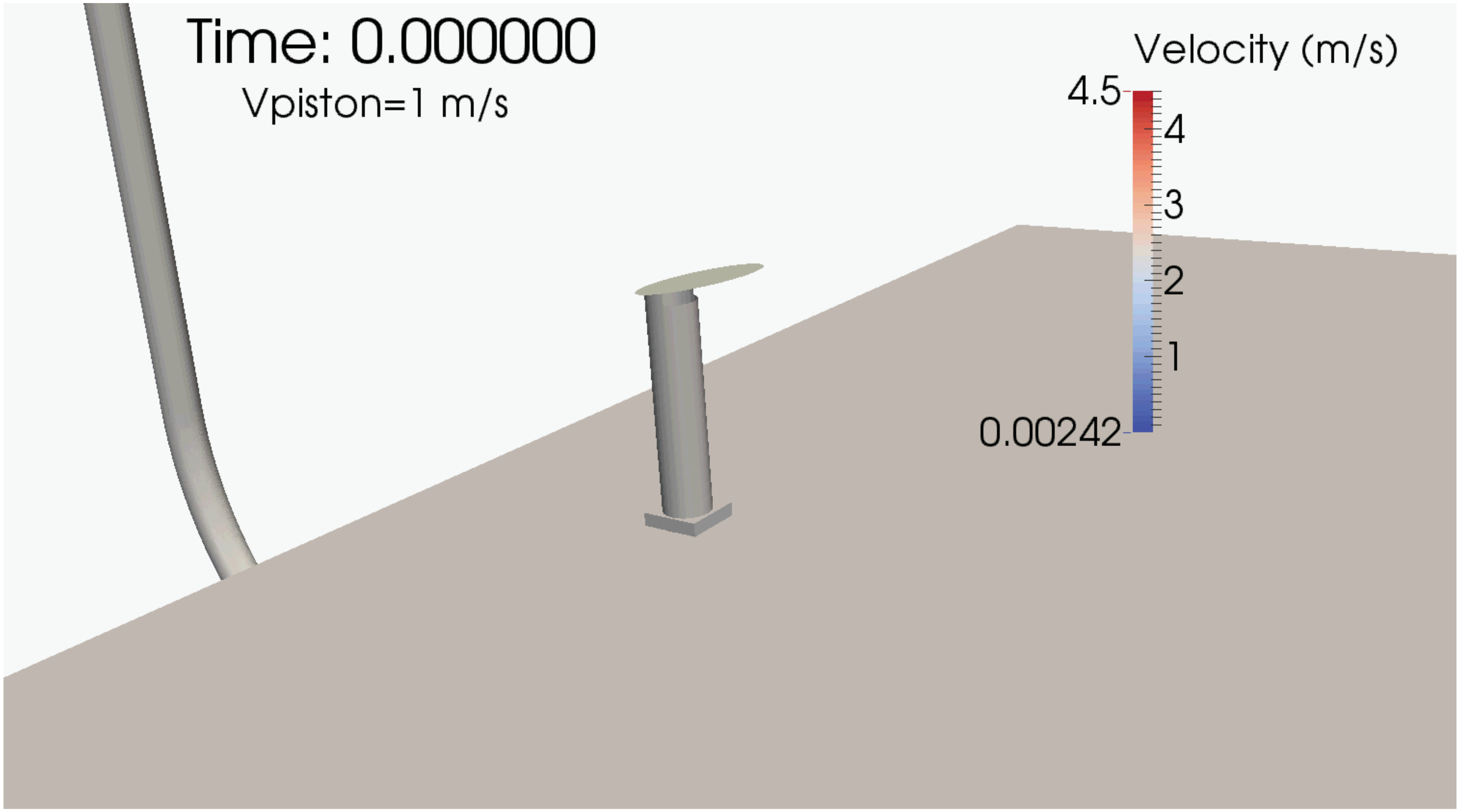
Test case 1



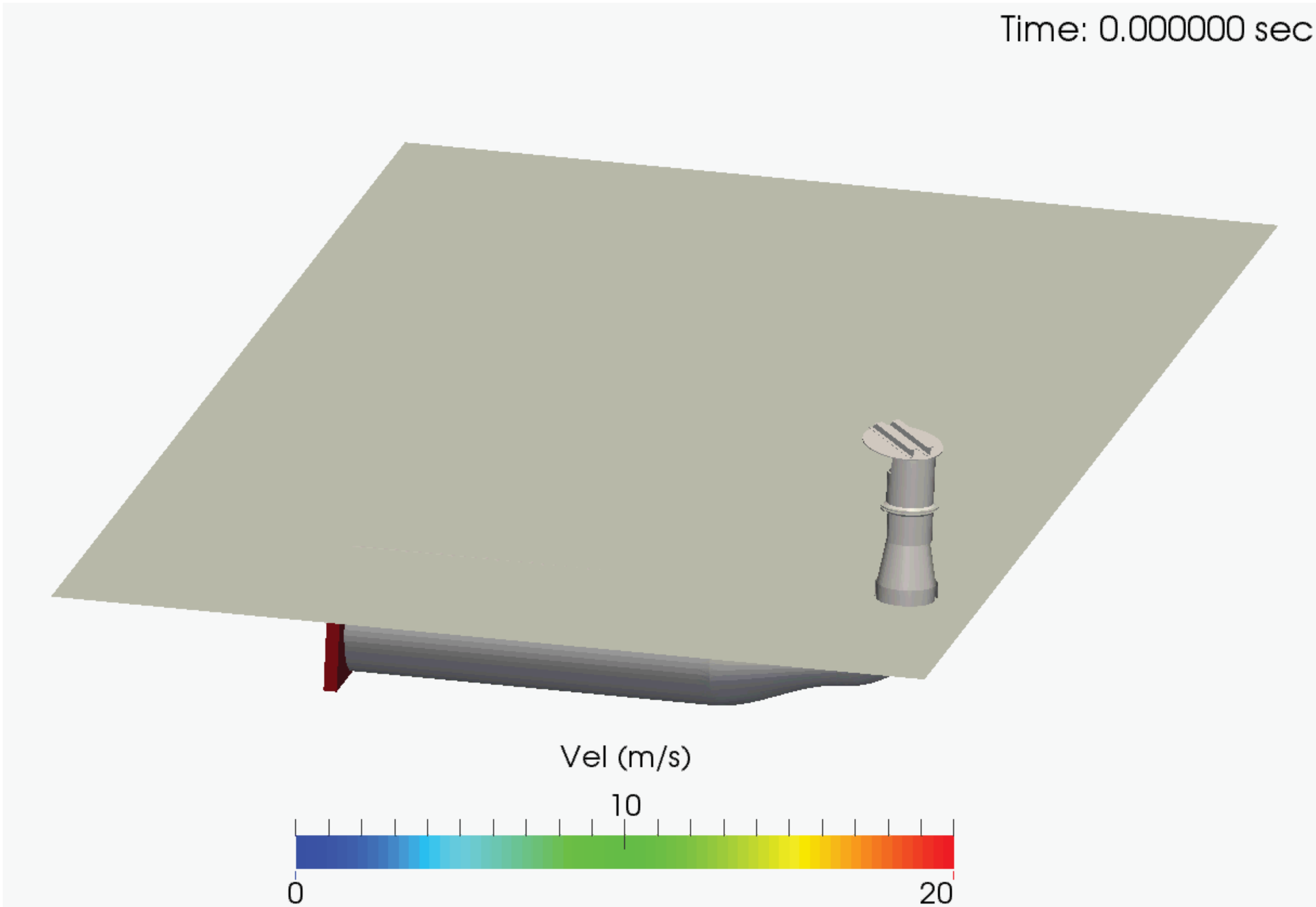
Test case 2



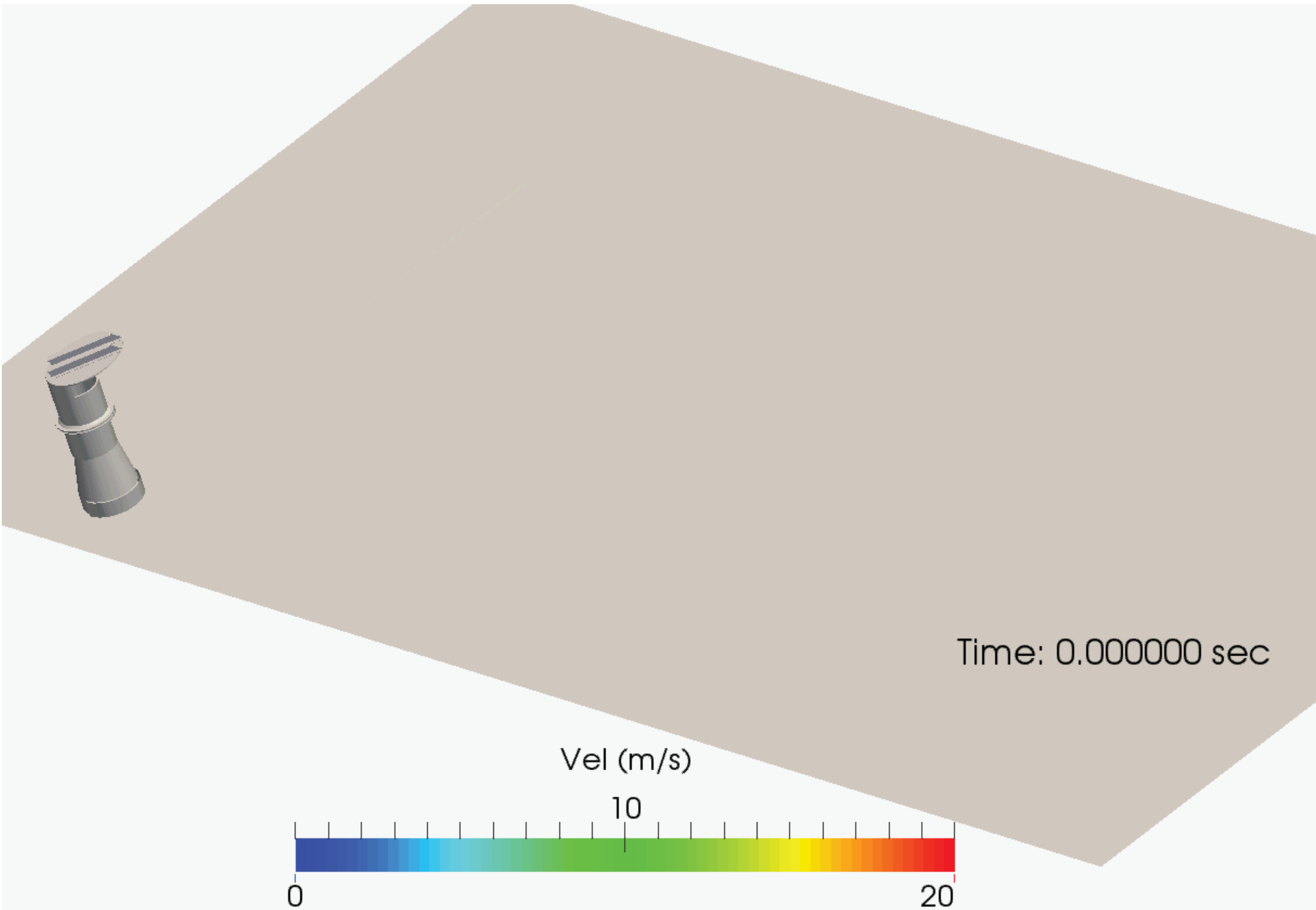
Test case 3



SPH Rainbird

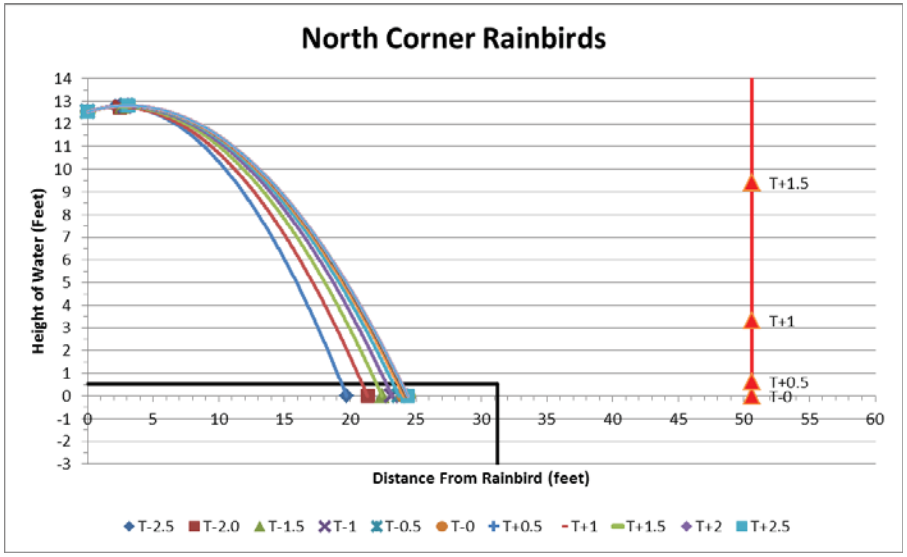


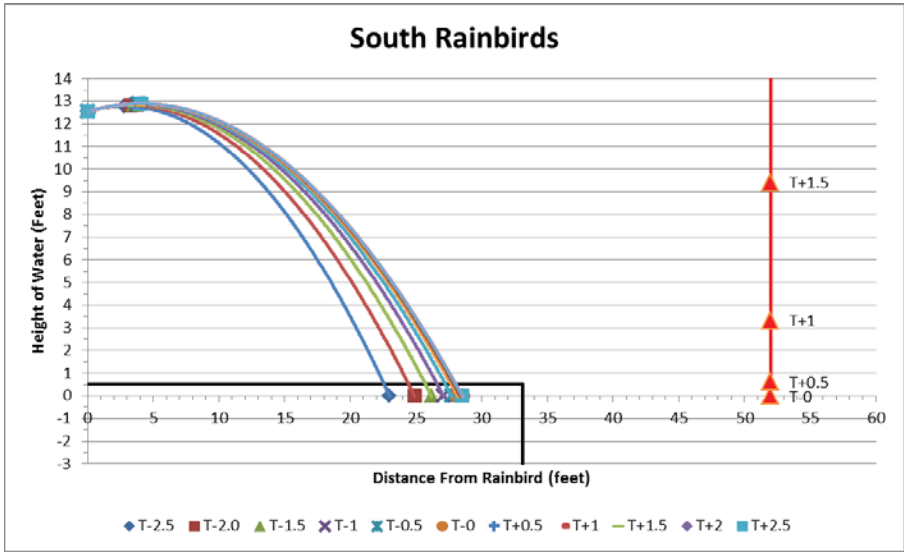
SPH Rainbird



Verification

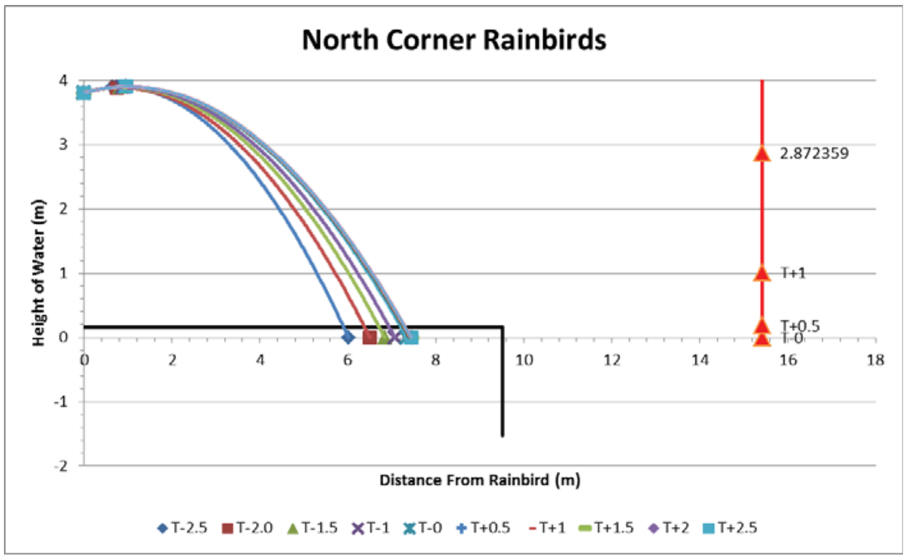
- Traj Plots CSE with bypass (from Nick Moss' Rainbird Water Throws)
  - North Corner Rainbirds: 28,381 GPM
  - South Rainbirds: 56,762 GPM

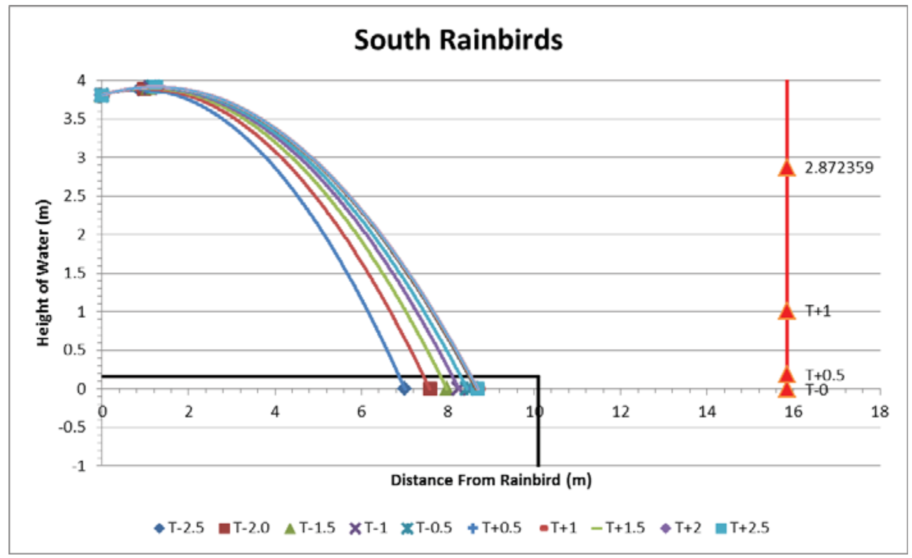




Verification

- Traj Plots CSE with bypass (from Nick Moss' Rainbird Water Throws)
  - North Corner Rainbirds: 6.01m – 7.433m
  - South Rainbirds: 7.0m – 8.7m





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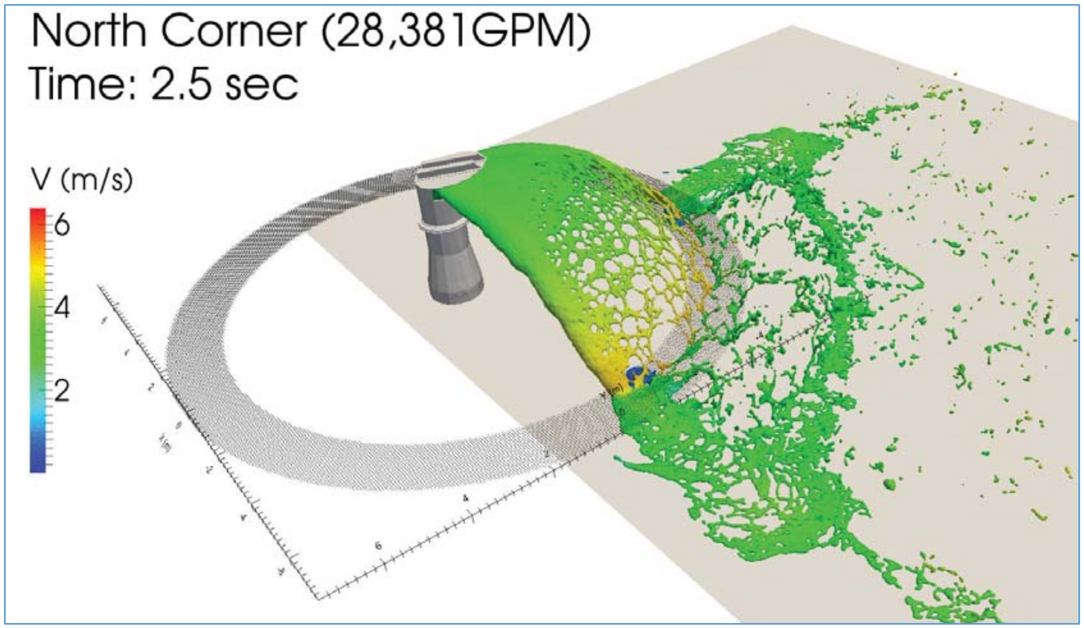

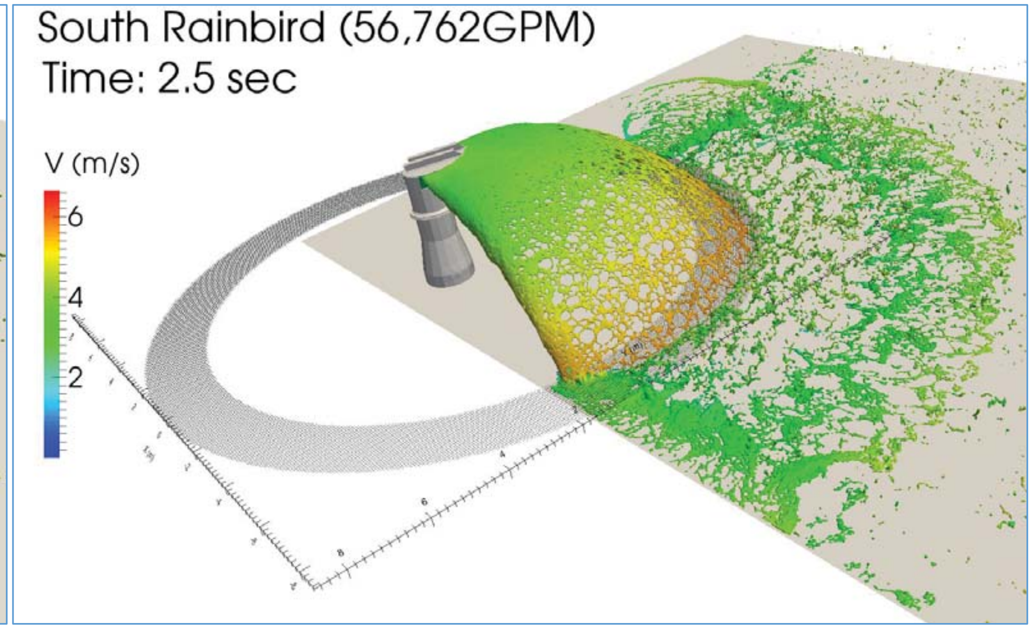

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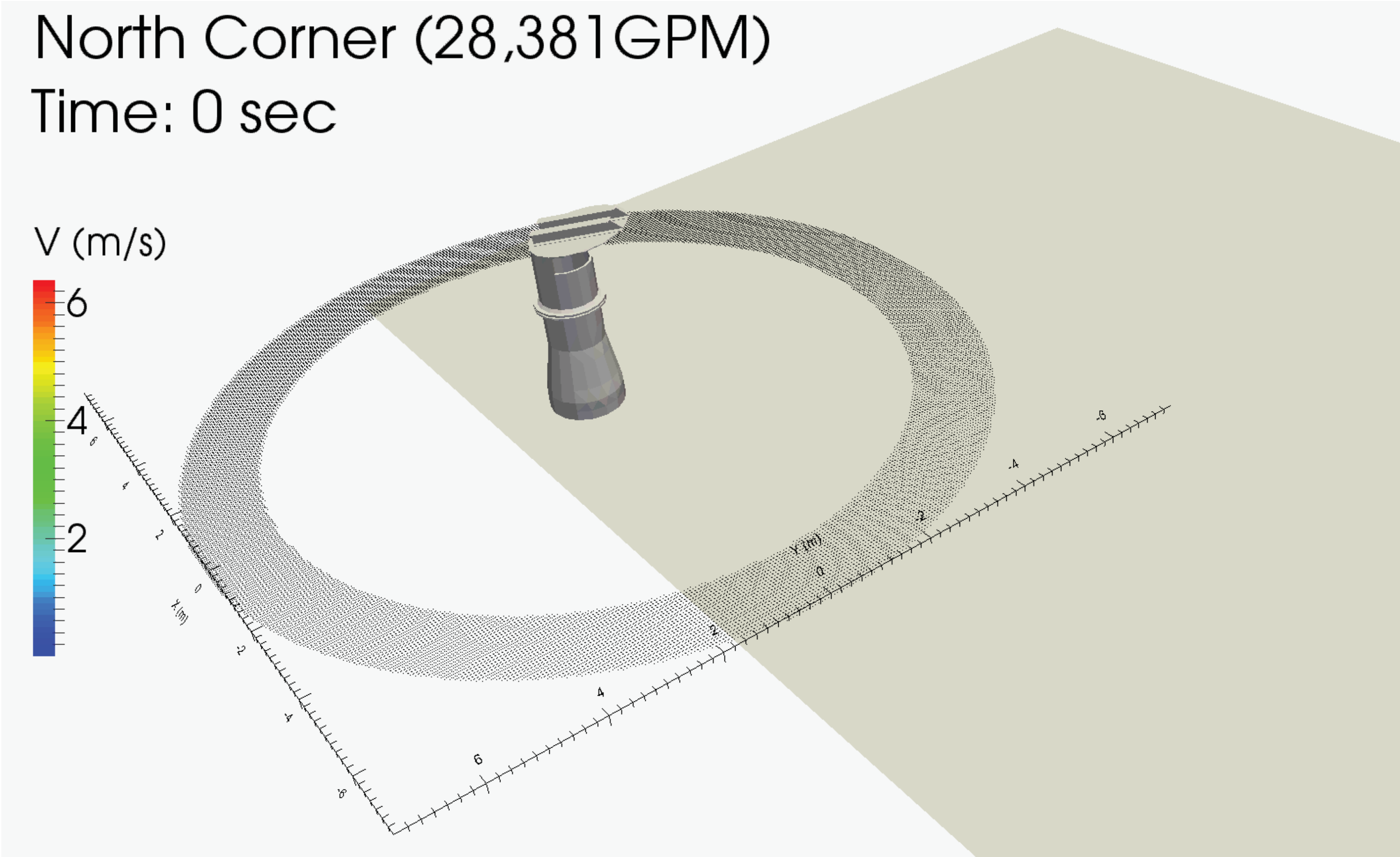

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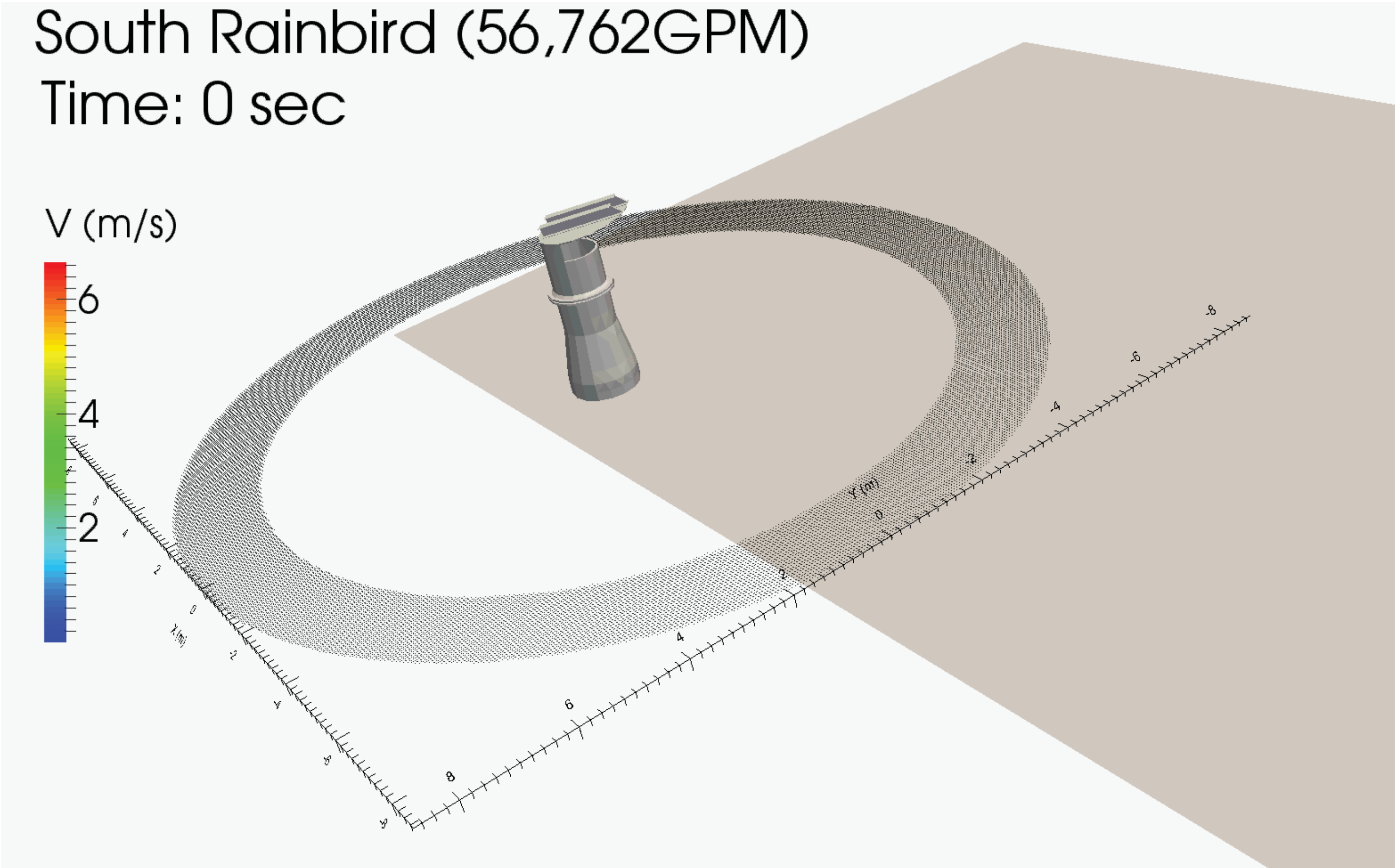

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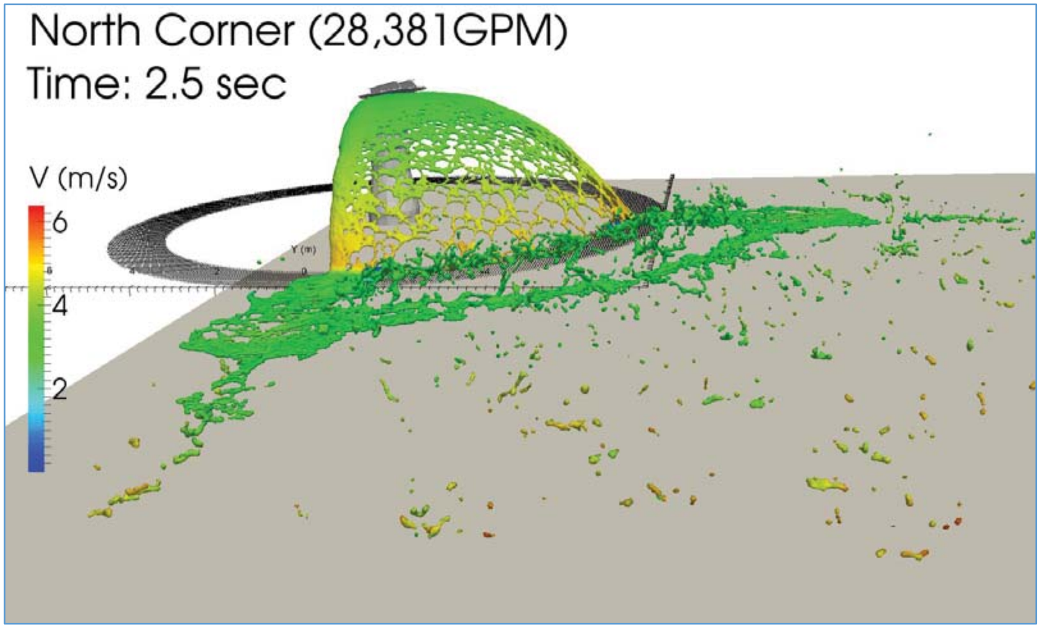

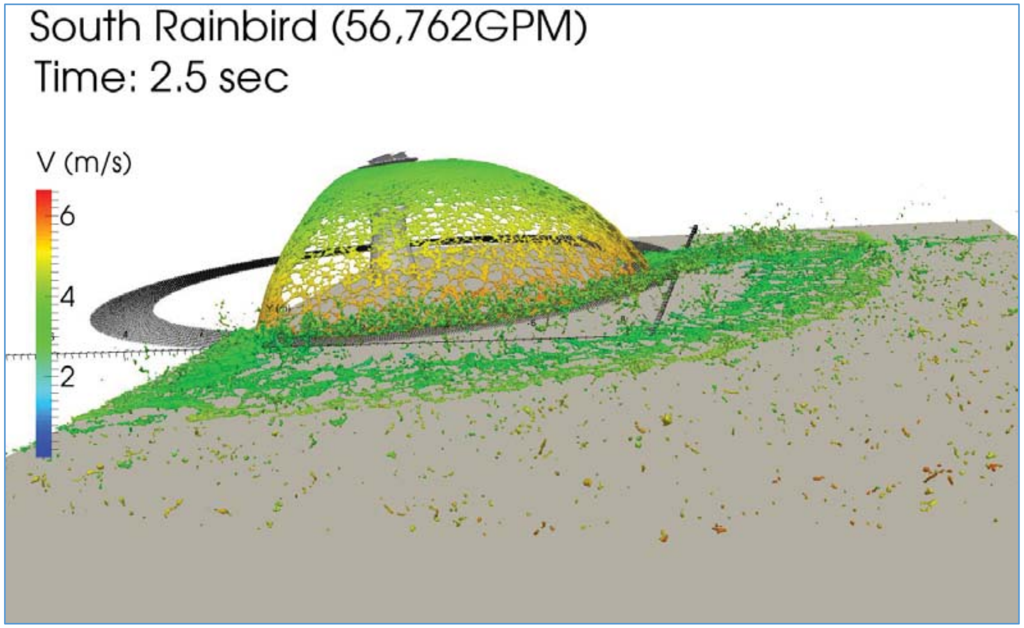

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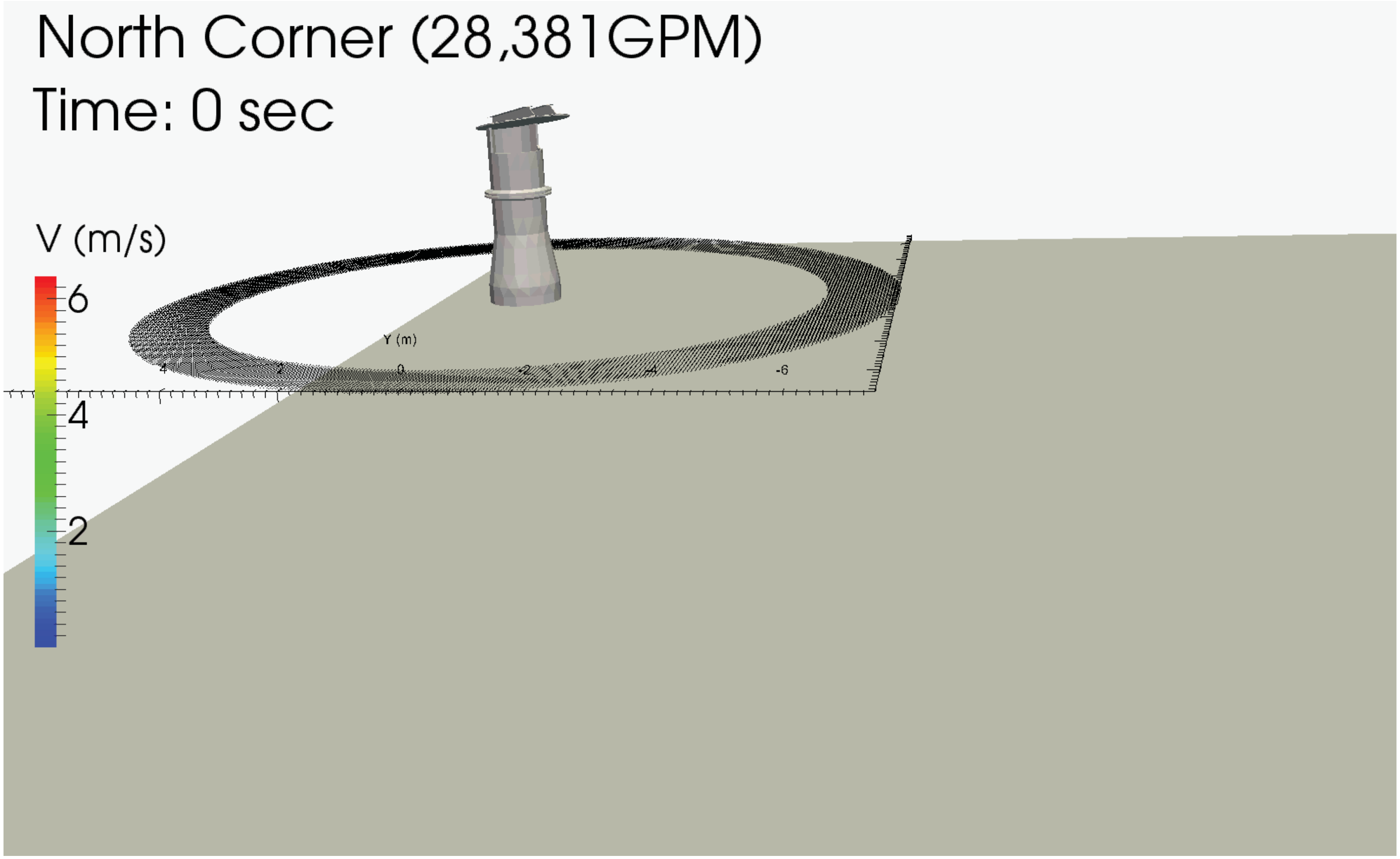

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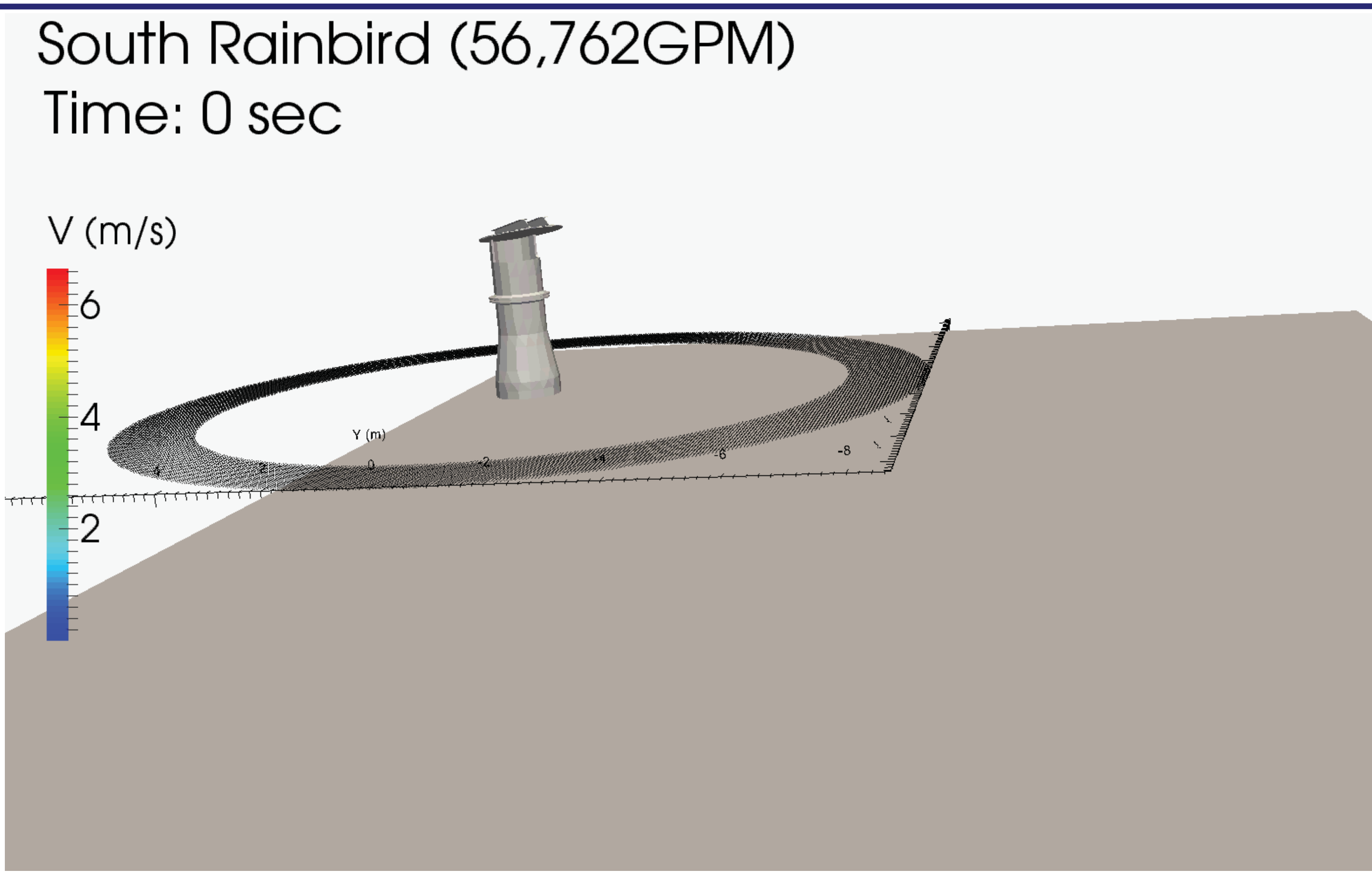
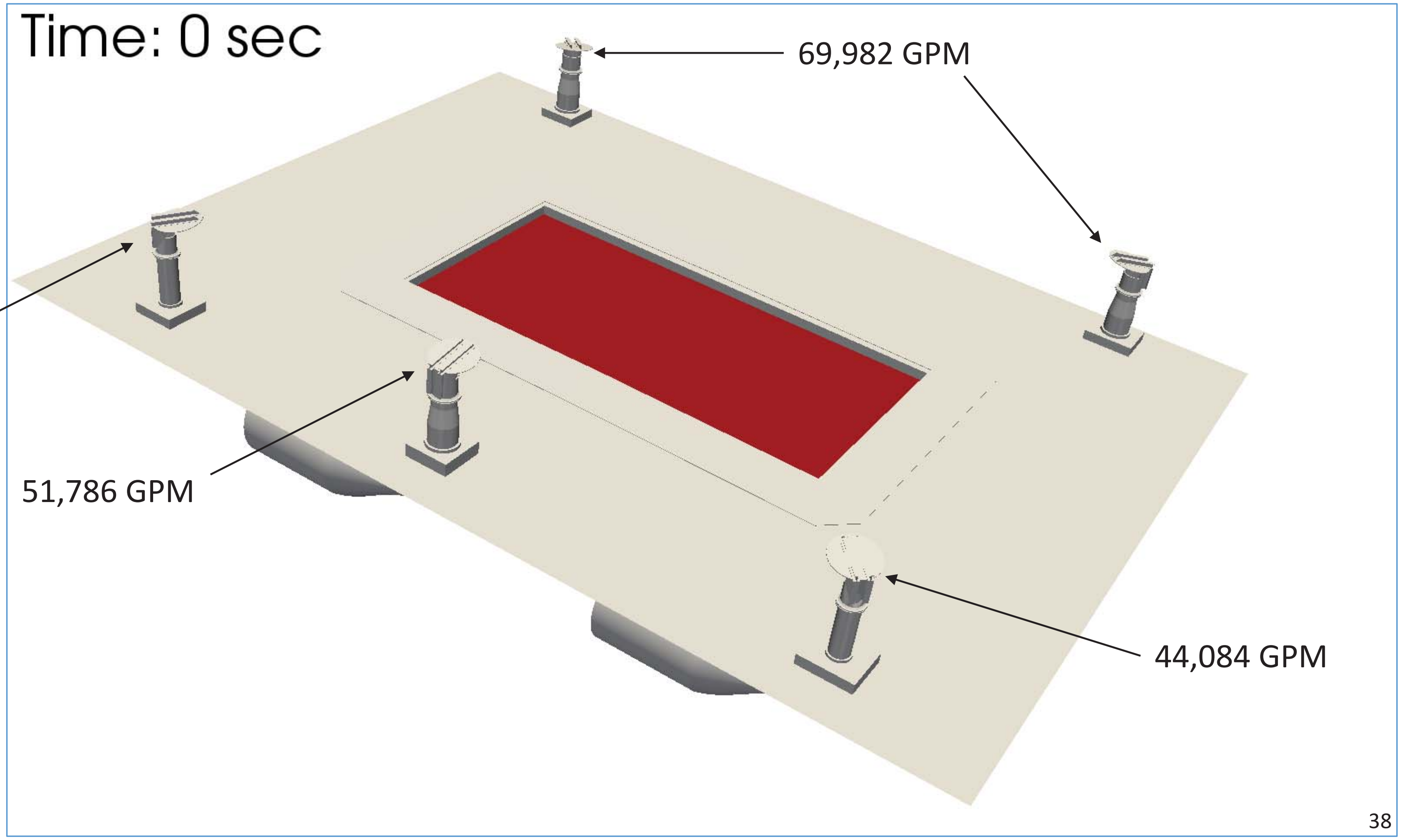


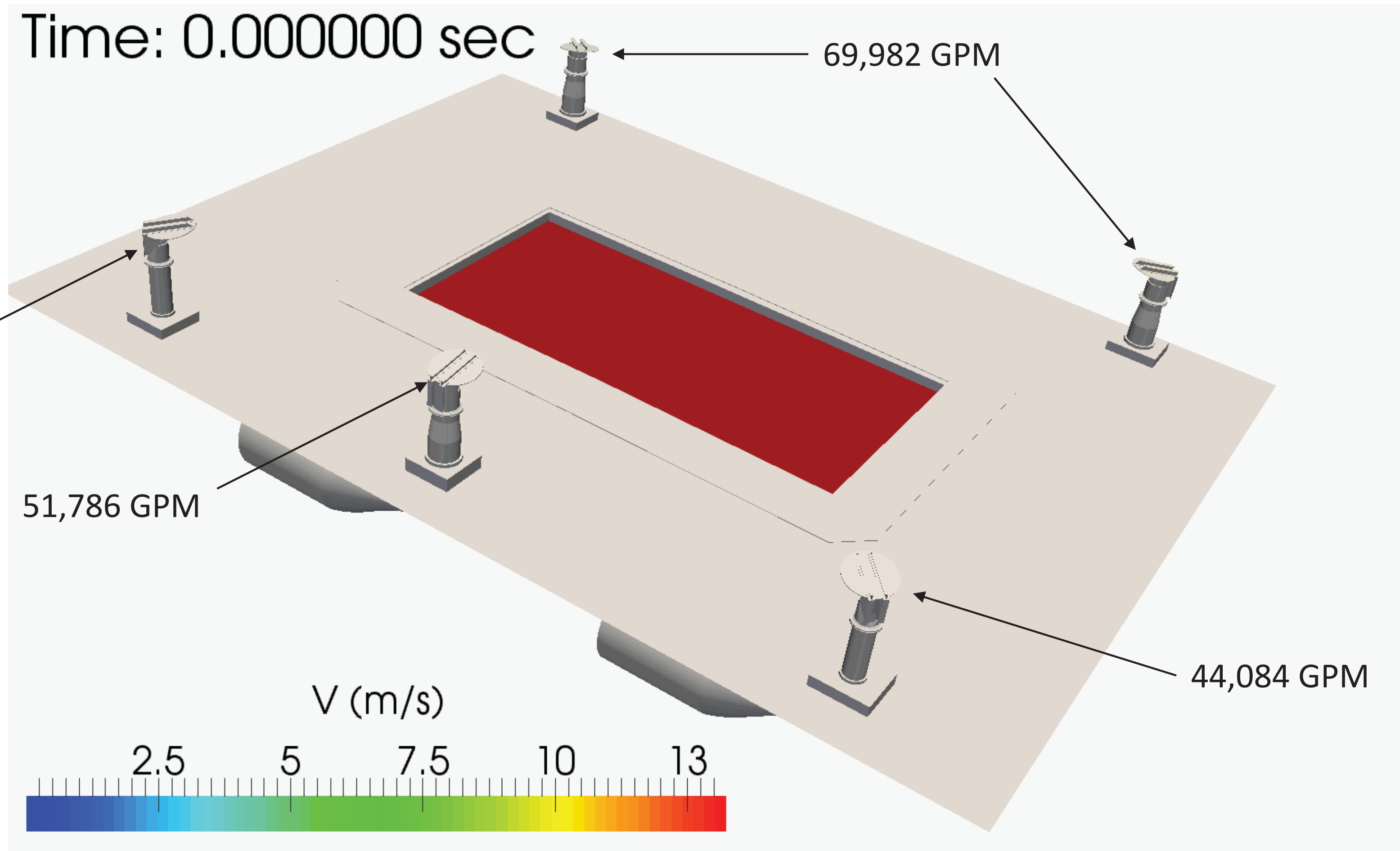
Verification

- Flow time=3.5s
- Total time=6.5s

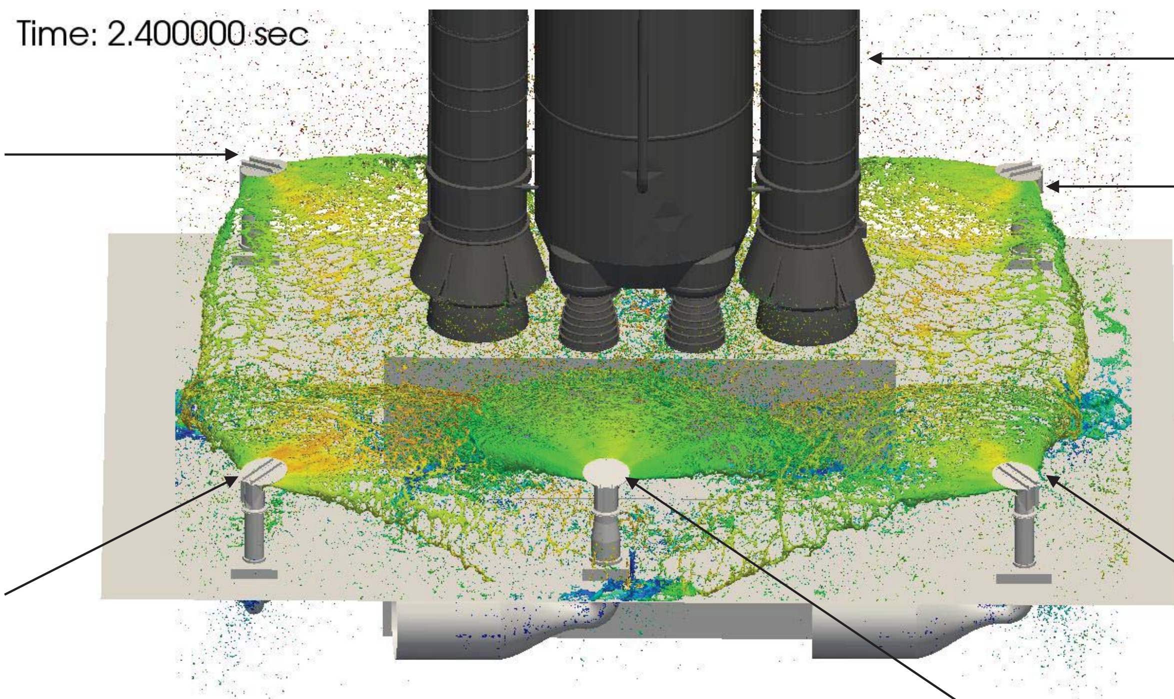


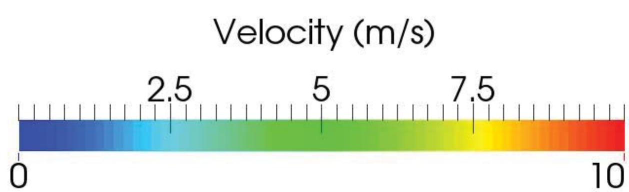
Verification

- Flow time=3.5s
- Total time=6.5s



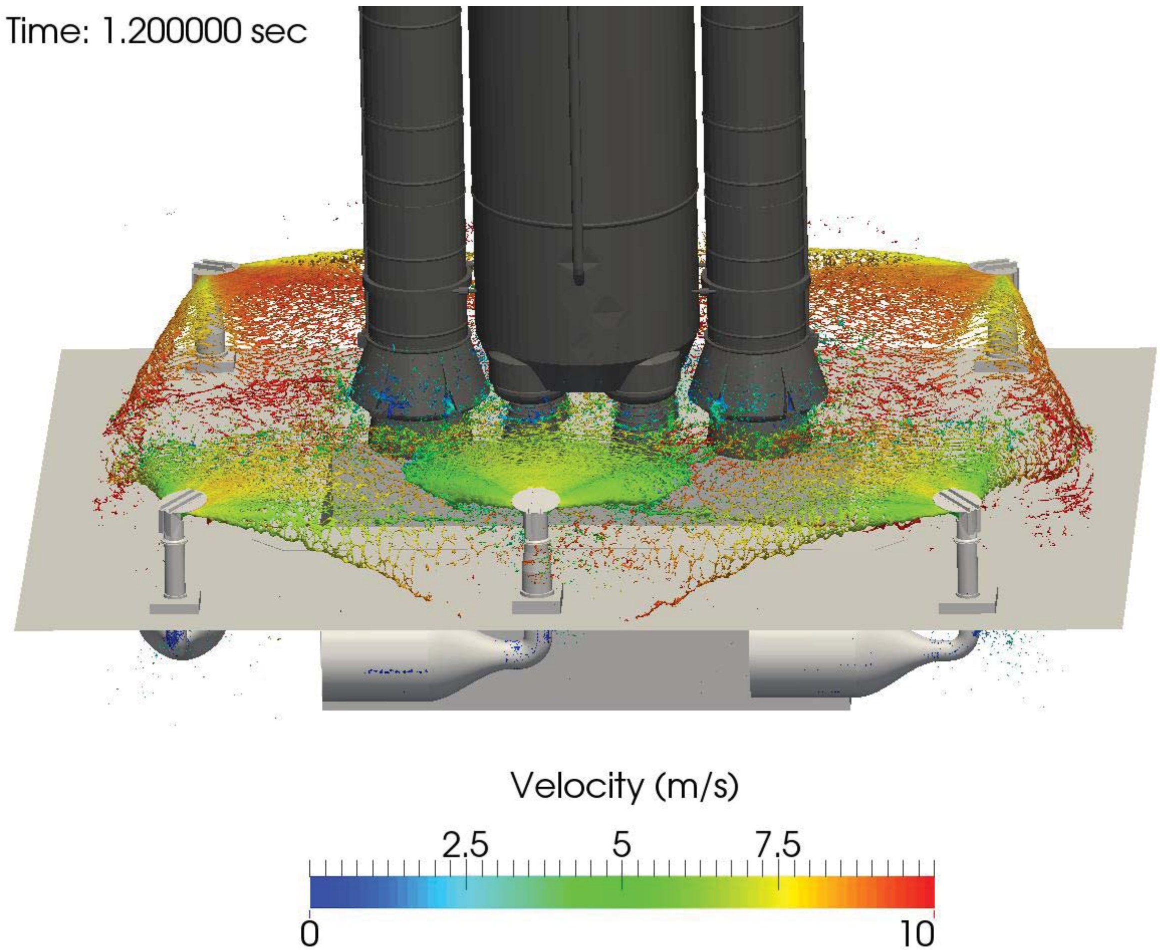
Full Simulations



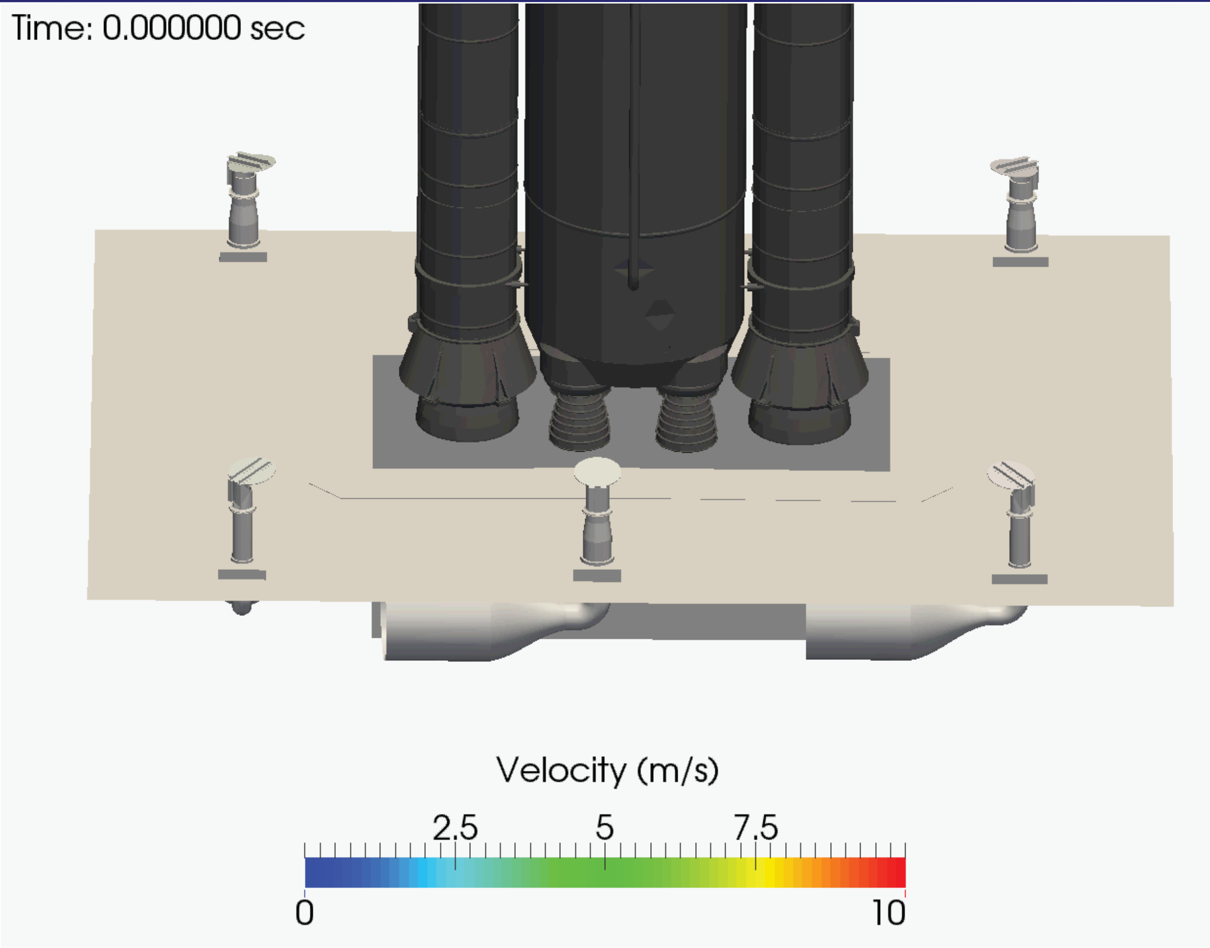


Water volume flow was based on a maximum nominal rainbird flow during T-10 to T+20sec

Full Simulations



Full Simulations



Next Iteration

- Correct rainbird flow timing and volume flow rates; make it variable based on Nominal or Abort operation to reduce conservatism.
- Correct vehicle motion; add correct velocity or acceleration profile
- Add geometry complexity to include TSM, ML deck roughness, and exhaust hole features

Nominal RB Flows and SLS Motion

Time	Nominal Lau	North East	North Center	North West	South East	South West
-11	150.40	23.69	27.82	23.69	37.60	37.60
-10.9919	150.40	23.69	27.82	23.69	37.60	37.60
-10.9838	150.40	23.69	27.82	23.69	37.60	37.60
-10.9757	150.40	23.69	27.82	23.69	37.60	37.60
-10.9677	150.40	23.69	27.82	23.69	37.60	37.60
-10.9596	150.40	23.69	27.82	23.69	37.60	37.60
-10.9515	150.40	23.69	27.82	23.69	37.60	37.60
-8.18E-04	223970.34	35275.33	41434.51	35275.33	55992.59	55992.59
7.27E-03	223906.23	35265.23	41422.65	35265.23	55976.56	55976.56
9.62E-02	224876.86	35418.11	41602.22	35418.11	56219.22	56219.22
0.104321	224768.70	35401.07	41582.21	35401.07	56192.18	56192.18
0.201373	230832.24	36356.08	42703.96	36356.08	57708.06	57708.06
0.306512	251825.97	39662.59	46587.80	39662.59	62956.49	62956.49
0.403564	256285.29	40364.93	47412.78	40364.93	64071.32	64071.32
0.500615	257607.13	40573.12	47657.32	40573.12	64401.78	64401.78
0.605754	260813.08	41078.06	48250.42	41078.06	65203.27	65203.27
0.702806	280546.00	44186.00	51901.01	44186.00	70136.50	70136.50
0.807945	286032.51	45050.12	52916.01	45050.12	71508.13	71508.13
0.904997	288221.27	45394.85	53320.93	45394.85	72055.32	72055.32
1.002048	290497.30	45753.32	53742.00	45753.32	72624.33	72624.33
...	...	...	...	...	...	...
19.91094	193616.32	30494.57	35819.02	30494.57	48404.08	48404.08
19.91902	193195.61	30428.31	35741.19	30428.31	48298.90	48298.90
19.92711	192774.99	30362.06	35663.37	30362.06	48193.75	48193.75
19.9352	192355.81	30296.04	35585.82	30296.04	48088.95	48088.95
19.94329	191938.81	30230.36	35508.68	30230.36	47984.70	47984.70
19.95137	191520.57	30164.49	35431.31	30164.49	47880.14	47880.14
19.95946	191100.31	30098.30	35353.56	30098.30	47775.08	47775.08
19.96755	190684.90	30032.87	35276.71	30032.87	47671.23	47671.23
19.97564	190264.95	29966.73	35199.02	29966.73	47566.24	47566.24
19.98372	189846.94	29900.89	35121.68	29900.89	47461.74	47461.74
19.99181	189427.82	29834.88	35044.15	29834.88	47356.96	47356.96
19.9999	189005.44	29768.36	34966.01	29768.36	47251.36	47251.36

Ascent Elevation		TPS
time	elev	elev
sec	ft	ft
0	0	5.098333
0.1	0	5.098333
0.2	0	5.098333
0.3	0.12501	5.223343
0.4	0.333347	5.43168
0.5	0.625018	5.723351
0.6	1.000021	6.098354
0.7	1.458358	6.556691
0.8	2.000029	7.098362
0.9	2.625033	7.723366
1	3.33337	8.431703
1.1	4.125041	9.223374
1.2	5.000045	10.09838
1.3	6.39535	11.49368
1.4	7.8414	12.93973
1.5	9.42375	14.52208
1.6	11.1424	16.24073
1.7	12.99735	18.09568
1.8	14.9886	20.08693
1.9	17.11615	22.21448
2	19.38	24.47833
2.1	21.78015	26.87848
2.2	24.3166	29.41493
2.3	26.98935	32.08768
2.4	29.7984	34.89673
2.5	32.74375	37.84208
2.6	35.8254	40.92373
2.7	39.04335	44.14168
2.8	42.3976	47.49593
2.9	45.88815	50.98648
3	49.515	54.61333

Nominal RB Flows and SLS Motion

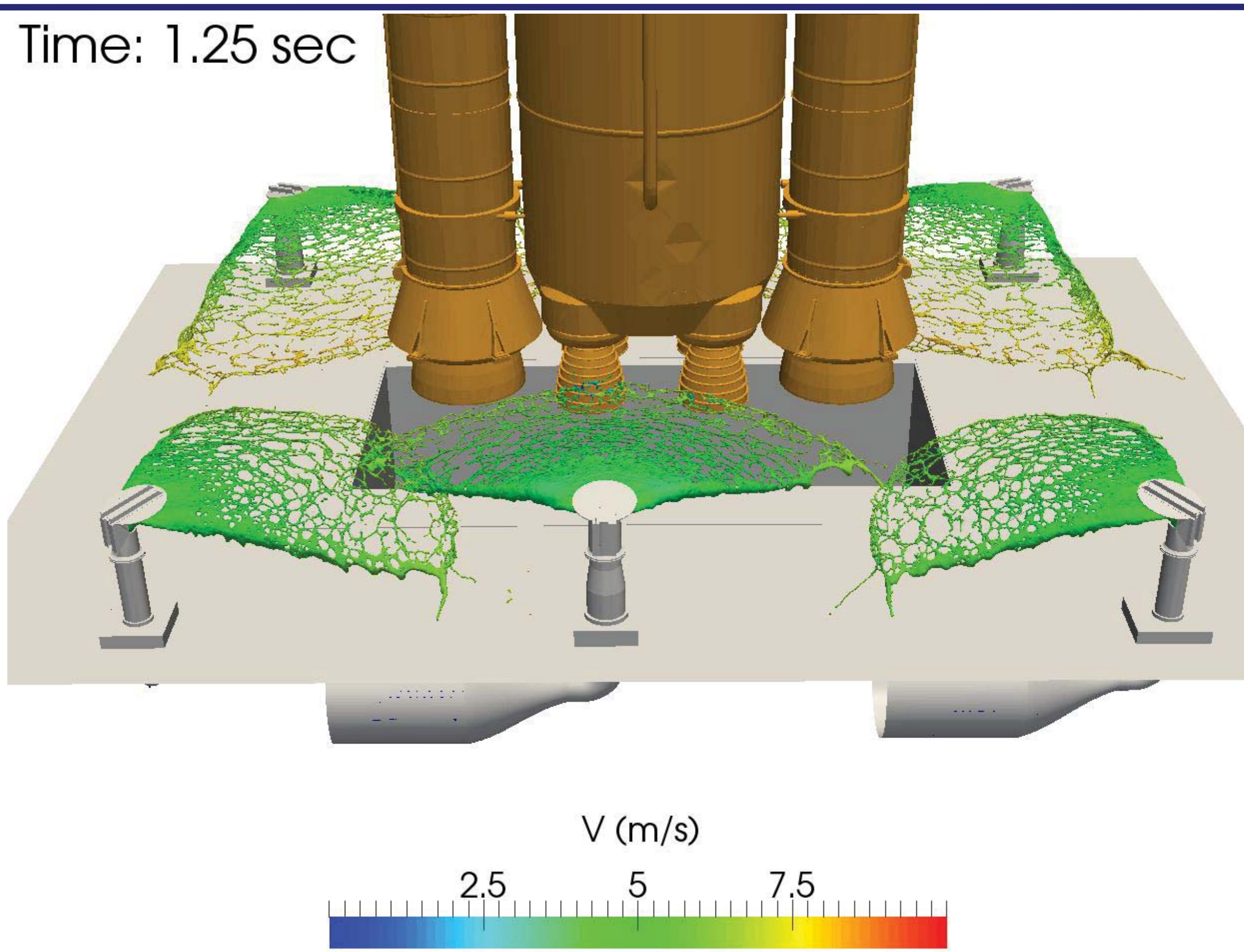
Time (sec)			vel (m/s)				
	NE	NC	NW	SE/SW	NE/NW	NC	SE/SW
-8.18E-04	0.2368	0.2781	0.2368	0.3759			
7.27E-03	0.2367	0.2781	0.2367	0.3758			
9.62E-02	0.2377	0.2793	0.2377	0.3774			
0.1043212	0.2376	0.2791	0.2376	0.3772			
0.2013728	0.2440	0.2867	0.2440	0.3874			
0.306512	0.2662	0.3127	0.2662	0.4226			
0.4035636	0.2710	0.3183	0.2710	0.4301			
0.5006152	0.2724	0.3199	0.2724	0.4323			
0.6057544	0.2757	0.3239	0.2757	0.4377			
0.7028061	0.2966	0.3484	0.2966	0.4708			
0.8079453	0.3024	0.3552	0.3024	0.4800			
0.9049969	0.3047	0.3579	0.3047	0.4837	0.2677	0.3145	0.4250
1.002048	0.3071	0.3608	0.3071	0.4875			
1.107188	0.3207	0.3768	0.3207	0.5091			
1.204239	0.3302	0.3879	0.3302	0.5241			
1.301291	0.3327	0.3908	0.3327	0.5281			
1.40643	0.3360	0.3947	0.3360	0.5334			
1.503482	0.3433	0.4032	0.3433	0.5449			
1.600533	0.3533	0.4150	0.3533	0.5608			
1.705673	0.3596	0.4224	0.3596	0.5708			
1.802724	0.3594	0.4222	0.3594	0.5705			
1.907863	0.3654	0.4292	0.3654	0.5800	0.3408	0.4003	0.5409
2.004915	0.3737	0.4389	0.3737	0.5931			
2.101967	0.3796	0.4459	0.3796	0.6026			
2.207106	0.3803	0.4467	0.3803	0.6036			
2.304157	0.3848	0.4520	0.3848	0.6108			
2.401209	0.3910	0.4593	0.3910	0.6207			
2.506348	0.3966	0.4659	0.3966	0.6296			

Time (sec)			vel (m/s)				
	NE	NC	NW	SE/SW	NE/NW	NC	SE/SW
2.6034	0.4006	0.4706	0.4006	0.6359			
2.700452	0.4015	0.4716	0.4015	0.6374			
2.805591	0.4069	0.4780	0.4069	0.6459			
2.902642	0.4111	0.4828	0.4111	0.6525	0.3926	0.4612	0.6232
3.007782	0.4165	0.4892	0.4165	0.6611			
3.104833	0.4167	0.4894	0.4167	0.6614			
3.201885	0.4204	0.4938	0.4204	0.6673			
3.307024	0.4242	0.4983	0.4242	0.6734			
3.404076	0.4289	0.5038	0.4289	0.6808			
3.501127	0.4301	0.5052	0.4301	0.6827			
3.606266	0.4324	0.5079	0.4324	0.6863			
3.703318	0.4355	0.5115	0.4355	0.6913			
3.80037	0.4384	0.5150	0.4384	0.6959			
3.905509	0.4416	0.5188	0.4416	0.7010	0.4285	0.5033	0.6801
4.002561	0.4427	0.5200	0.4427	0.7027			
4.1077	0.4449	0.5226	0.4449	0.7062			
4.204751	0.4477	0.5259	0.4477	0.7107			
4.301803	0.4508	0.5295	0.4508	0.7155			
4.406942	0.4517	0.5306	0.4517	0.7170			
4.503994	0.4529	0.5320	0.4529	0.7189			
4.601046	0.4554	0.5349	0.4554	0.7228			
4.706185	0.4580	0.5379	0.4580	0.7269			
4.803236	0.4593	0.5395	0.4593	0.7291			
4.900288	0.4602	0.5406	0.4602	0.7305	0.4524	0.5313	0.7180
5.005427	0.4617	0.5423	0.4617	0.7328			

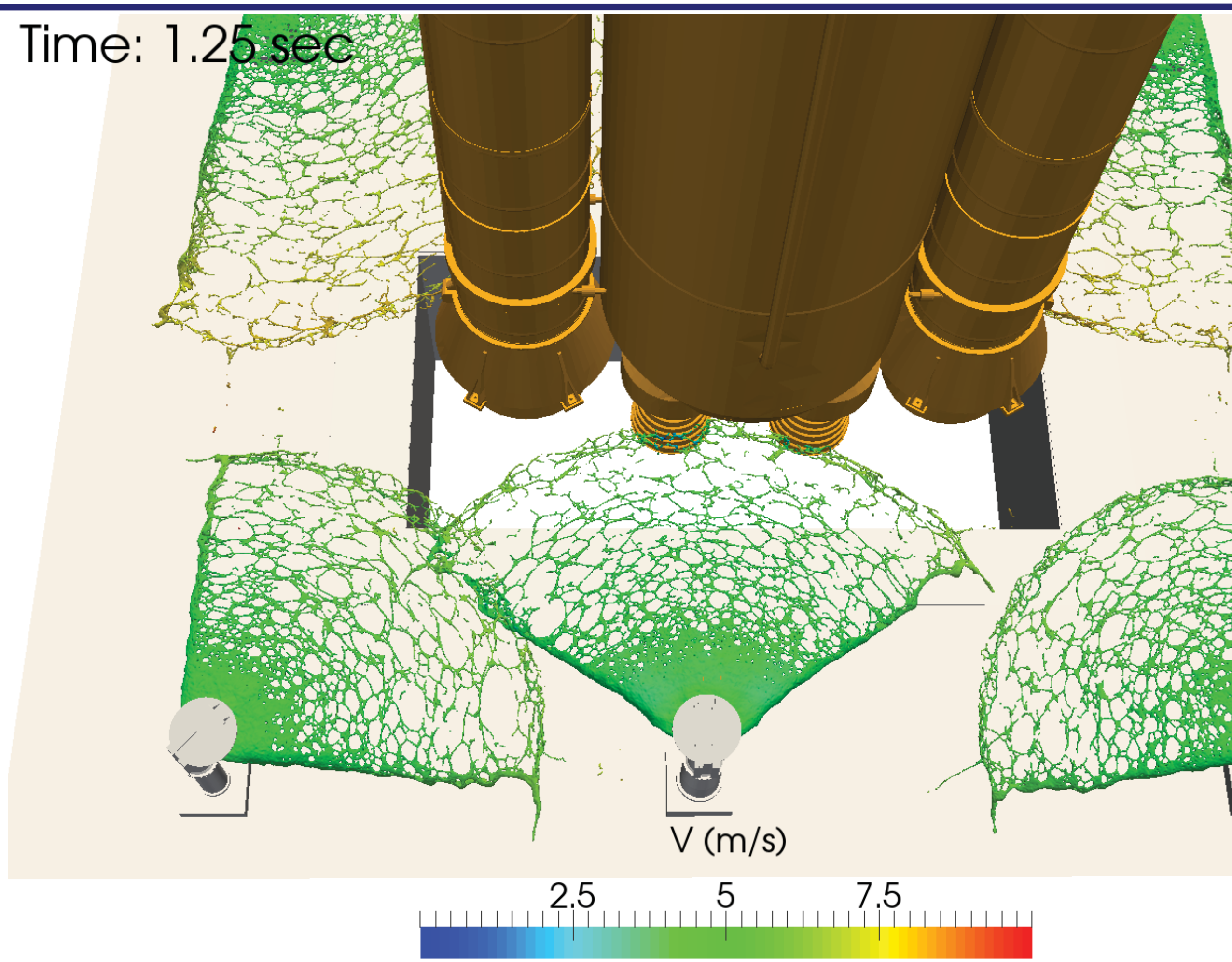
time	elev	elev	vel	accel	
sec	ft	m	m/s	m/s2	
0	0	0			
0.1	0	0	0		
0.2	0	0	0	0	
0.3	0.12501	0.038103	0.38103	1.905152	
0.4	0.333347	0.101604	0.635011	2.539807	
0.5	0.625018	0.190505	0.889013	2.54002	
0.6	1.000021	0.304806	1.143009	2.539959	
0.7	1.458358	0.444508	1.397011	2.54002	
0.8	2.000029	0.609609	1.651013	2.54002	
0.9	2.625033	0.80011	1.905012	2.53999	
1	3.33337	1.016011	2.159011	2.53999	
1.1	4.125041	1.257312	2.413013	2.54002	
1.2	5.000045	1.524014	2.667012	2.53999	2.53998
1.3	6.39535	1.949303	4.25289	15.85877	
1.4	7.8414	2.390059	4.40756	1.546708	
1.5	9.42375	2.872359	4.823003	4.154424	
1.6	11.1424	3.396204	5.238445	4.154424	
1.7	12.99735	3.961592	5.653888	4.154424	
1.8	14.9886	4.568525	6.06933	4.154424	
1.9	17.11615	5.217003	6.484772	4.154424	
2	19.38	5.907024	6.900215	4.154424	
2.1	21.78015	6.63859	7.315657	4.154424	
2.2	24.3166	7.4117	7.7311	4.154424	
2.3	26.98935	8.226354	8.146542	4.154424	
2.4	29.7984	9.082552	8.561984	4.154424	
2.5	32.74375	9.980295	8.977427	4.154424	
2.6	35.8254	10.91958	9.392869	4.154424	
2.7	39.04335	11.90041	9.808312	4.154424	
2.8	42.3976	12.92279	10.22375	4.154424	
2.9	45.88815	13.98671	10.6392	4.154424	
3	49.515	15.09217	11.05464	4.154424	

RB Flows Based on 3.5-m Water Tank

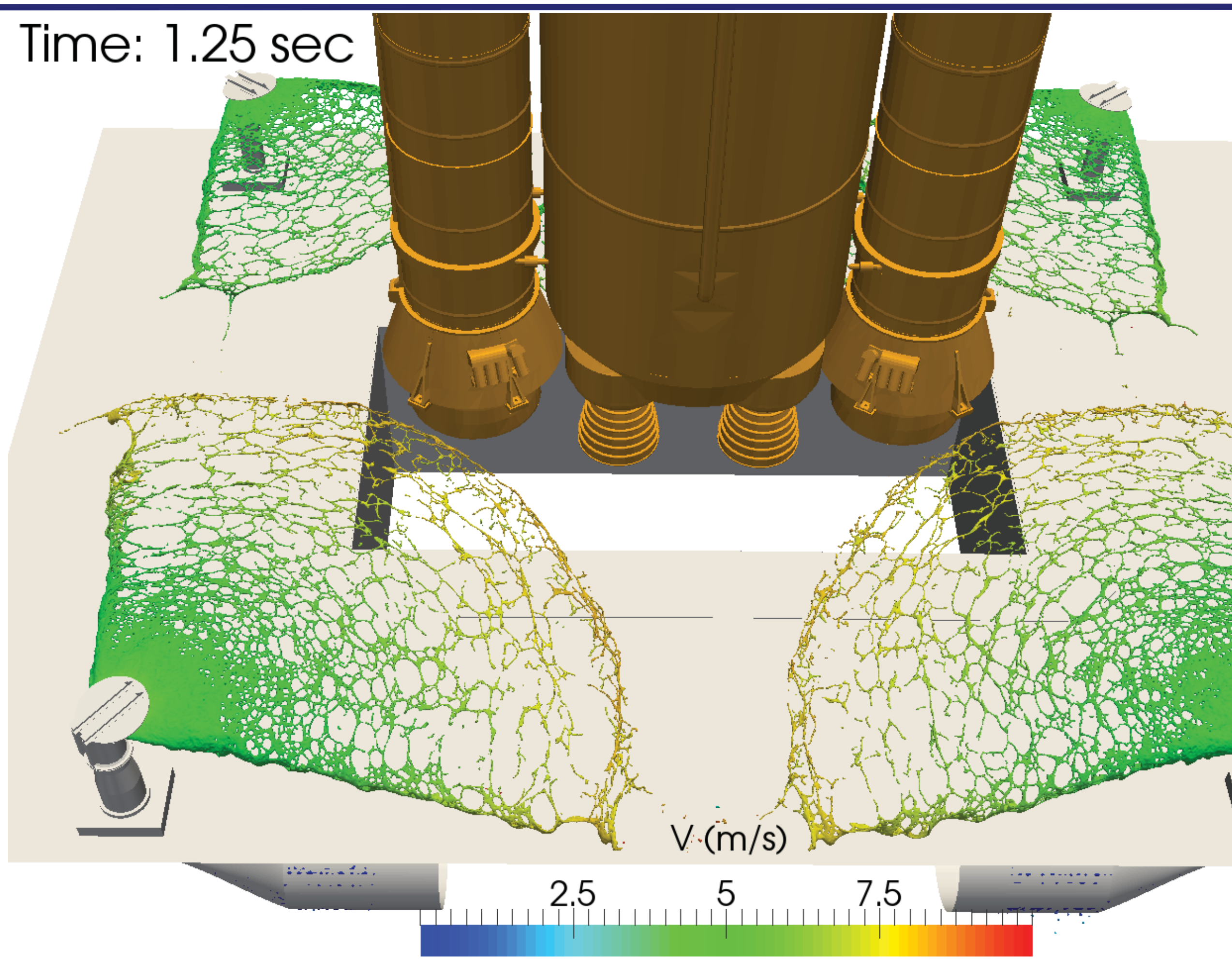
Full Simulations



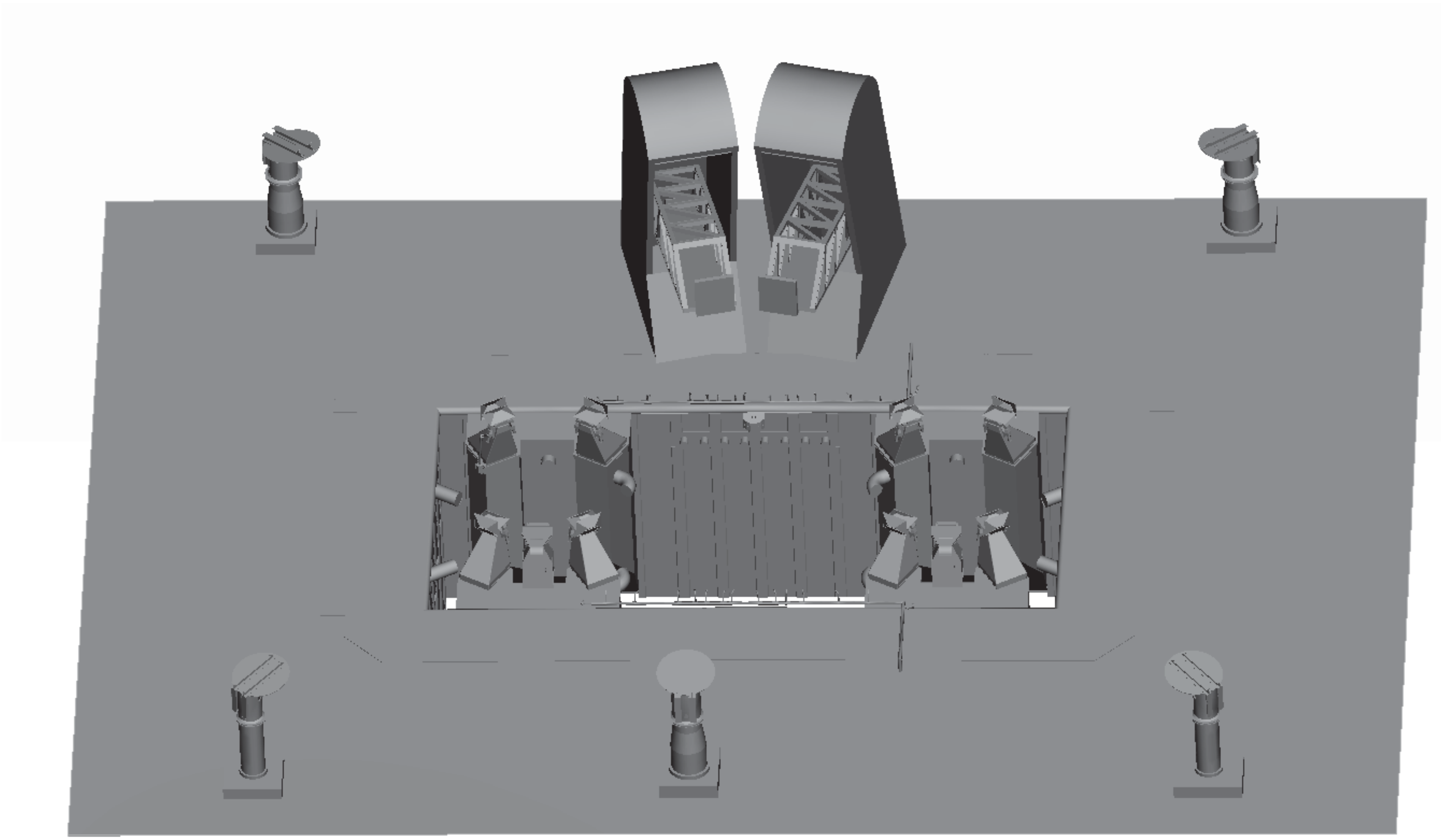
Full Simulations



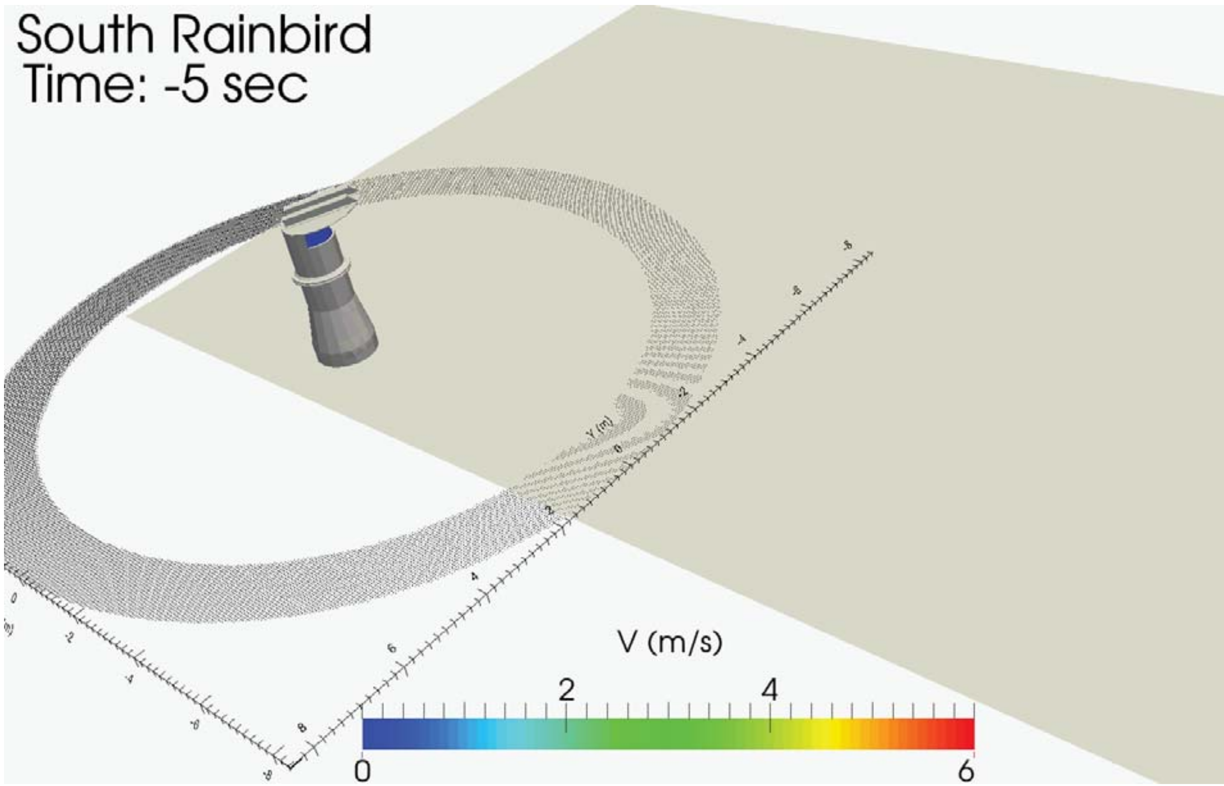
Full Simulations



ML Geometry

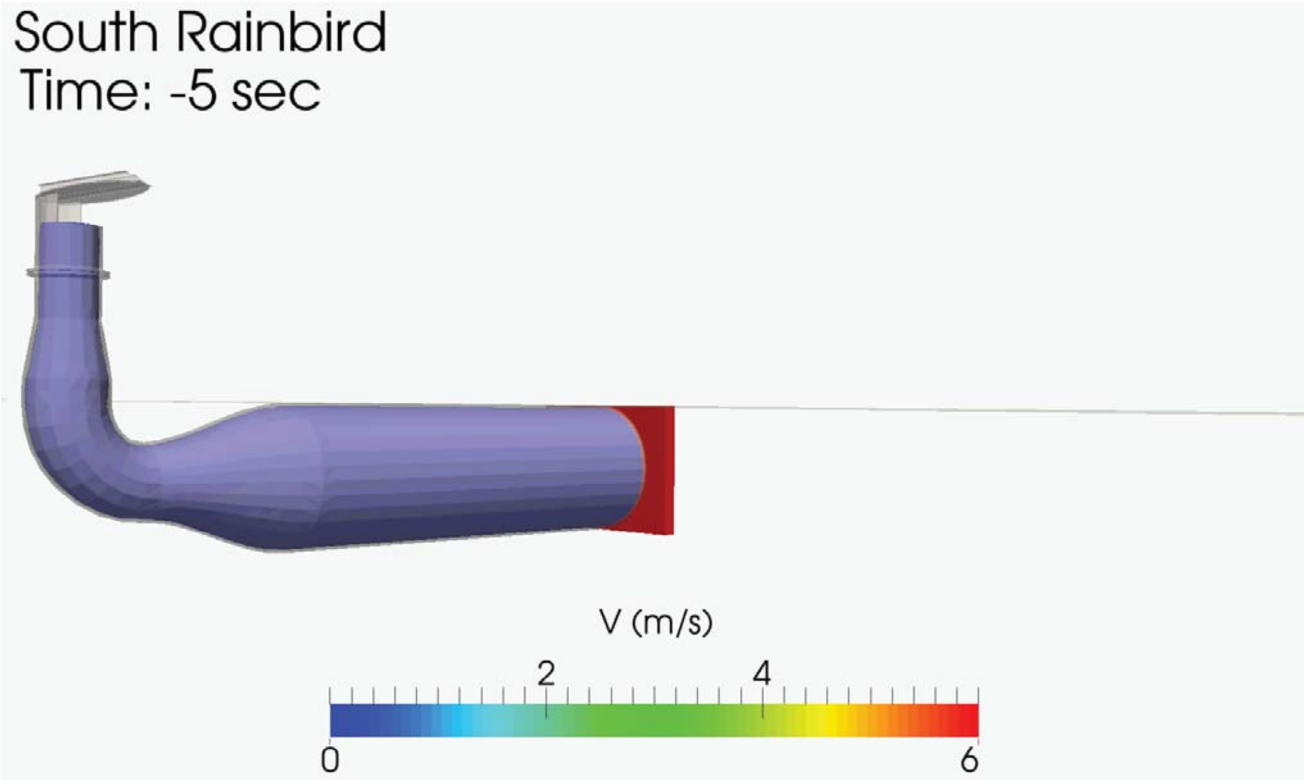


Correct Flow Ramp-up



Peak Flow = 56,762GPM

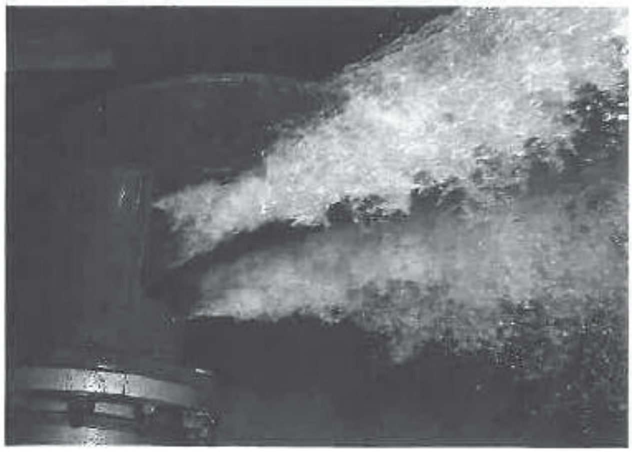
Correct Flow Ramp-up

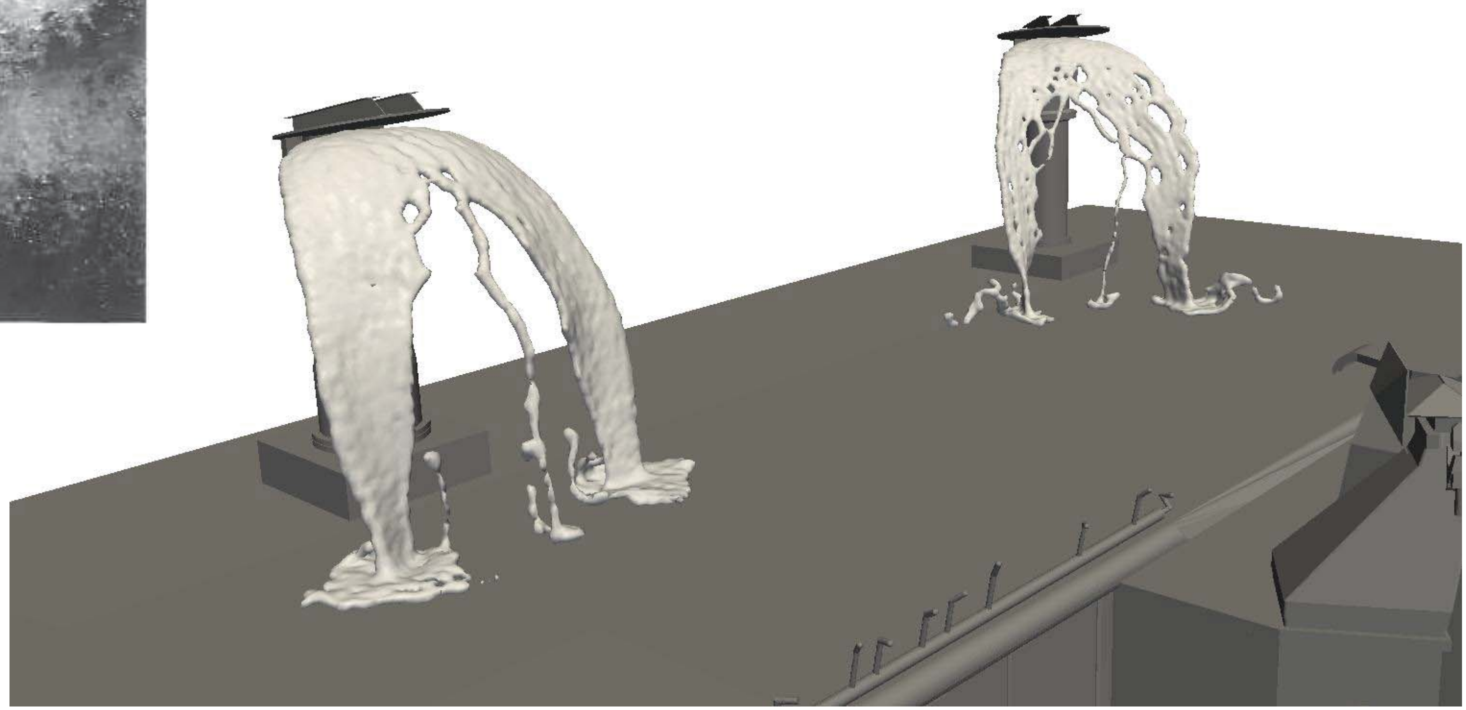


Peak Flow = 56,762GPM

Double Jet

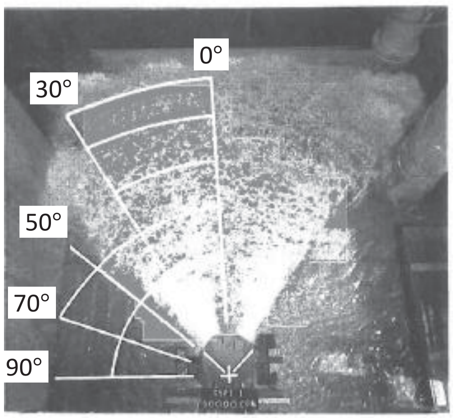
Source: "*Hydraulic Model Studies of Spray Nozzles for a Sound Suppression Water System*," Joseph Wetzel and John Ripken, University of Minnesota, March 1977.





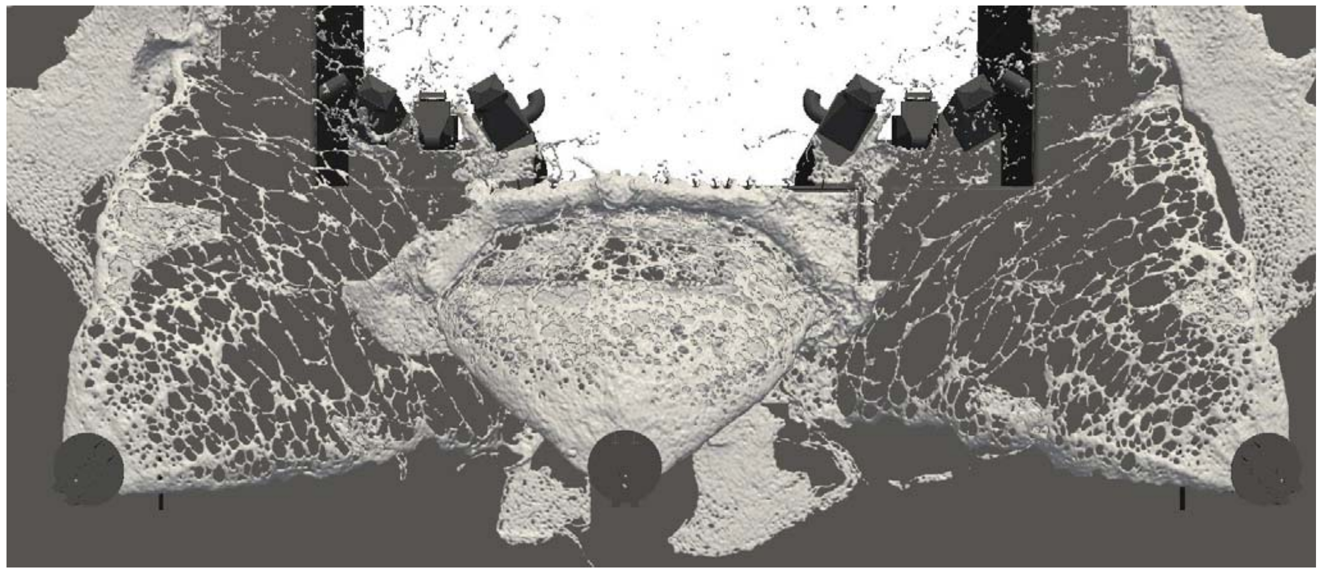
Spray Patterns

Source: “*Hydraulic Model Studies of Spray Nozzles for a Sound Suppression Water System*,” Joseph Wetzel and John Ripken, University of Minnesota, March 1977.



Type 1, 50,000 GPM
Nozzle span angle = 100°, Jet fan angle = 80°

(Not Shown)
Type 2, 40,000 GPM
Nozzle span angle = 190°, Jet fan angle = 150°

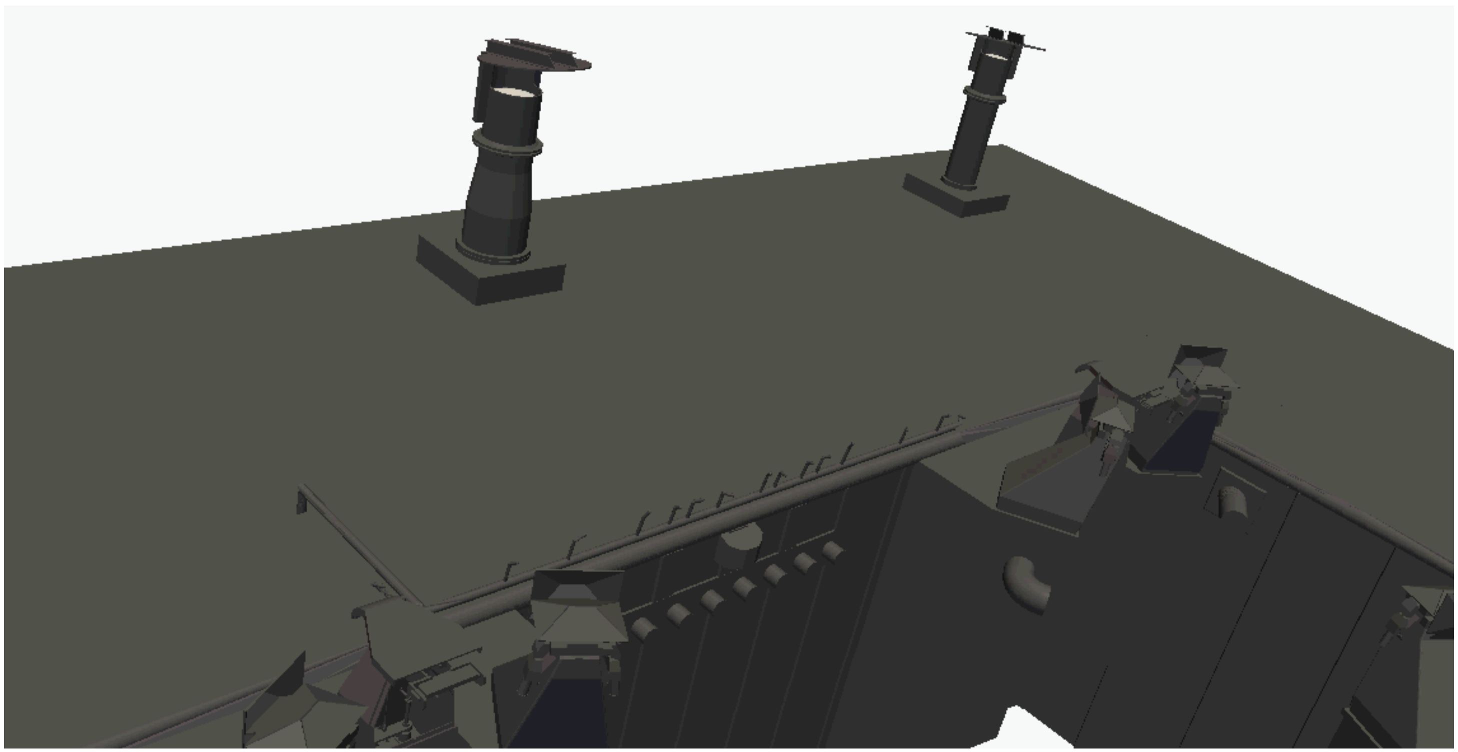


Nozzle span angle = 190°
Jet fan angle ≈ 120°
66,543 GPM

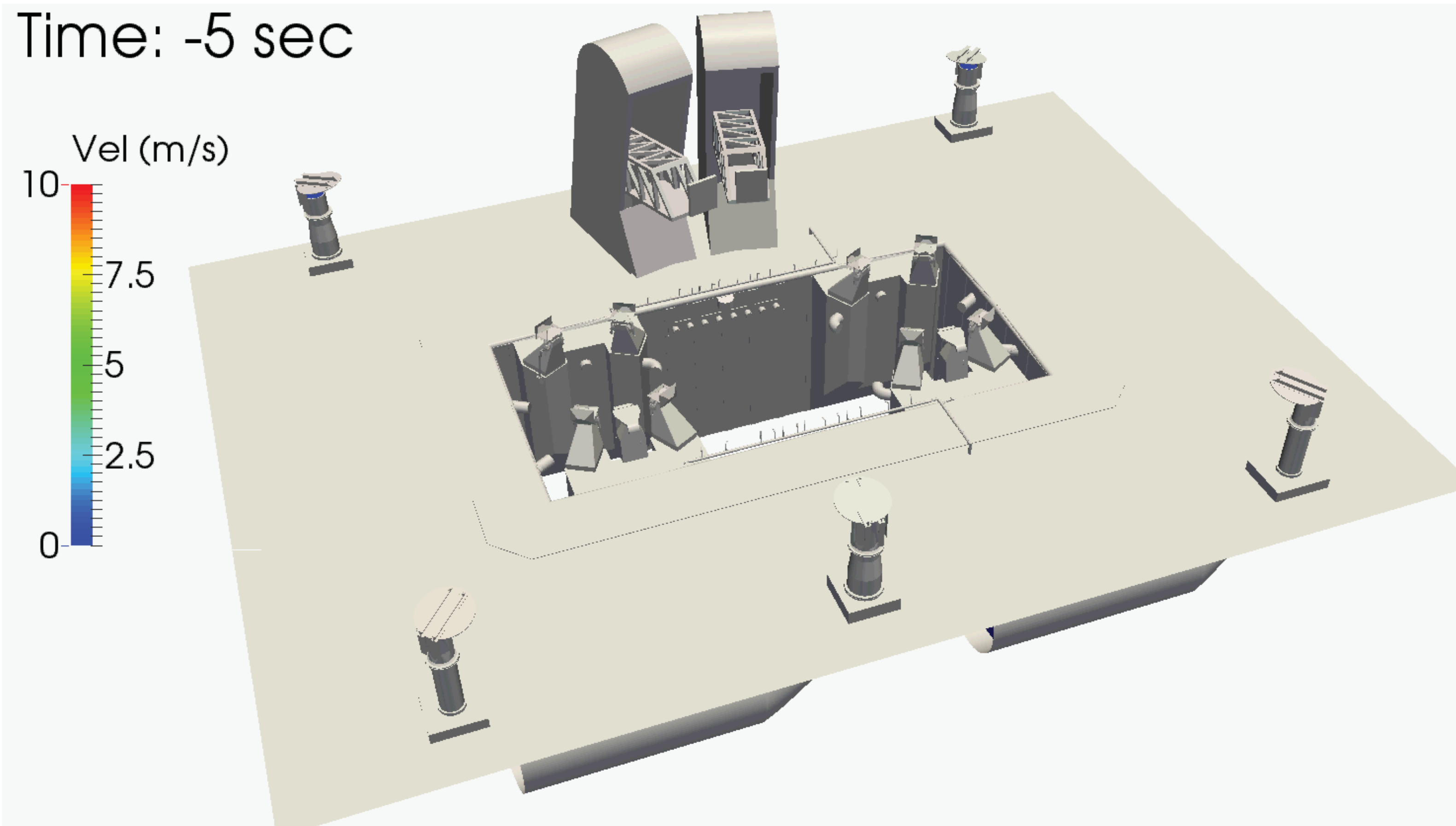
Nozzle span angle = 180°
Jet fan angle ≈ 80°
56,652 GPM

- 1:2.8 scale ratio
- Dissimilar pipe transition

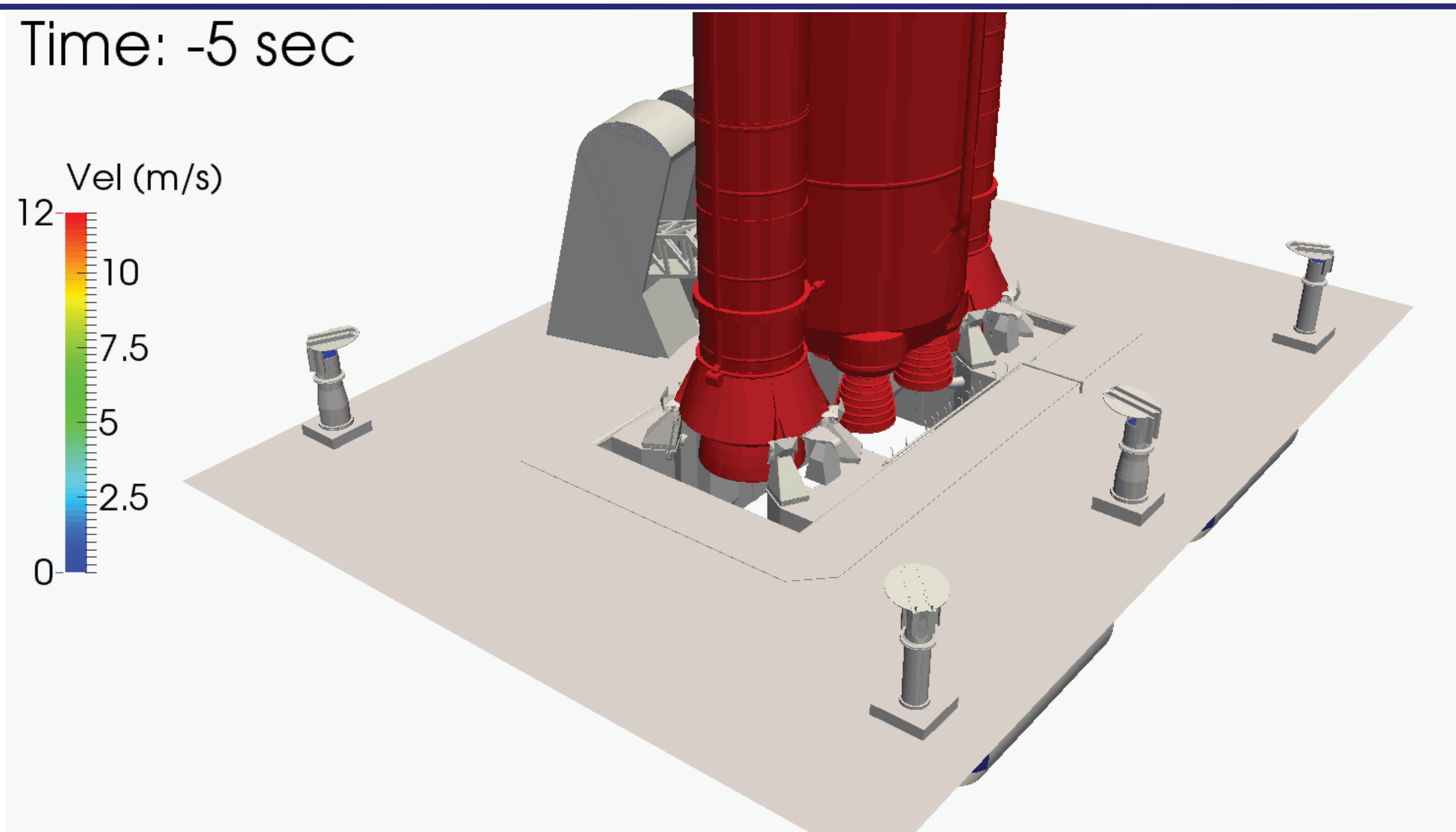
Jet Spray Patterns



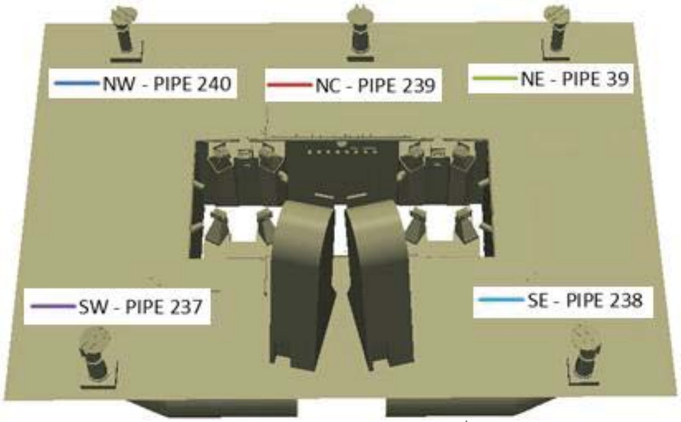
No SLS (-5s to 6.6s)

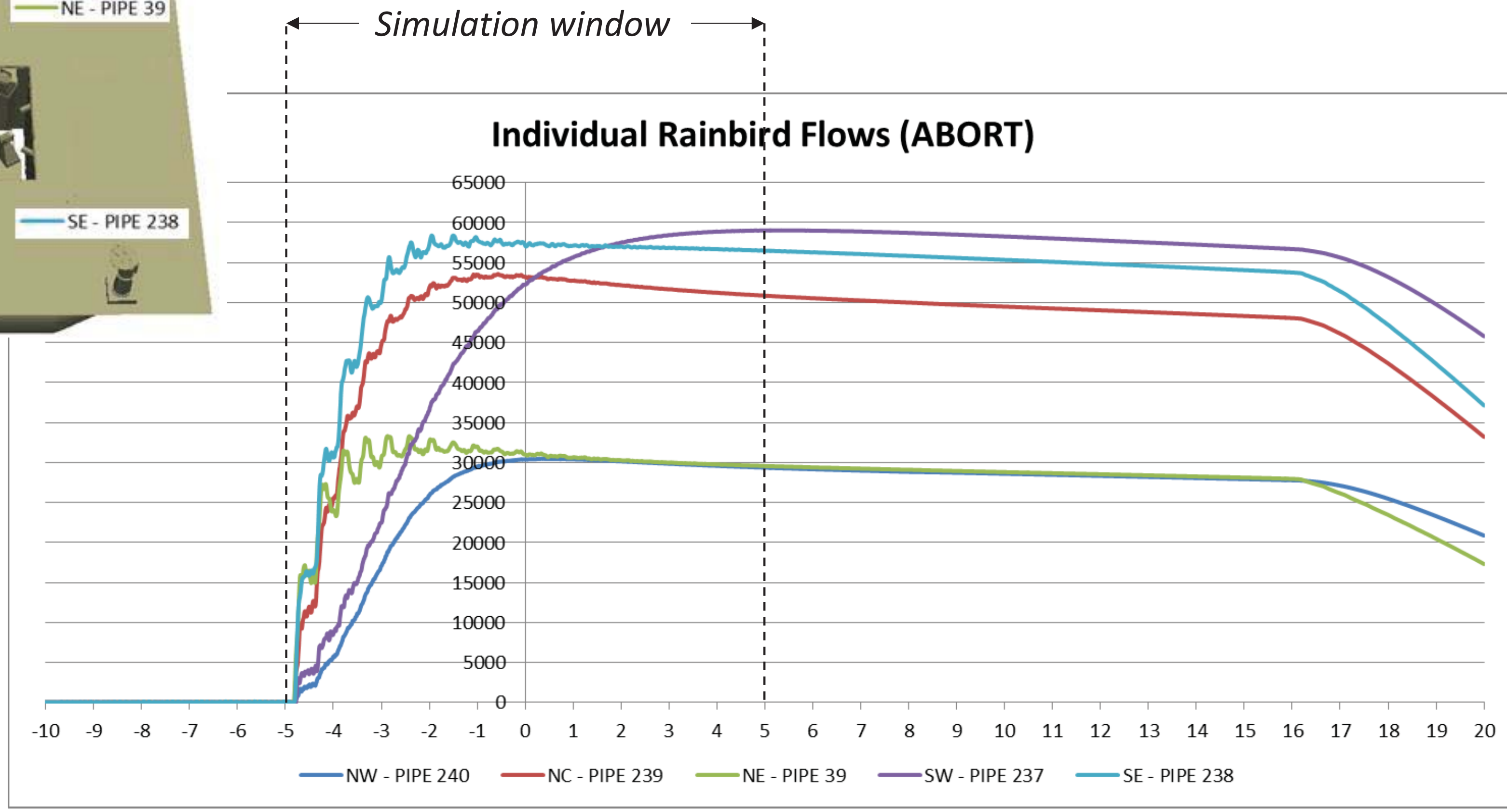


With SLS (-5s to 9s)

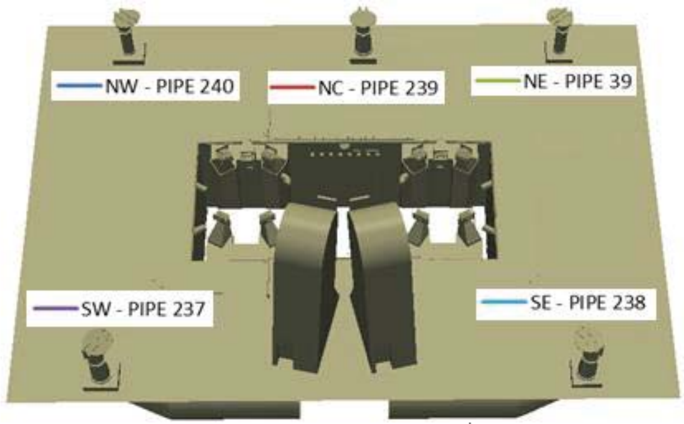


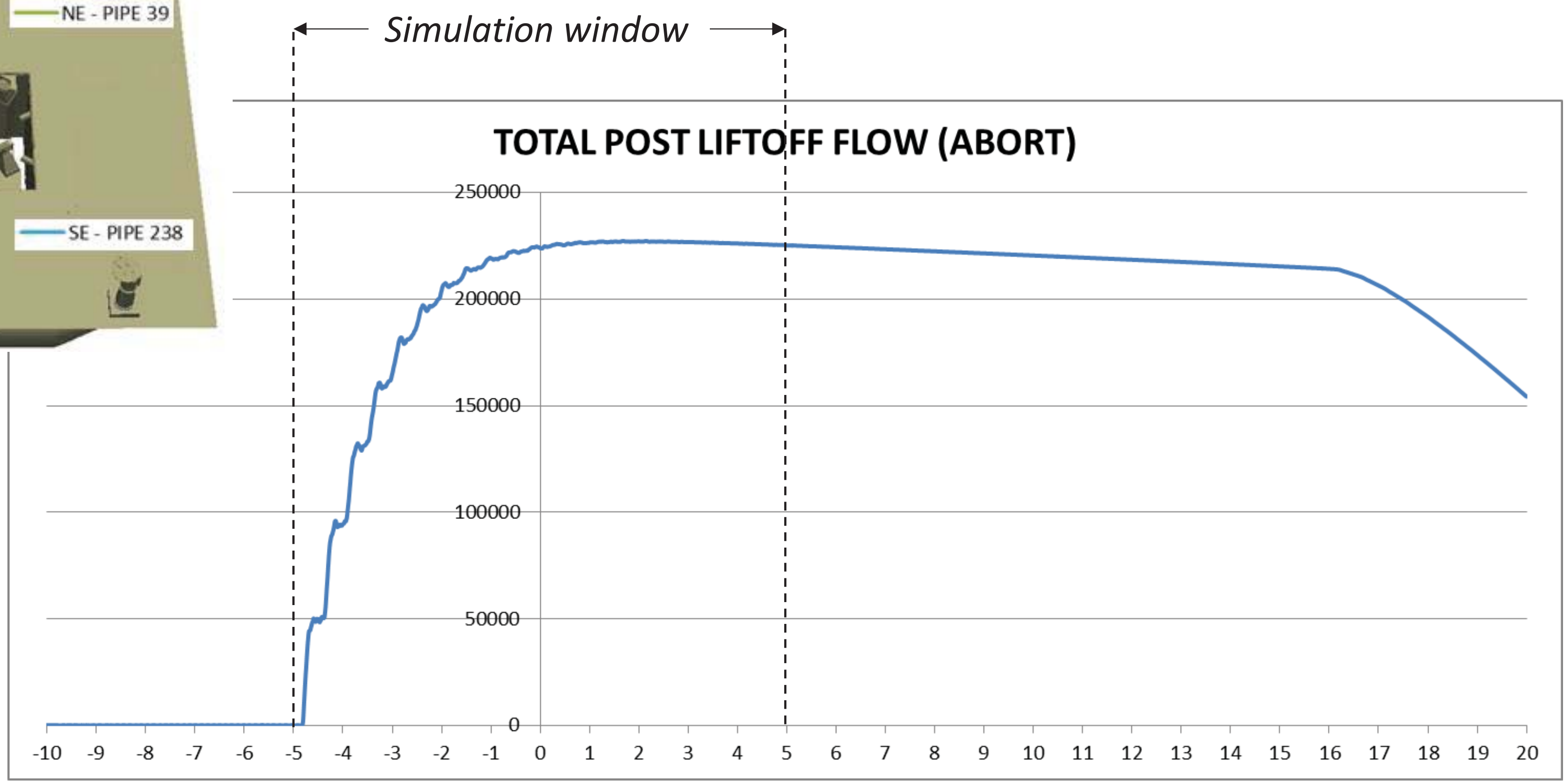
Abort Simulation



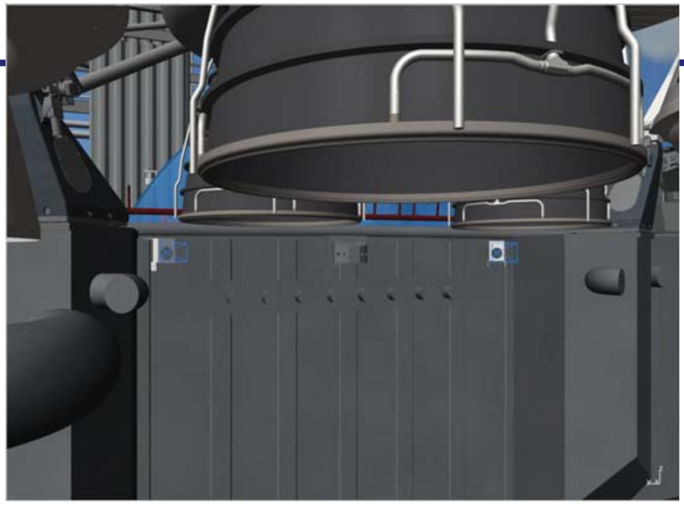


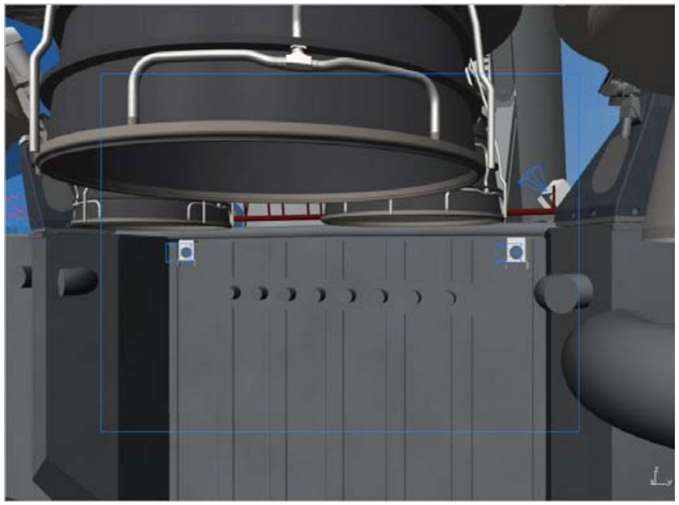
Abort Simulation

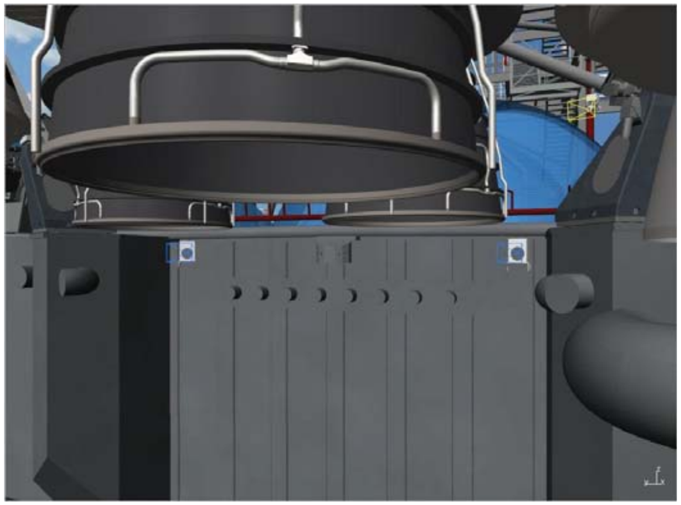




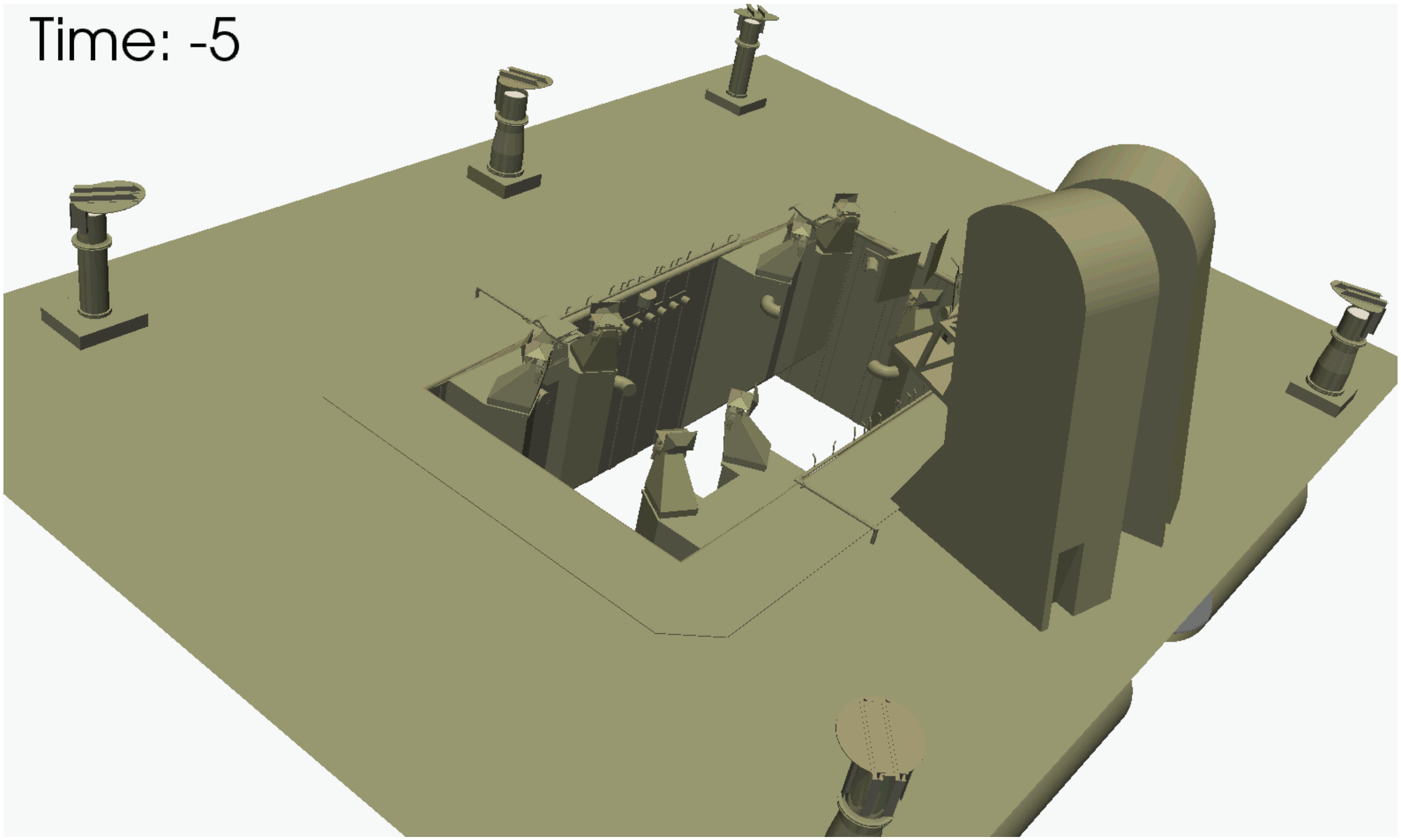
Region of Interest



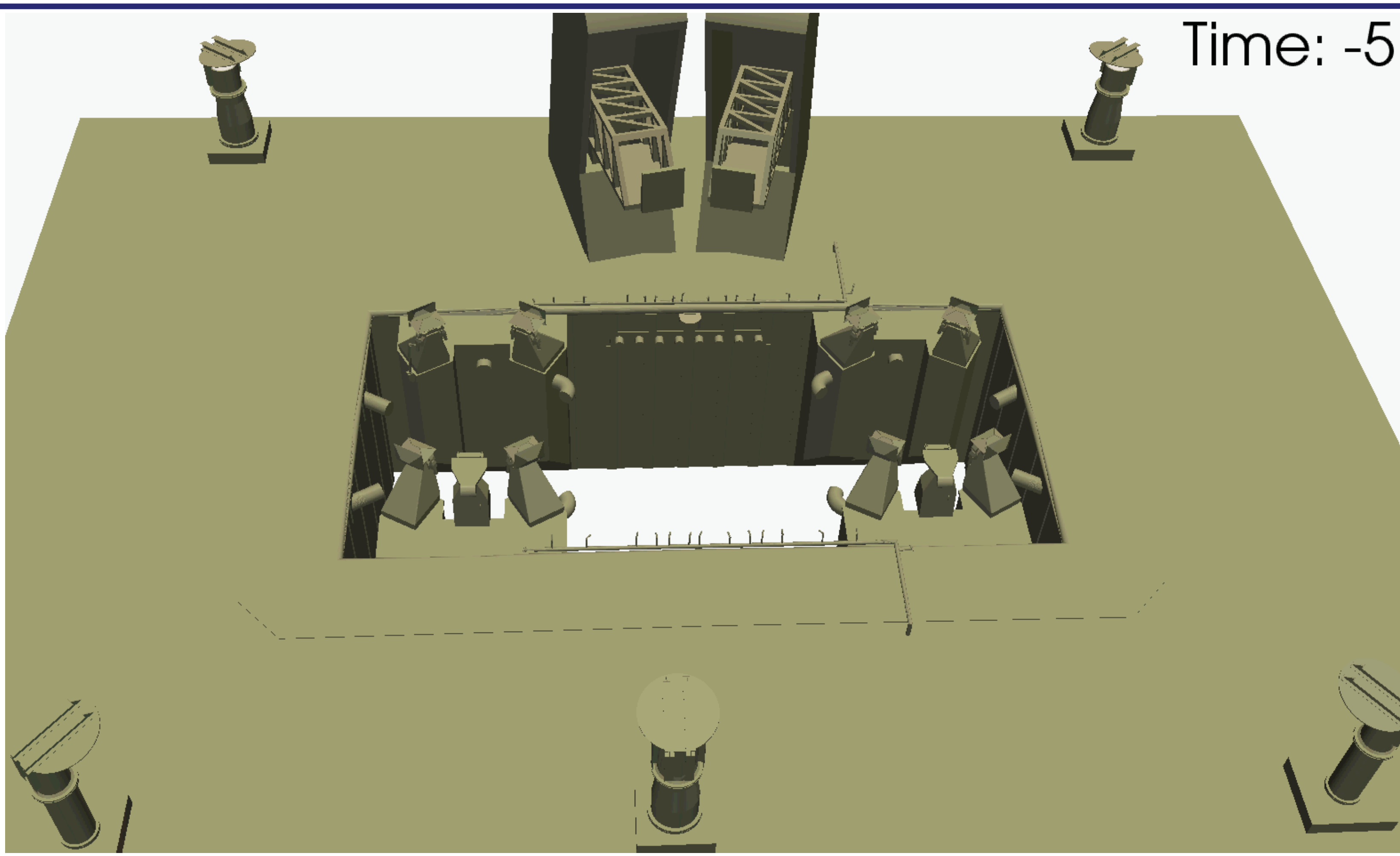




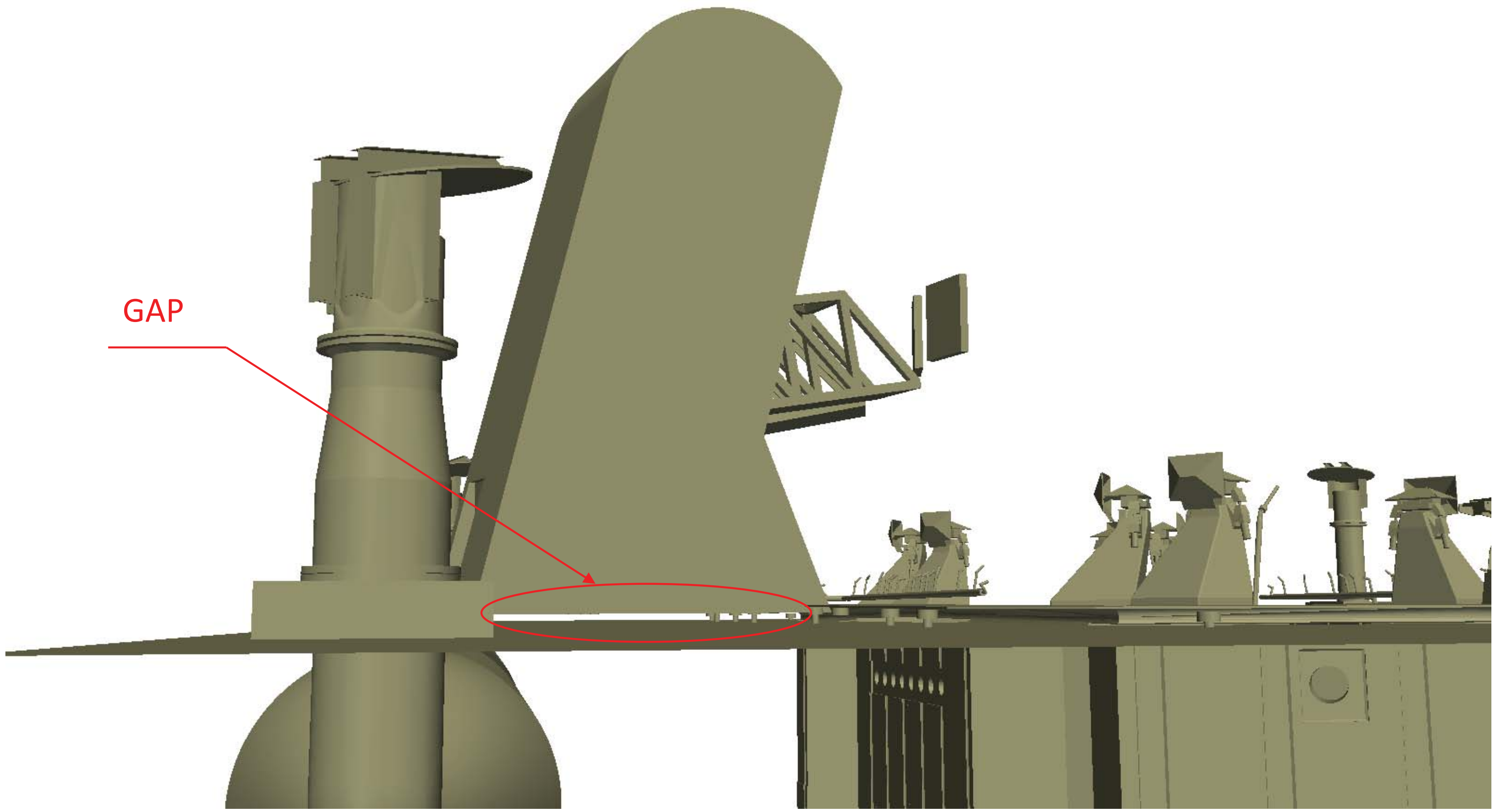
Abort Simulation



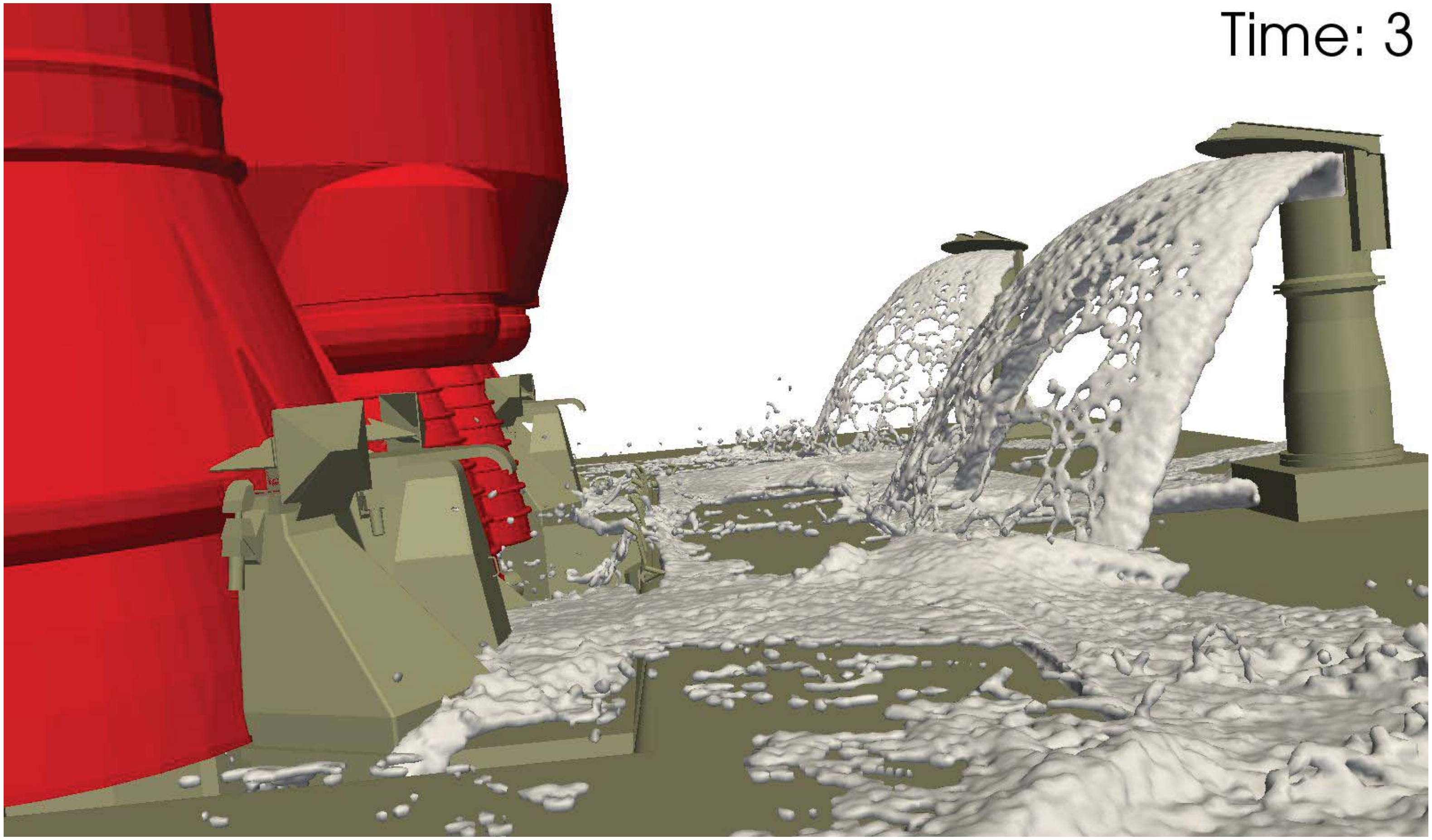
Abort Simulation



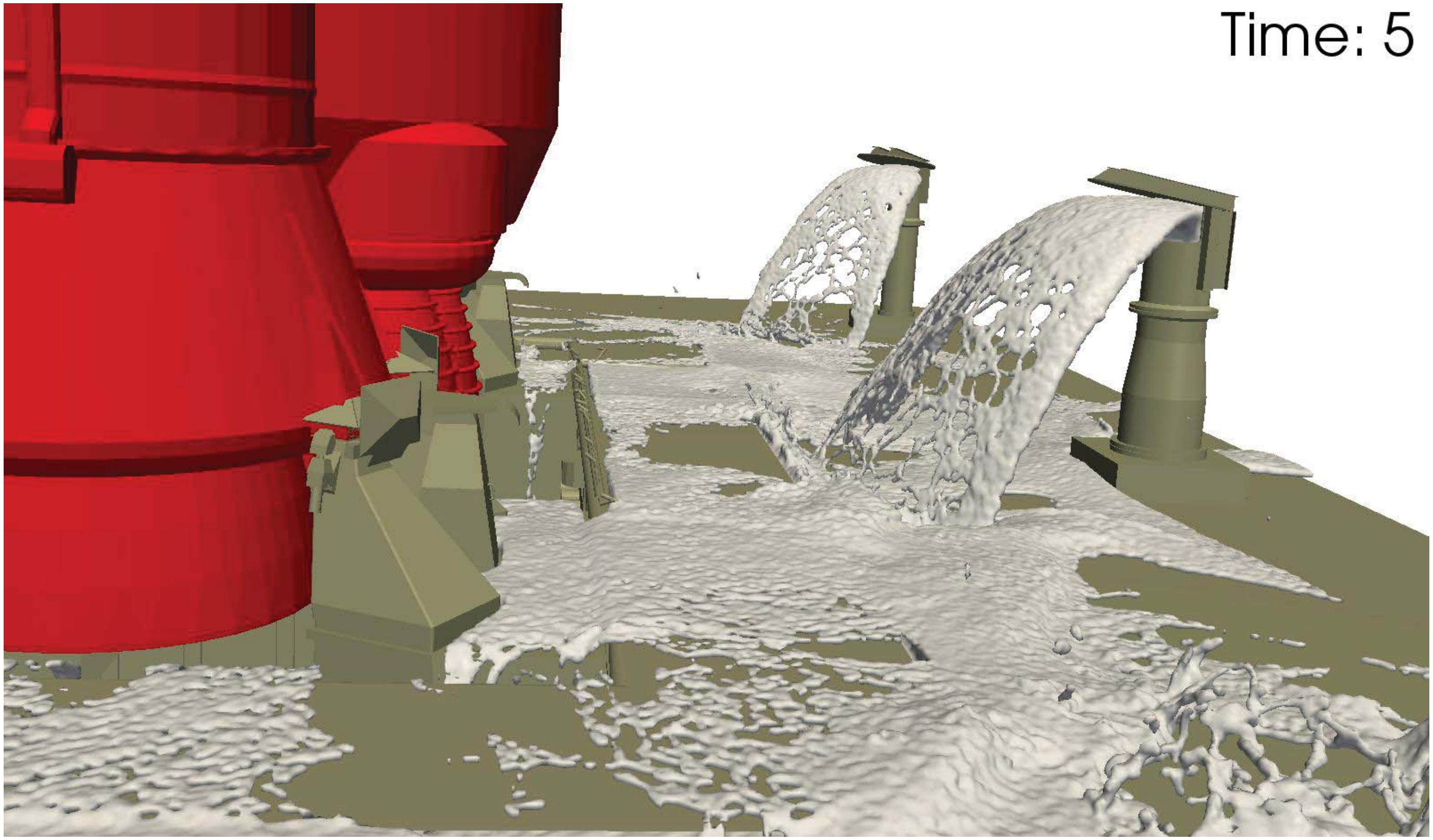
Geometry Issues



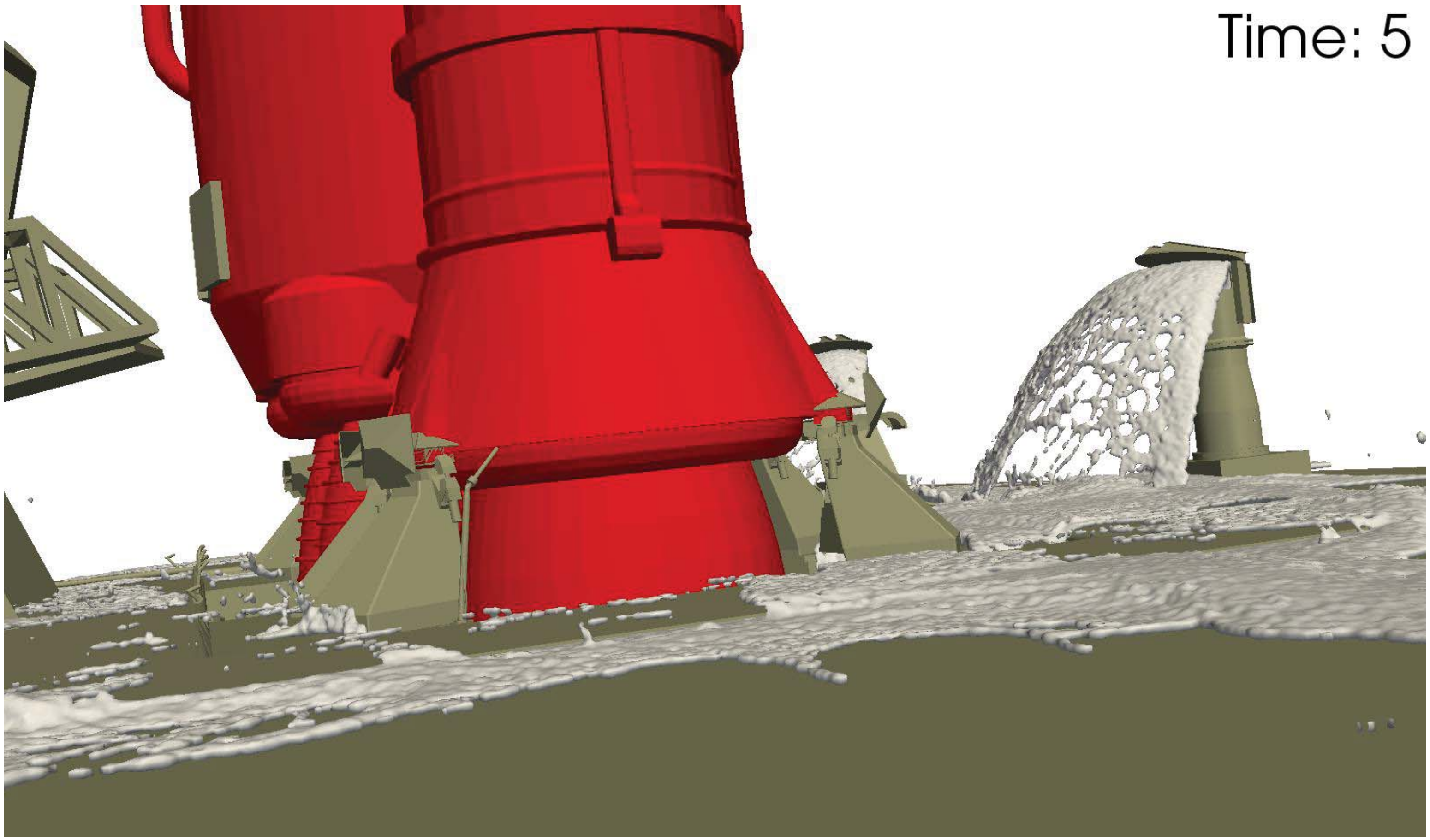
Water Depth



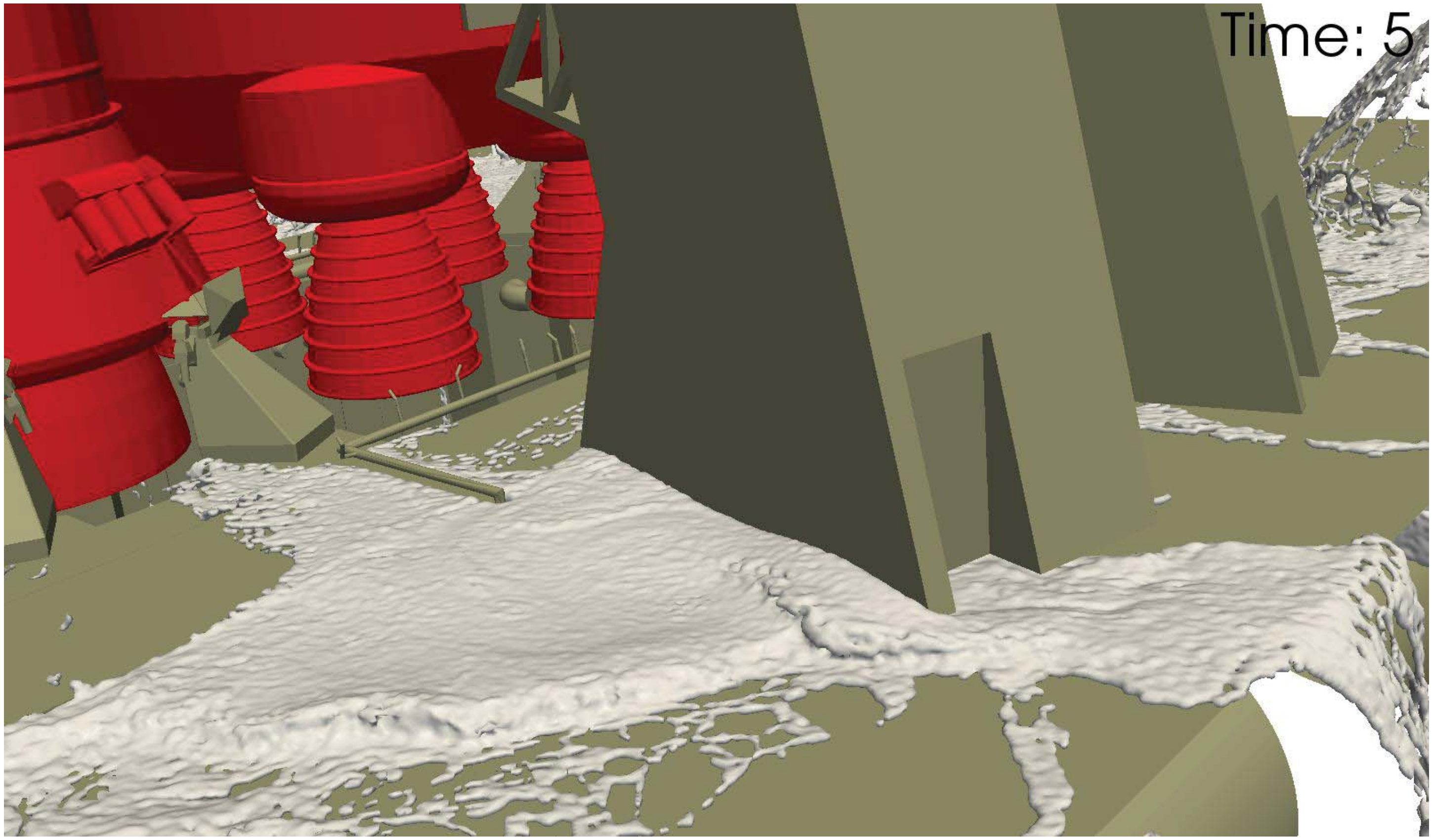
Water Depth



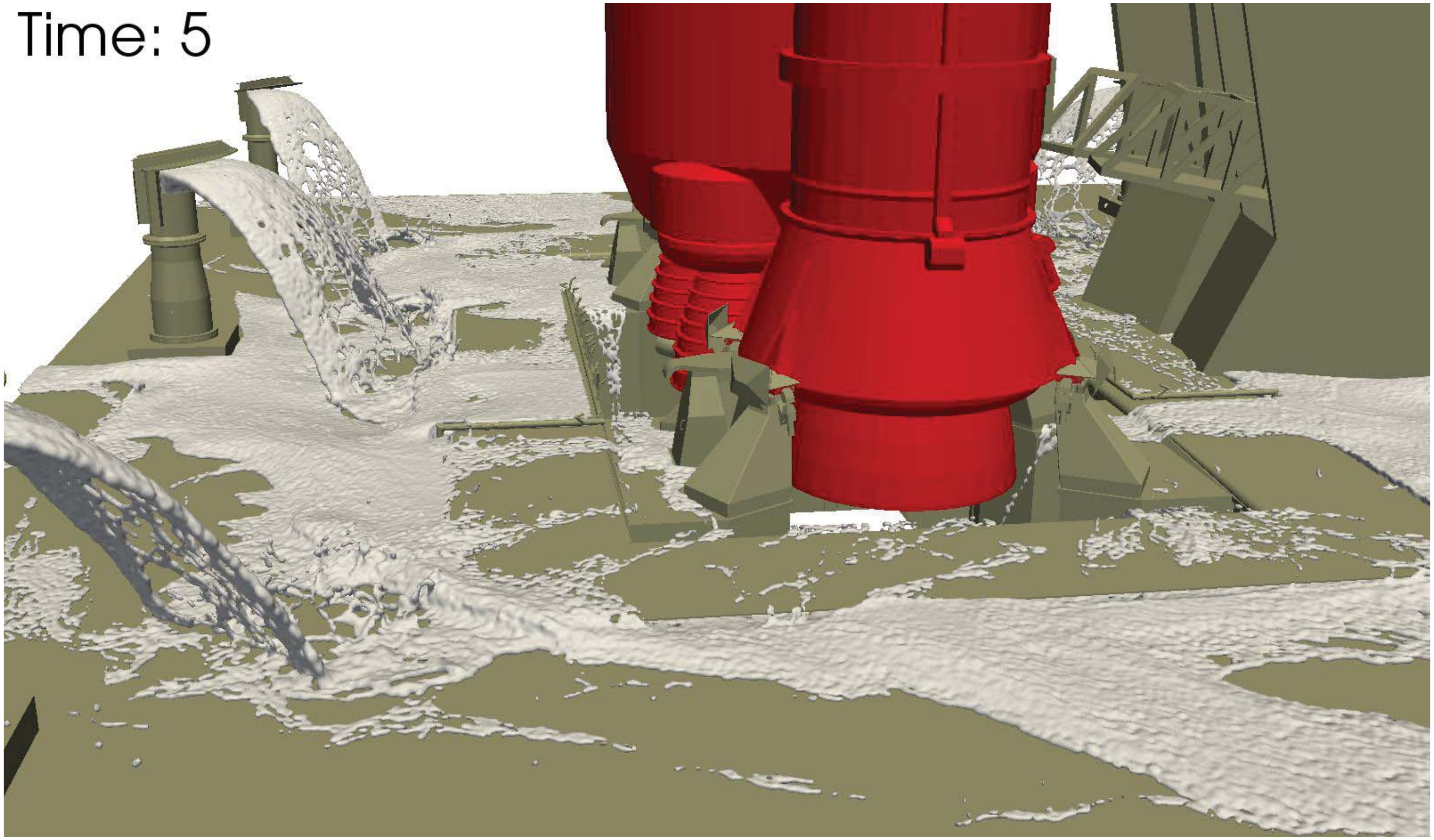
Water Depth



Water Depth



Water Depth



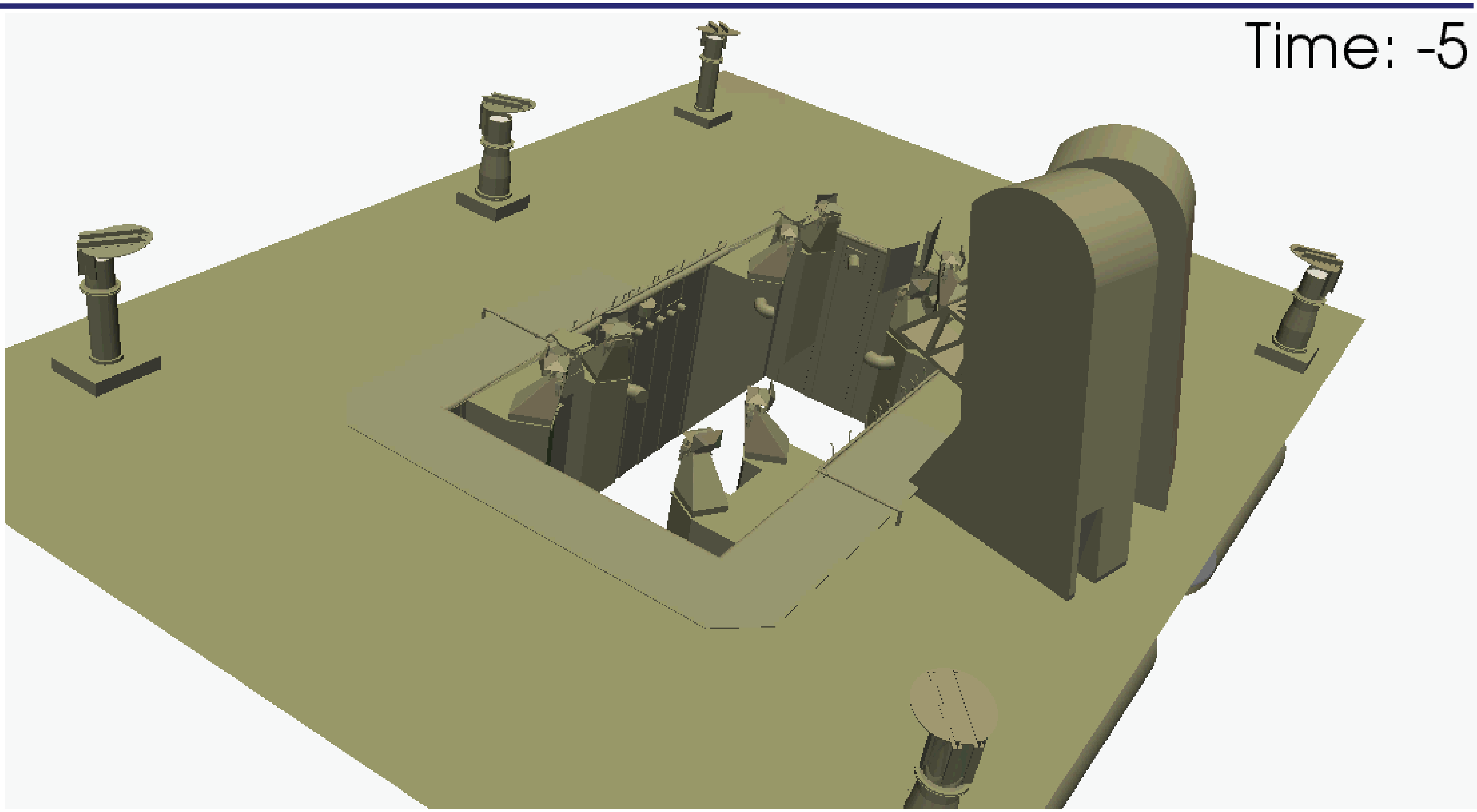
Summary

- New GPU cards were installed and performing as expected
- Cameras will get minimal impact
- Water puddle is as deep as 0.3m = 12”
- TSM gap could result in shallow water depth

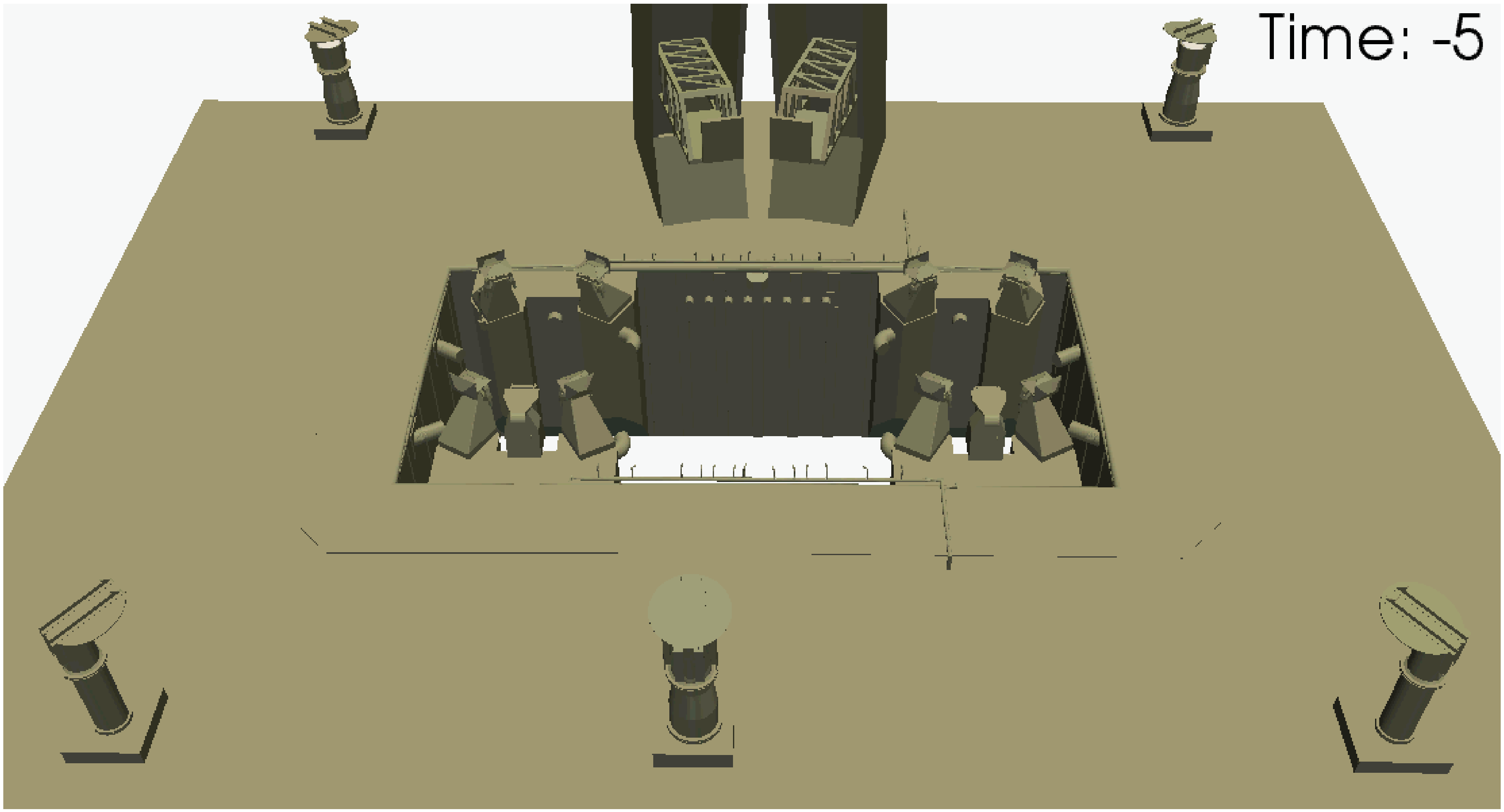
Updates

- Quadro K600 outperformed Tesla K40c
- Fix TSM gap
- Incorporate design of water barrier for HBOI
- Install camera locations

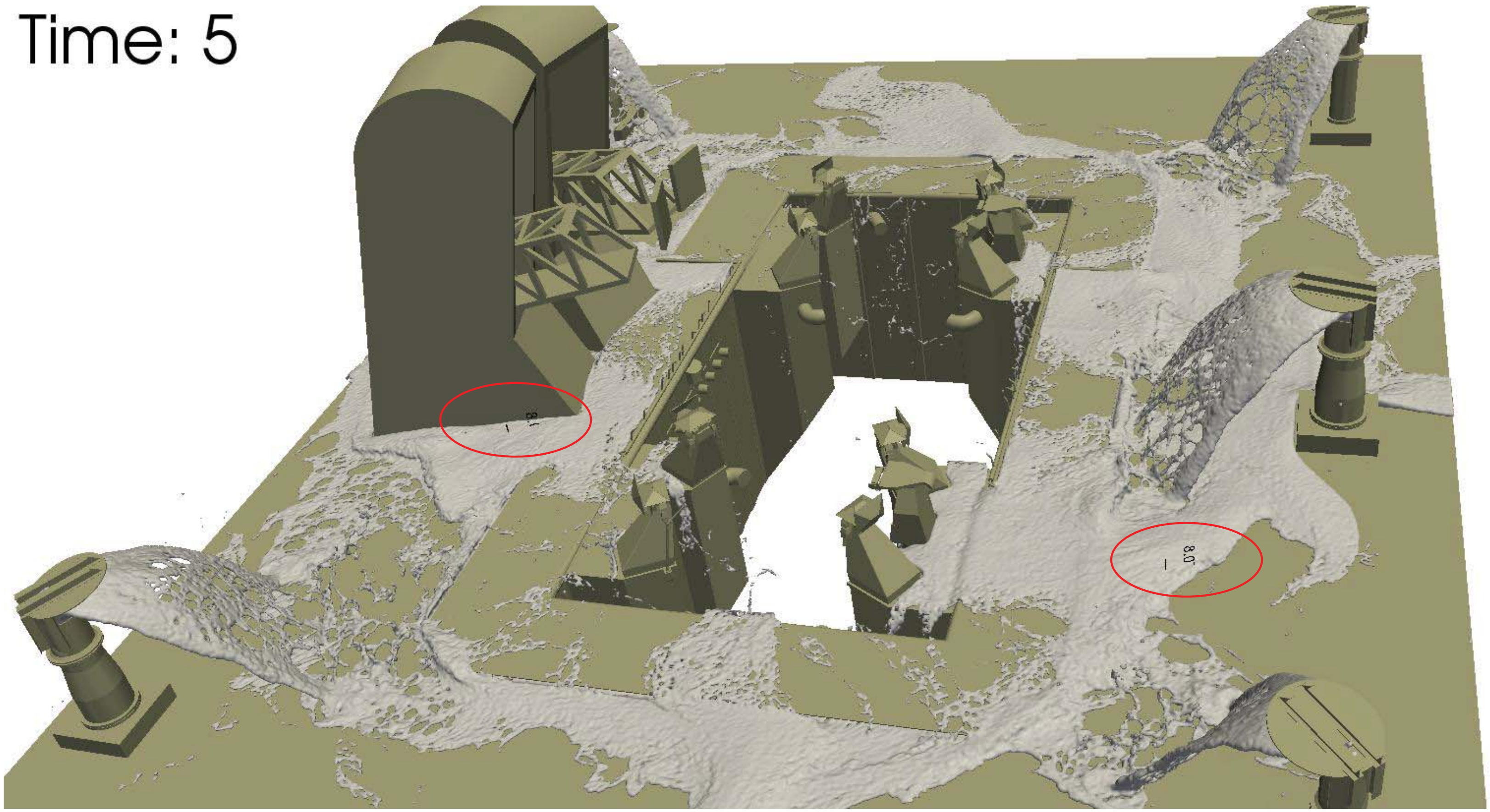
Abort Simulation (fixed TSM)



Abort Simulation (fixed TSM)

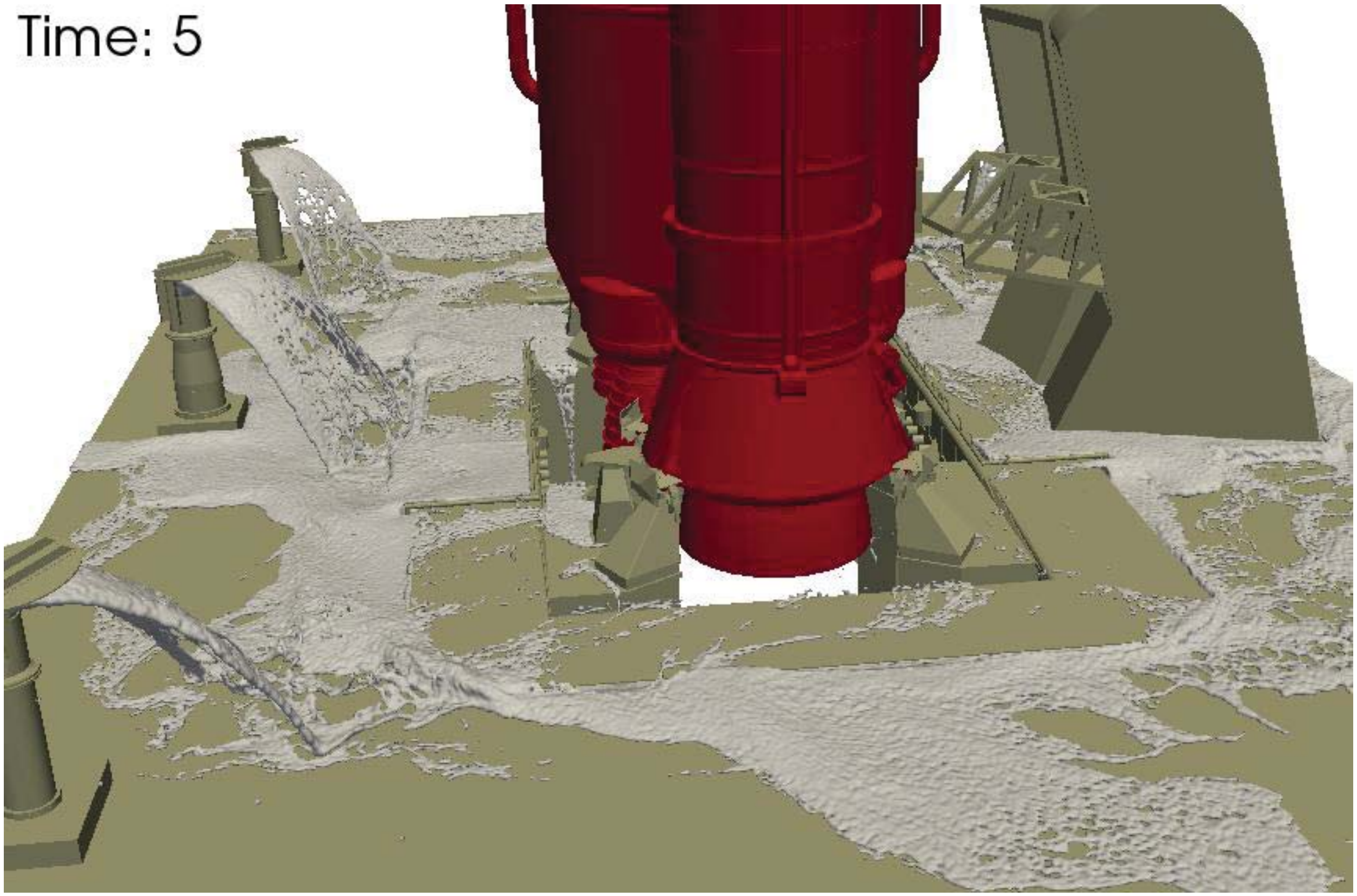


No TSM Gap

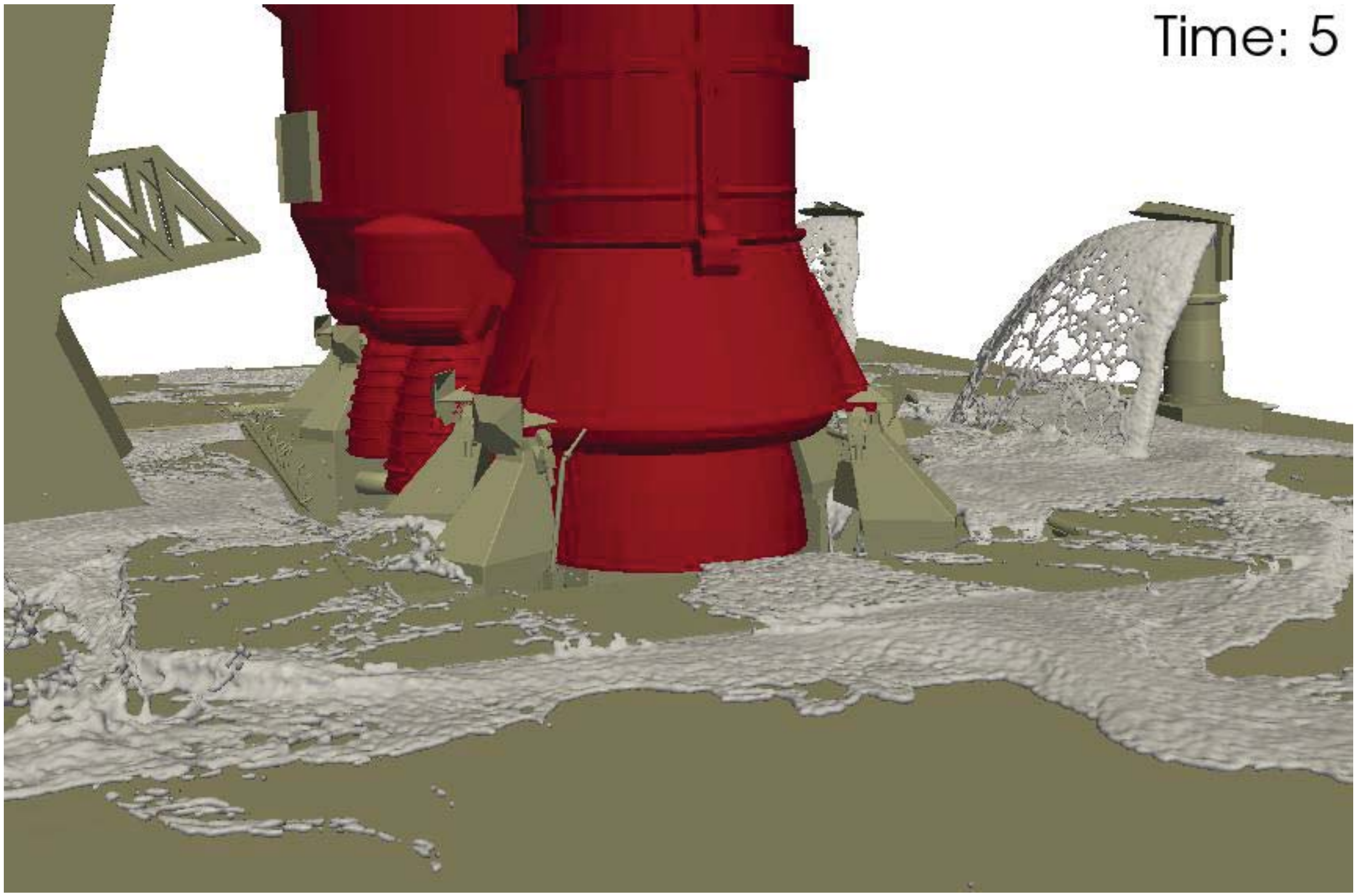


- Water puddle as deep as 0.4m = 16” near the TSM and on the South side

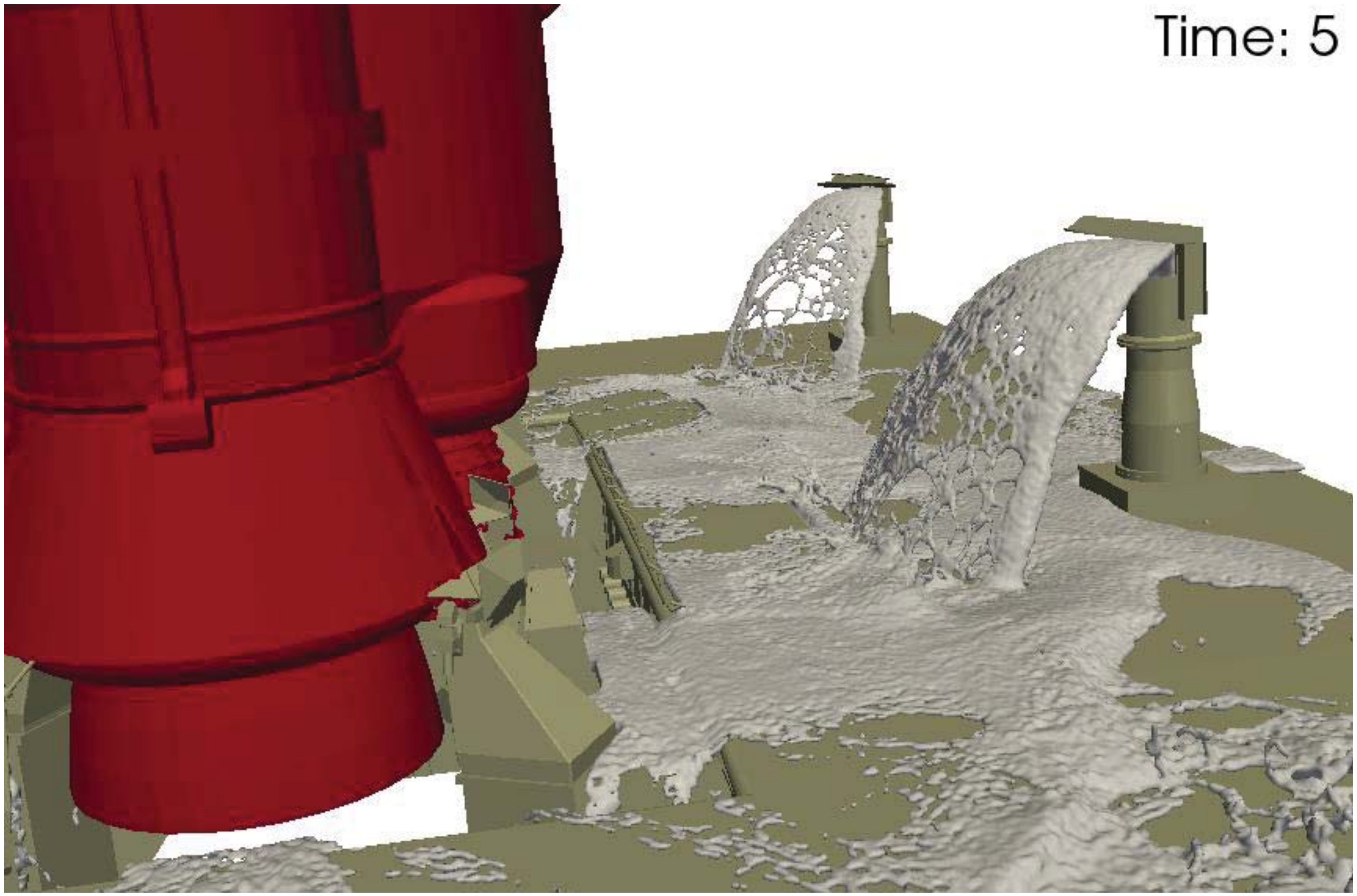
Fixed TSM



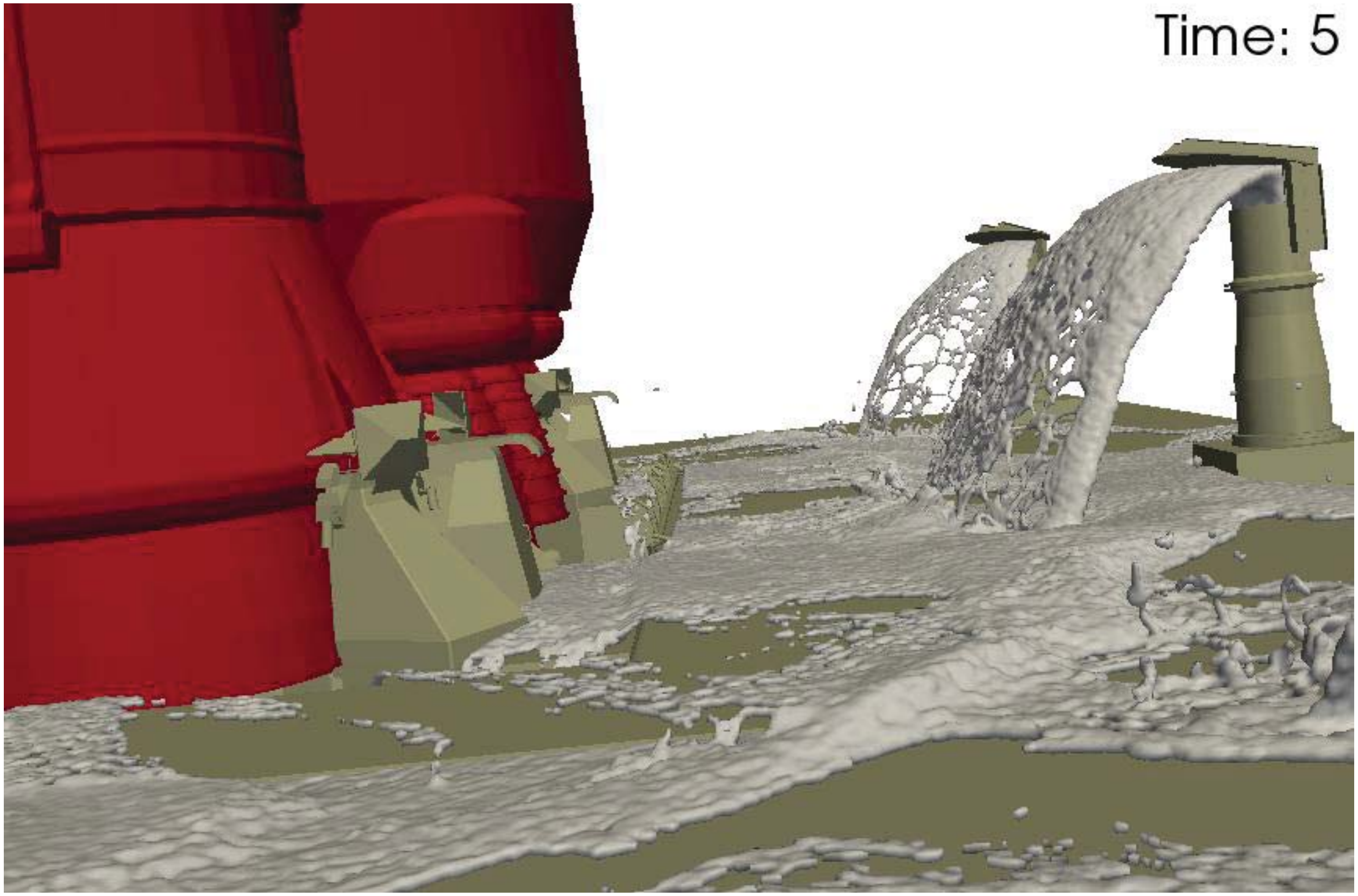
Fixed TSM



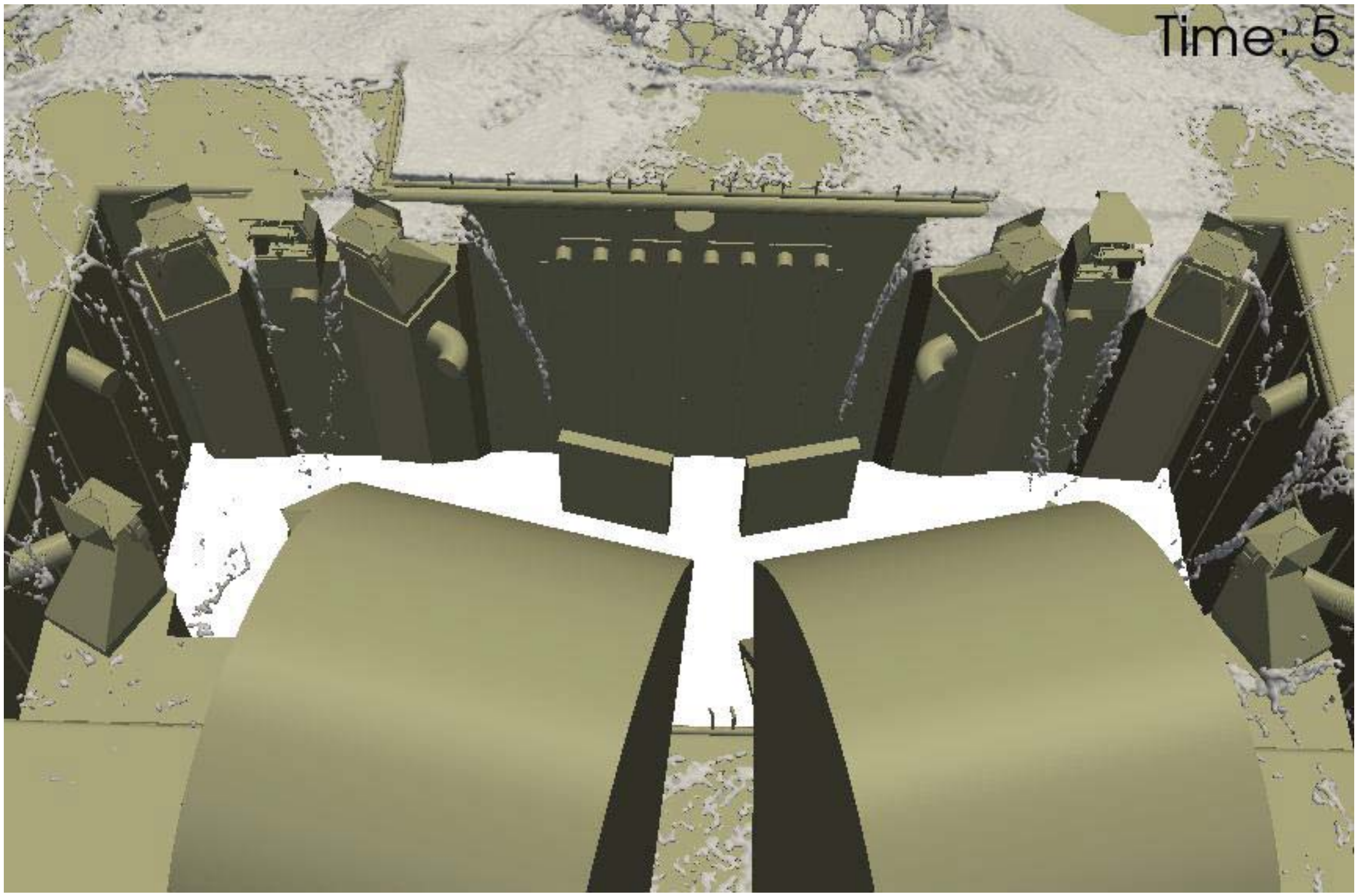
Fixed TSM



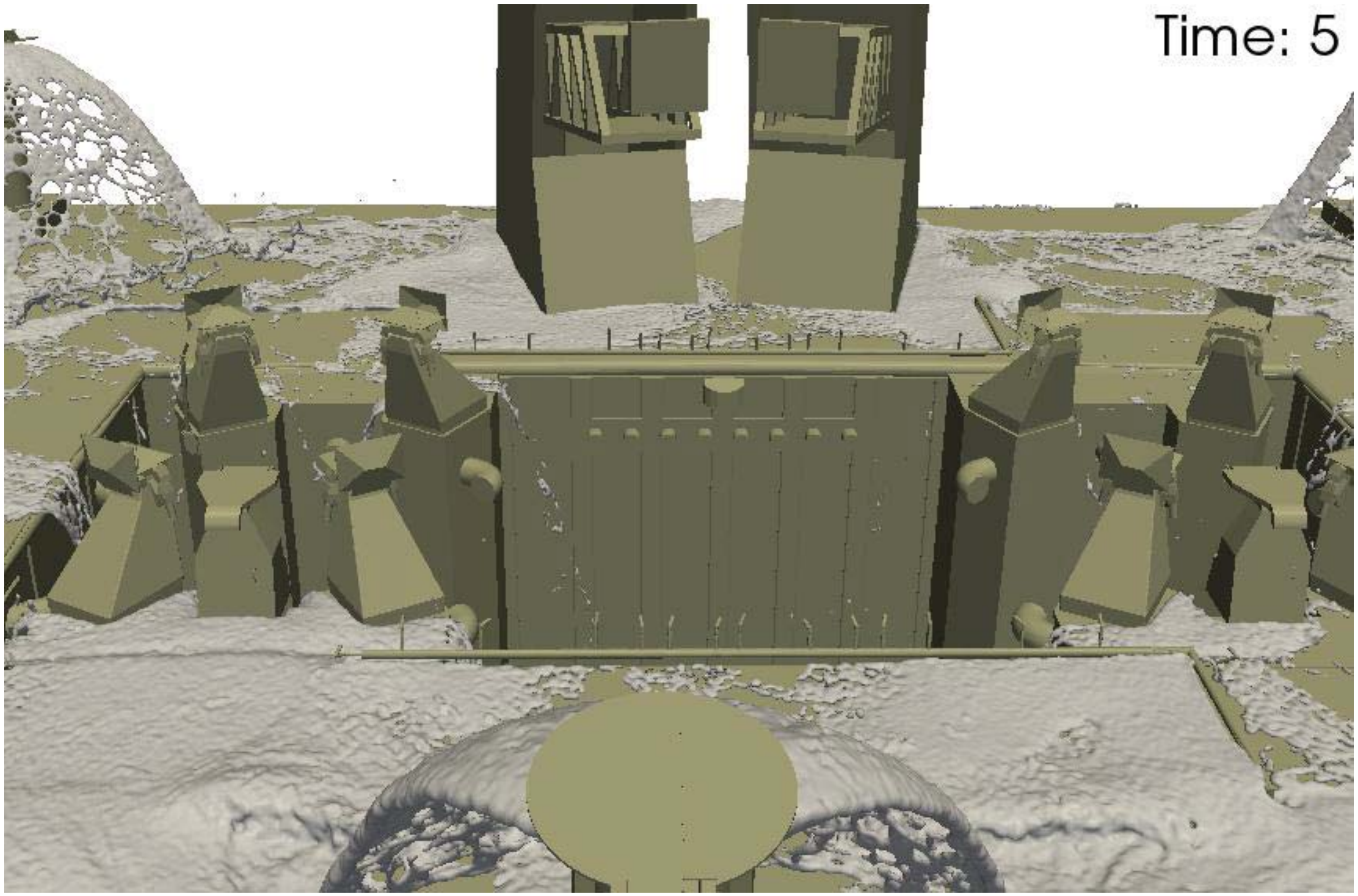
Fixed TSM



Fixed TSM



Fixed TSM



Forward Plan

- Build a multi-GPU cluster and equip the Beast with the best resources
- Recruit doctoral student and post doc through Graduate STEM Fellowship to conduct research in meshfree method
- Collaborate with UCF (A. Kassab), University of Cincinnati (G.R. Liu) and University of Manchester Research Group (A. Crespo)

References

- Crespo AJC, Dominguez JM, Barreiro A, Gómez-Gesteira M and Rogers BD, 2011, *“GPUs, a new tool of acceleration in CFD: Efficiency and reliability on Smoothed Particle Hydrodynamics methods,”* PLoS ONE. doi:10.1371/journal.pone.0020685.
- B.D. Rogers, *“Developing smoothed particle hydrodynamics (SPH) on CUDA – work by the SPHysics group,”* School of Mechanical, Aerospace and Civil Engineering (MACE), University of Manchester, UK.
- G.R. Liu, *“Smoothed Particle Hydrodynamics: A Meshfree Particle Method,”* World Scientific, ISBN-13: 978-9812384560

Websites

- Free open-source SPHysics code:
  http://wiki.manchester.ac.uk/sphysic

- GPU-SPHysics: a GPU-based SPH model for free-surface flows
  http://www.ce.jhu.edu/dalrymple/GPU

- SPHERIC = SPH European Research Interest Community:
  http://wiki.manchester.ac.uk/spheric