Launch Environment Water Flow Simulation Using Smoothed Particle Hydrodynamics (SPH)

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Presented at the Applied Modeling and Simulation (AMS) seminar
NASA Ames Research Center, 18 April, 2014

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

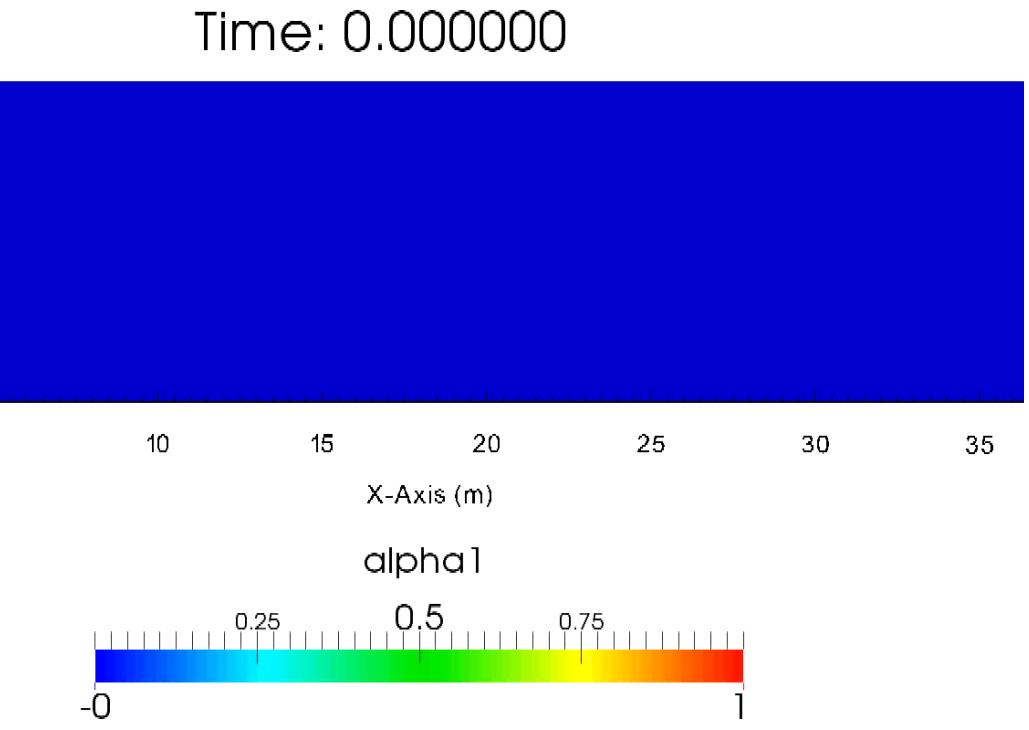
2 simulations using a 2-D structured mesh of rainbird nozzle mounted
12’ above the deck based on OpenFOAM multiphase flow solver.

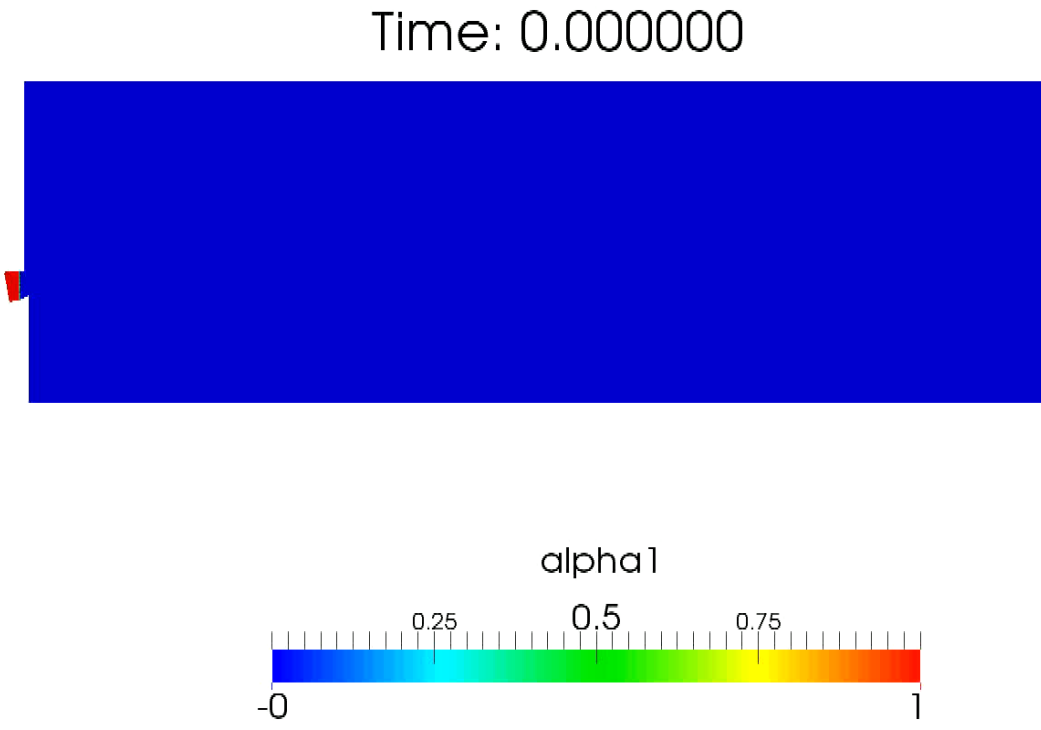
Simulation 1 - “corner rainbird” case: Water injection at 112,500 gpm

Simulation 2 - “center rainbird” case: Water injection at 55,250 gpm.

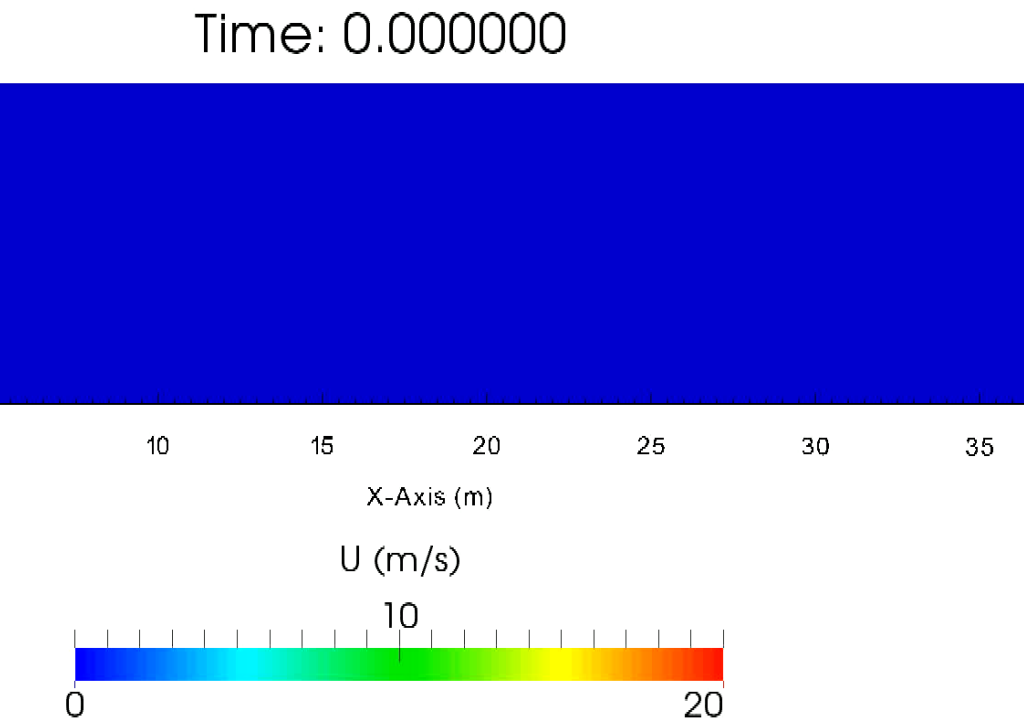
Both simulations were run up to 5 seconds.

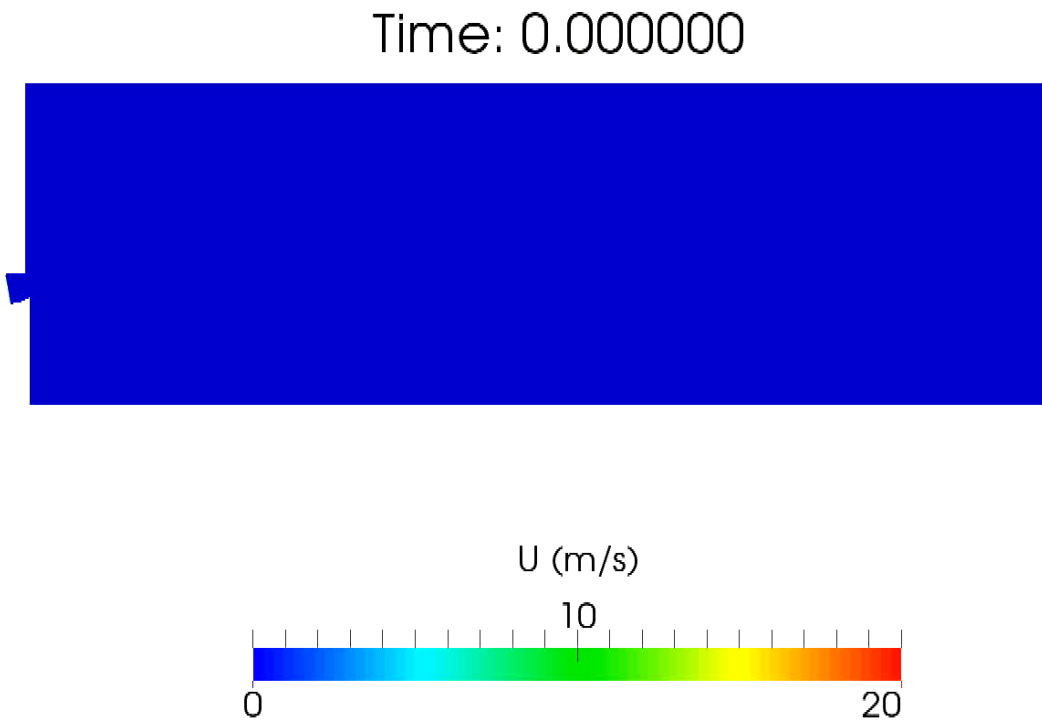
55,250 GPM


Time: 0.000000
10
15
20
25
30
35
X-Axis (m)
alpha1
0.25
0.5
0.75
-0
1

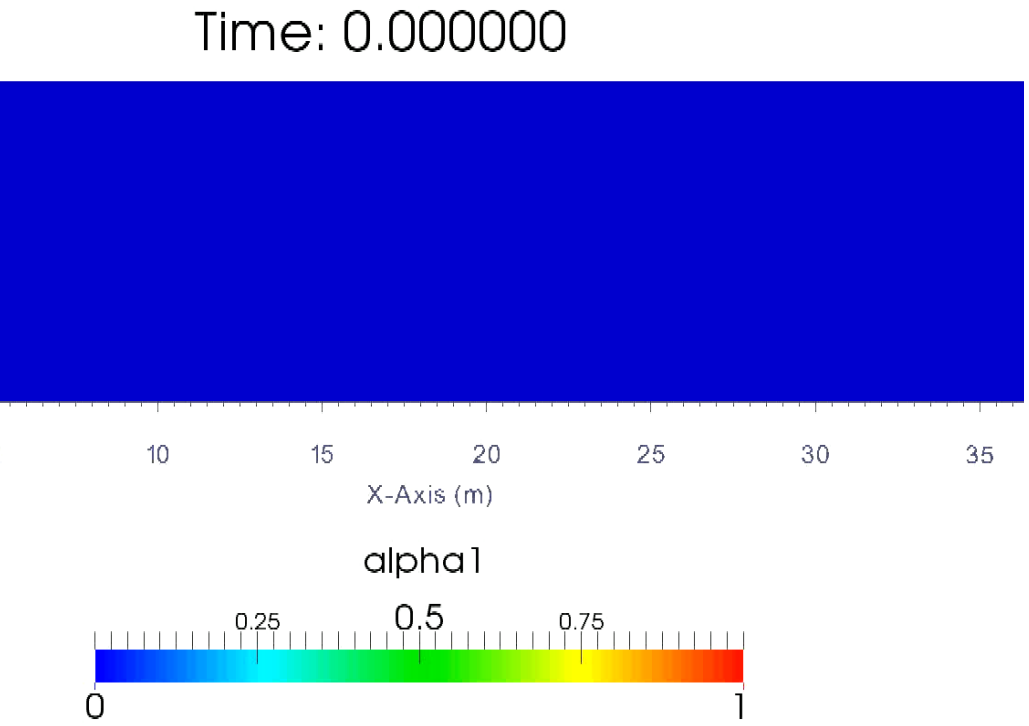

Time: 0.000000
alpha1
0.25
0.5
0.75
-0
1

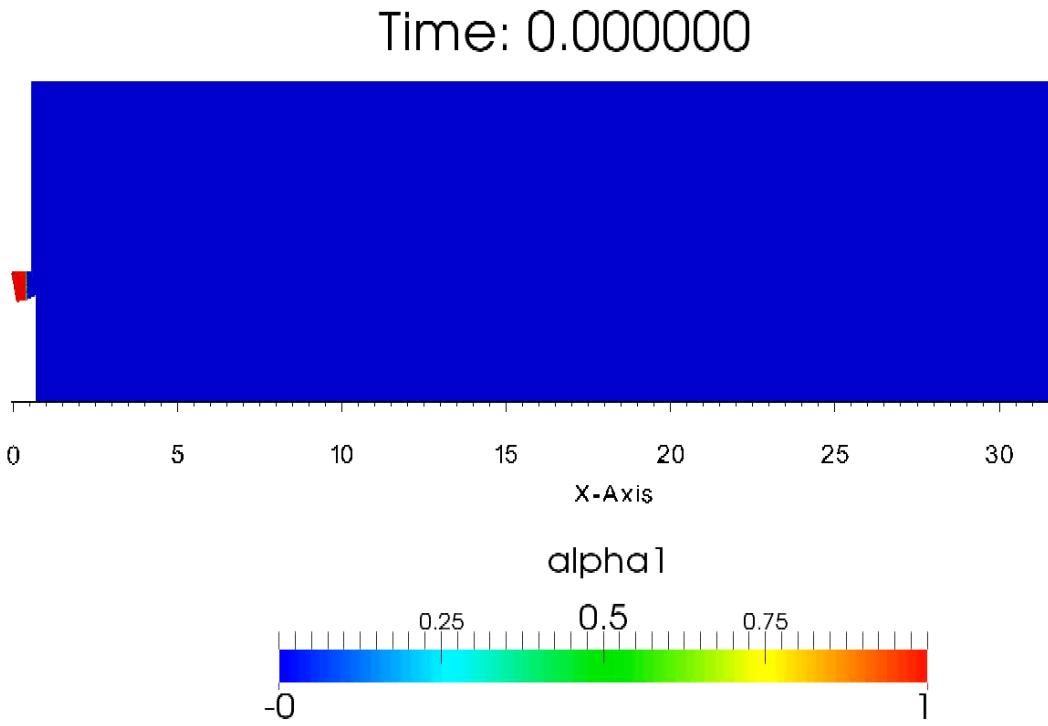
55,250 GPM


Time: 0.000000
10
15
20
25
30
35
X-Axis (m)
U (m/s)
10
0
20

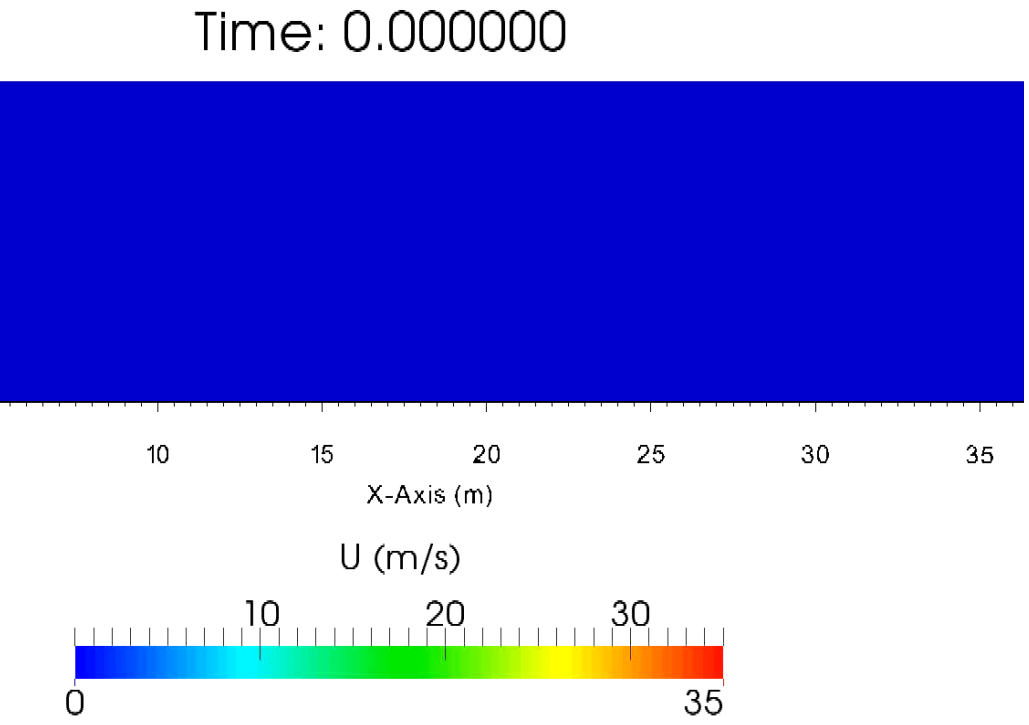

Time: 0.000000
U (m/s)
10
0
20

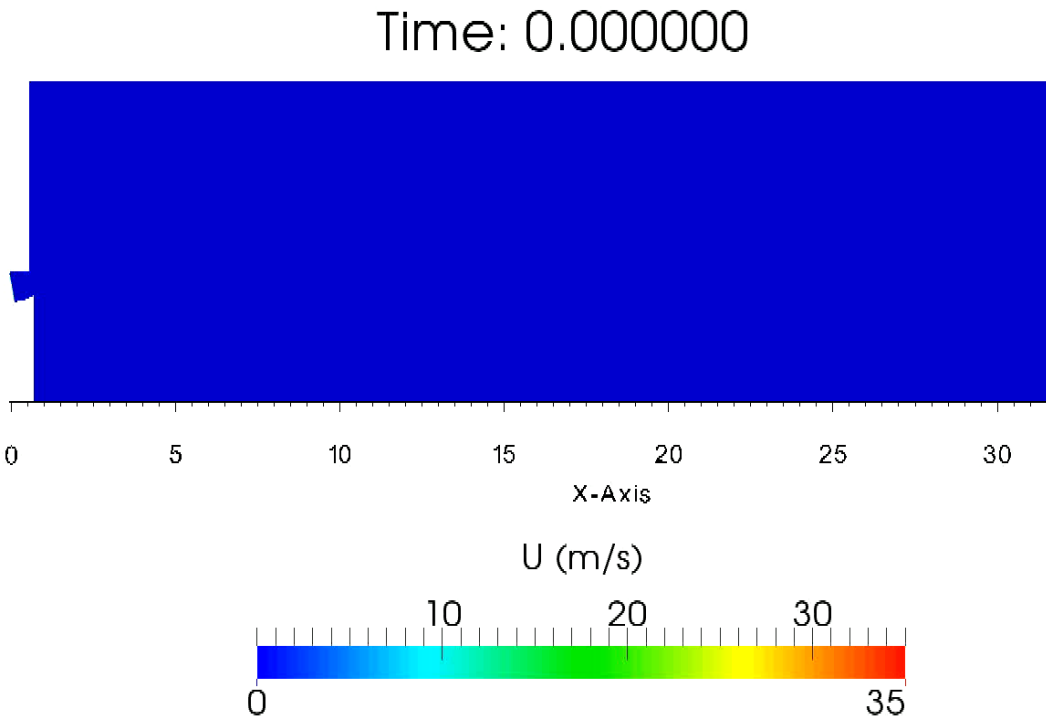
112,500 GPM


Time: 0.000000
10
15
20
25
30
35
X-Axis (m)
alpha1
0.25
0.5
0.75
0
1


Time: 0.000000
0
5
10
15
20
25
30
X-Axis
alpha1
0.25
0.5
0.75
-0
1

112,500 GPM


Time: 0.000000
10
15
20
25
30
35
X-Axis (m)
U (m/s)
10
20
30
0
35


Time: 0.000000
0
5
10
15
20
25
30
X-Axis
U (m/s)
10
20
30
0
35

Recommendation

3-D VOF

Smoothed Particle Hydrodynamics

SPH Formulation

a meshfree method with nodal collocation, spatial discretization, and kernel
ximation

originally developed by Gingold-Monaghan and Lucy (1977) for astrophysical
ems.

ng with the conservation equation of mass and momentum:

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

en in compact matrix form:

$$A(f(r)) = \nabla\sigma + F, \quad \forall r\in\Omega$$
$$B(f(r)) = \bar{f}, \quad \forall r\in\Gamma$$

Let $f^h(r)$ be 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

(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,

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

Test function v can be constructed by some basis function Φ_i

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

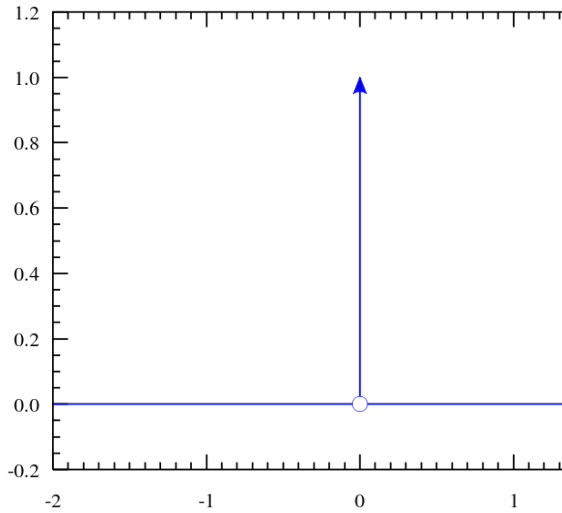
ading to the final weighted residual function

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

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:

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

Here 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:

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

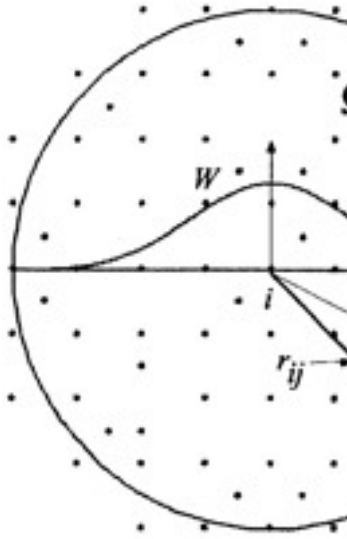
$$w(r-r',h) = 0 \ \text{ for } \ |r-r'| > \kappa h$$

where constant κ defines the compact support of the smoothing function, and $f(r)$ can be approximated as $f^h(r) = \int_{\Omega} f(r')w(r-r',h)dr'$

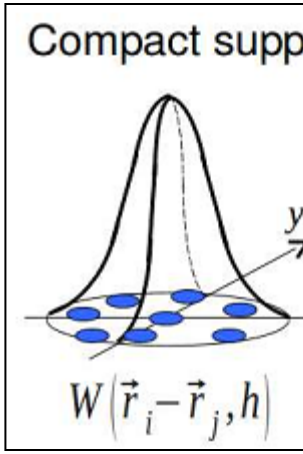
The integral form can be discretized by particle approximation:

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

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



Water Partic



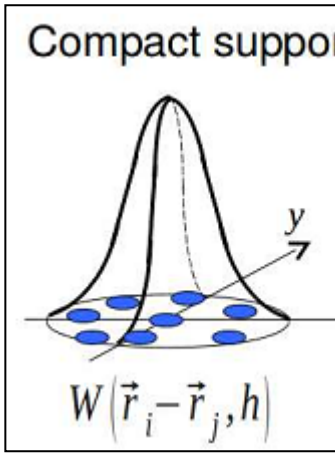
SPH Formulation

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

$$m_i = \rho_i \Delta V_i$$

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

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

here $w_{ij}=w(r_i-r_j, h)$, 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**"

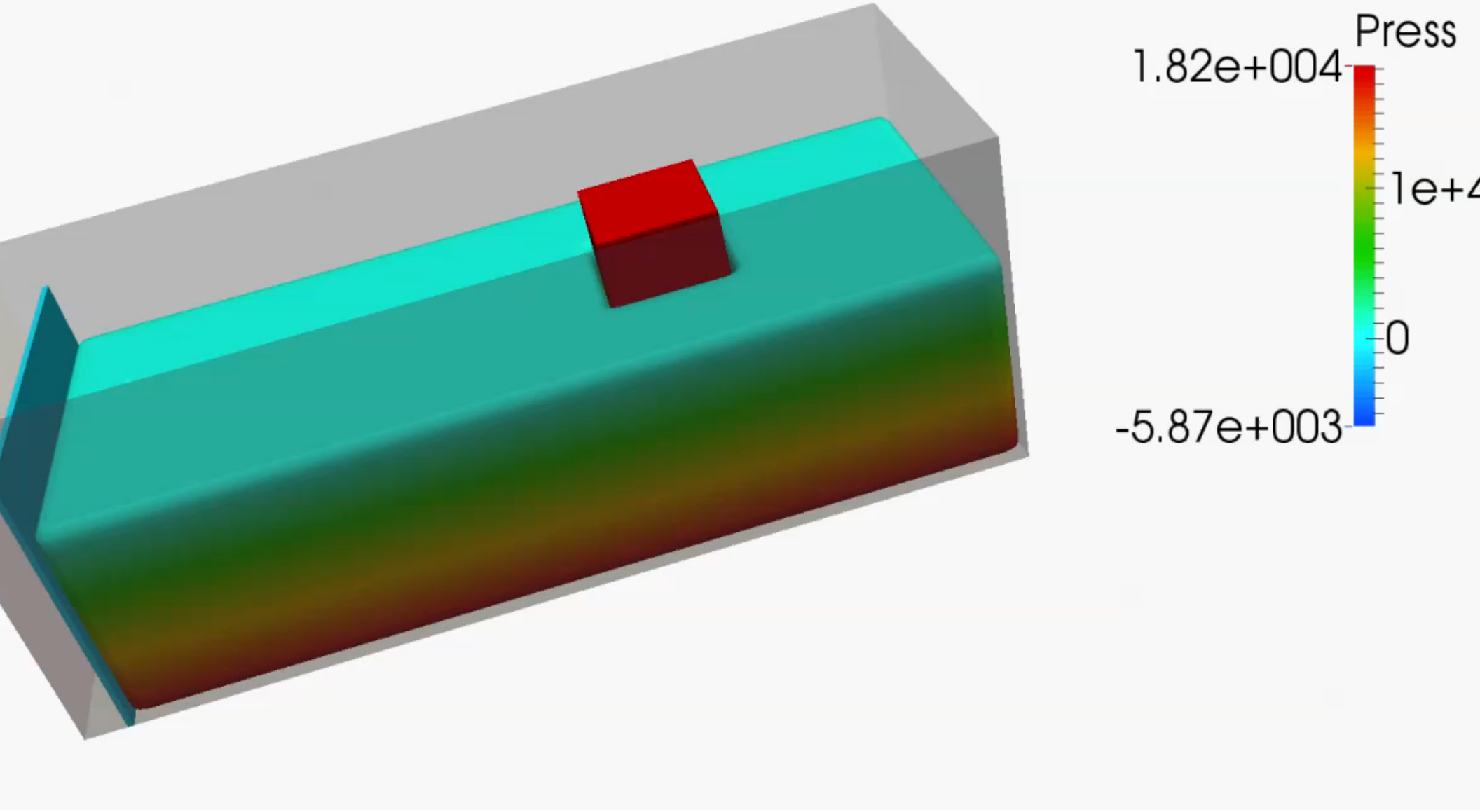
SPH Formulation

SPH is a particle based, meshfree Lagrangian method.

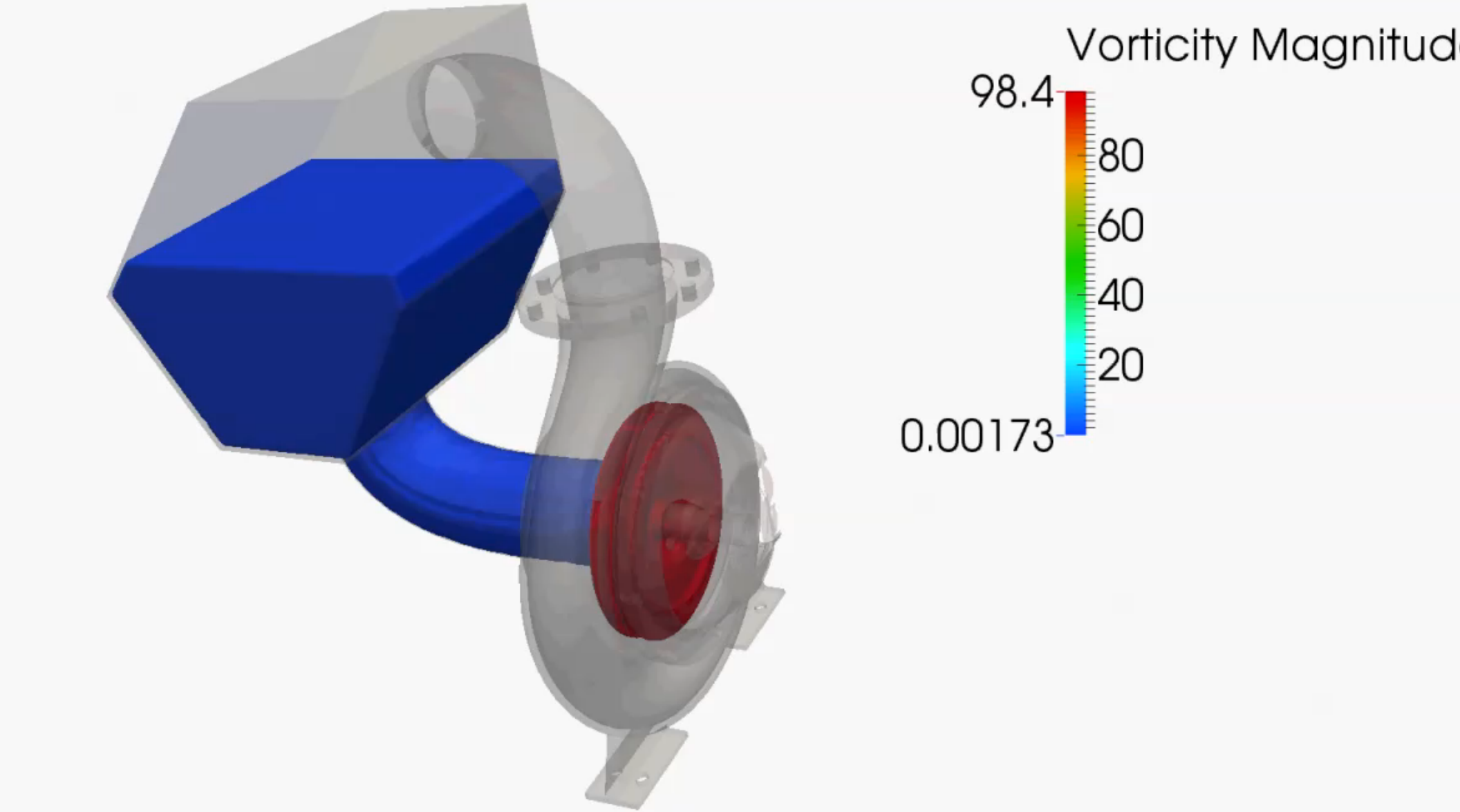
There is no connectivity between the particles and only initial particle distribution is needed.

SPH approximation consists of a kernel approximation in the continuum domain and a particle approximation in the support domain at the current time step.

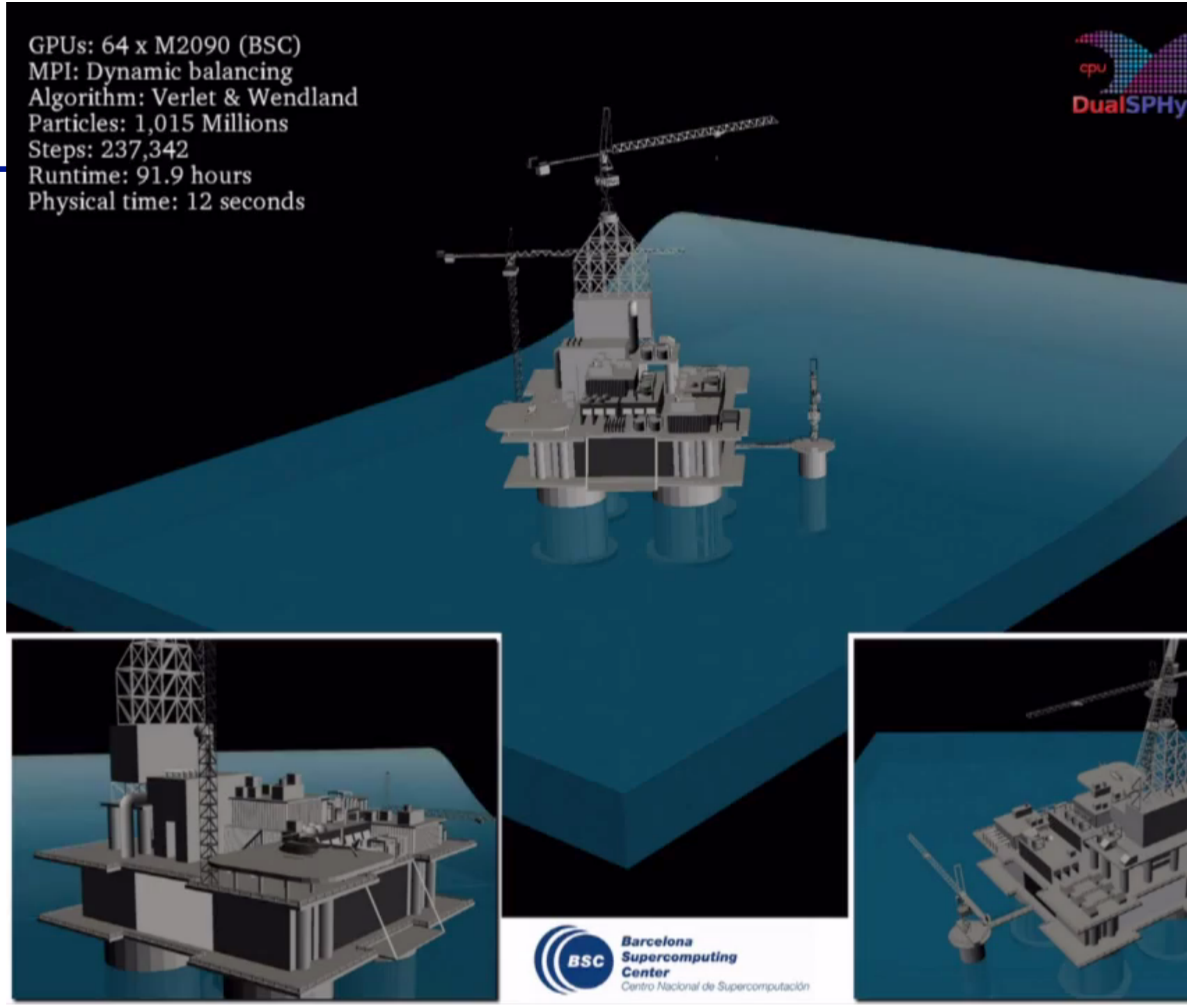
Floating



Pump



ulti-GPU
SPH


GPUs: 64 x M2090 (BSC)
MPI: Dynamic balancing
Algorithm: Verlet & Wendland
Particles: 1,015 Millions
Steps: 237,342
Runtime: 91.9 hours
Physical time: 12 seconds
DualSPHy
Barcelona
Supercomputing
Center
Centro Nacional de Supercomputación

Computational Resource

Original 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)

Upgraded 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

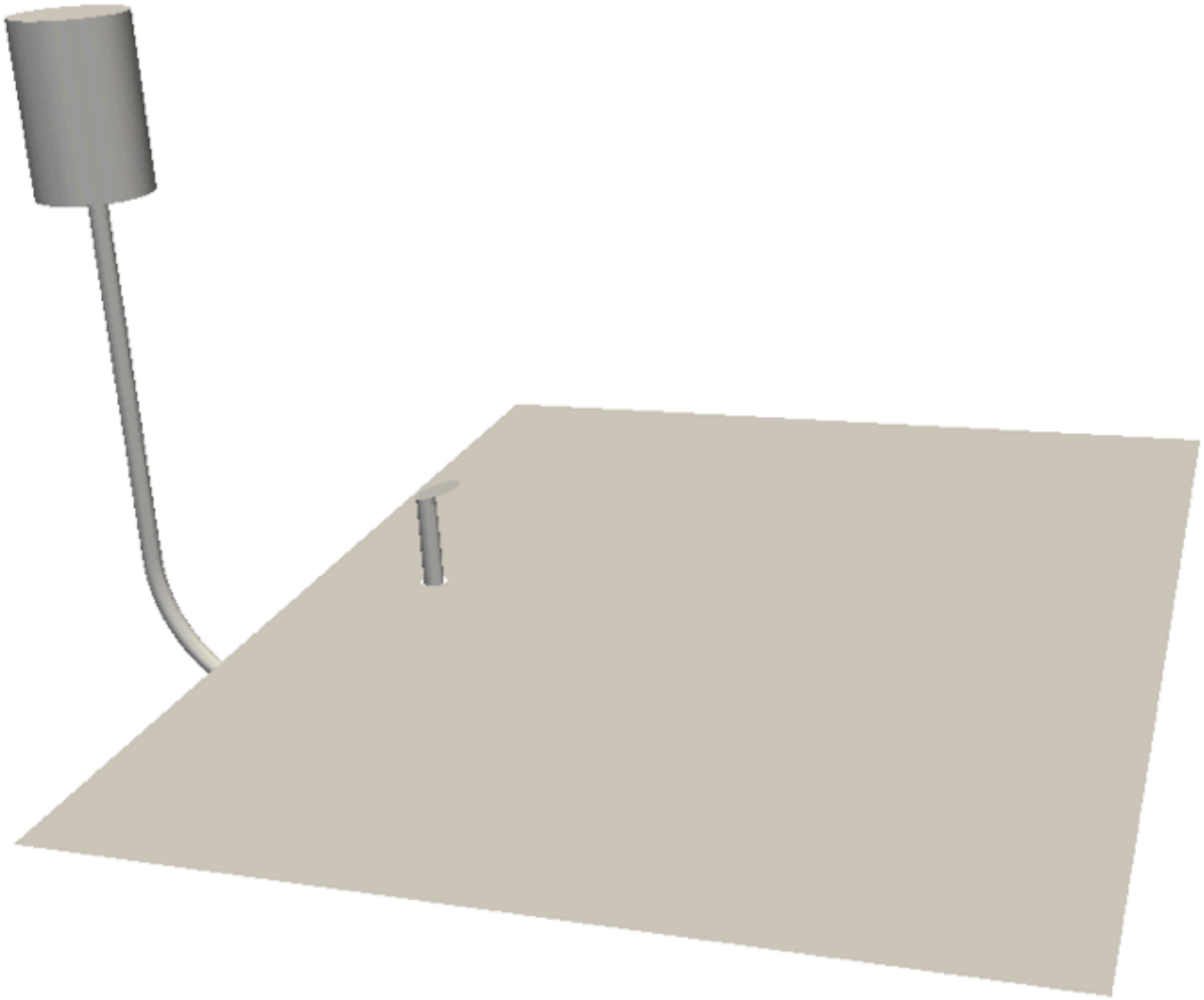
Approach

Import full ML CAD Model

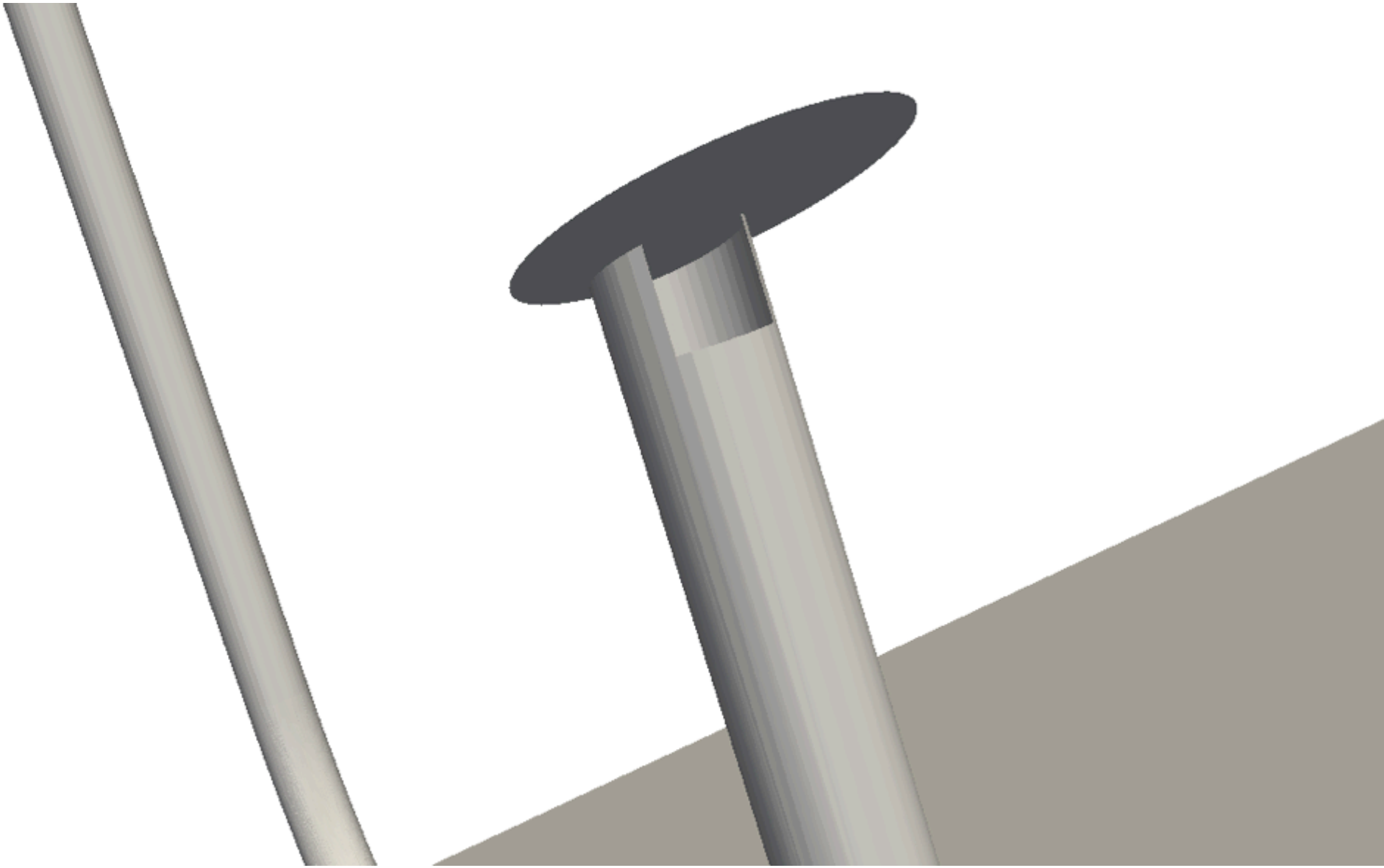
Run multiple rainbirds with variable flowrates and timing sequence

Activate vehicle motion with velocity/acceleration profile extracted from MSFC trajectory analysis

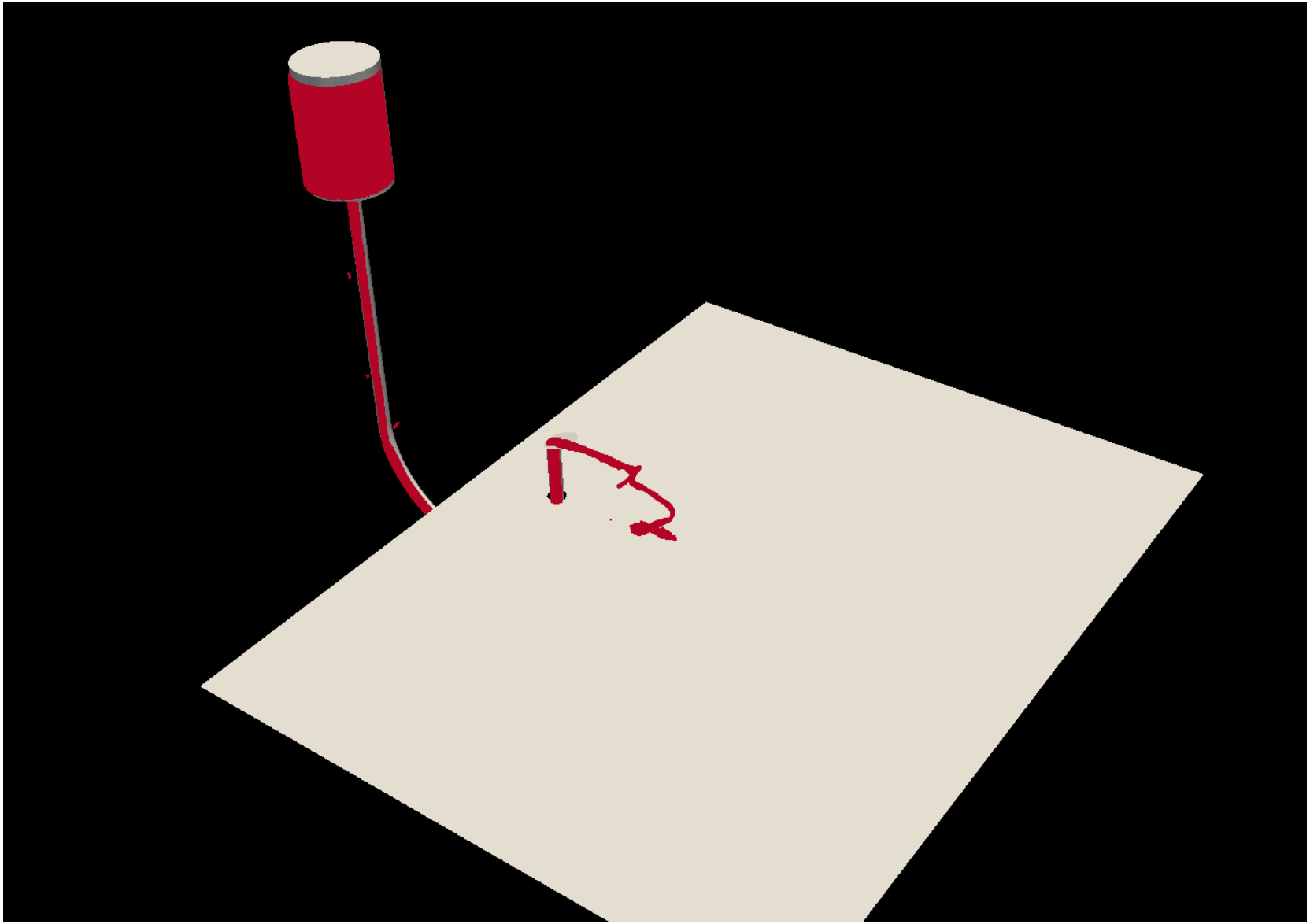
Water Tank & Rainbird



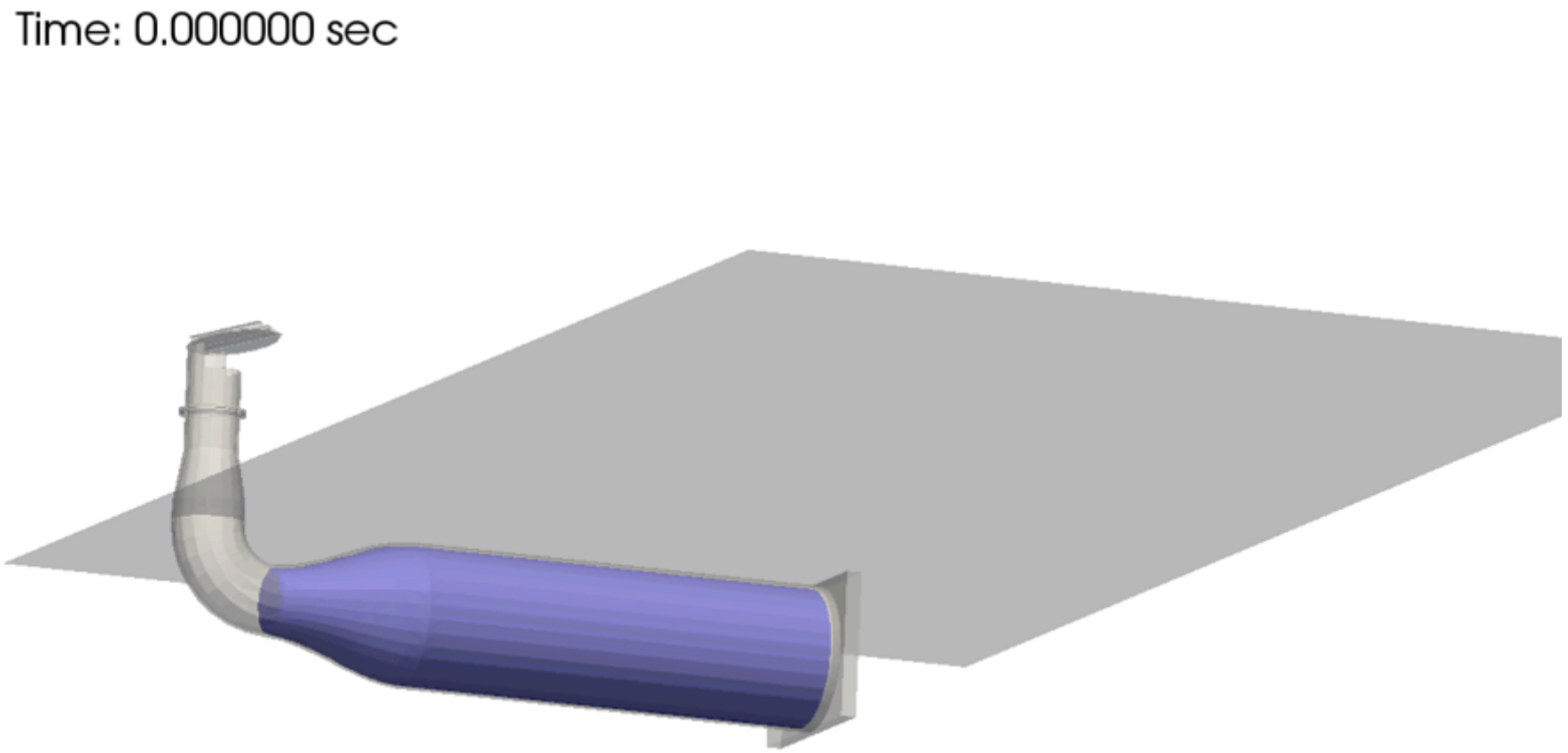
Rainbird



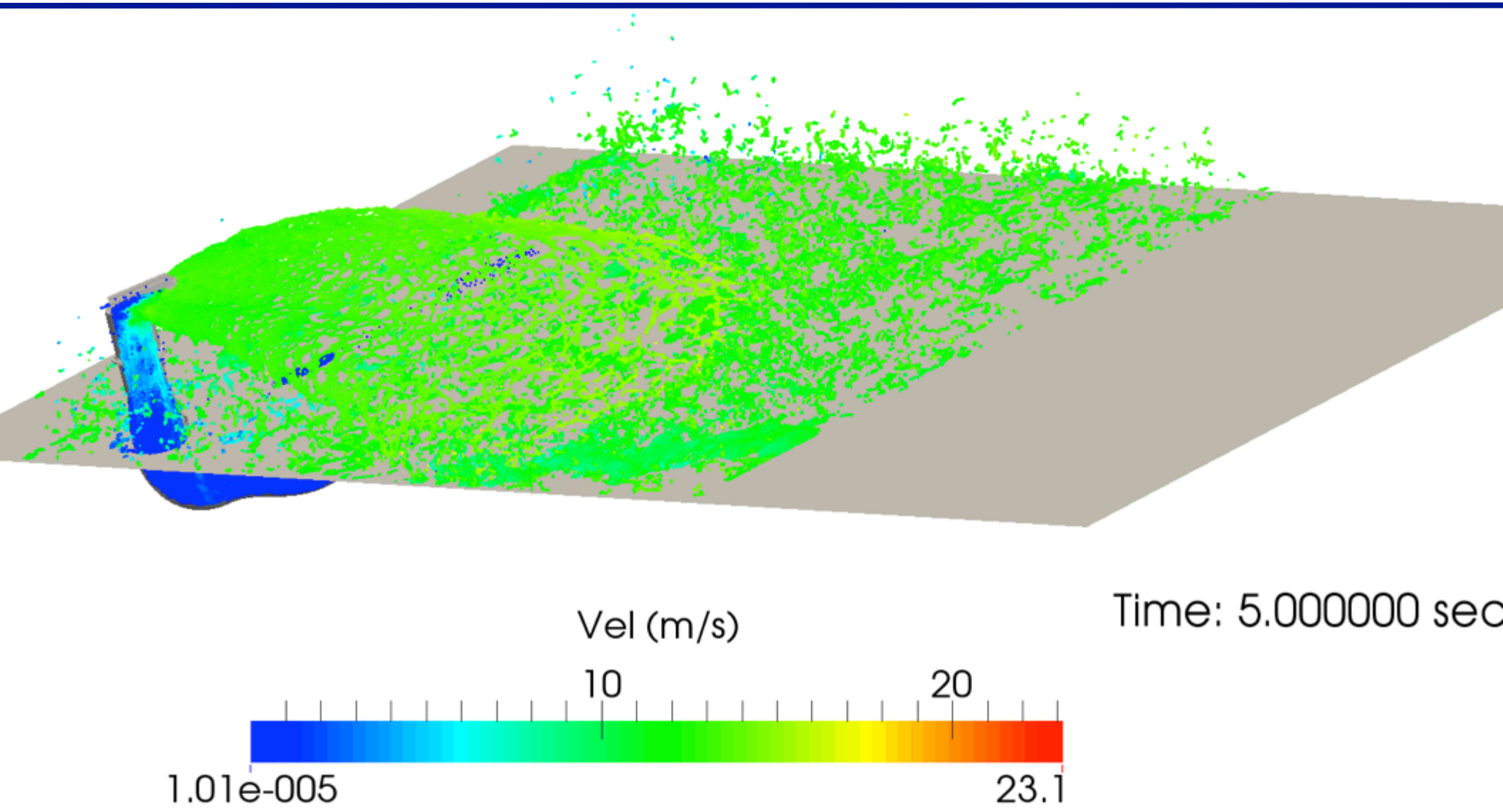
SPH Rainbird



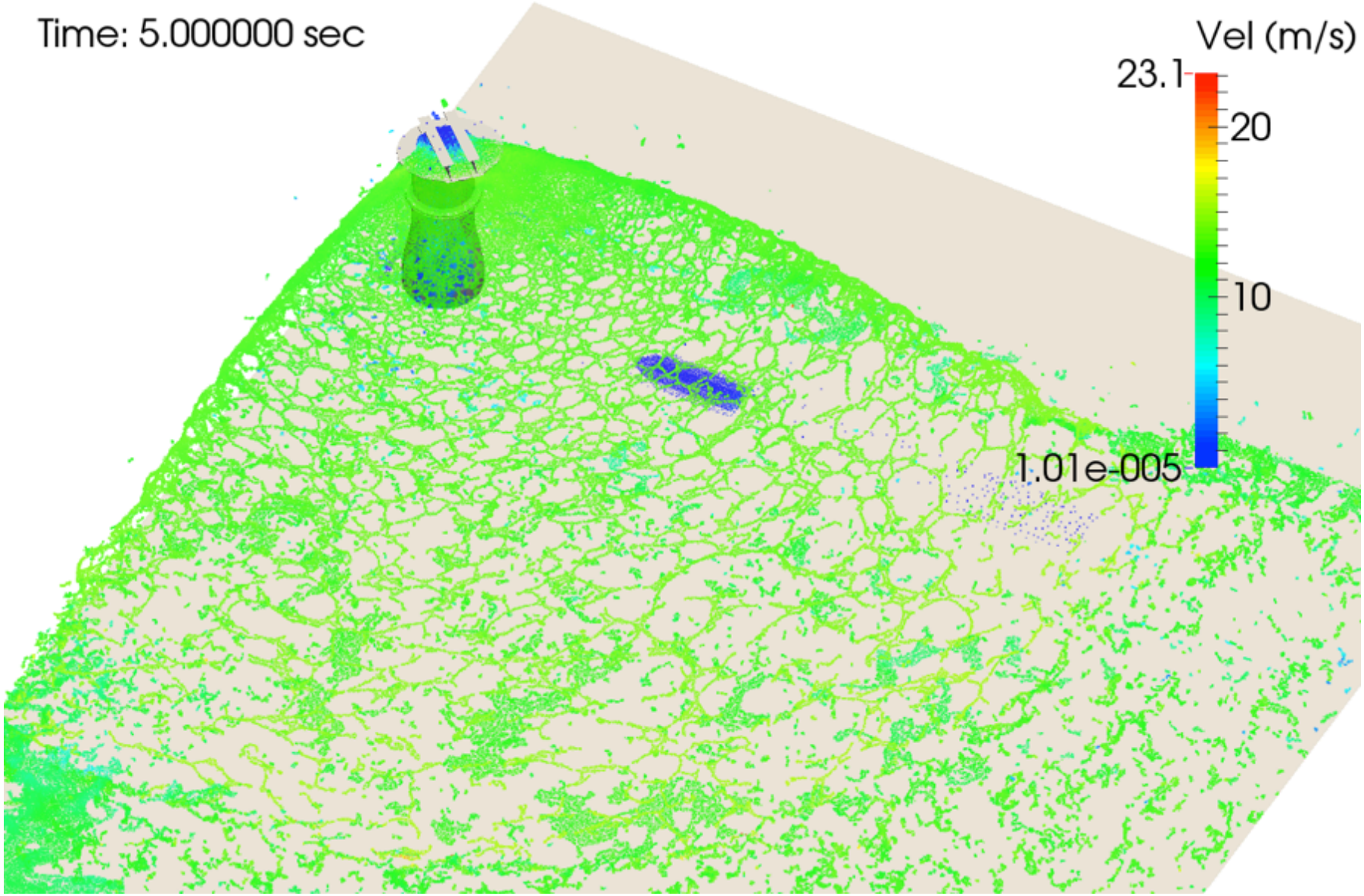
SPH Rainbird



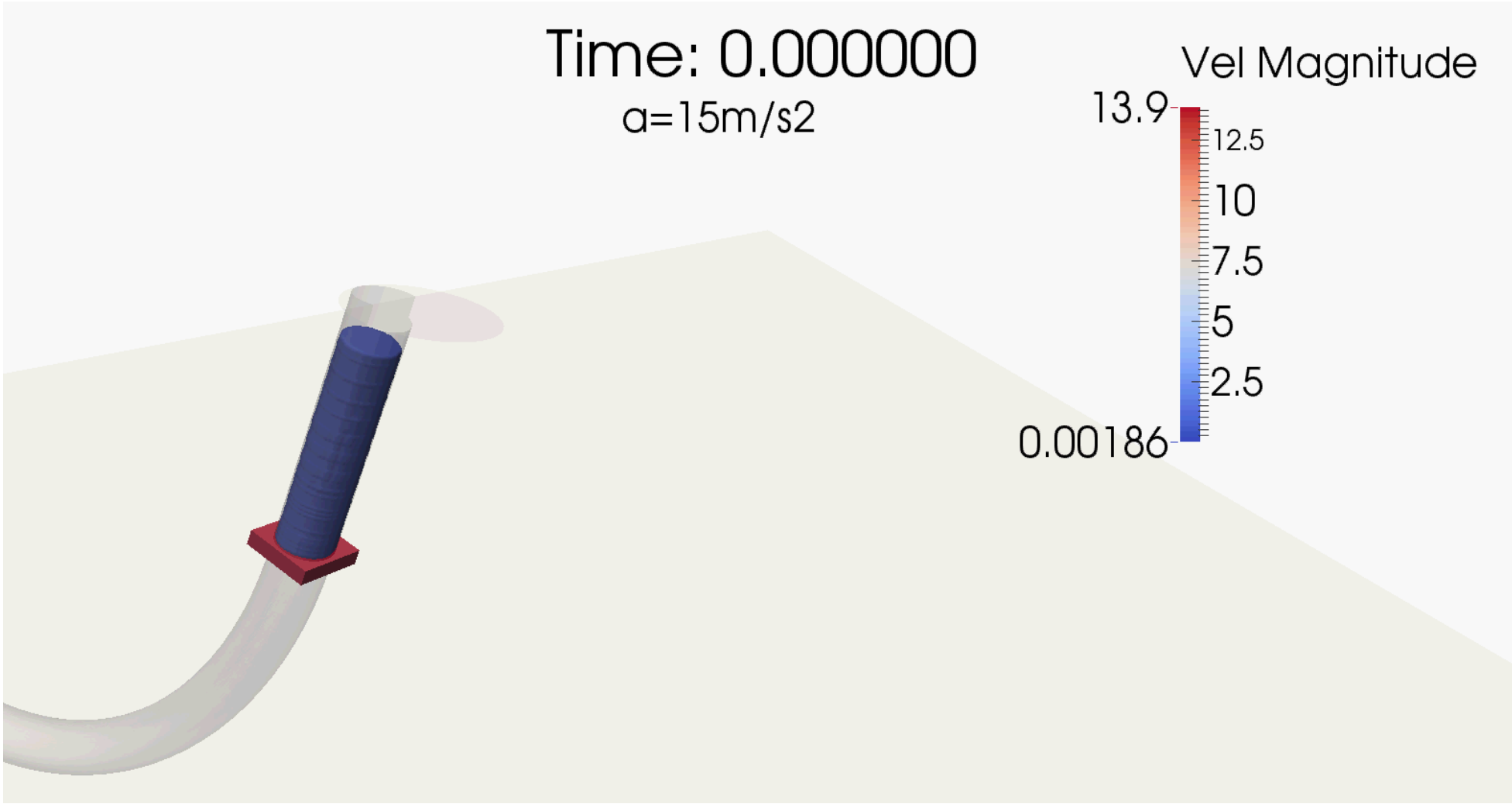
SPH Rainbird



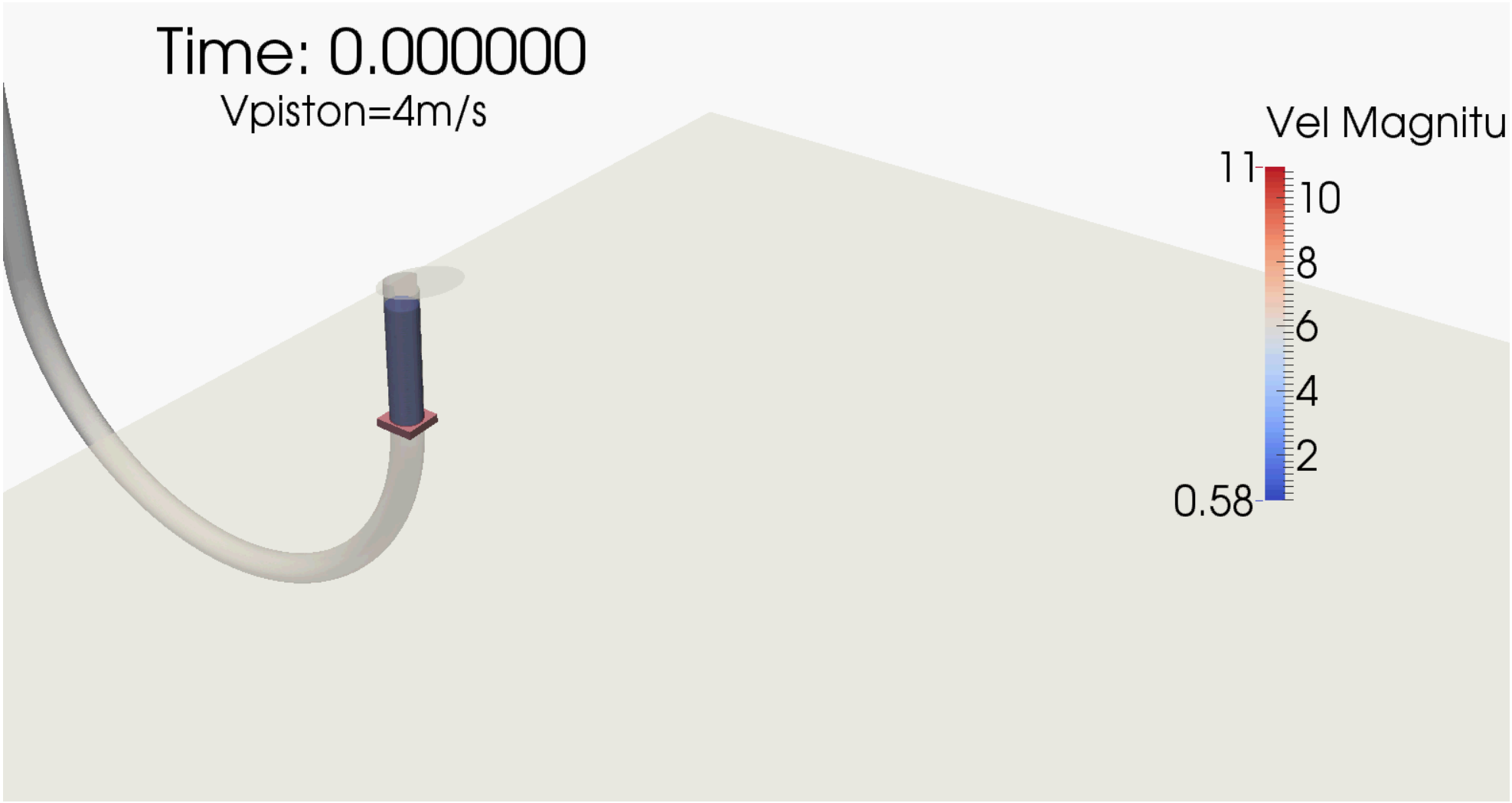
SPH Rainbird



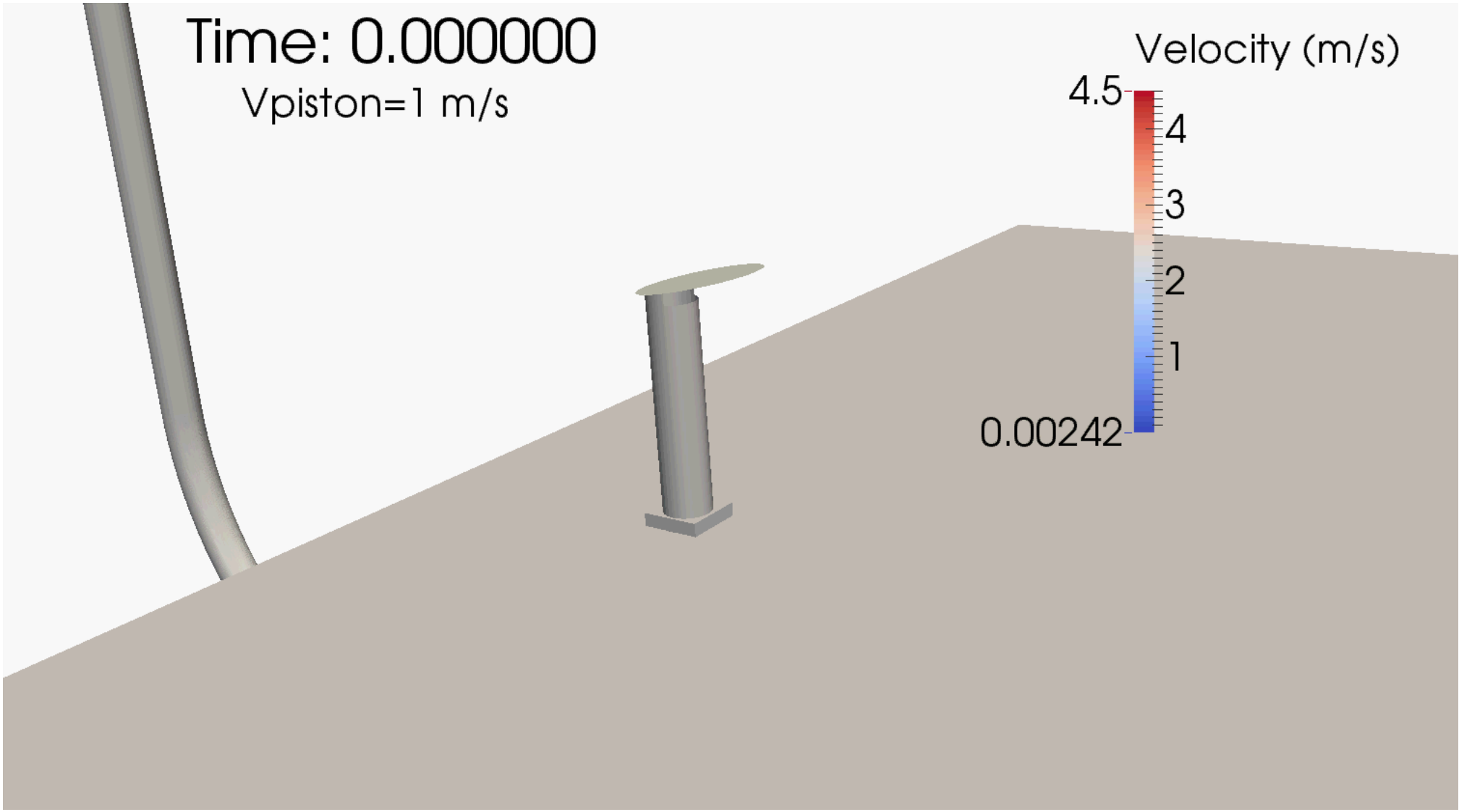
Test case 1



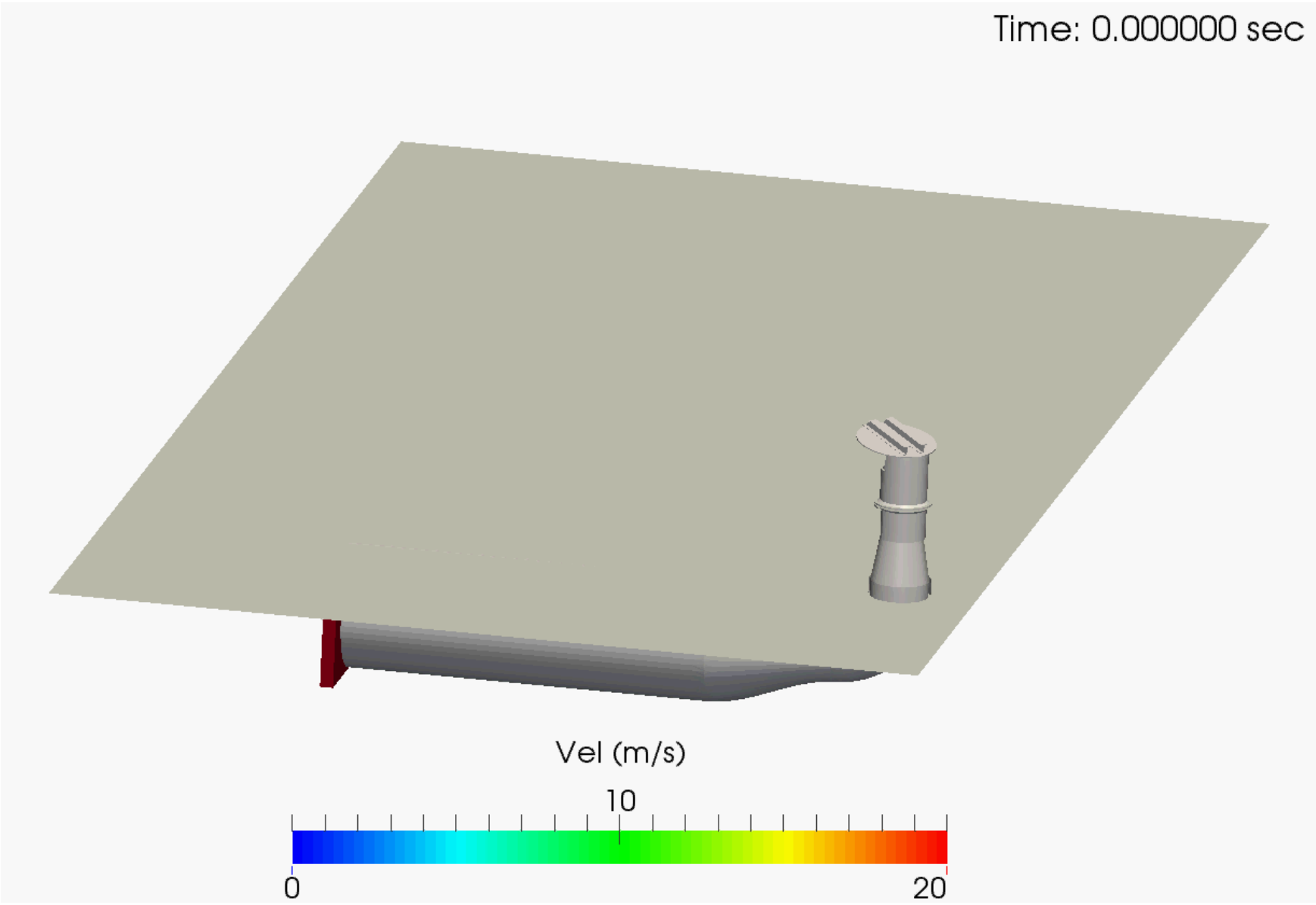
Test case 2



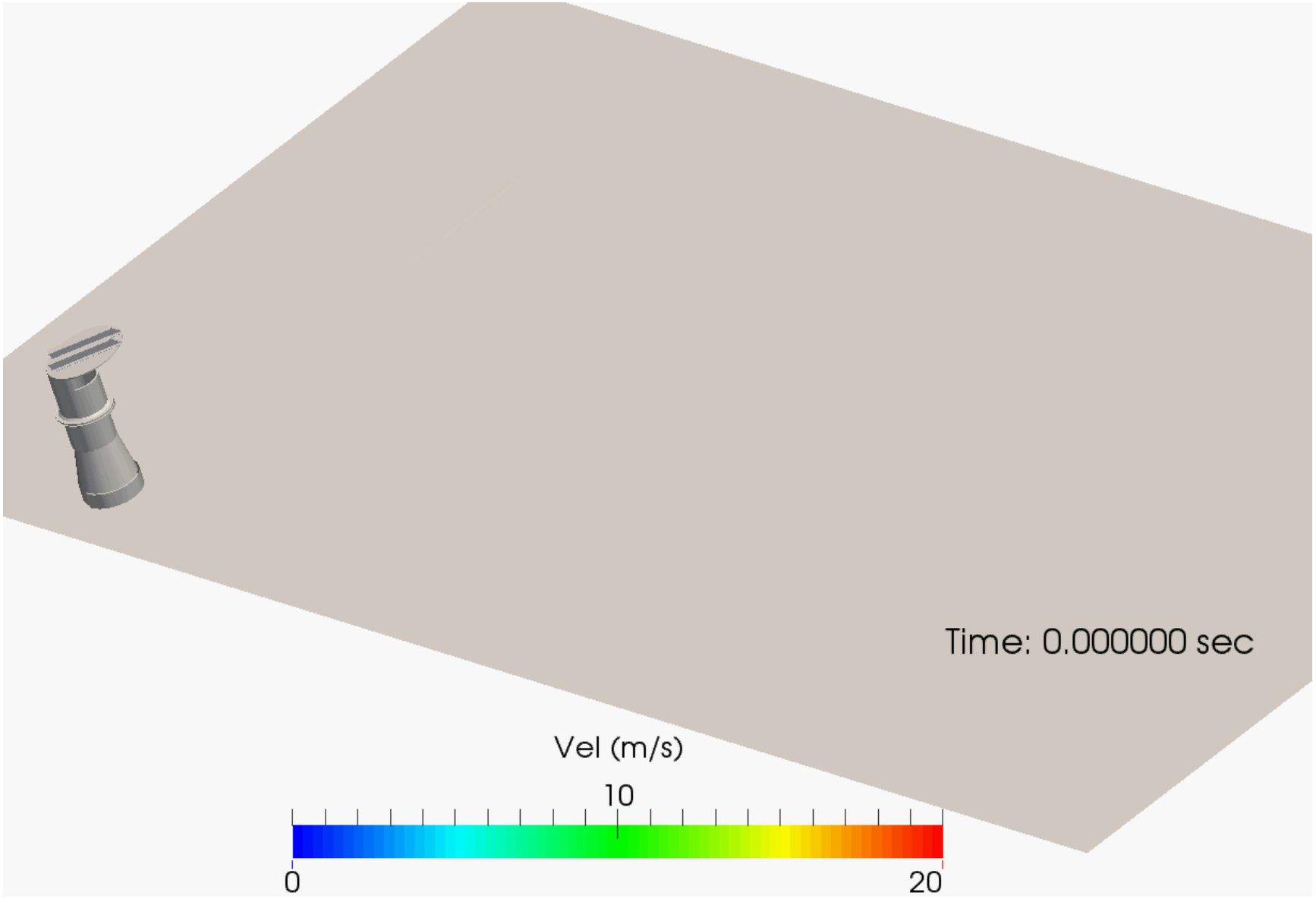
Test case 3



SPH Rainbird



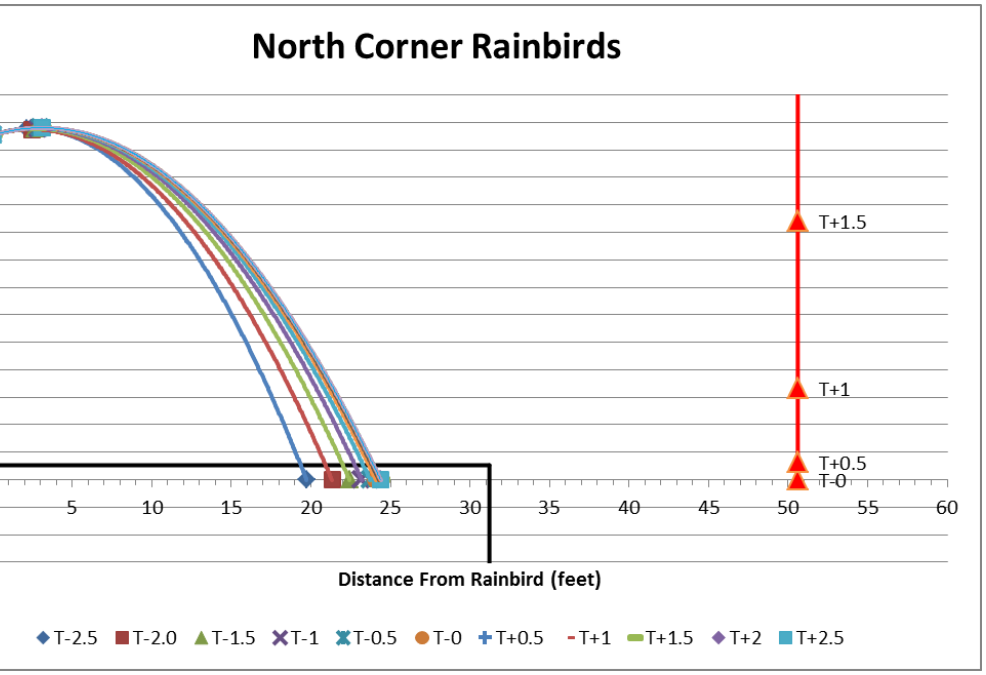
SPH Rainbird

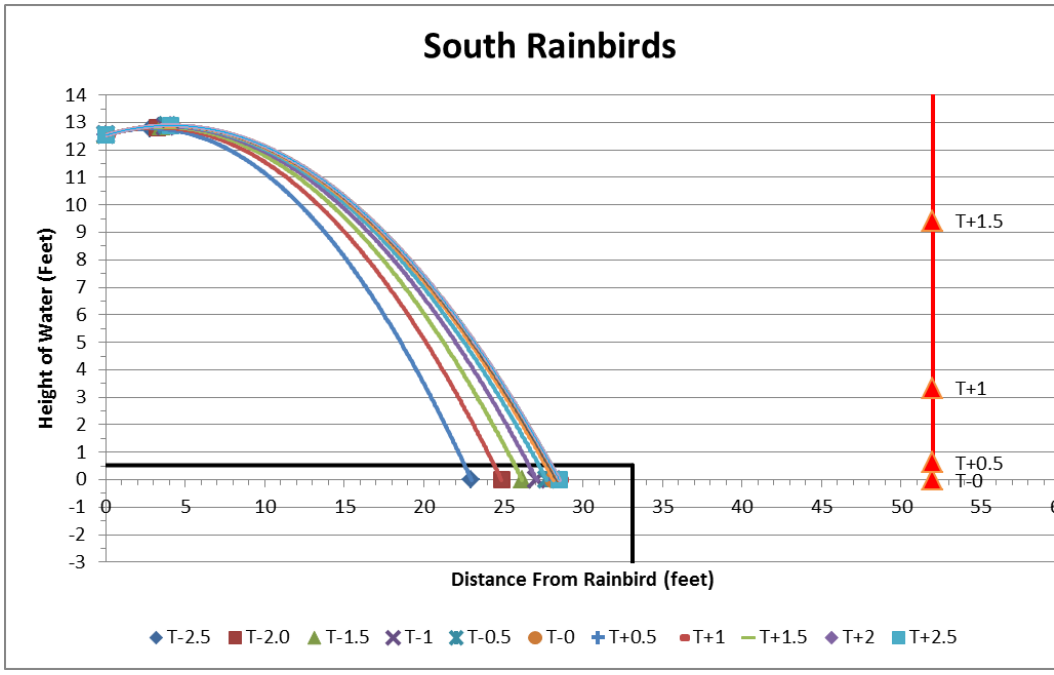


Verification

Traj Plots CSE with bypass (from Nick Moss' Rainbird Water Throws)

- North Corner Rainbirds: 28,381 GPM
- South Rainbirds: 56,762 GPM

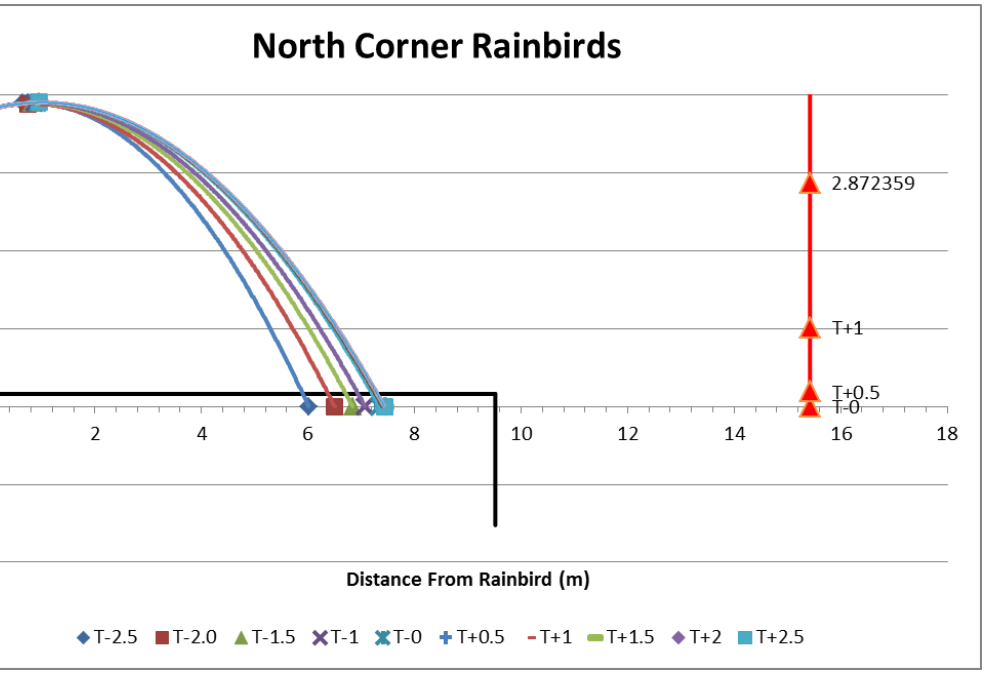


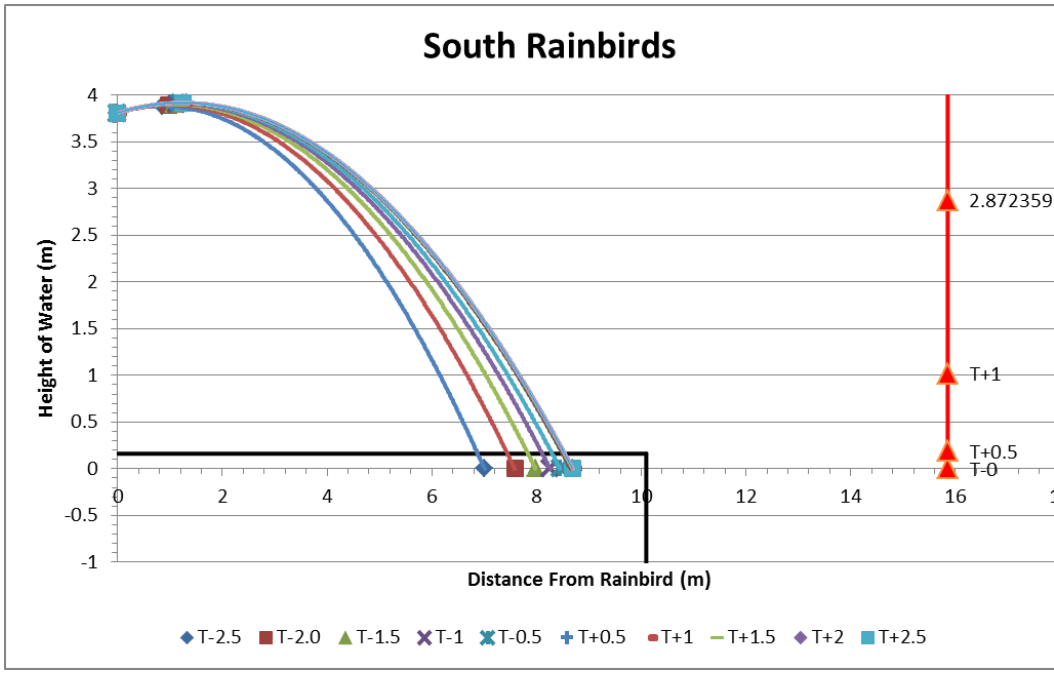


Verification

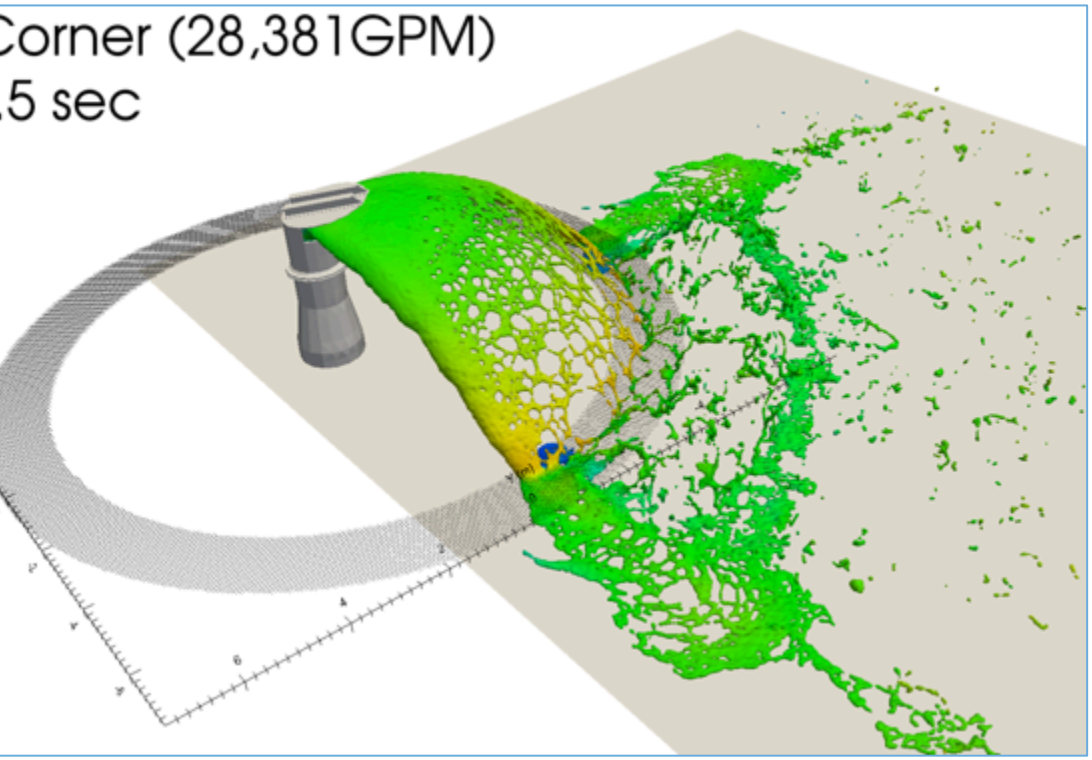
Traj Plots CSE with bypass (from Nick Moss' Rainbird Water Throws)

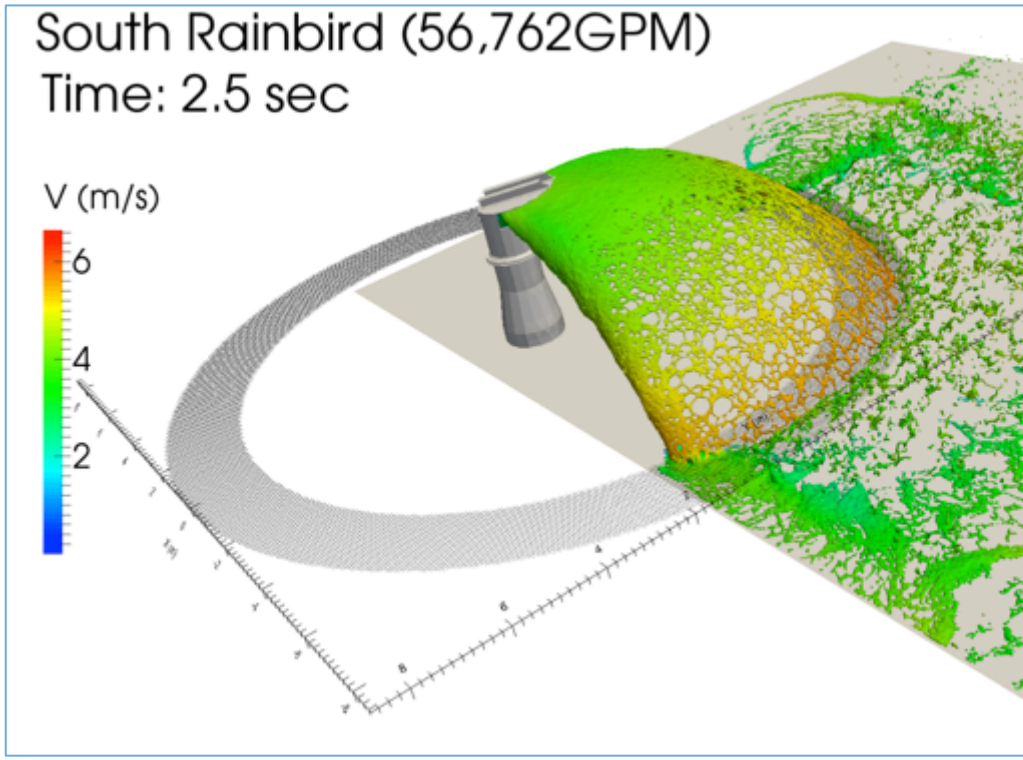
- North Corner Rainbirds: 6.01m – 7.433m
- South Rainbirds: 7.0m – 8.7m



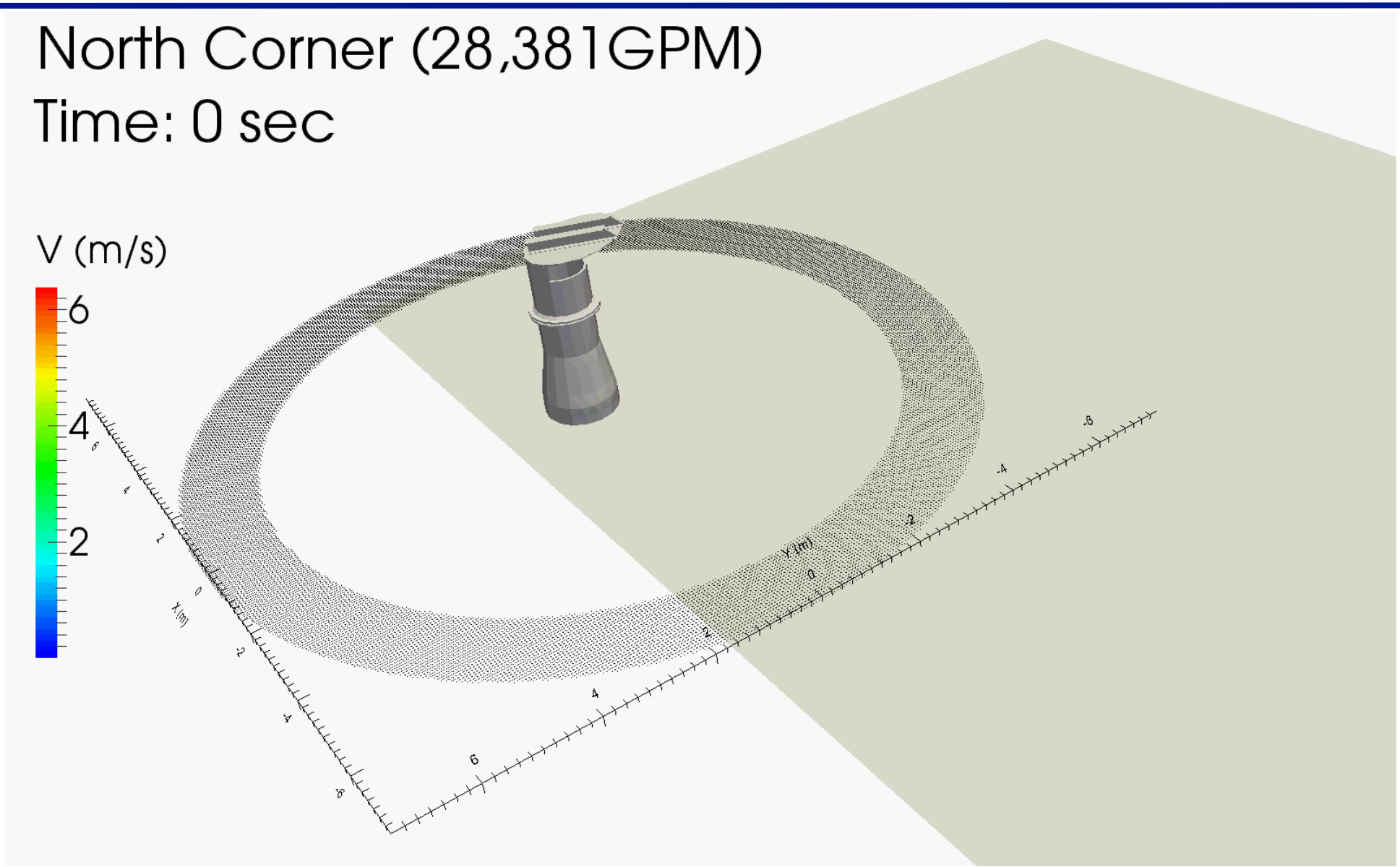


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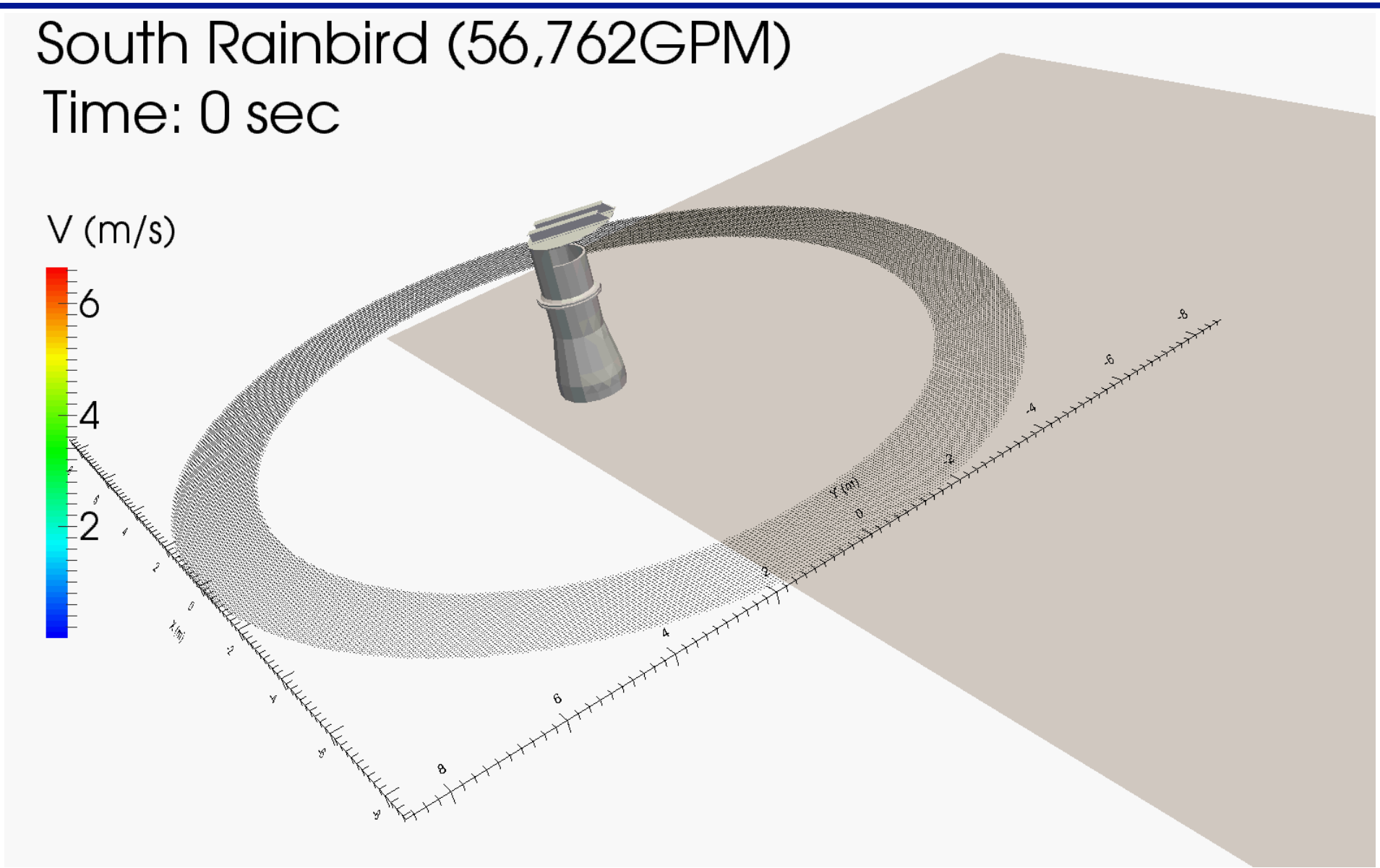




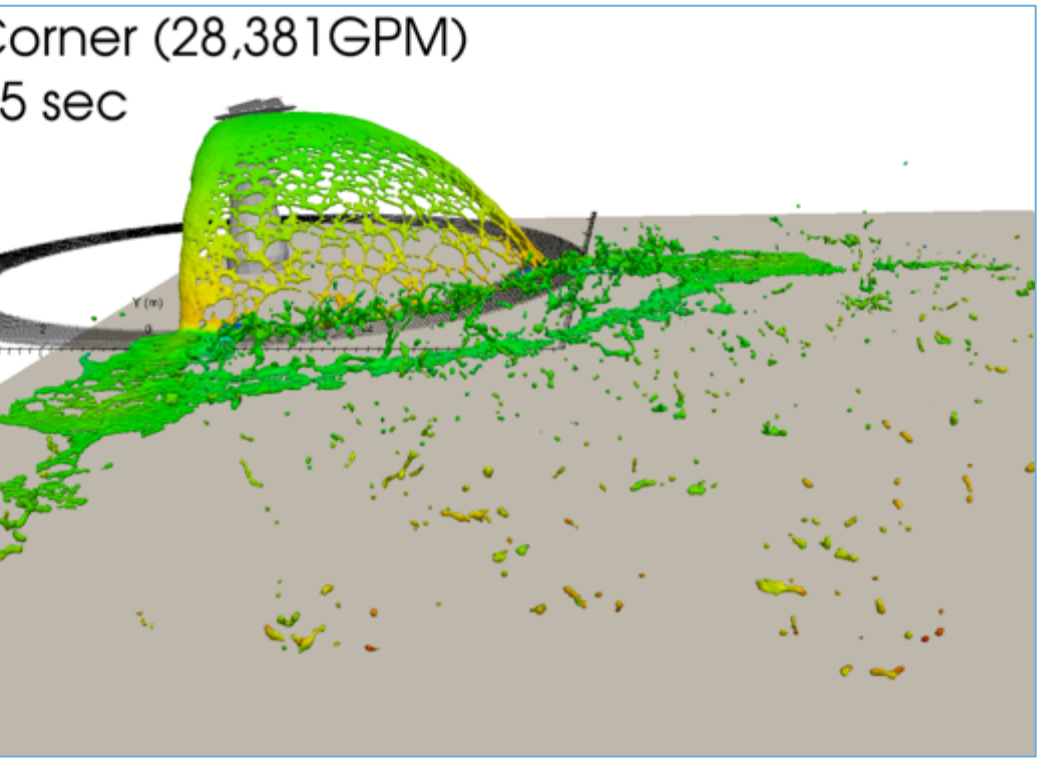
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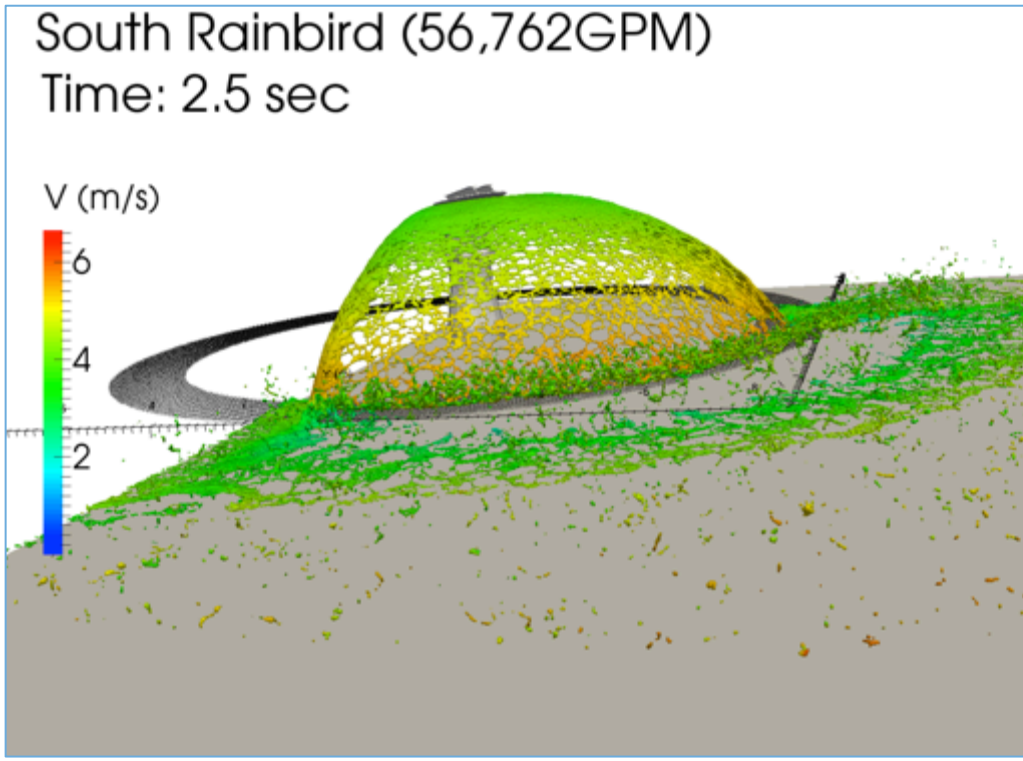


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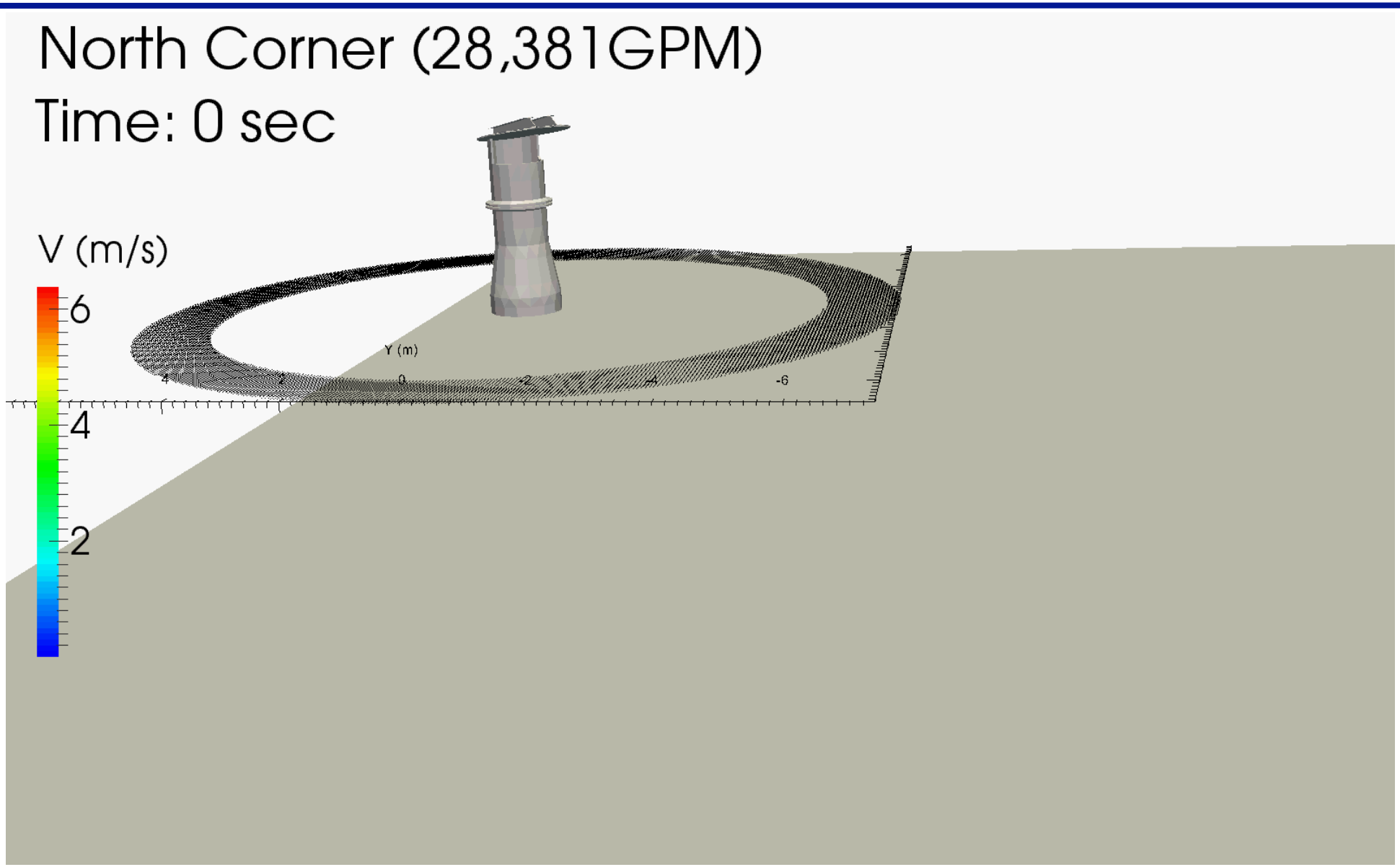


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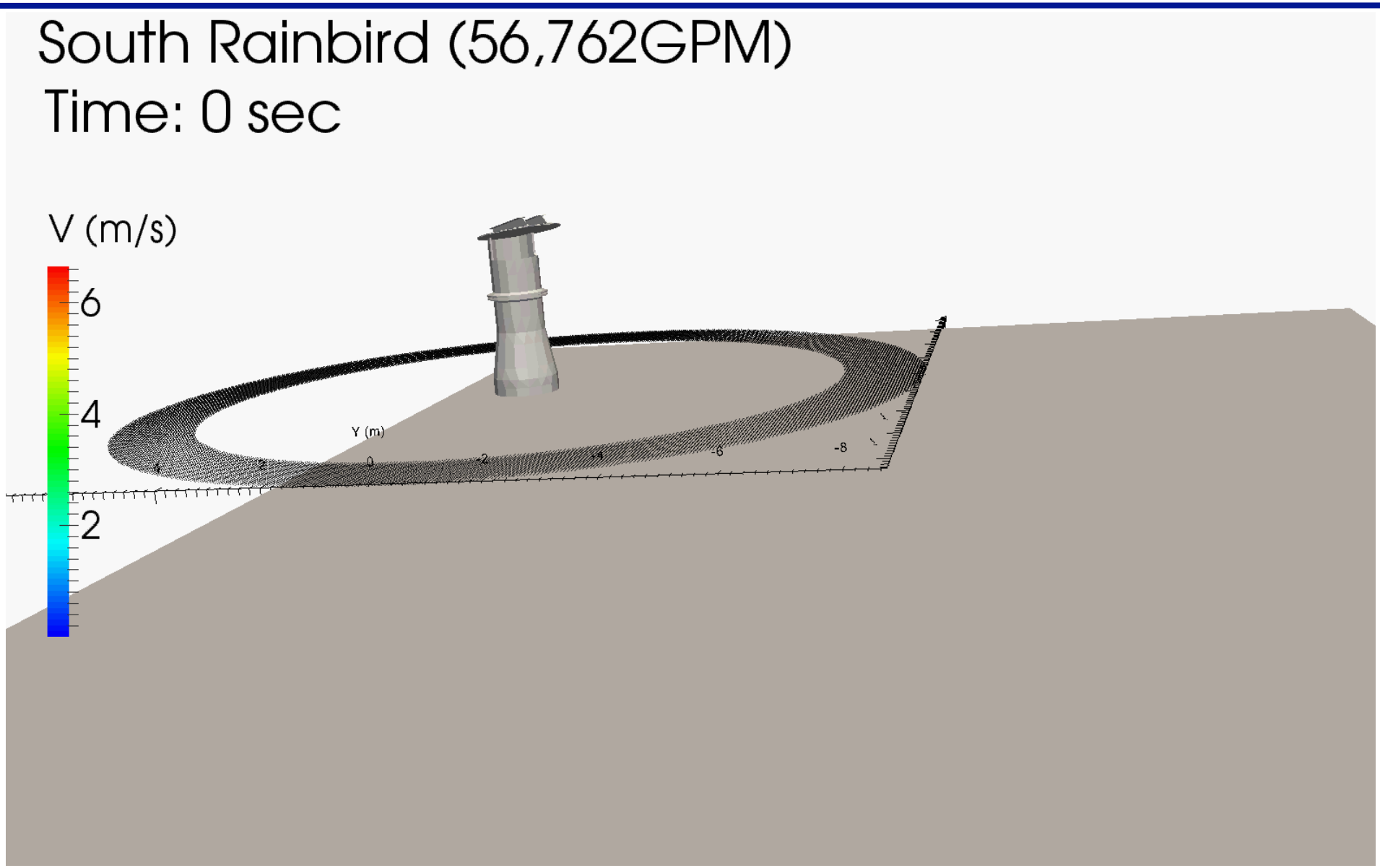




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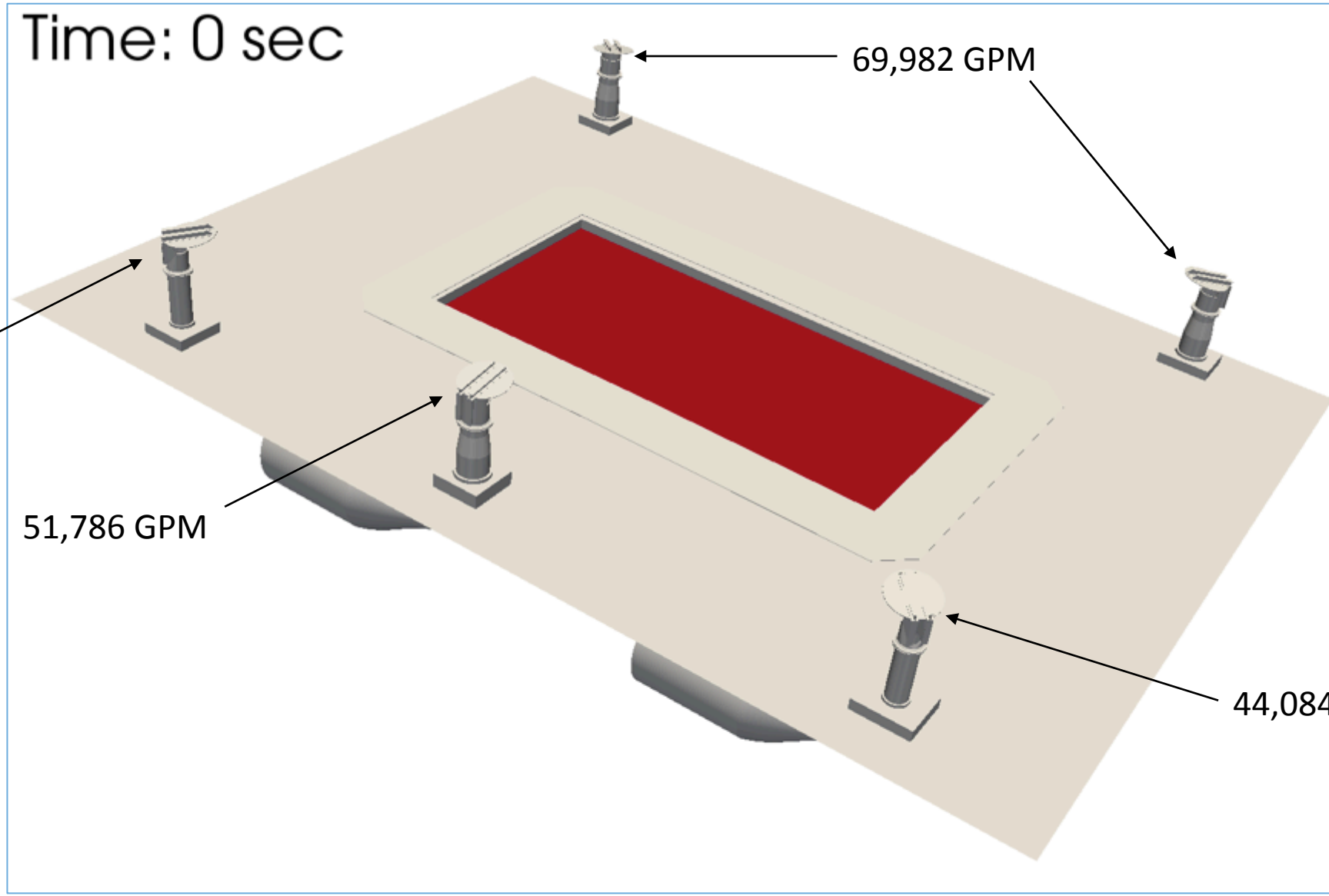
Verification



Verification

time=3.5s

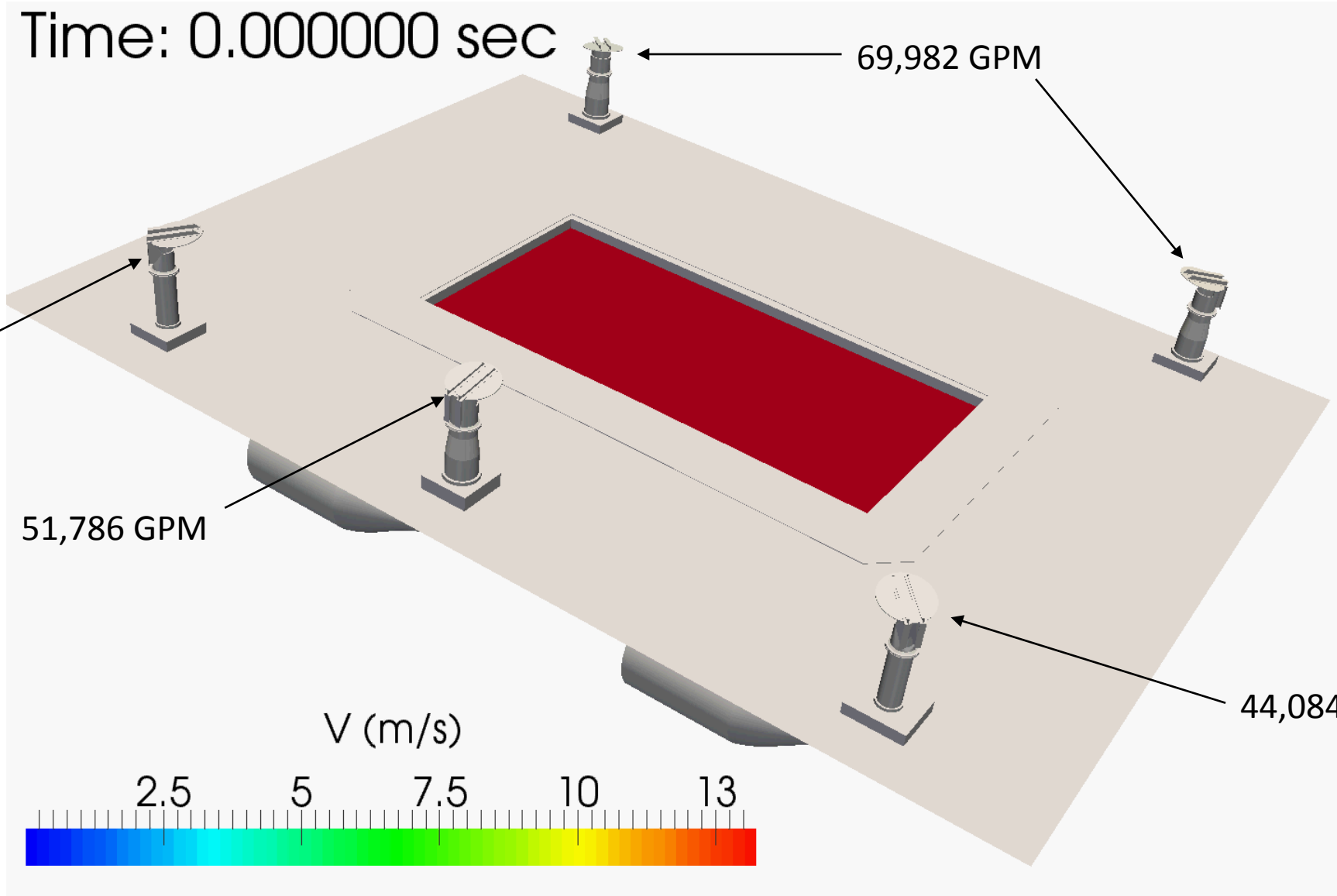
time=6.5s



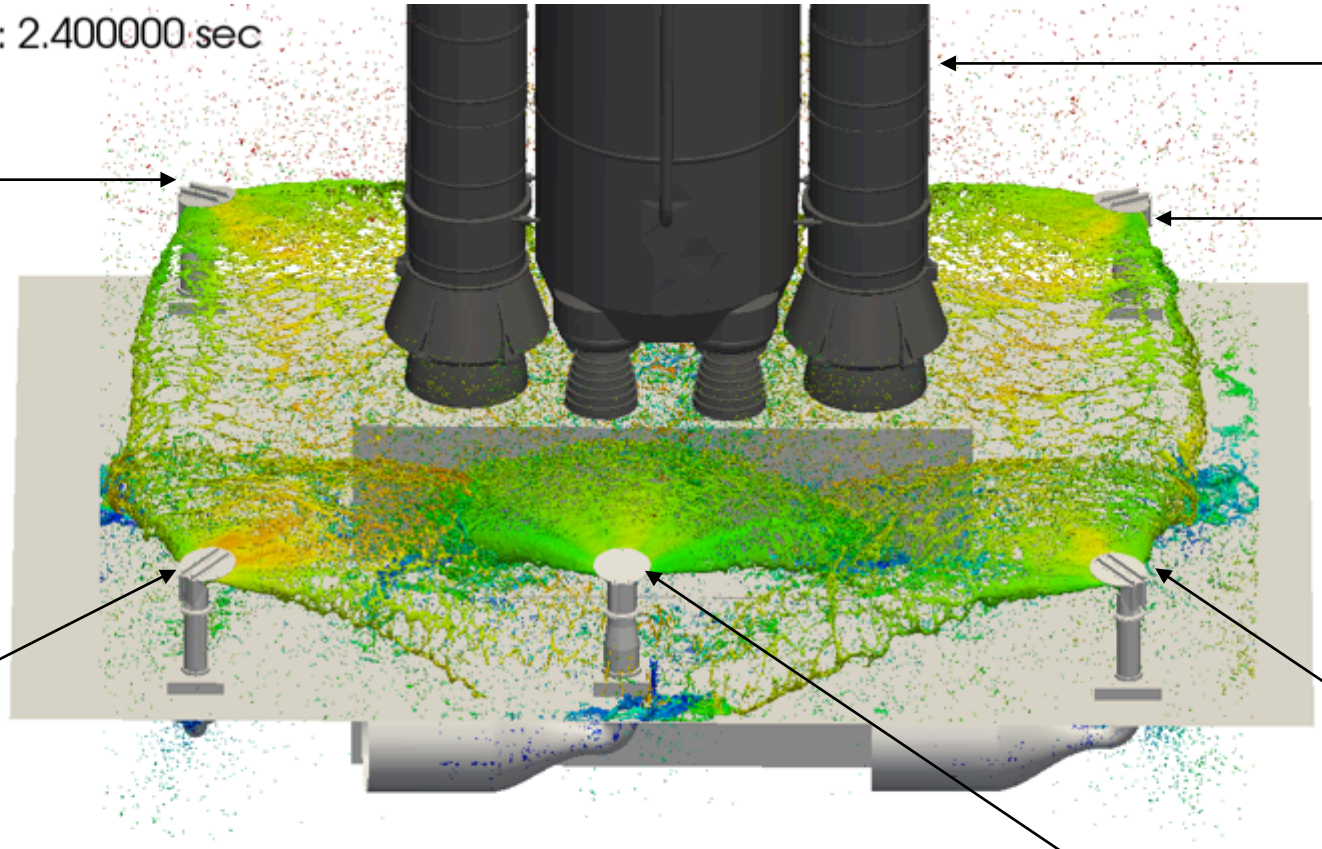
Verification

time=3.5s

time=6.5s



Full Simulations



5,000 GPM

2 m

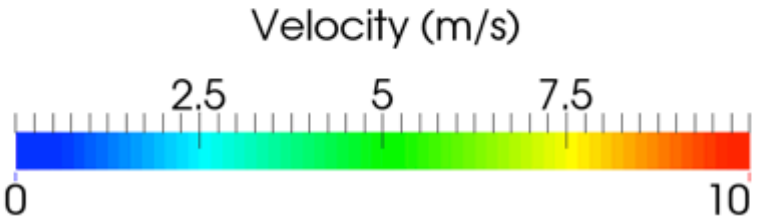
115,00

2,491 GPM

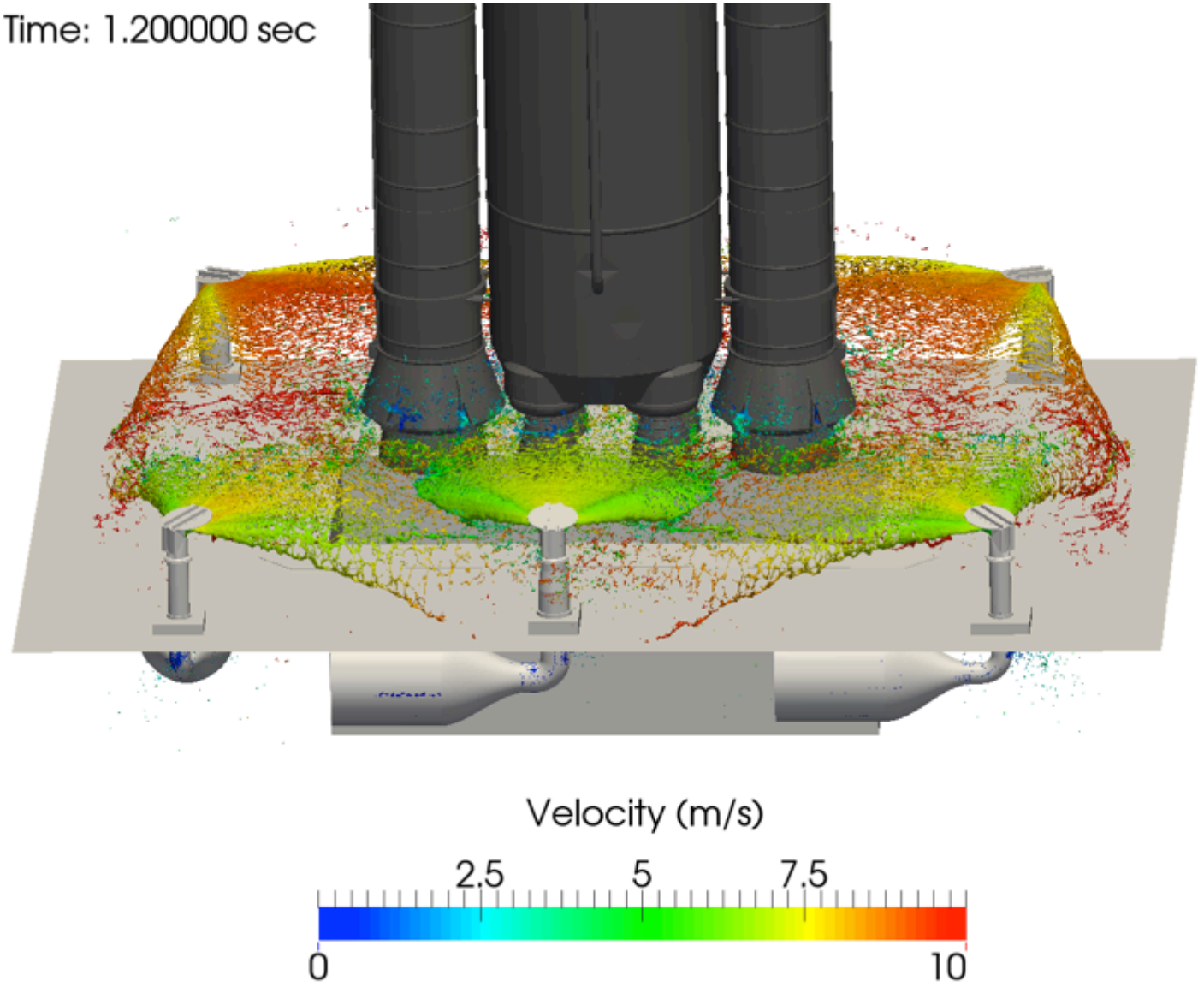
72,491

85,150 GPM

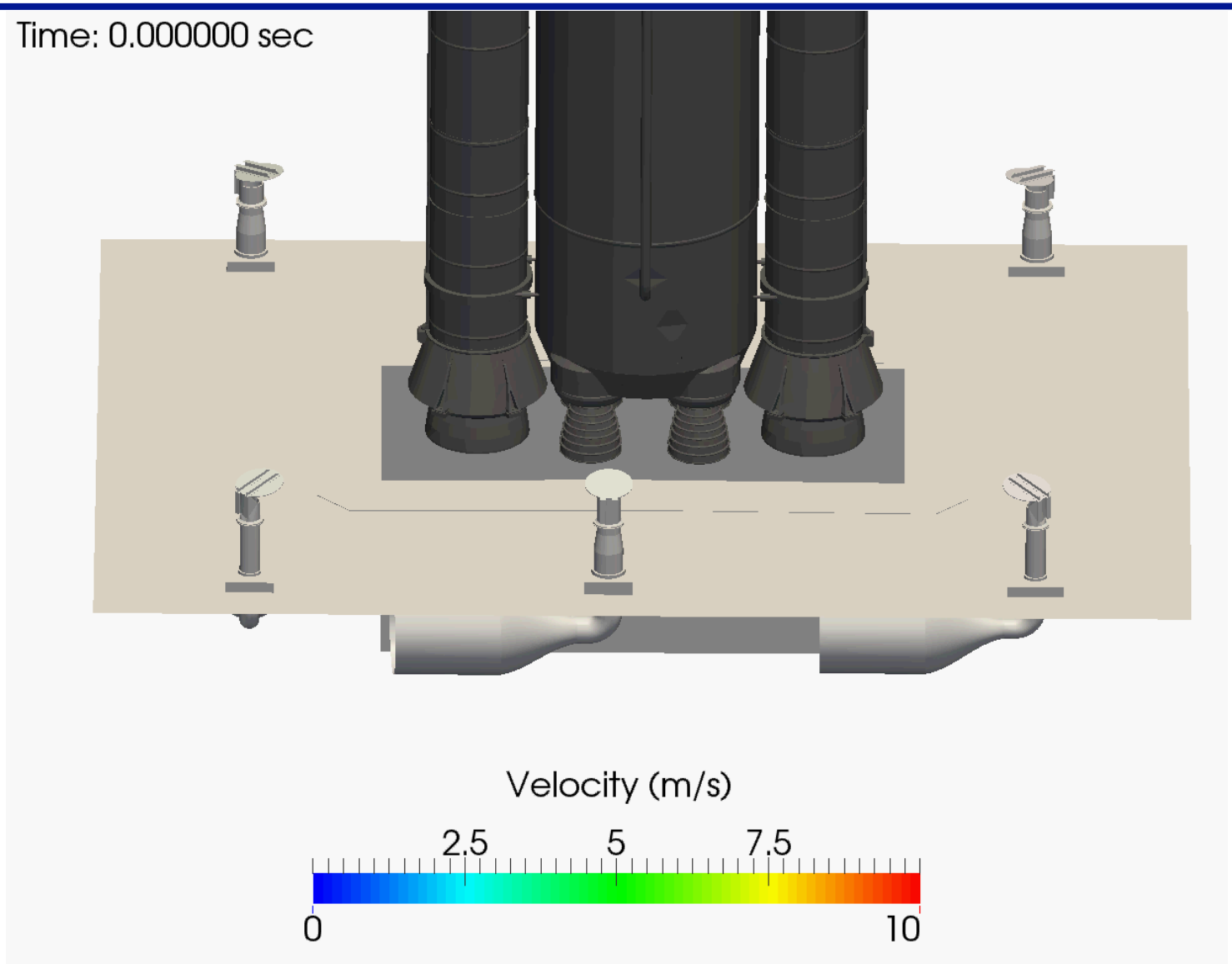
volume flow was
on a maximum
al rainbird flow
T-10 to T+20sec



Full Simulations



Full Simulations



Next Iteration

- Correct rainbird flow timing and volume flow rates; make it variable ba
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 exh
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

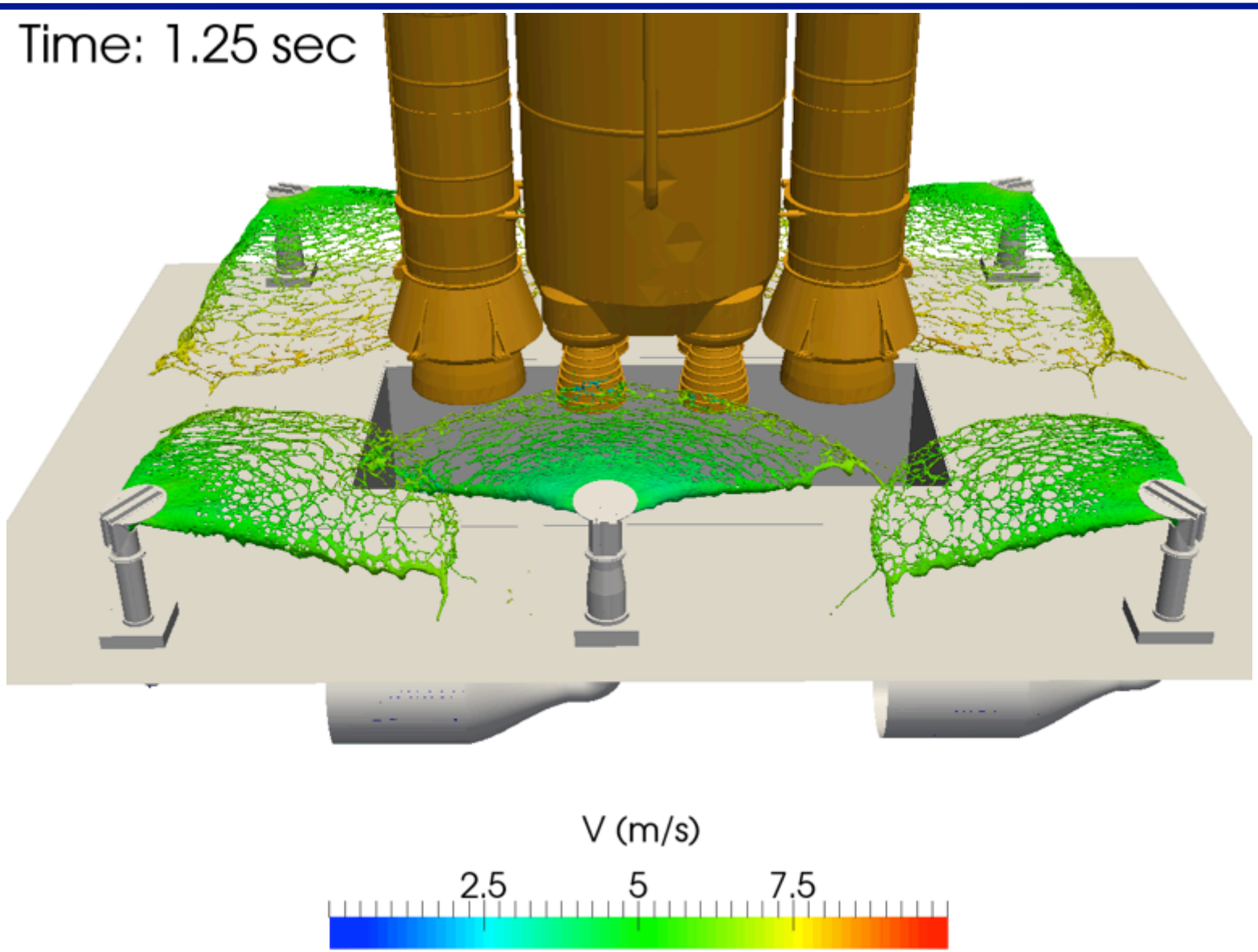
		vel (m/s)				
NE	NC	NW	SE/SW	NE/NW	NC	SE/SW
0.2368	0.2781	0.2368	0.3759			
0.2367	0.2781	0.2367	0.3758			
0.2377	0.2793	0.2377	0.3774			
0.2376	0.2791	0.2376	0.3772			
0.2440	0.2867	0.2440	0.3874			
0.2662	0.3127	0.2662	0.4226			
0.2710	0.3183	0.2710	0.4301			
0.2724	0.3199	0.2724	0.4323			
0.2757	0.3239	0.2757	0.4377			
0.2966	0.3484	0.2966	0.4708			
0.3024	0.3552	0.3024	0.4800			
0.3047	0.3579	0.3047	0.4837	0.2677	0.3145	0.4250
0.3071	0.3608	0.3071	0.4875			
0.3207	0.3768	0.3207	0.5091			
0.3302	0.3879	0.3302	0.5241			
0.3327	0.3908	0.3327	0.5281			
0.3360	0.3947	0.3360	0.5334			
0.3433	0.4032	0.3433	0.5449			
0.3533	0.4150	0.3533	0.5608			
0.3596	0.4224	0.3596	0.5708			
0.3594	0.4222	0.3594	0.5705			
0.3654	0.4292	0.3654	0.5800	0.3408	0.4003	0.5409
0.3737	0.4389	0.3737	0.5931			
0.3796	0.4459	0.3796	0.6026			
0.3803	0.4467	0.3803	0.6036			
0.3848	0.4520	0.3848	0.6108			
0.3910	0.4593	0.3910	0.6207			
0.3966	0.4659	0.3966	0.6296			

ows Based on 3.5-m Water Tank

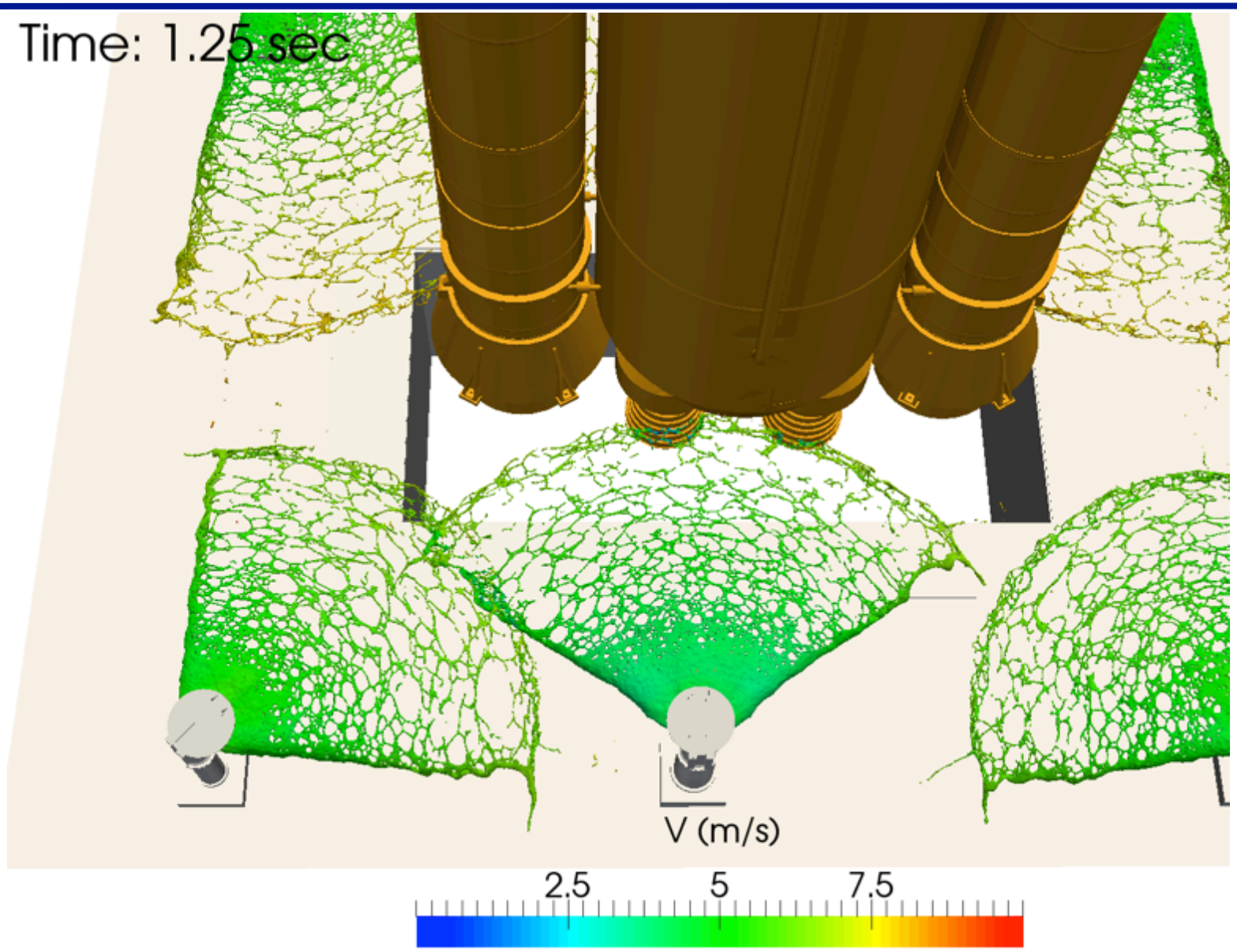
Time (sec)			vel (m/s)				
	NE	NC	NW	SE/SW	NE/NW	NC	SE/SW
2.6034	0.4006	0.4706	0.4006	0.6359			
2.700452	0.4015	0.4716	0.4015	0.6374			
2.805591	0.4069	0.4780	0.4069	0.6459			
2.902642	0.4111	0.4828	0.4111	0.6525	0.3926	0.4612	0.6232
3.007782	0.4165	0.4892	0.4165	0.6611			
3.104833	0.4167	0.4894	0.4167	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	ac
sec	ft	m	m/s	m/
0	0	0		
0.1	0	0	0	
0.2	0	0	0	
0.3	0.12501	0.038103	0.38103	1
0.4	0.333347	0.101604	0.635011	2
0.5	0.625018	0.190505	0.889013	
0.6	1.000021	0.304806	1.143009	2
0.7	1.458358	0.444508	1.397011	
0.8	2.000029	0.609609	1.651013	
0.9	2.625033	0.80011	1.905012	
1	3.33337	1.016011	2.159011	
1.1	4.125041	1.257312	2.413013	
1.2	5.000045	1.524014	2.667012	
1.3	6.39535	1.949303	4.25289	1
1.4	7.8414	2.390059	4.40756	1
1.5	9.42375	2.872359	4.823003	4
1.6	11.1424	3.396204	5.238445	4
1.7	12.99735	3.961592	5.653888	4
1.8	14.9886	4.568525	6.06933	4
1.9	17.11615	5.217003	6.484772	4
2	19.38	5.907024	6.900215	4
2.1	21.78015	6.63859	7.315657	4
2.2	24.3166	7.4117	7.7311	4
2.3	26.98935	8.226354	8.146542	4
2.4	29.7984	9.082552	8.561984	4
2.5	32.74375	9.980295	8.977427	4
2.6	35.8254	10.91958	9.392869	4
2.7	39.04335	11.90041	9.808312	4
2.8	42.3976	12.92279	10.22375	4
2.9	45.88815	13.98671	10.6392	4
3	49.515	15.09217	11.05464	4

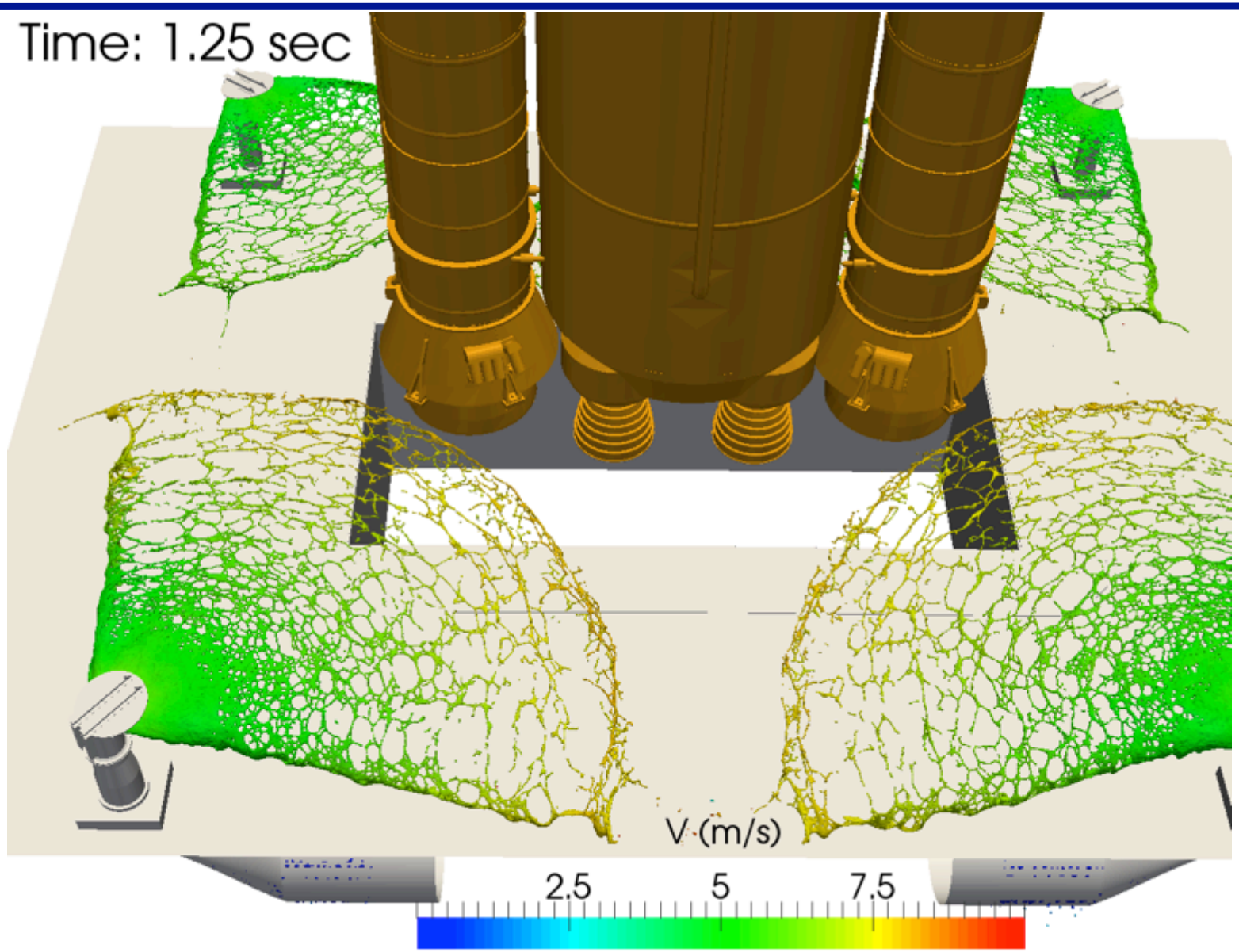
Full Simulations



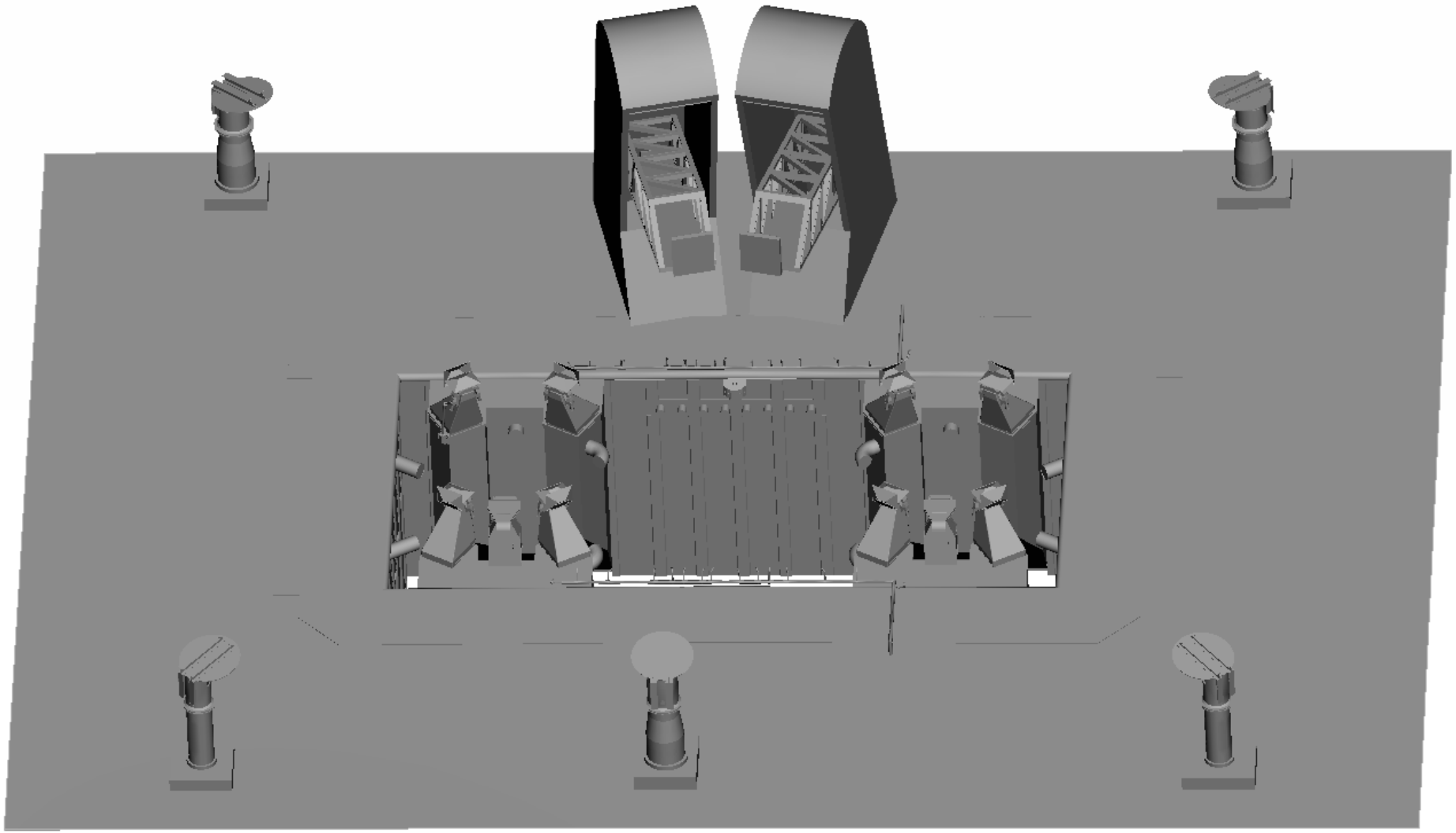
Full Simulations



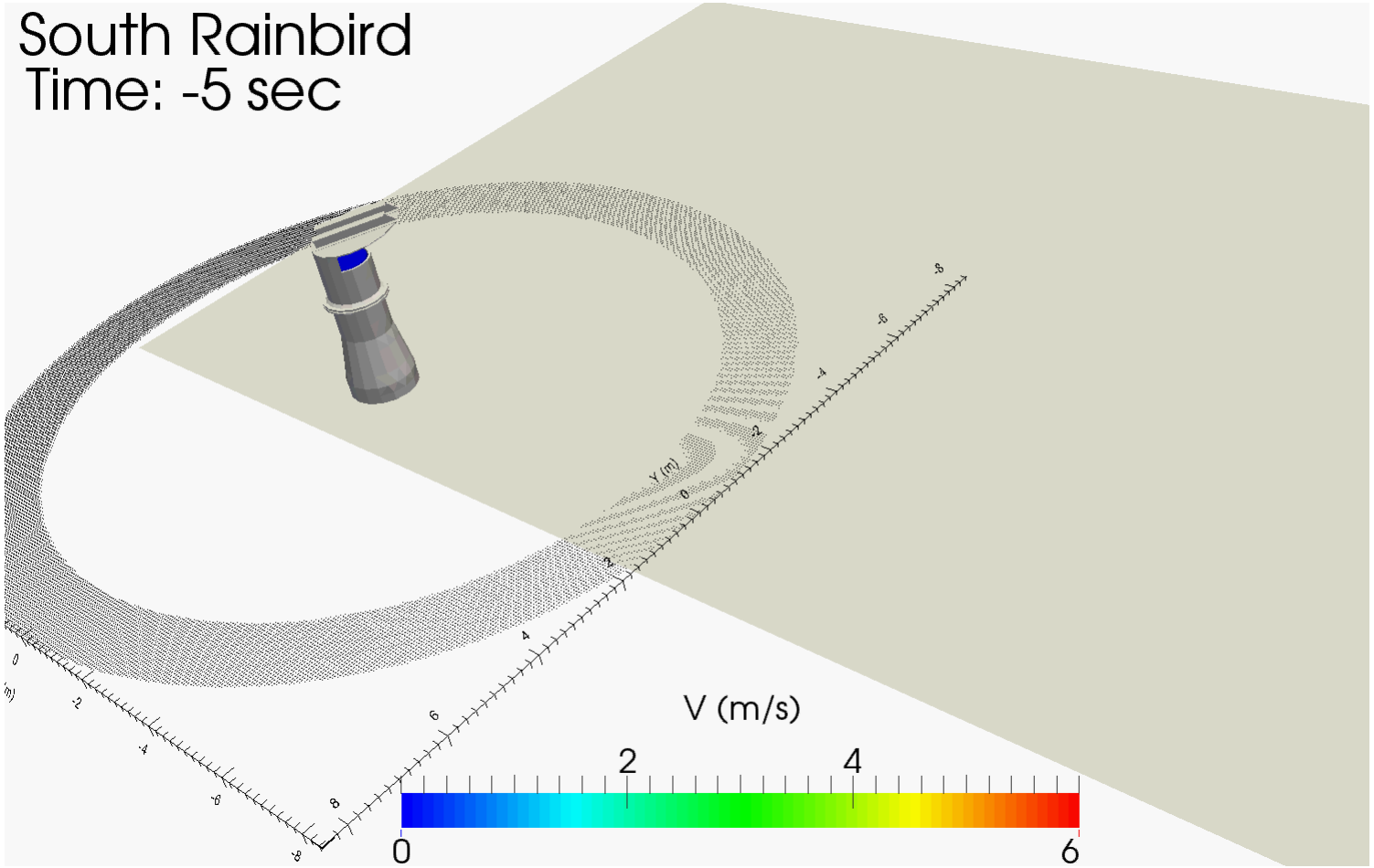
Full Simulations



ML Geometry

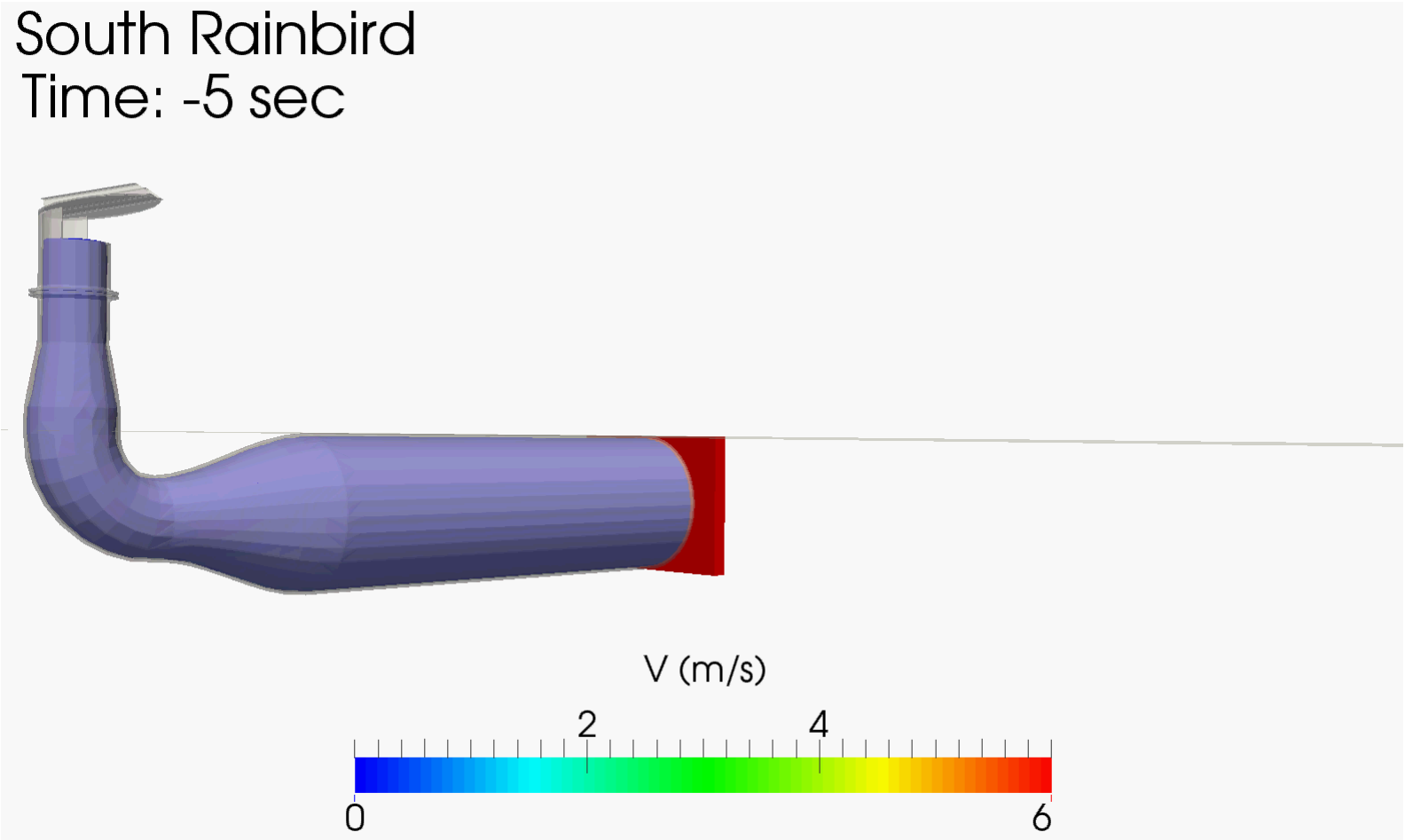


Correct Flow Ramp-up



Peak Flow = 56,76

Correct Flow Ramp-up

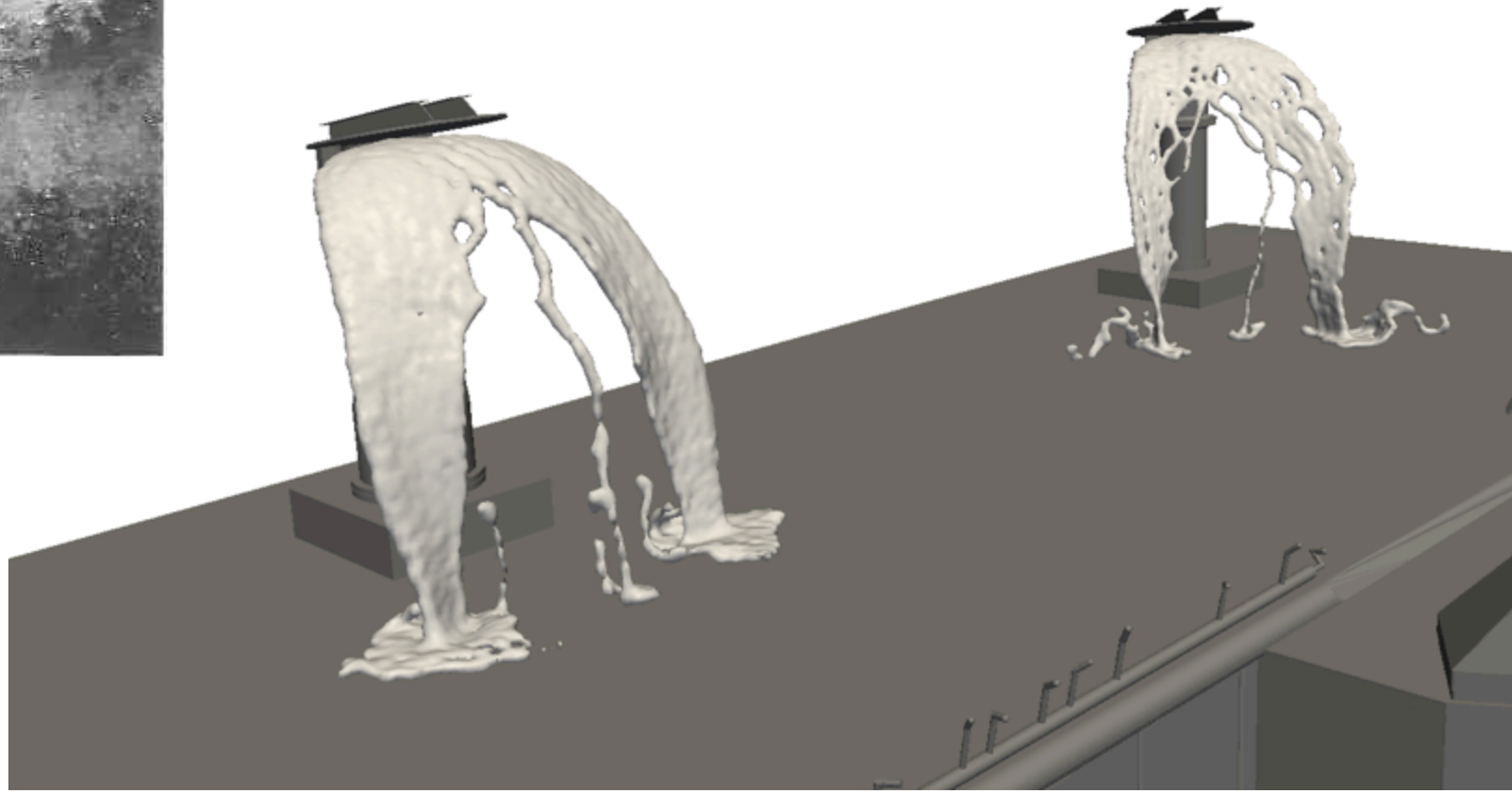


Peak Flow = 56,76

Double Jet

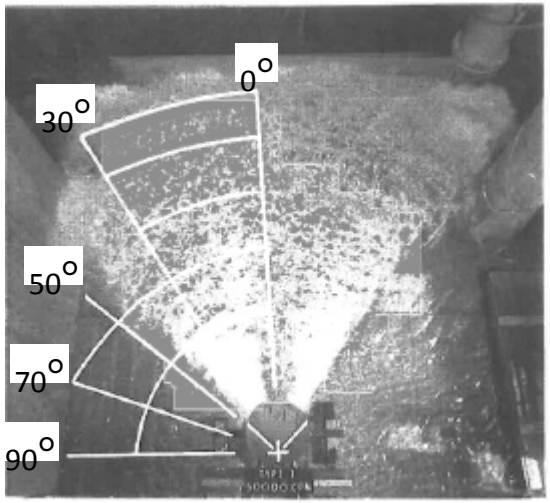
ydraulic Model Studies of Spray Nozzles for a Sound Suppression Water
seph Wetzel and John Ripken, University of Minnesota, March 1977.



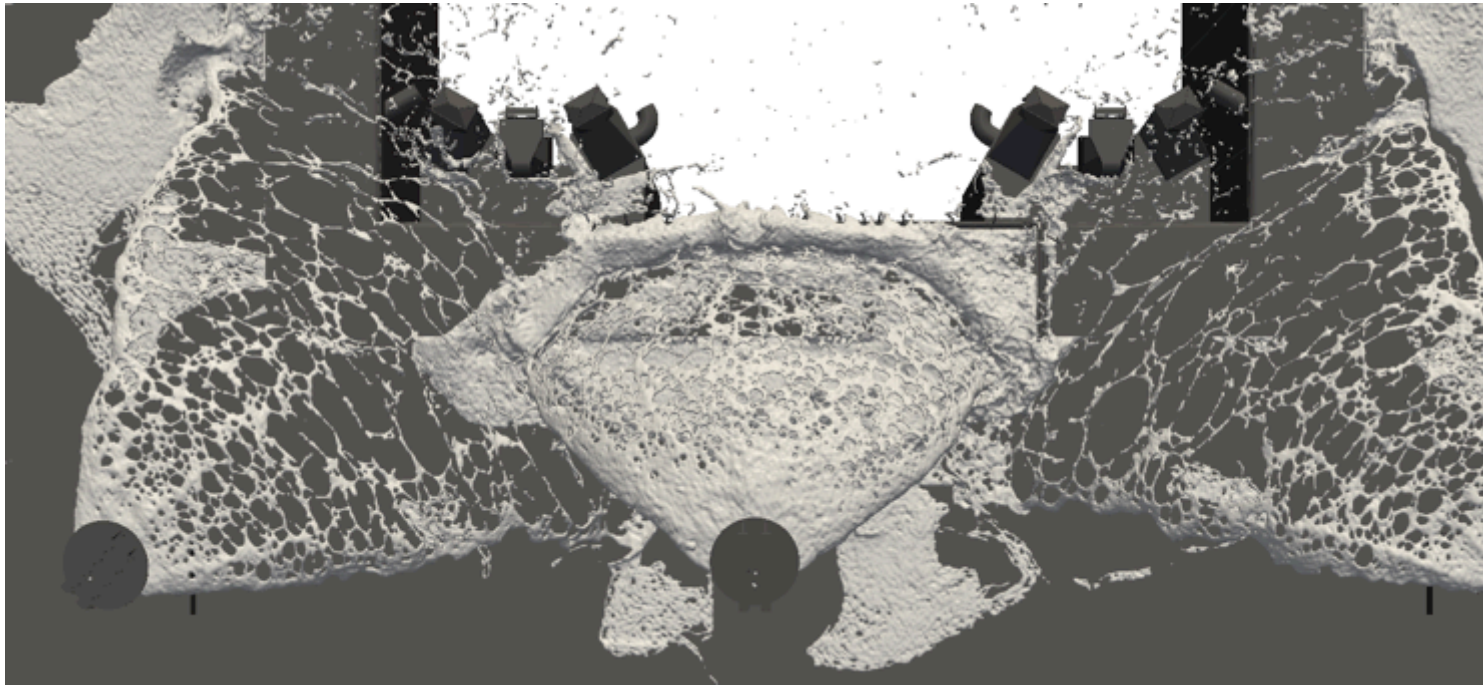


Spray Patterns

ydraulic Model Studies of Spray Nozzles for a Sound Suppression Water
seph Wetzel and John Ripken, University of Minnesota, March 1977.



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



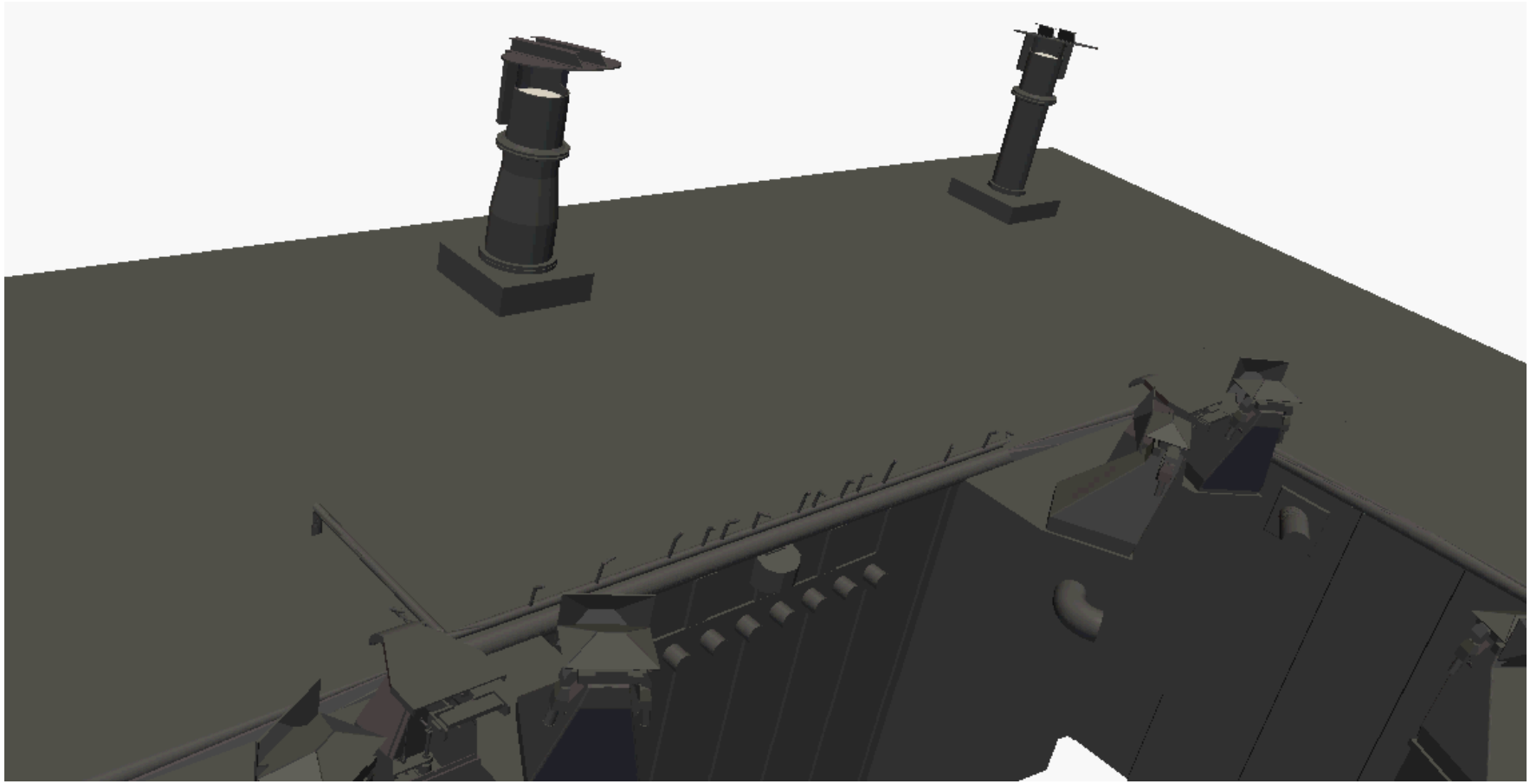
(Not Shown)
Type 2, 40,000 GPM
Nozzle span angle = 190°, Jet fan angle = 150°

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

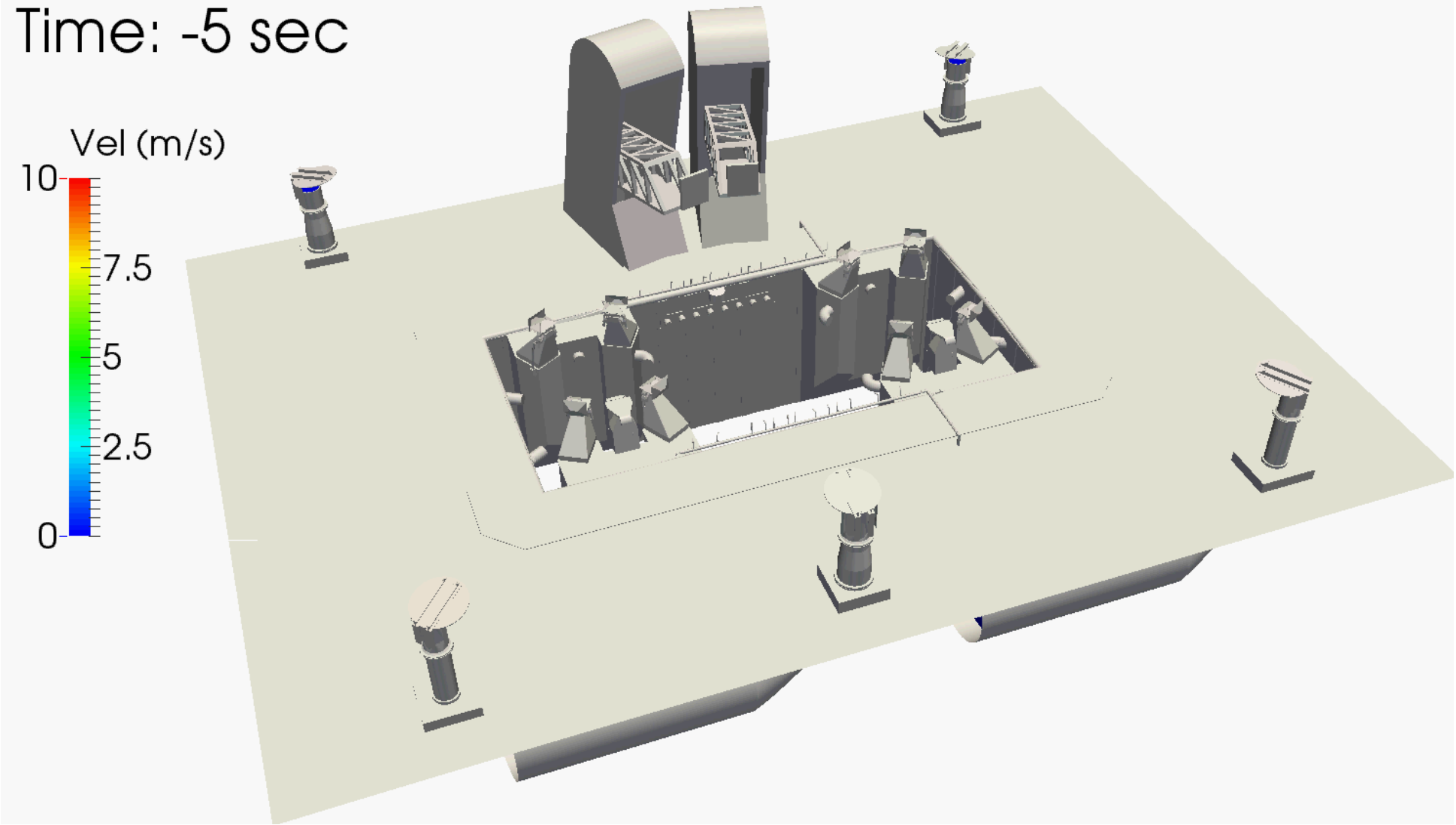
Nozzle span a
Jet fan angl
56,652

- 1:2.8 scale ratio
- Dissimilar pipe transition

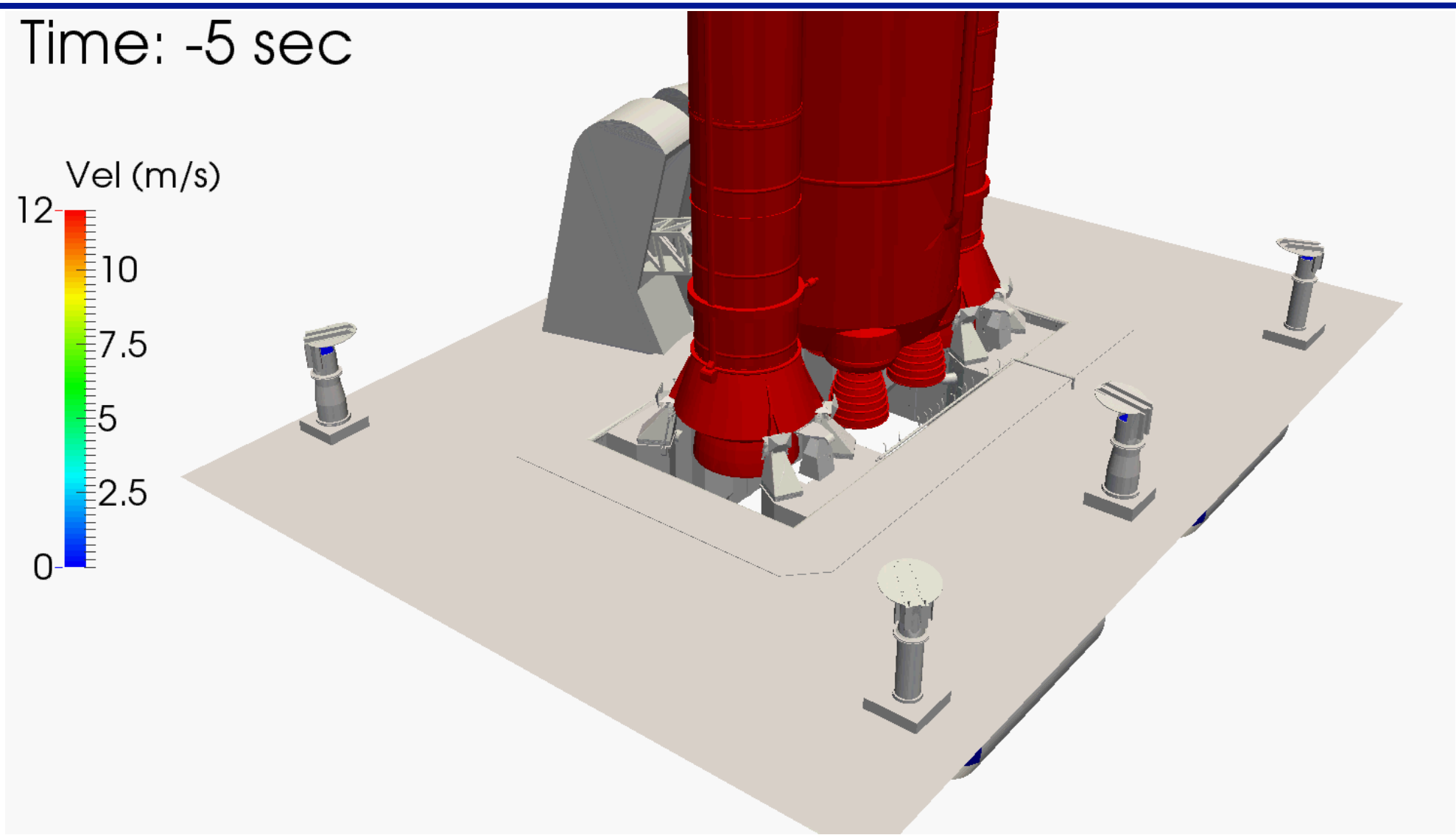
Jet Spray Patterns



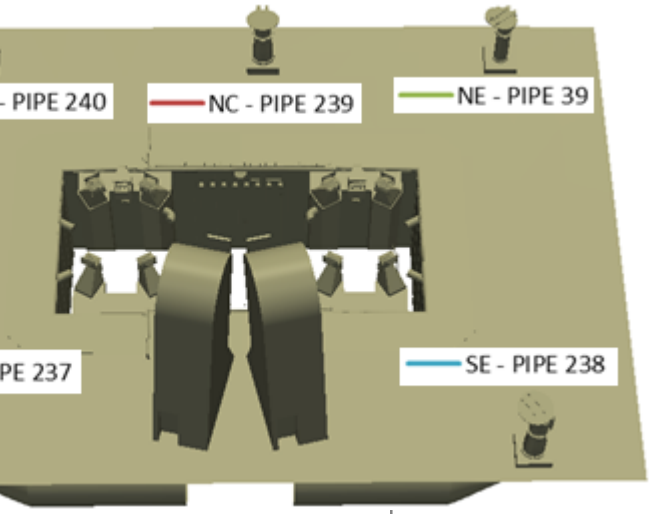
No SLS (-5s to 6.6s)

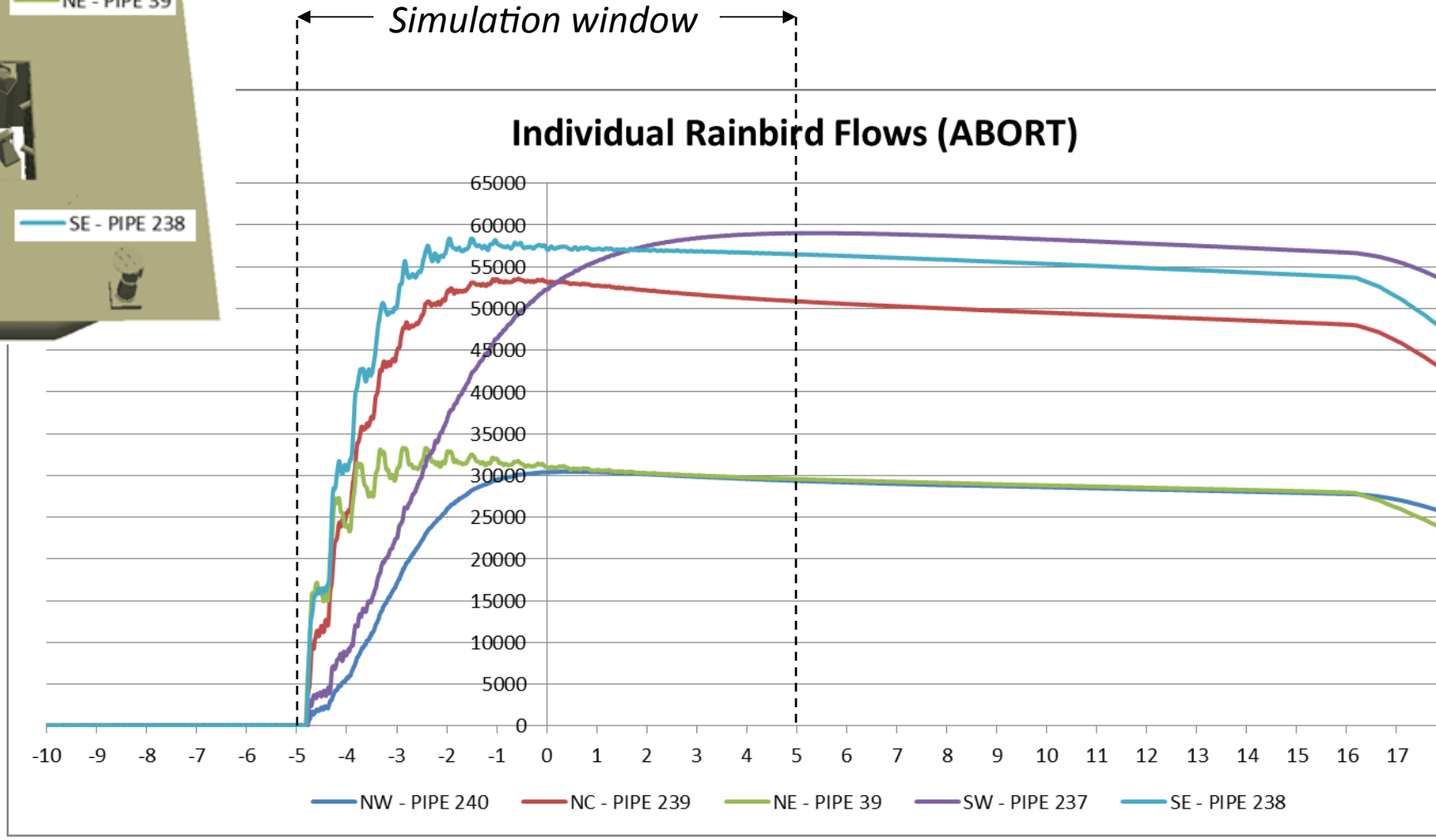


With SLS (-5s to 9s)

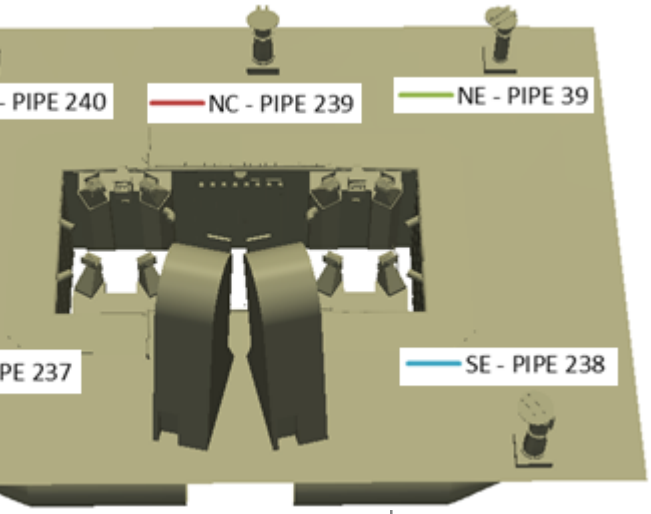


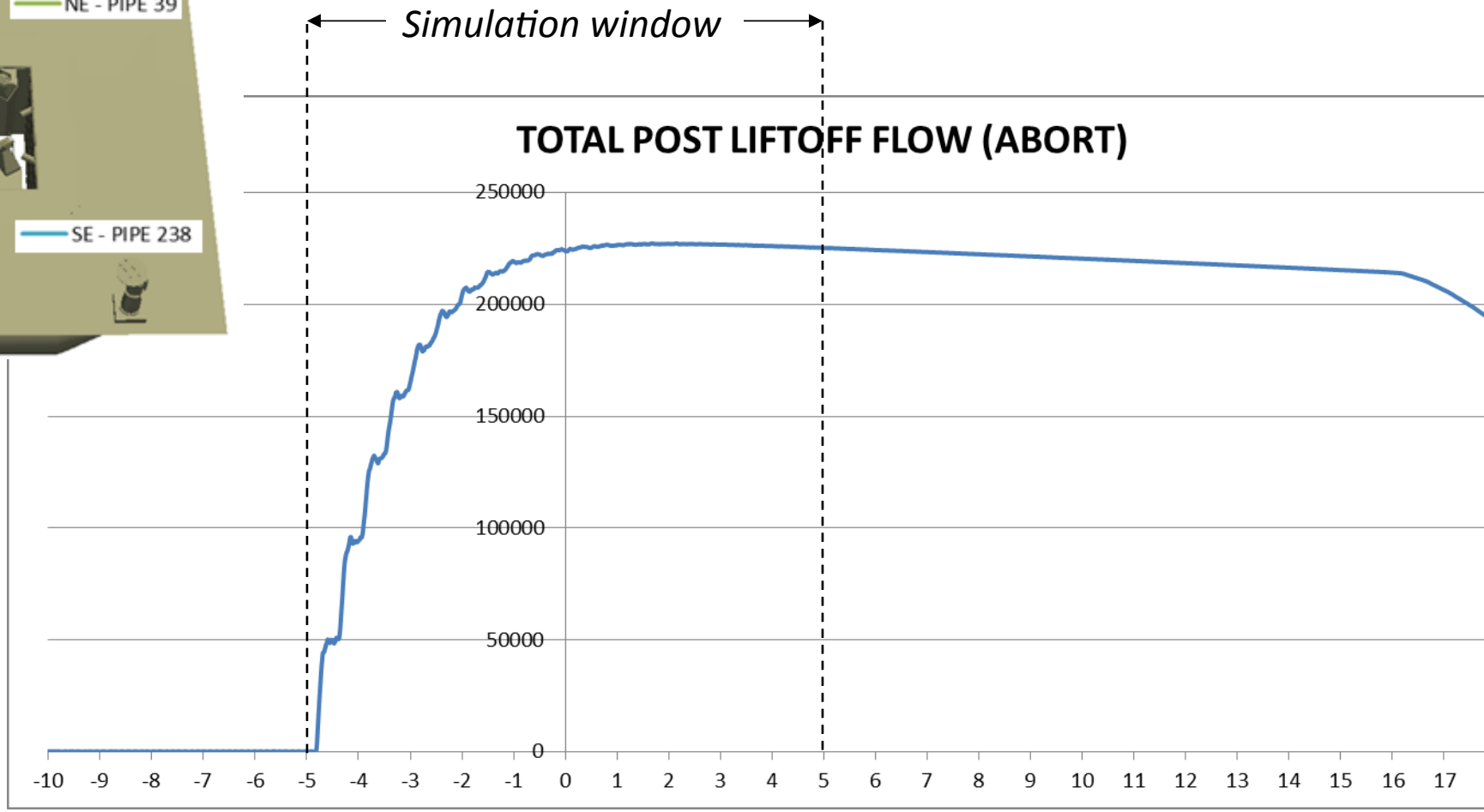
Abort Simulation



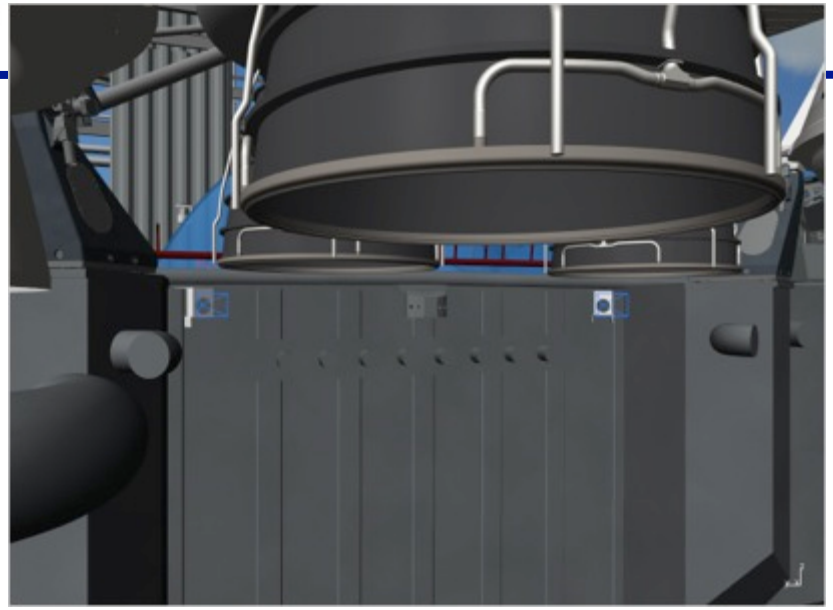


Abort Simulation

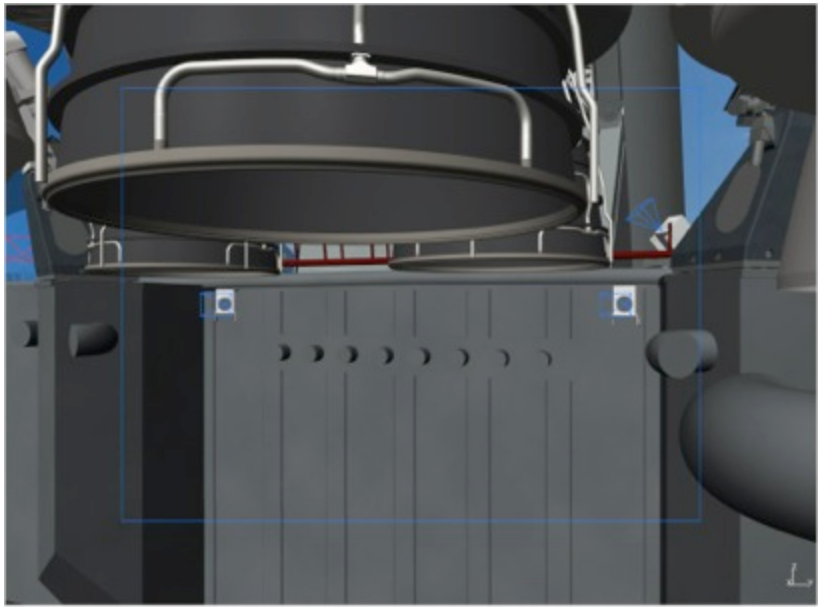




Region of Interest

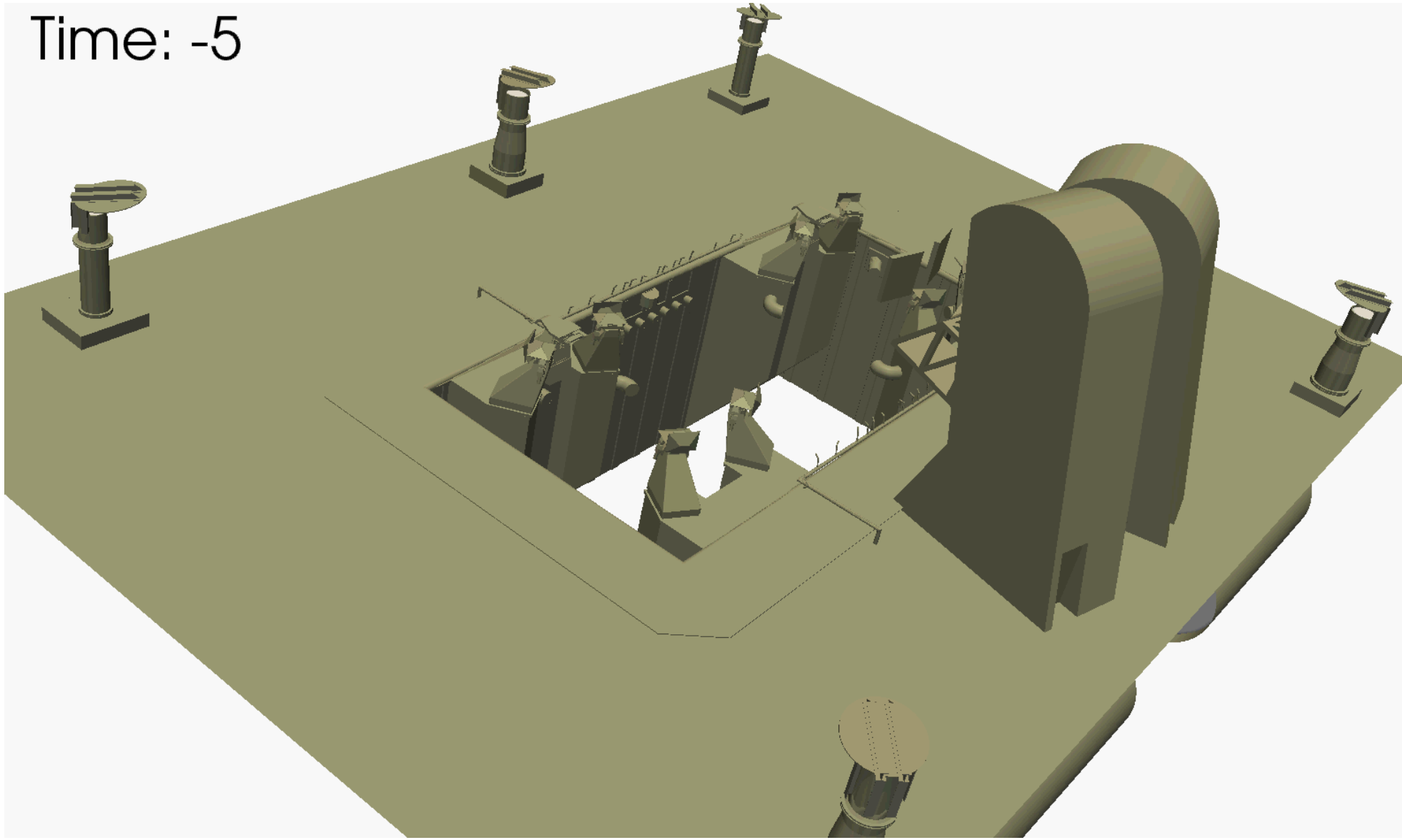




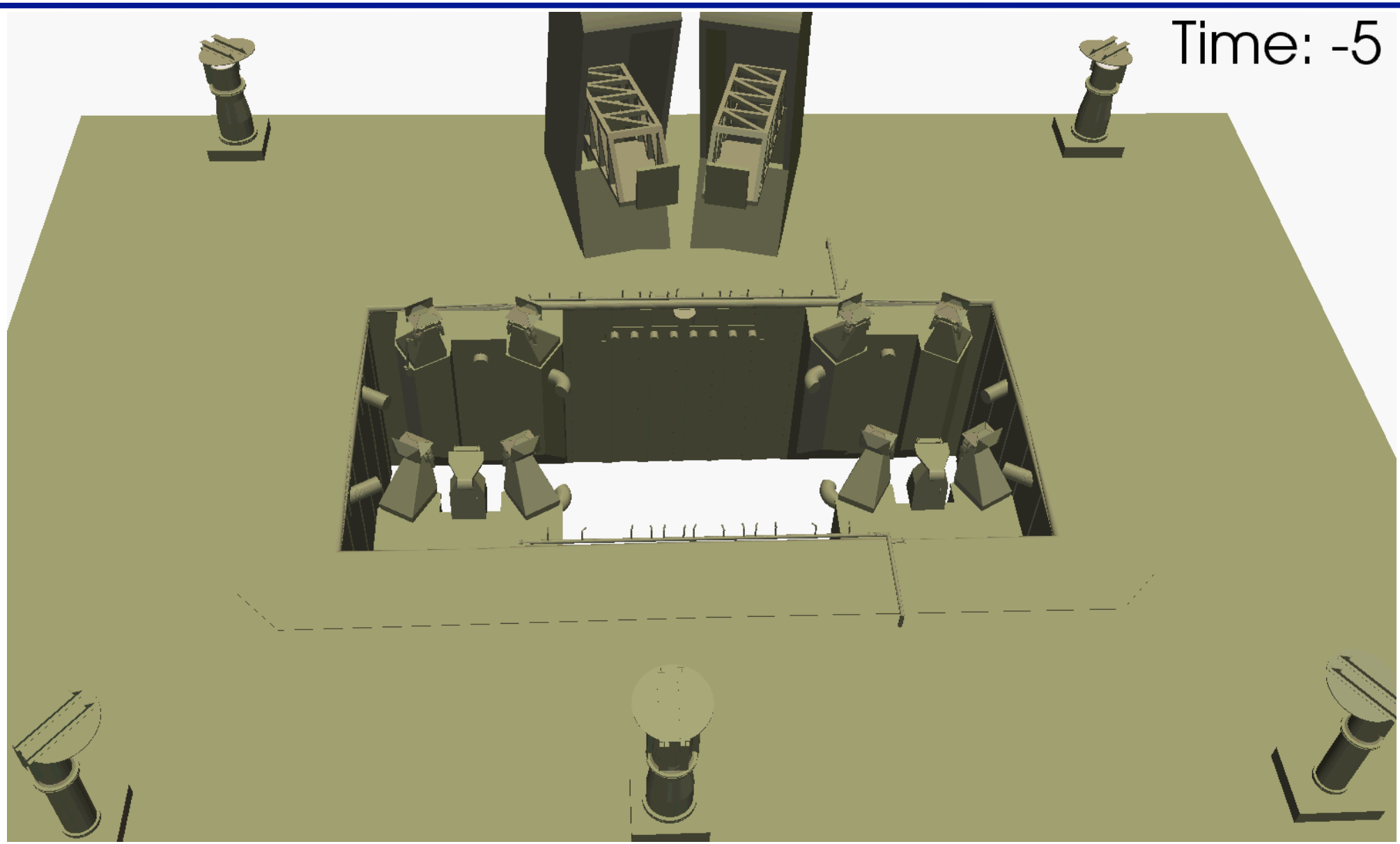




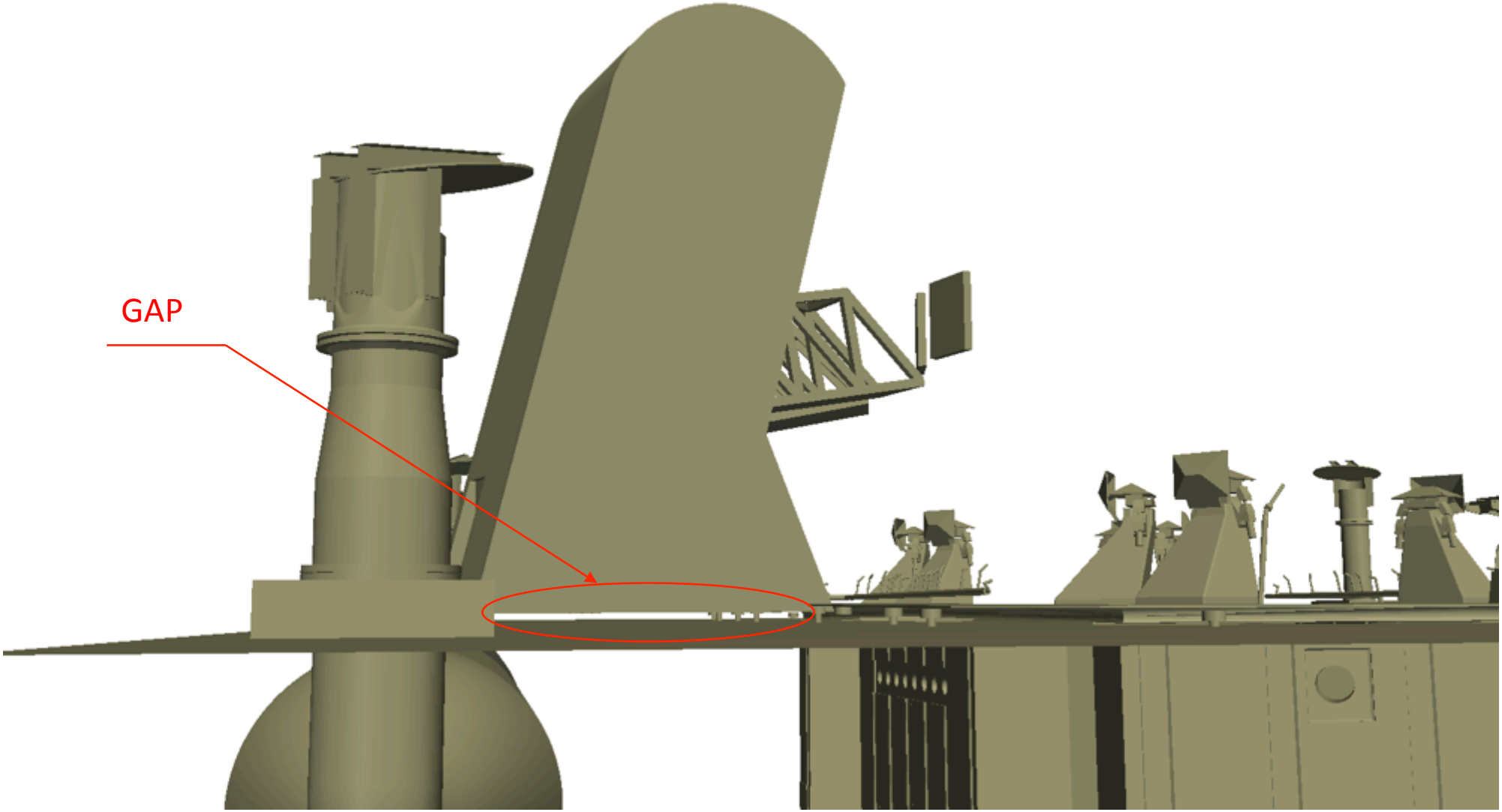
Abort Simulation



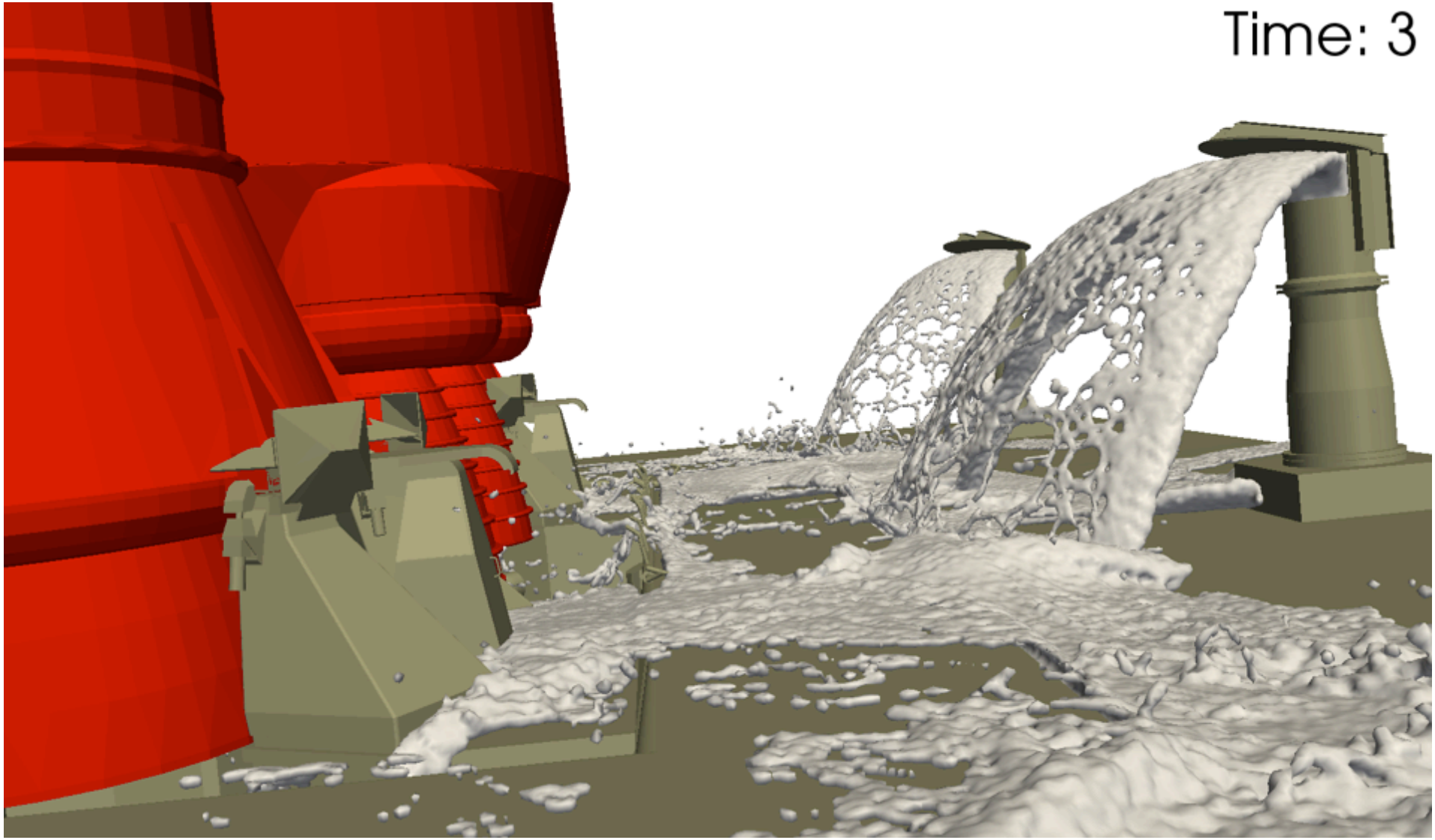
Abort Simulation



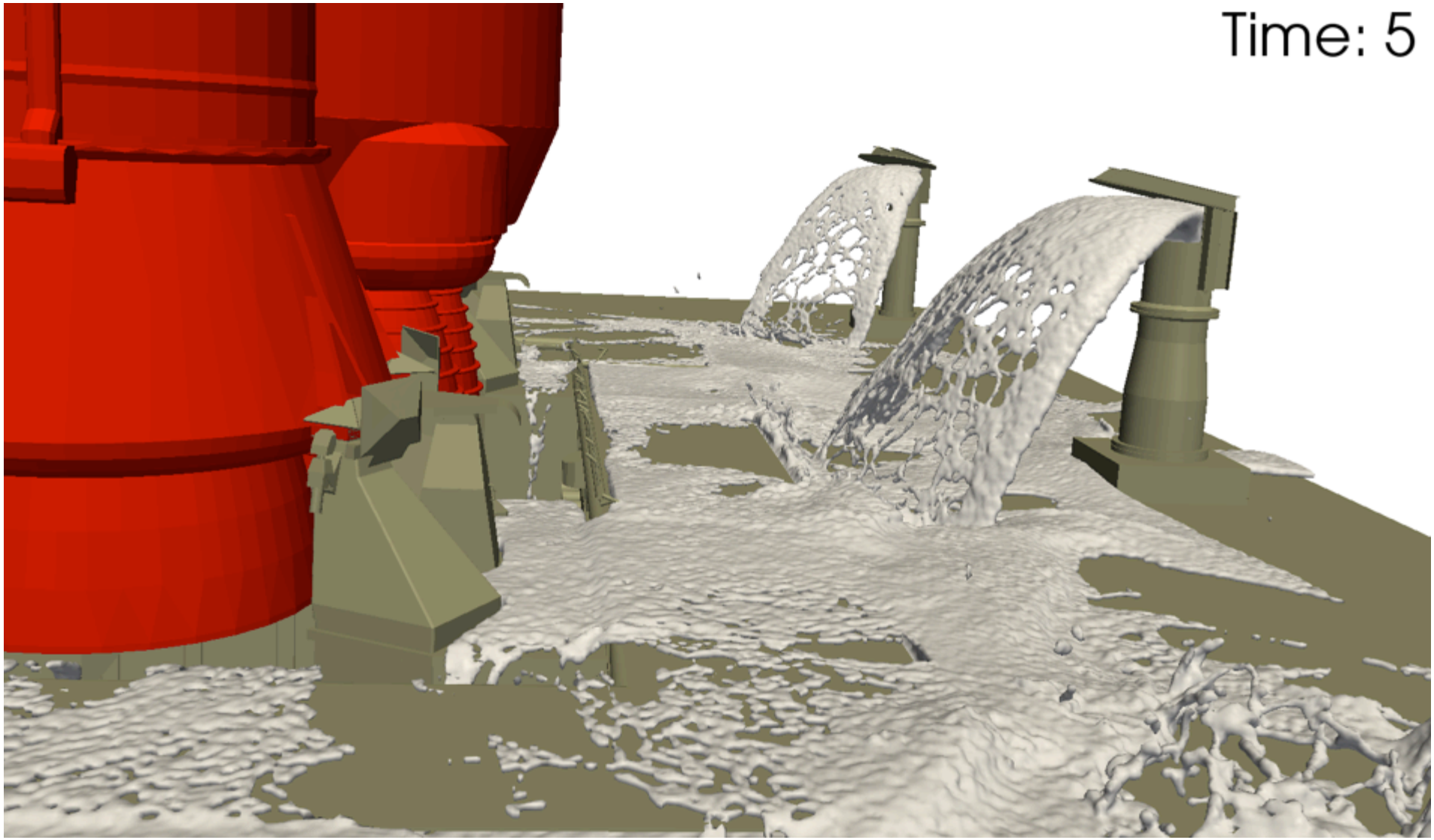
Geometry Issues



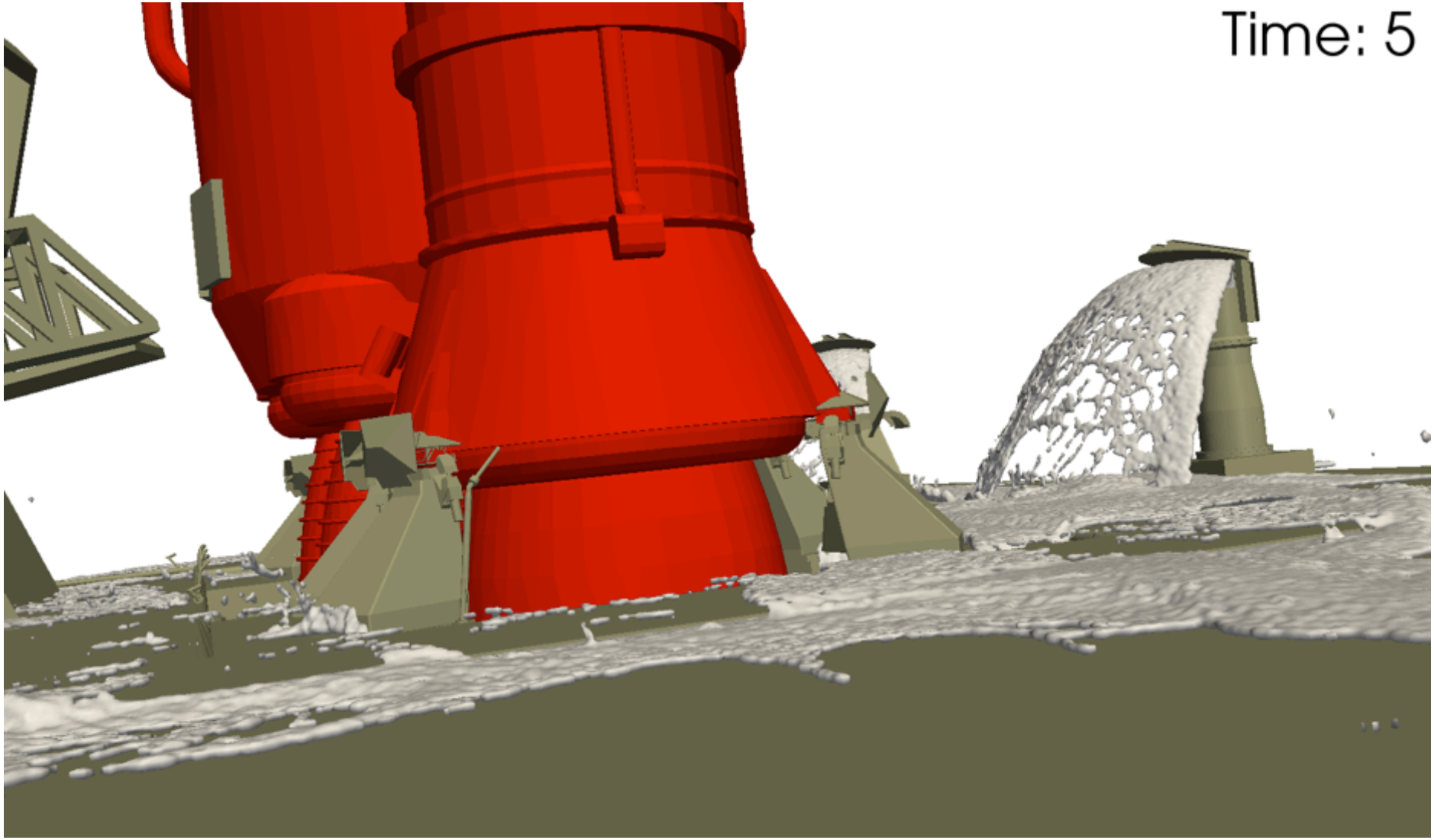
Water Depth



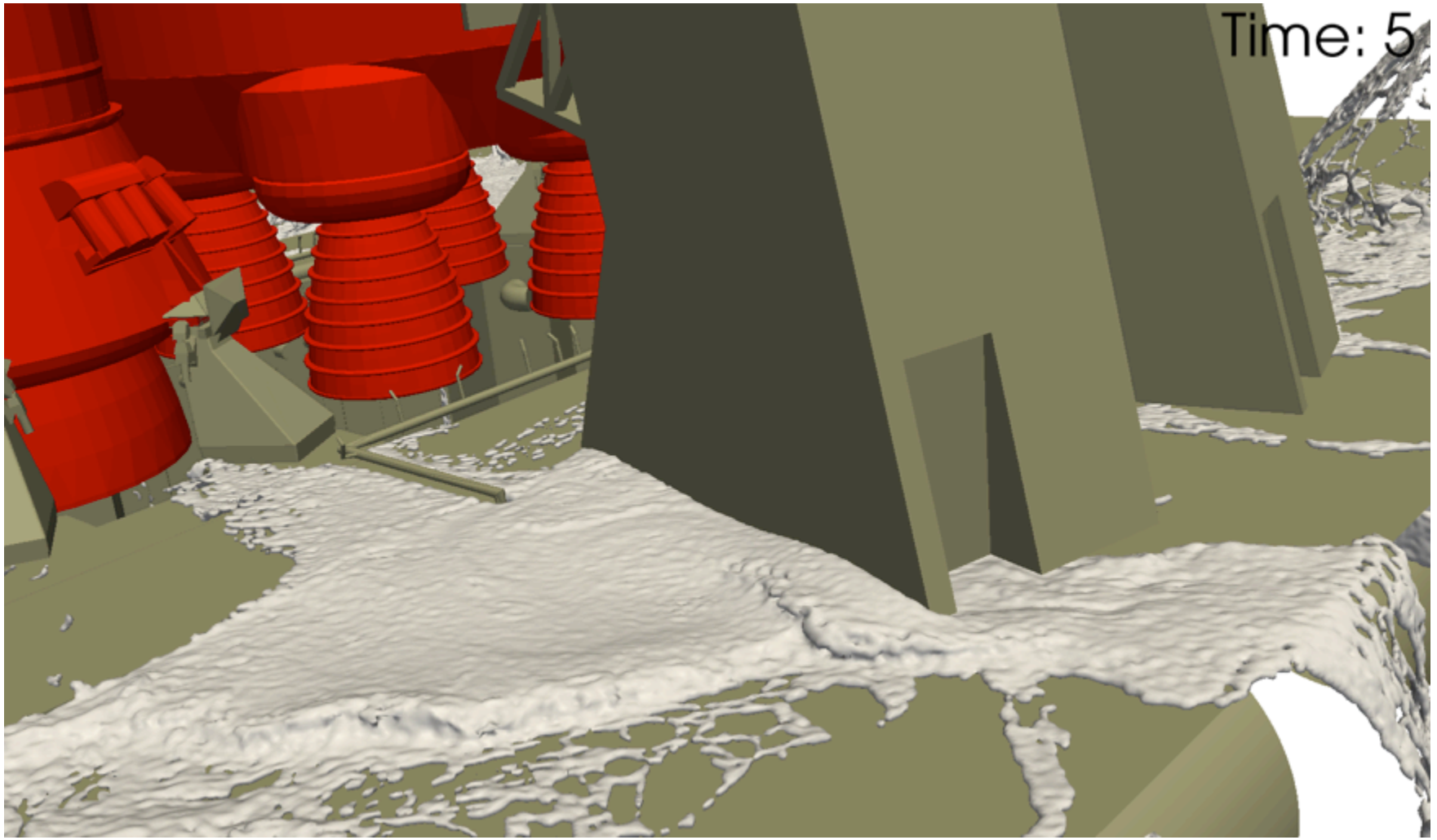
Water Depth



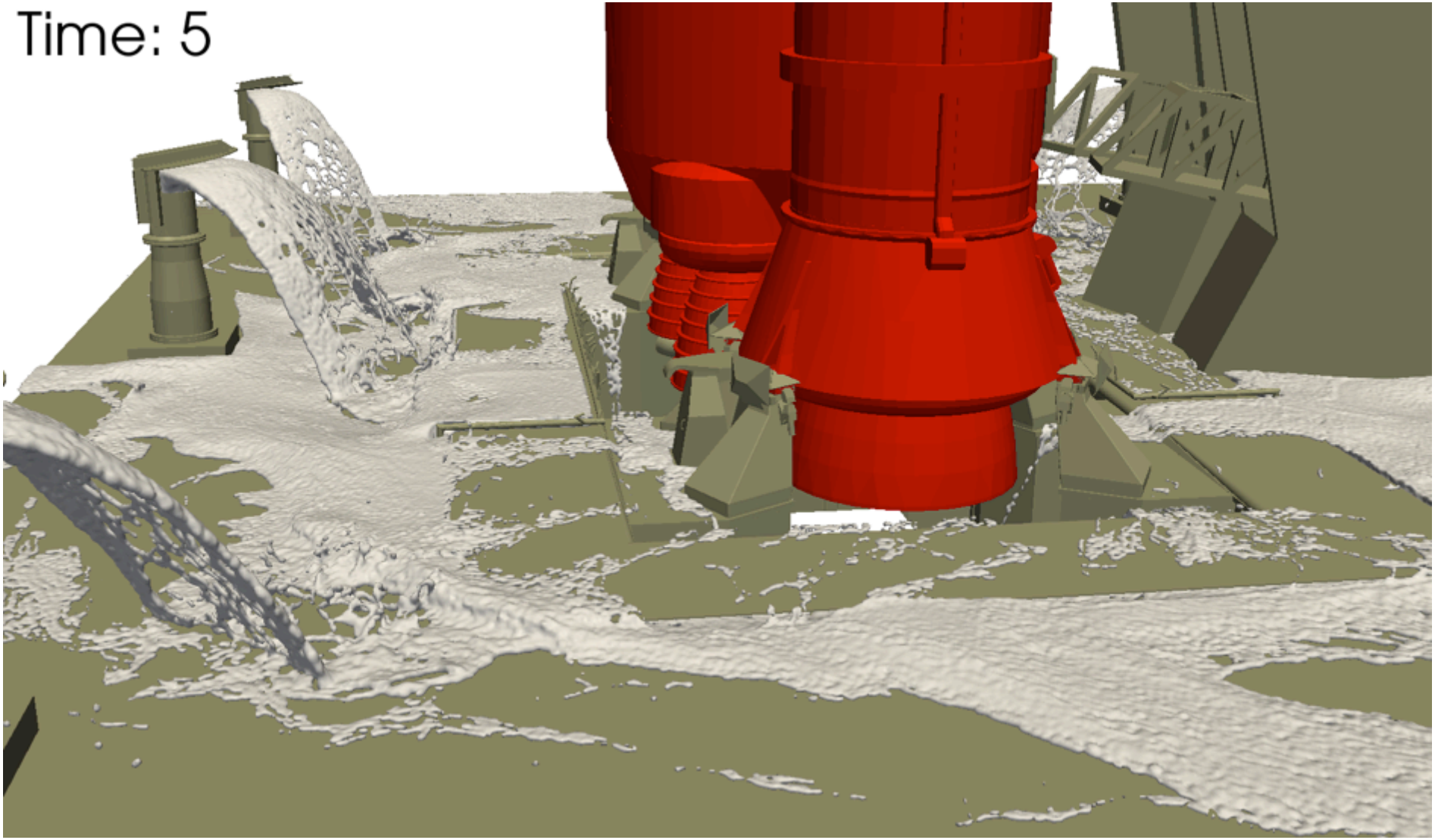
Water Depth



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

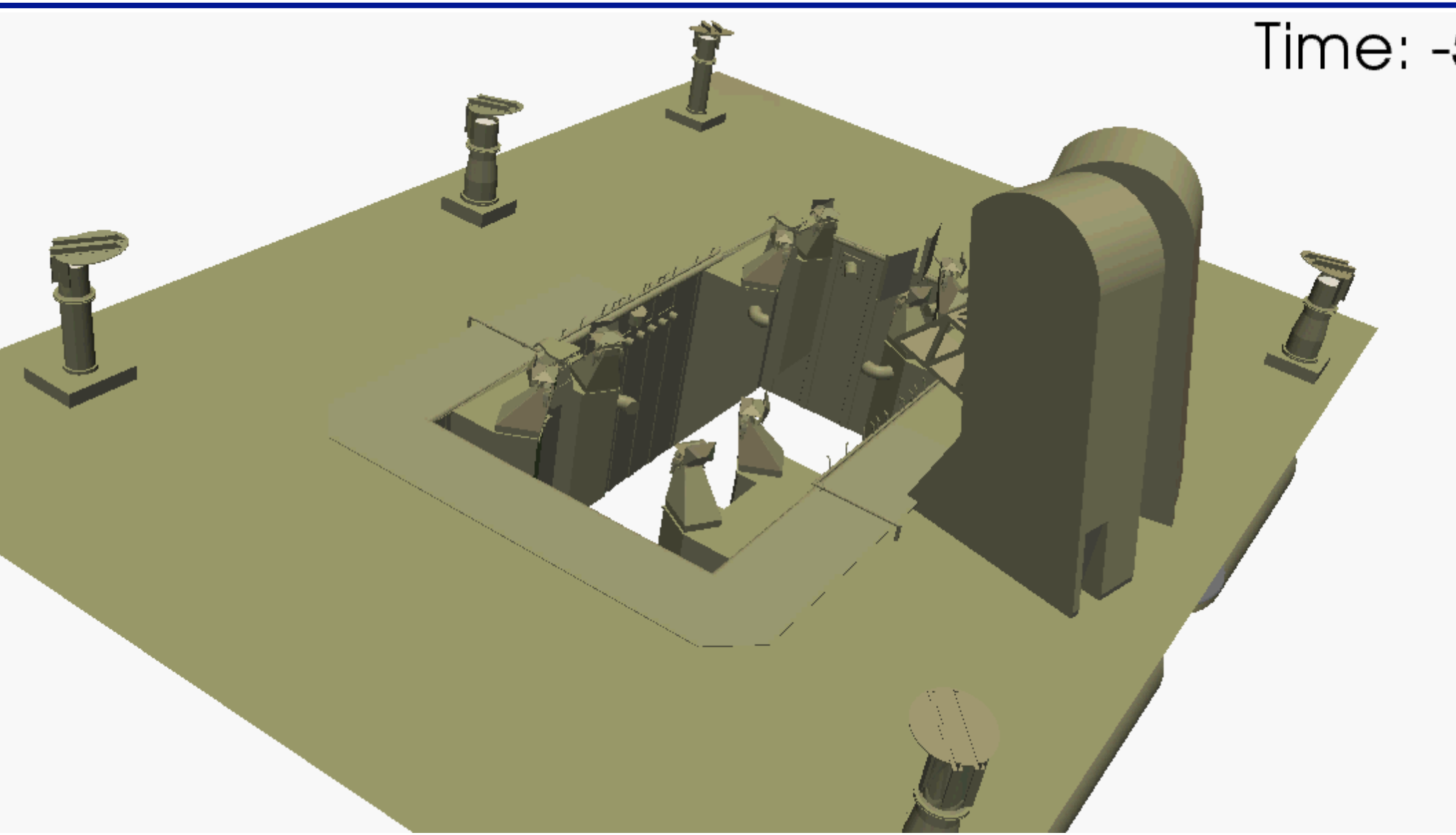
Quadro K600 outperformed Tesla K40c

Fix TSM gap

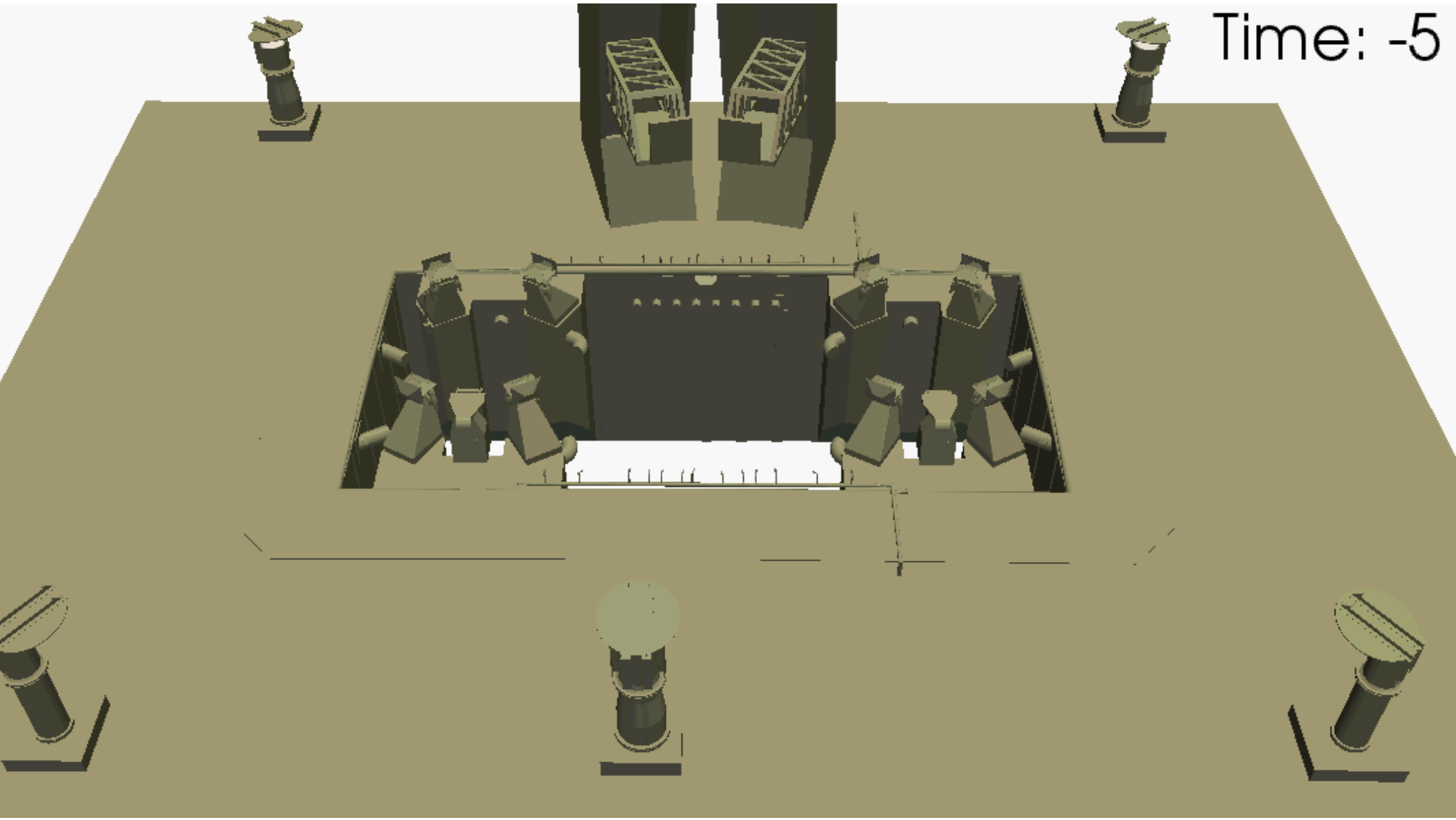
Incorporate design of water barrier for HBOI

Install camera locations

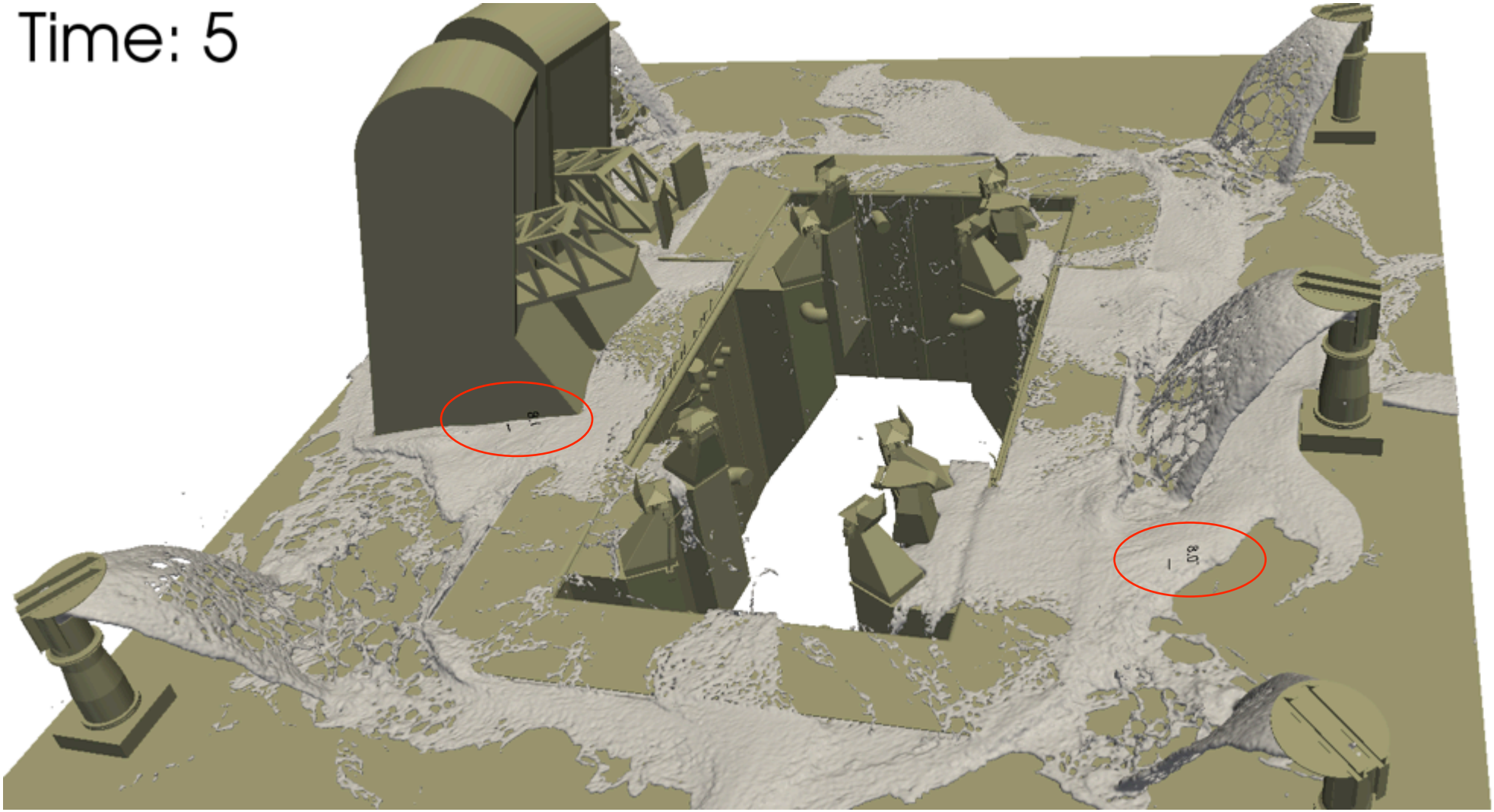
Abort Simulation (fixed TSM)



Abort Simulation (fixed TSM)

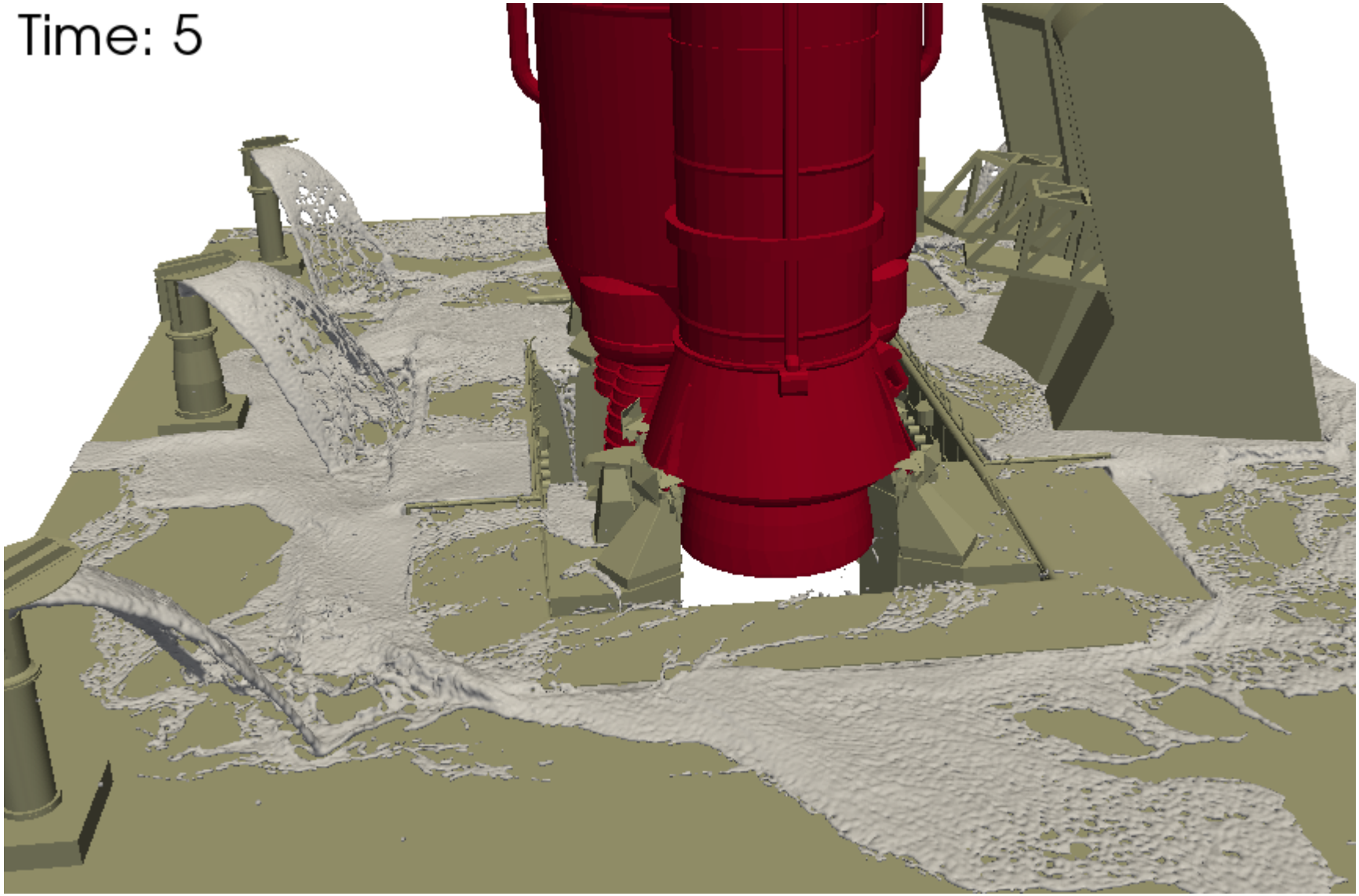


No TSM Gap

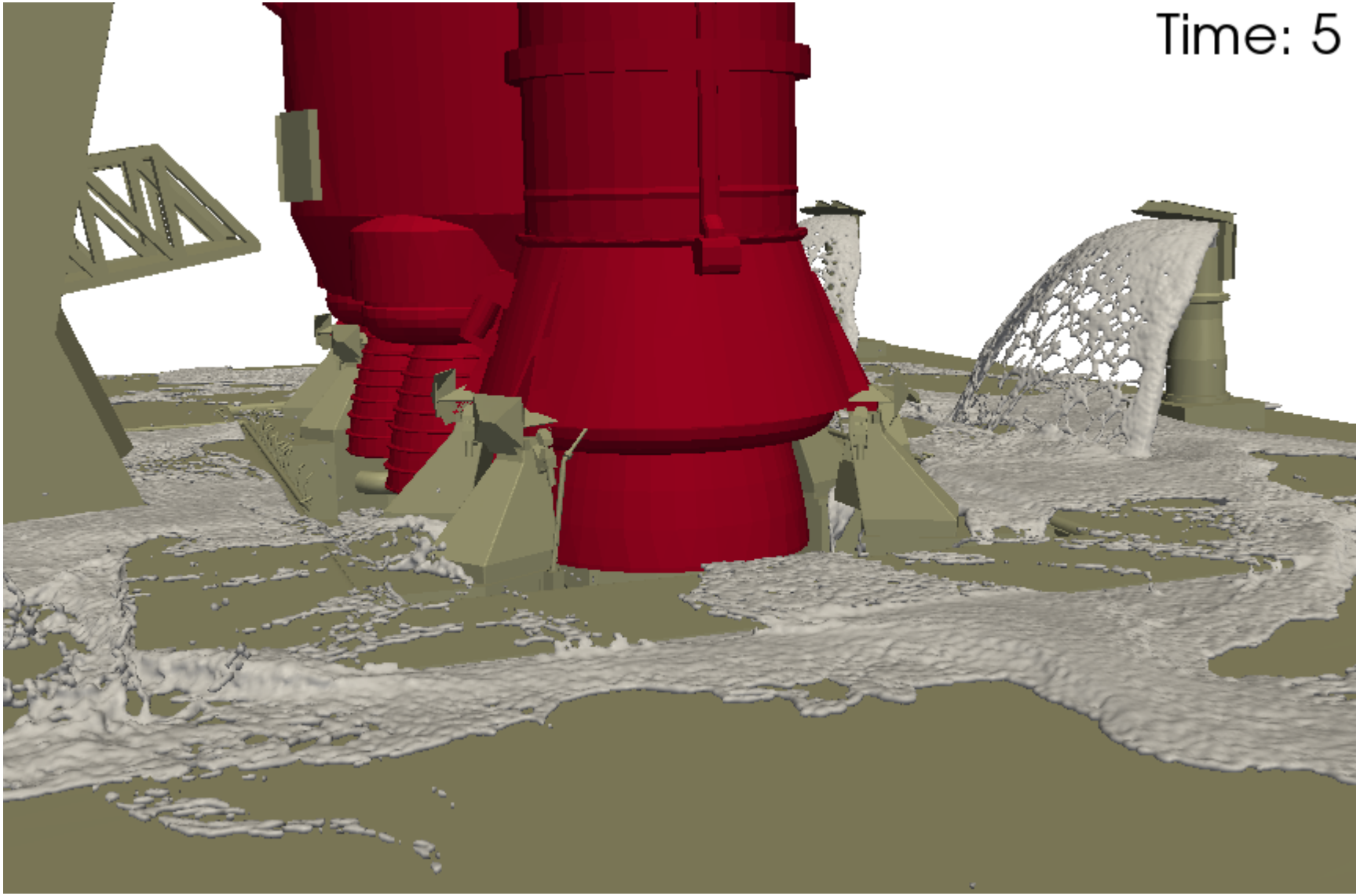


Water puddle as deep as 0.4m = 16” near the TSM and on the South side

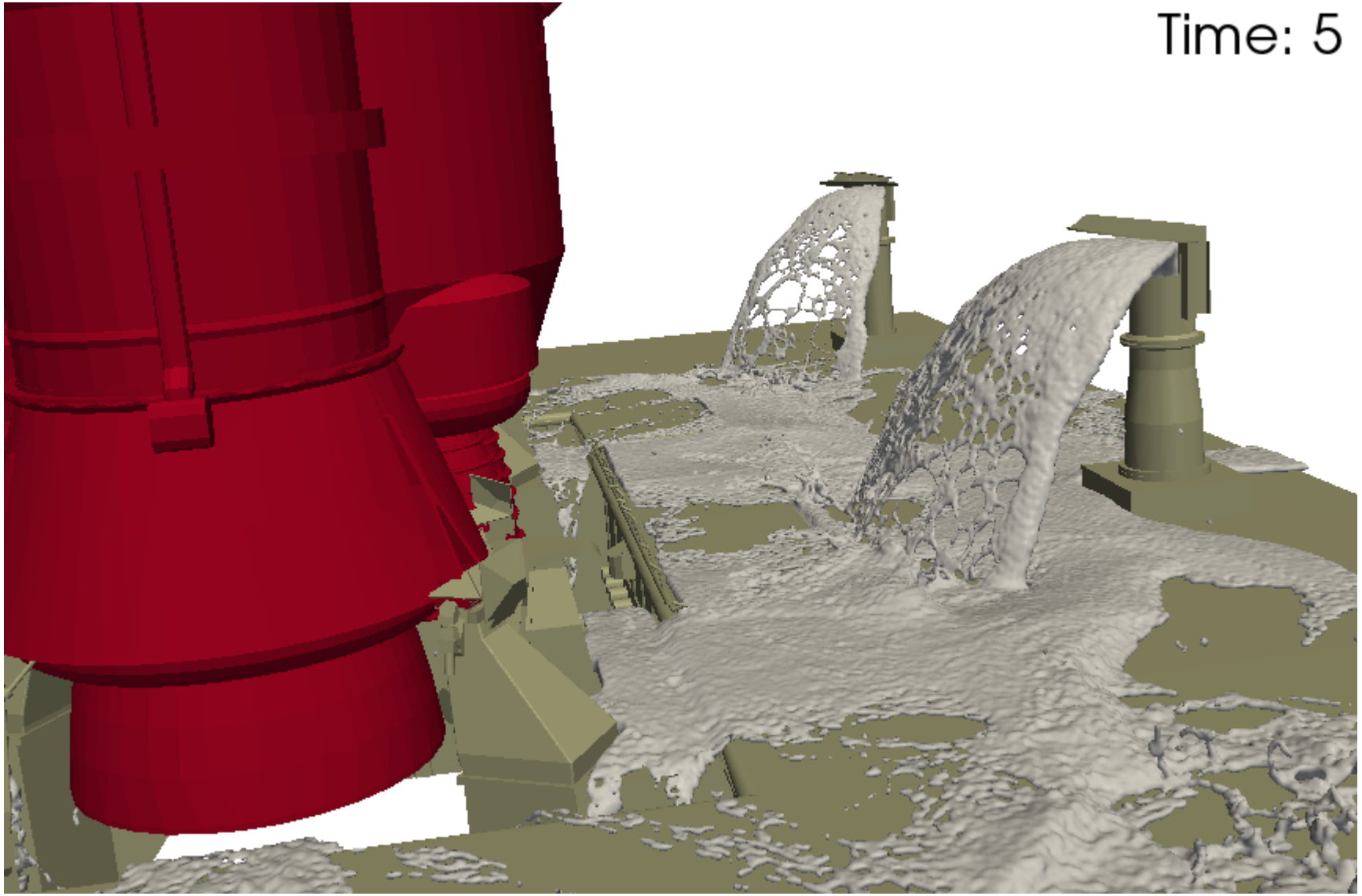
Fixed TSM



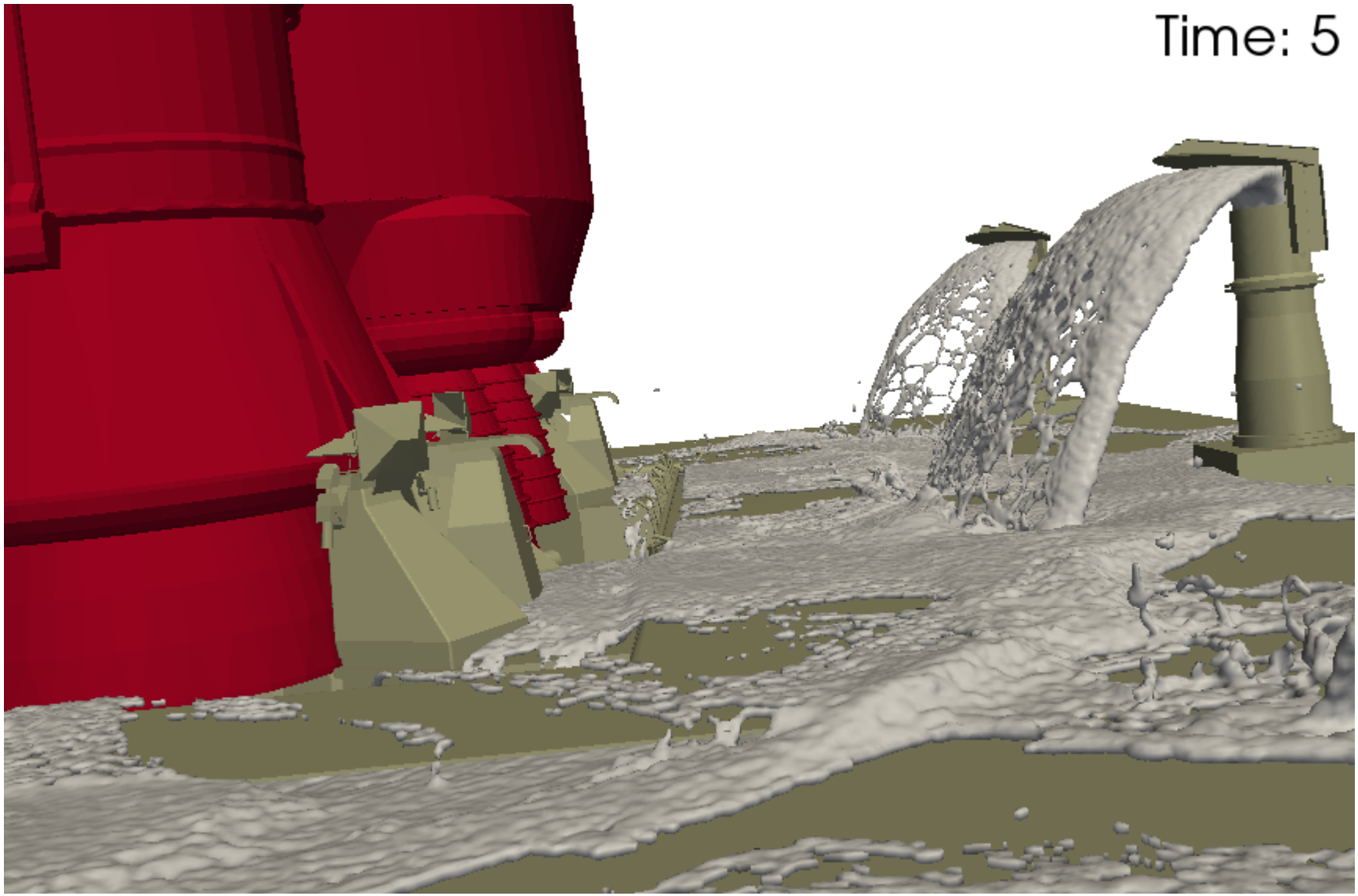
Fixed TSM



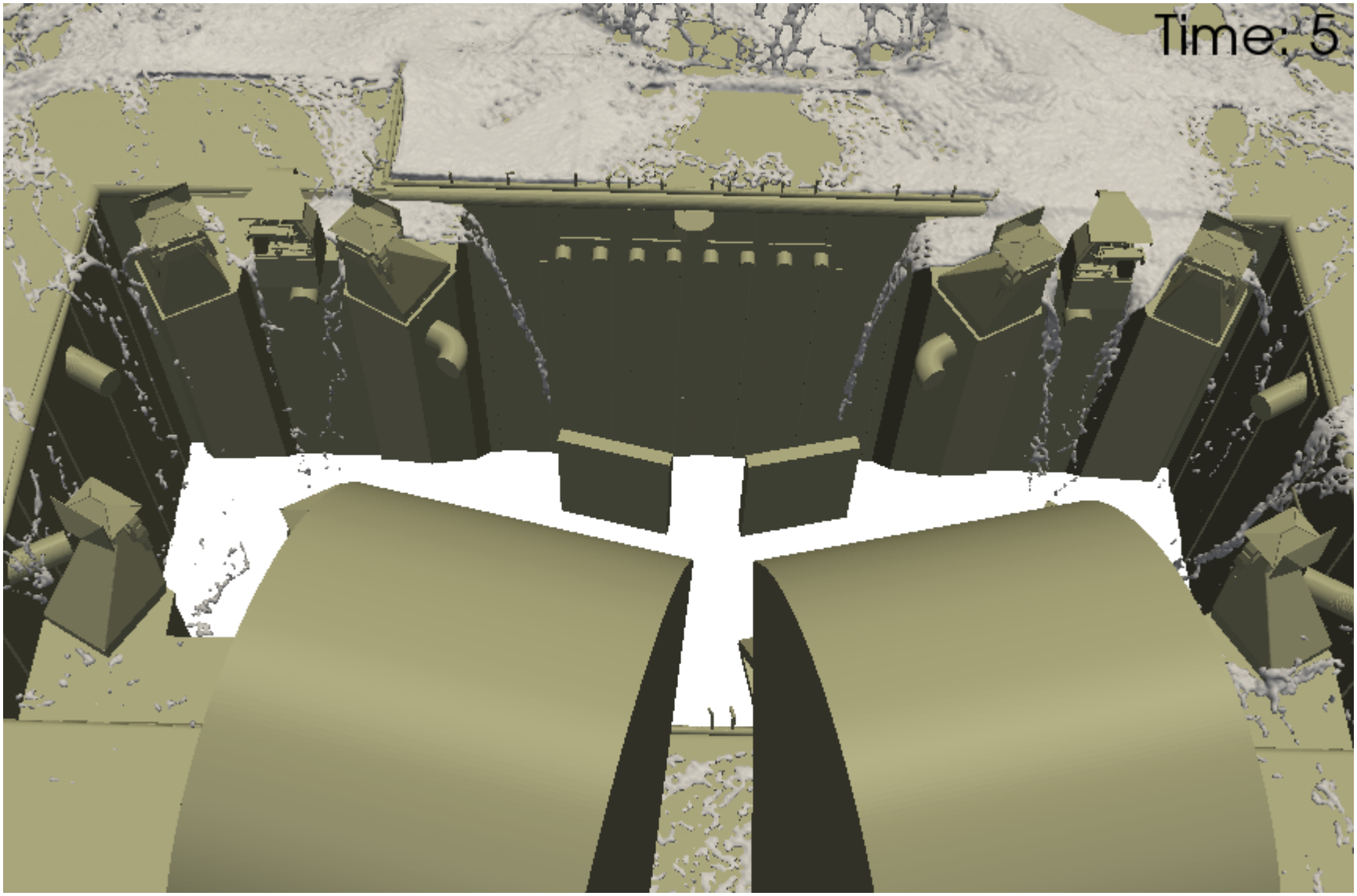
Fixed TSM



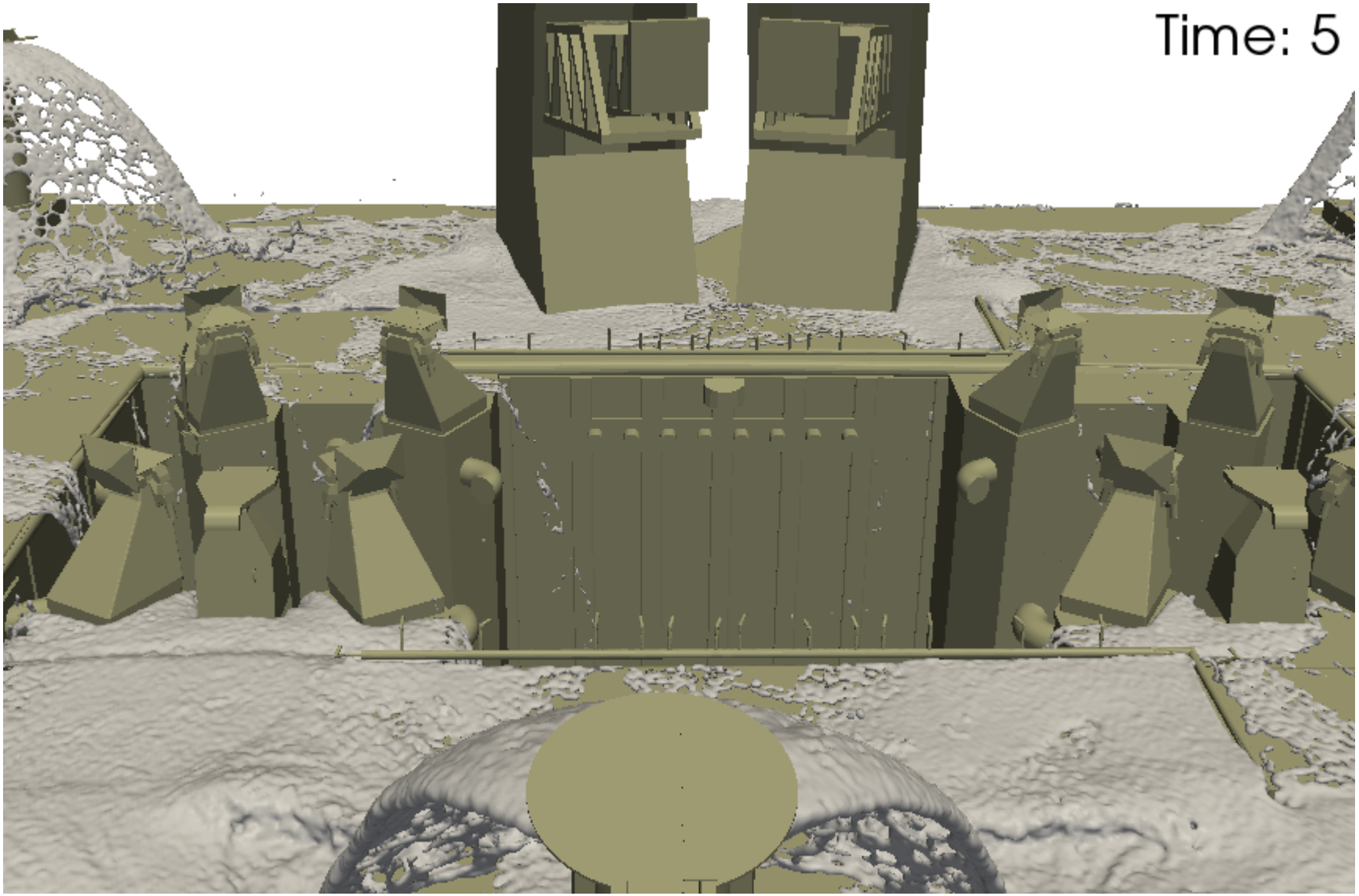
Fixed TSM



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