Energy for the Future – CO2 Sequestration in Hydrates with Associated Methane Gas Production

by

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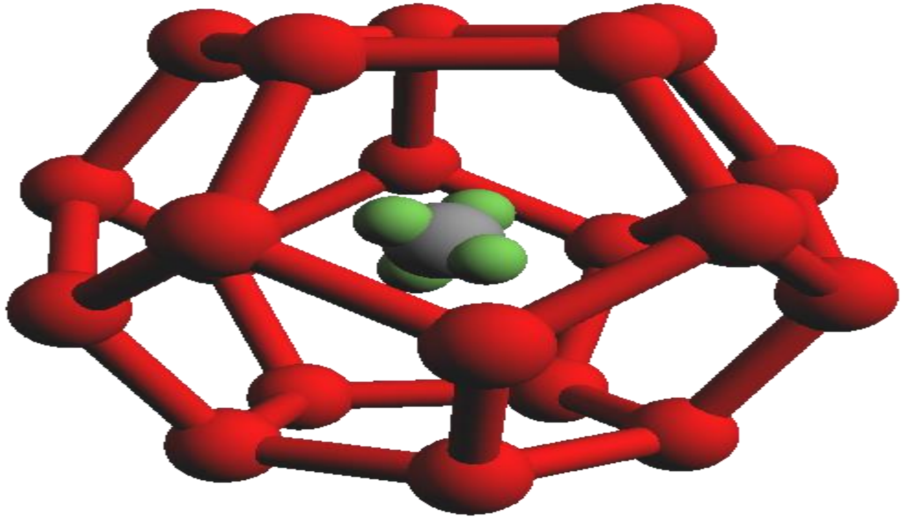
Whole Value Chain CCUS Student Week, Oct. 15th - 19th, 2018, Golden, CO, USA.

GAS HYDRATES

- Solid state of gas and water where the water molecules form a cavity that encapsulates the guest molecule.



What is natural gas hydrate?

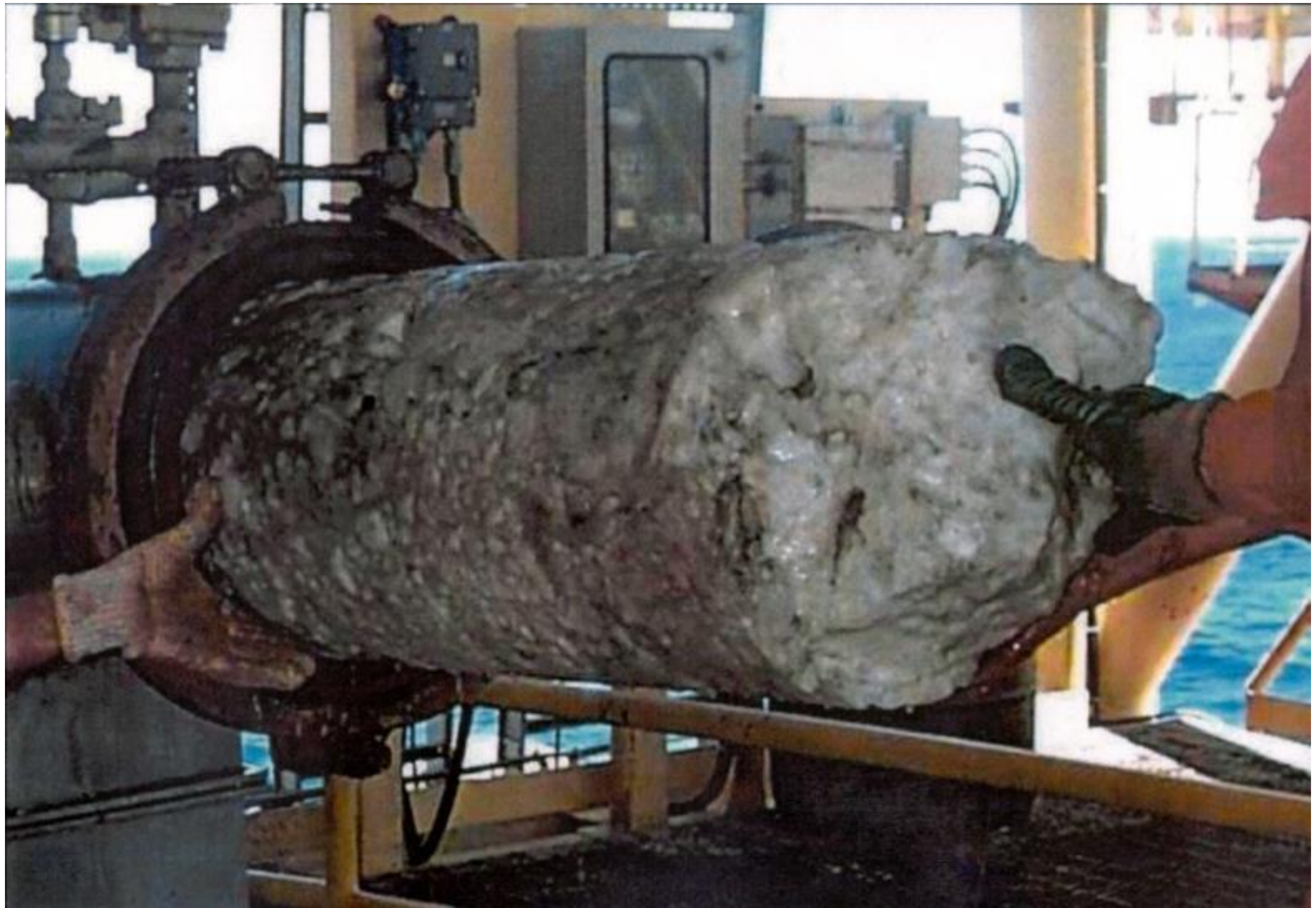
- Methane and other small non-polar (or slightly polar) molecules immersed in water will induce organisation of the water structure that maximizes the entropy.
- Above certain pressures, and below certain temperatures , this results in a phase transition over to a solid like structure.

The glass to the right contains water at 0 C

The pipe to the left contains hydrate at 5 C

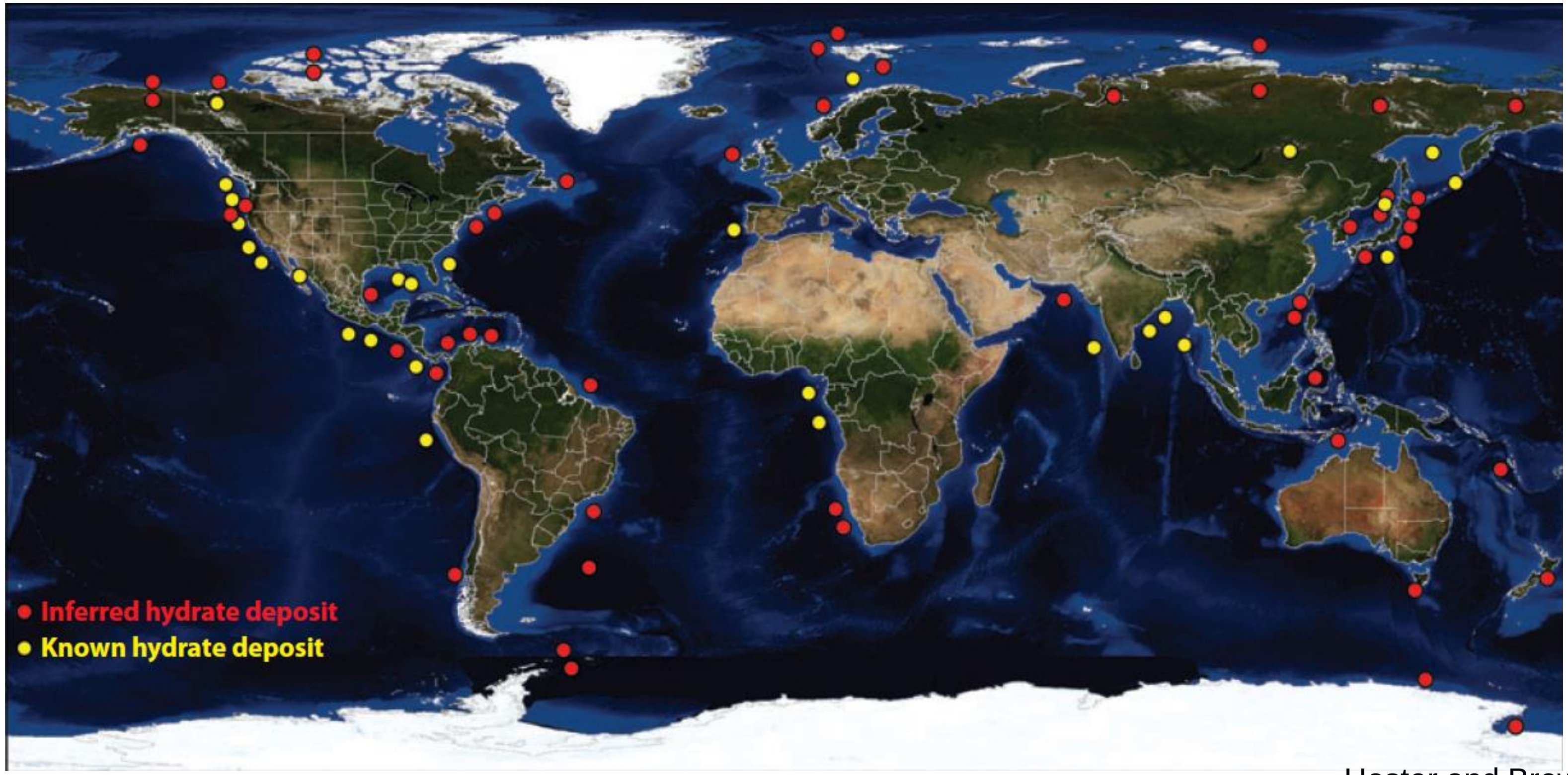
Why are hydrates of interest?

- Initial interest as a curiosity
- Plugging of production and transportation pipelines



Renewed interest

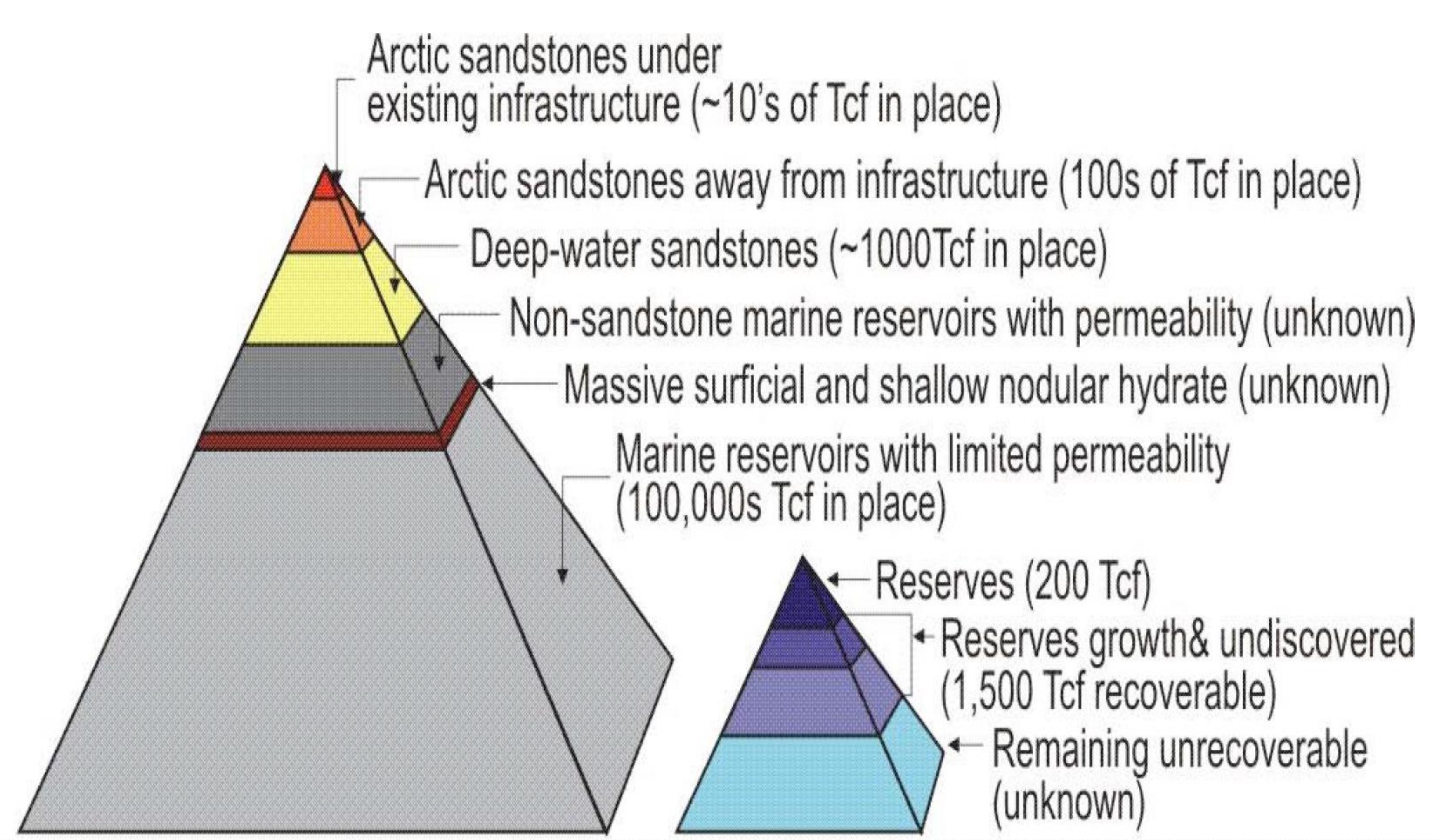
- Significant amount of energy
  - Permafrost regions
  - Marine environments (high water column)



Hester and Brewer, 2009

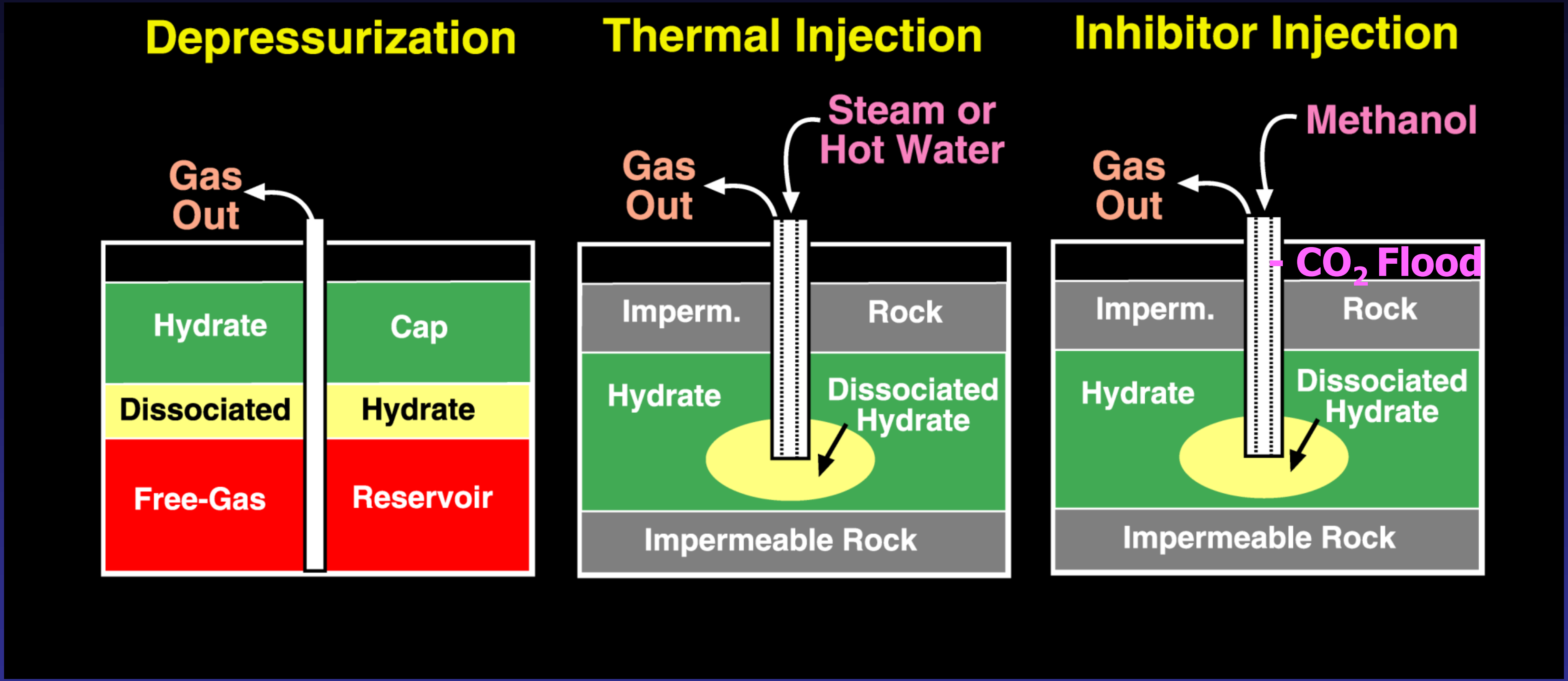
Hydrate as Energy Resource

Ref.: Fire in the Ice, U.S. Department of Energy • Office of Fossil Energy • National Energy Technology Laboratory



Gas Hydrates Resource Pyramid (left). To the right is an example gas resources pyramid for all non-gas-hydrate resources.

Gas Hydrate Production Methods



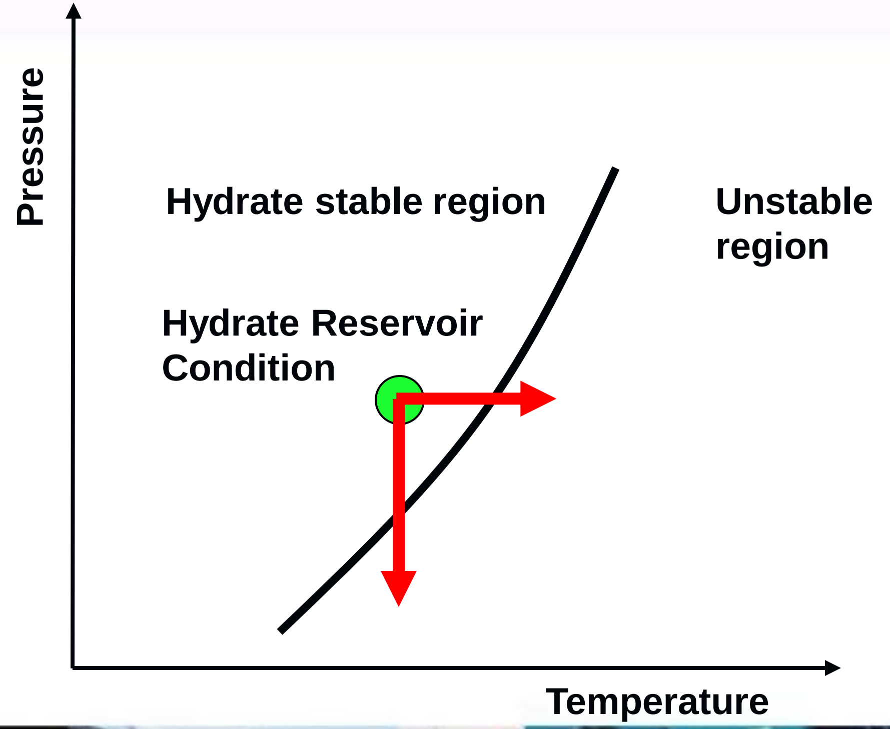
Modified from "GAS HYDRATES OF NORTHERN ALASKA", January 2005
Evaluation of Alaska North Slope Gas Hydrate Energy Resources: A Cooperative Energy Resource Assessment Project
US Bureau of Land Management, US Geological Survey, & State of Alaska Division of Geological and Geophysical Surveys
Bob Fisk, USBLM, Anchorage, Alaska, Tim Collett, USGS, Denver, Colorado & Jim Clough, DGGS, Fairbanks, Alaska

Depressurization: PROS AND CONS

- Pros
  - All of the methane is accessible for production by depressurization; at sufficient low pressures
- Cons
  - Large pressure drop may be needed to initiate hydrate dissociation
  - Water production may represent an economic challenge and an environmental issue
  - Hydrate melts; causing possible unstable formation

GAS HYDRATE PRODUCTION METHODS

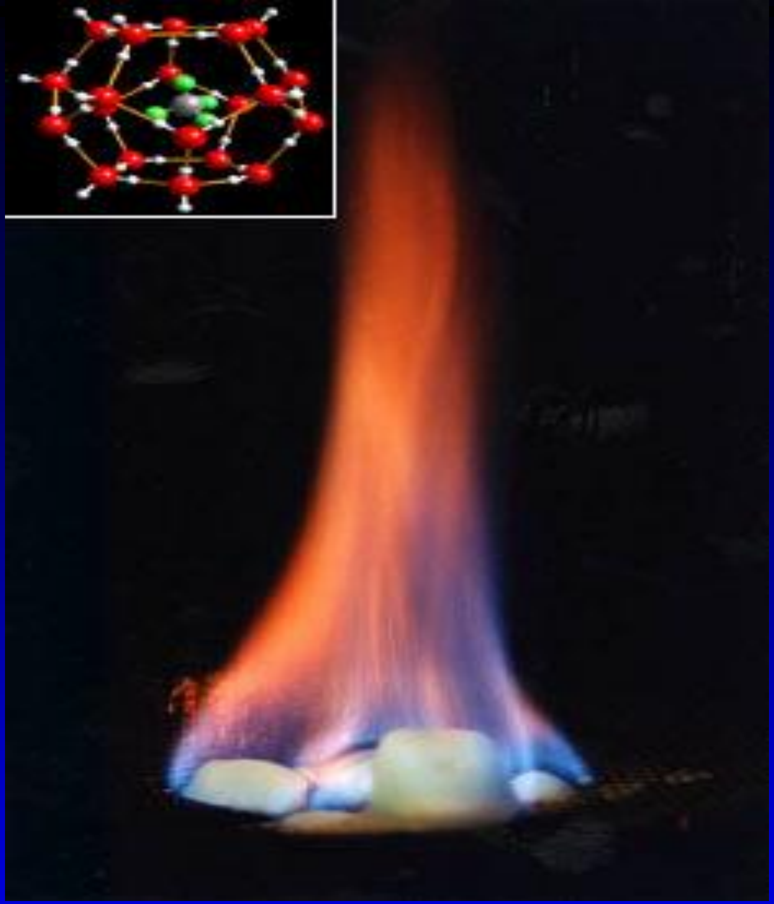
- **Move the gas hydrate outside its stability region**
  - **Depressurization**
  - **Thermal stimulation**
  - **Hydrate inhibitors**
- **CO2 exchange**



CO2 Exchange: Project Motivation

- The amount of energy bound in hydrates may be more than twice the world's total energy resources in conventional hydrocarbon reservoirs; i.e. oil-, gas- and coal reserves
- Simultaneous CO_2 Sequestration
- Win-win situation for gas production
- Need no hydrate melting or heat stimulation
- Spontaneous process
- No associated water production
- Formation integrity

CO2 storage in hydrates with associated methane gas production



Challenge:

Determine exchange mechanisms during potential sequestration of CO_2 to produce methane from hydrates

Three component Phase Field Theory

$$F = \int d\underline{r} \left\{ \frac{\varepsilon^2 T}{2} (\nabla\phi)^2 + \sum_{i,j=1}^{3} \frac{\varepsilon_{i,j}{}^2 T}{4} \left(c_i \nabla c_j - c_j \nabla c_i \right)^2 + f_{bulk}(\phi, c_1, c_2, c_3, T) \right\}$$

$$f_{bulk} = wTg(\phi) + [1 - p(\phi)] f_S(c_1, c_2, c_3, T) + p(\phi) f_L(c_1, c_2, c_3, T)$$

$$\dot{\phi} = -M_\phi \frac{\delta F}{\delta c} + \zeta_\phi$$

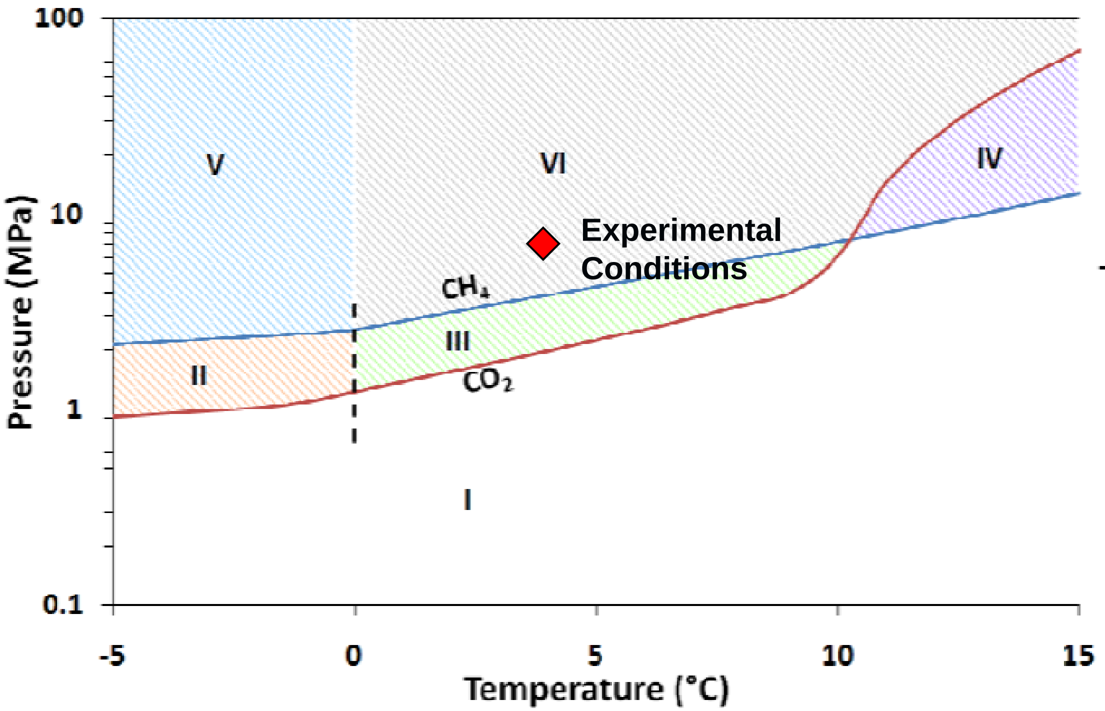
$$\sum_{i=1}^{3} c_i = 1$$

$$\dot{c}_i = \nabla M_{ci}(c_1, c_2, c_3) \nabla \left(\frac{\delta F}{\delta c_i} - \zeta_i \right)$$

Parameters ε and w can be fixed from the interface thickness and interface free energy. ε ij set equal to ε

CH_4 PRODUCTION INDUCED BY CO_2 INJECTION

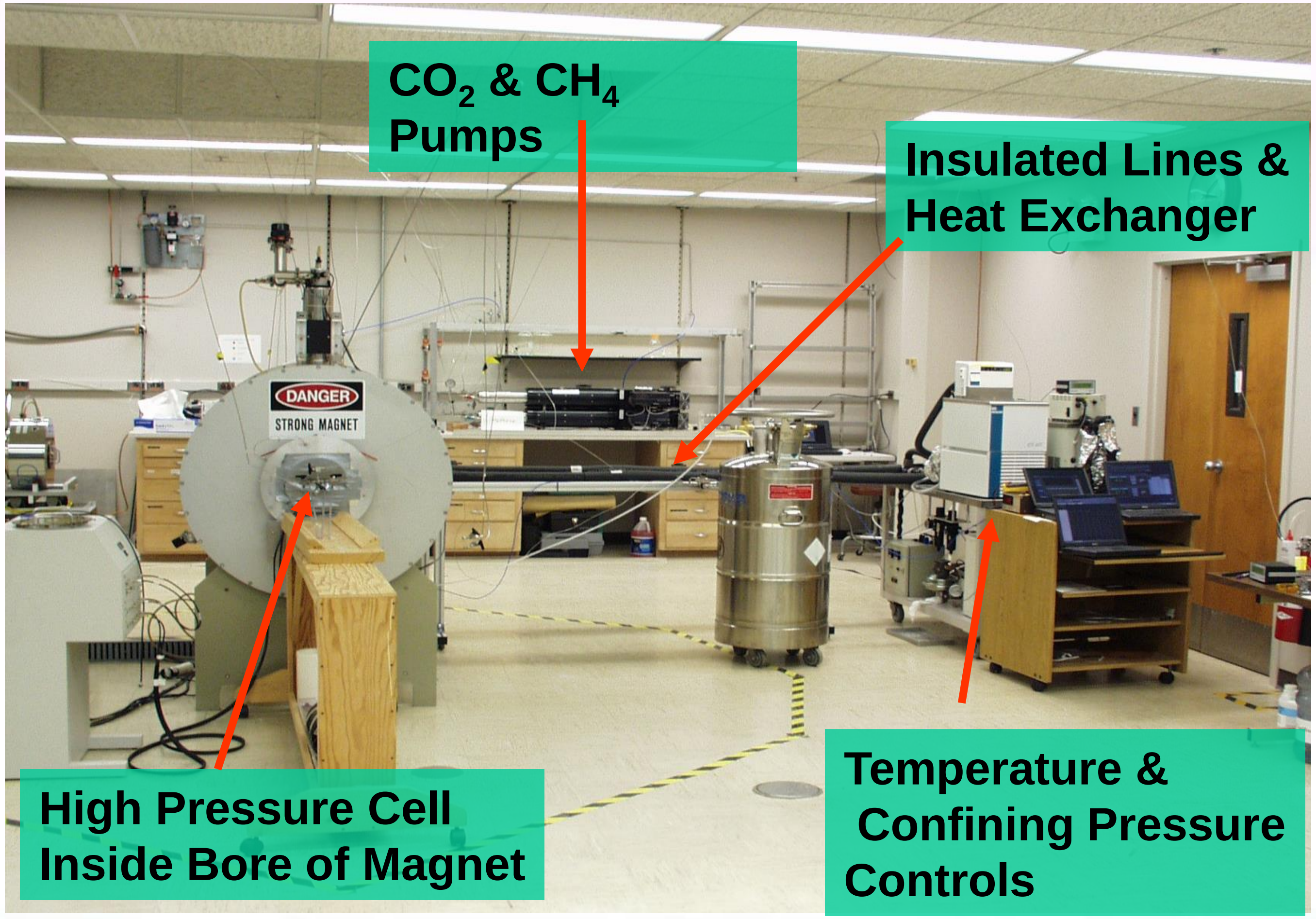
- Provides thermodynamically more stable gas hydrate than CH_4



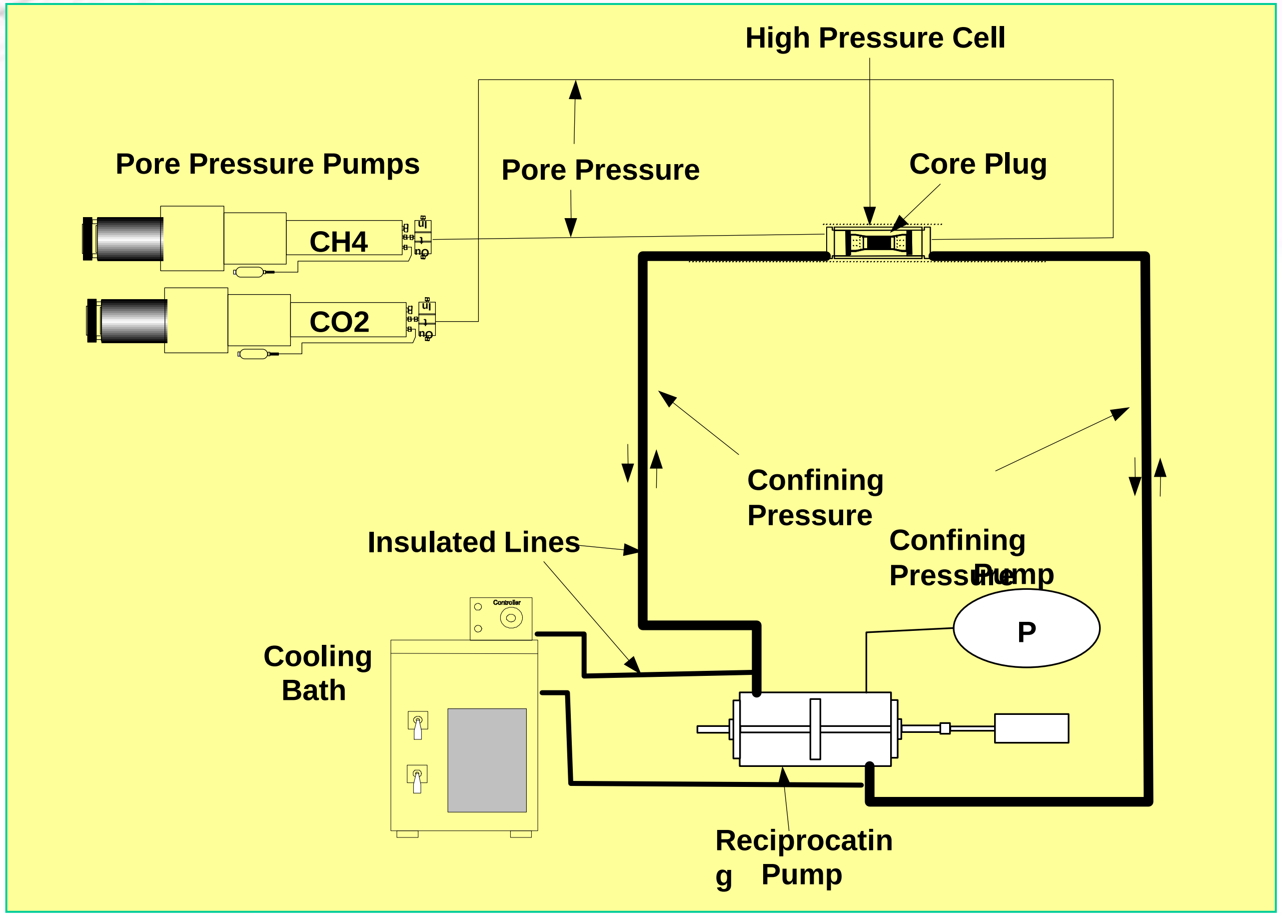
PT-Area	Water and Hydrate Phases
I	No hydrates
II	I-H_{CO2}
III	L_W-H_{CO2}
IV	L_W-H_{CH4}
V	I-H_{CO2}-H_{CH4}
VI	L_W-H_{CO2}-H_{CH4}

Husebø, 2008

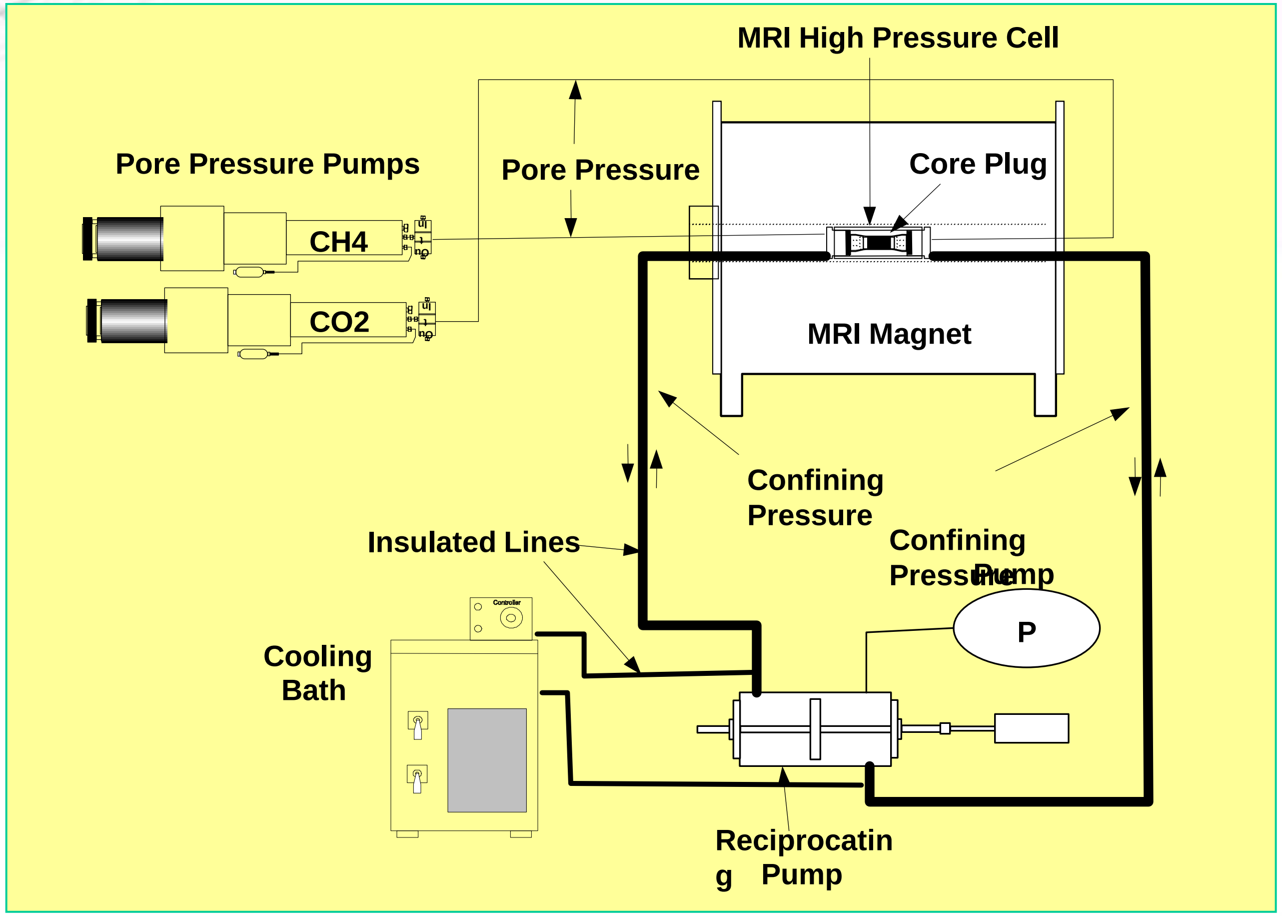
Experimental Setup



Experimental Setup



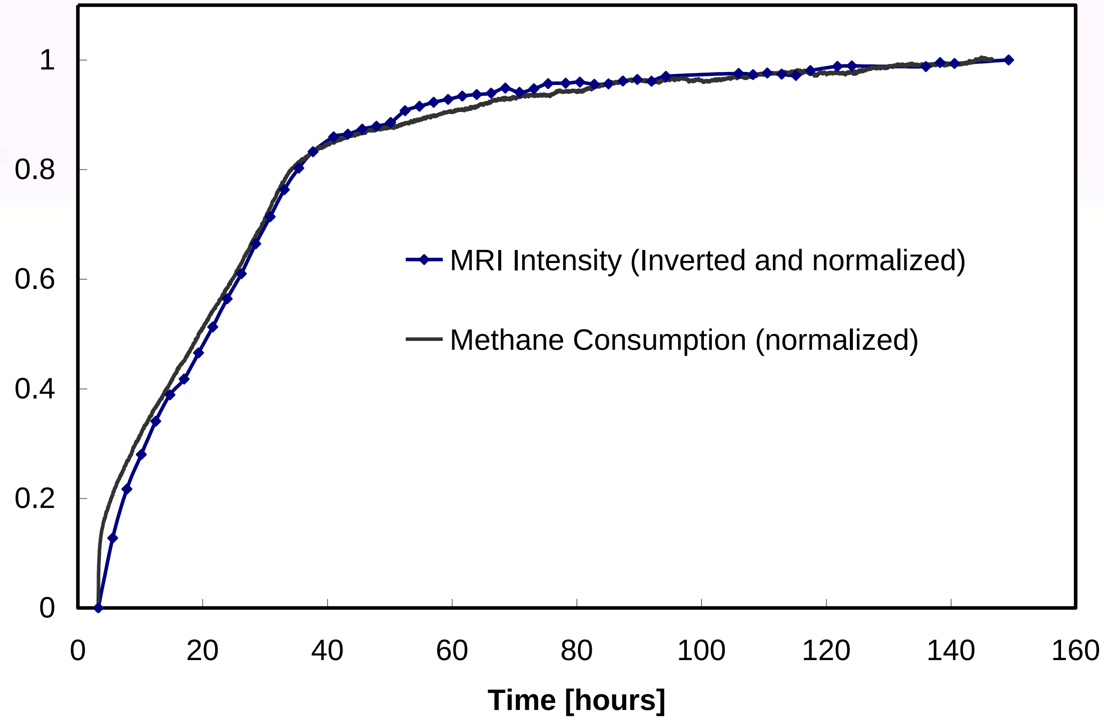
Experimental Setup



Monitor P-V-T and MRI Intensity

During Hydrate Formation

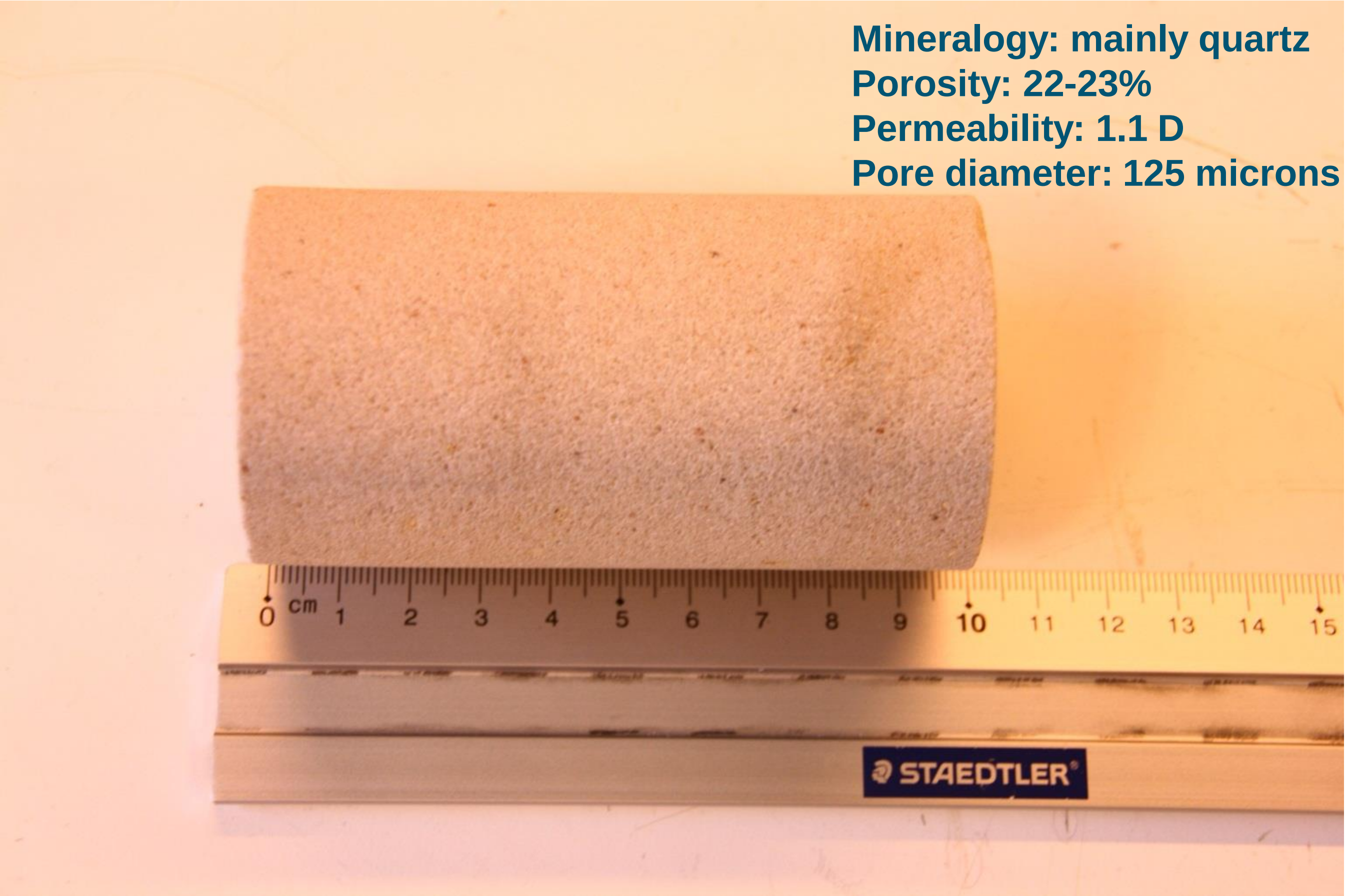
Volumetrics and MRI Results



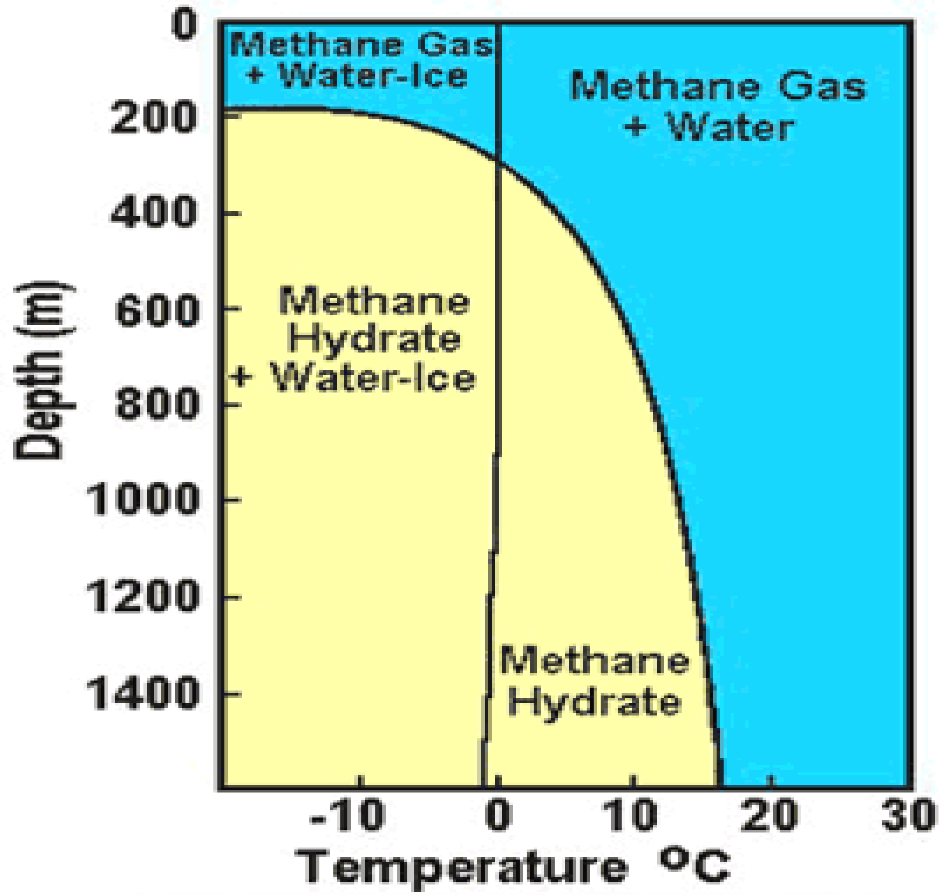
MRI Intensity in Core and CH_4 Volume Consumption

CONDITIONS OF A HYDRATE RESERVOIR

- Hydrate reservoirs are often found in porous media
  - Sedimentary rock



Conditions for Methane Hydrate Formation/Dissociation

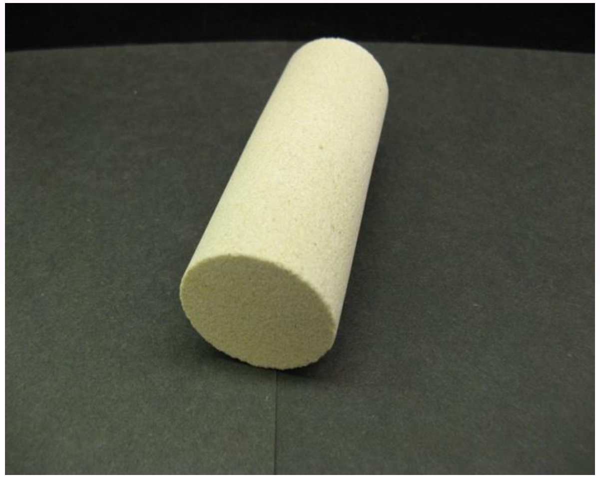


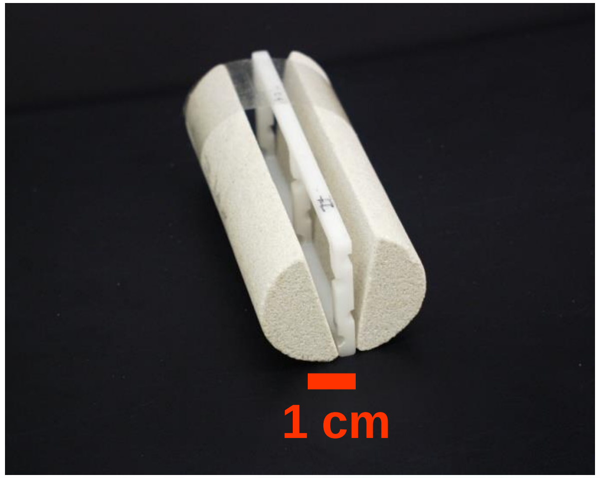
Core Sample Design

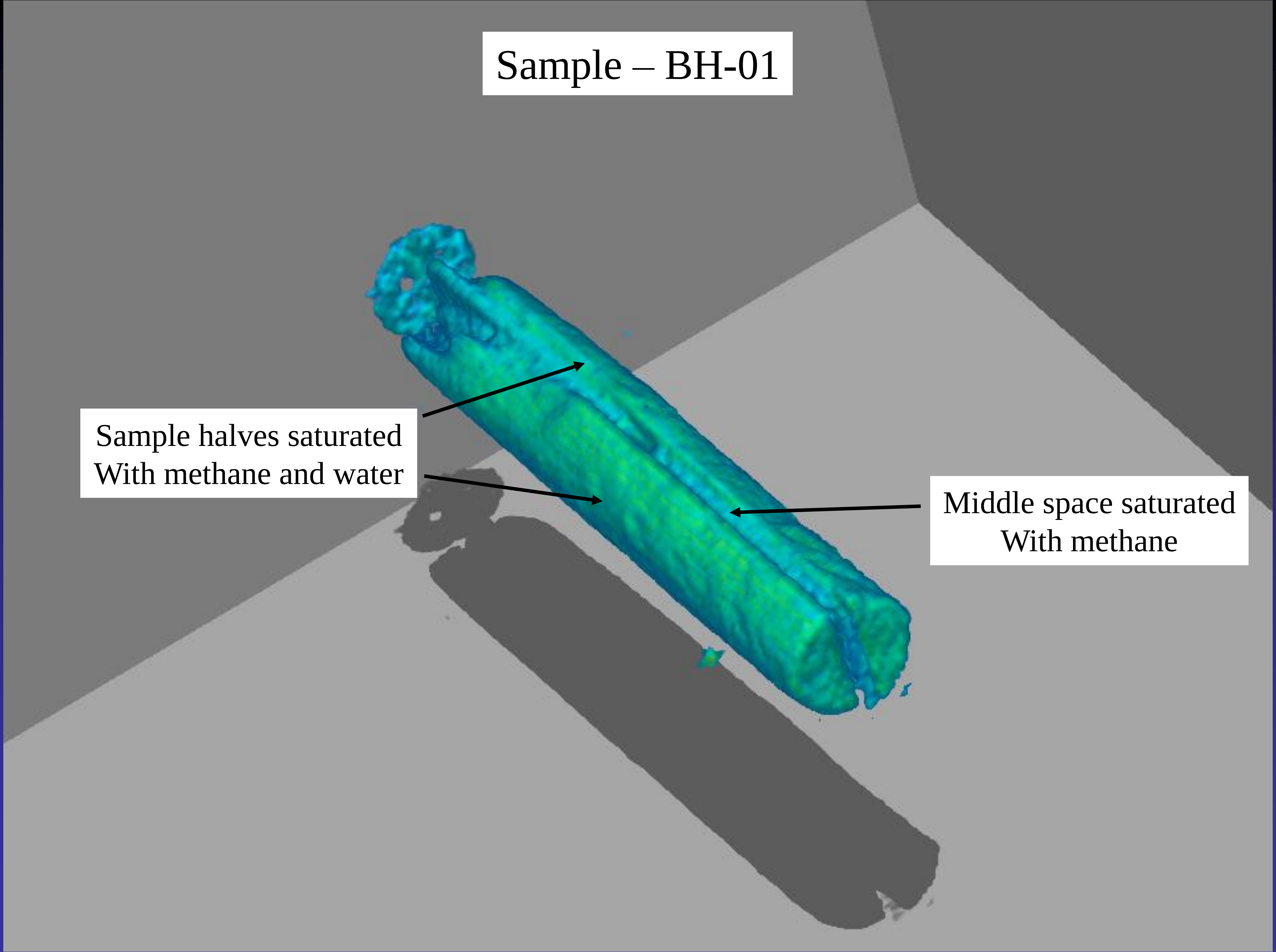
Bentheim Sandstone

20-25% porosity, ~1.1 D Perm

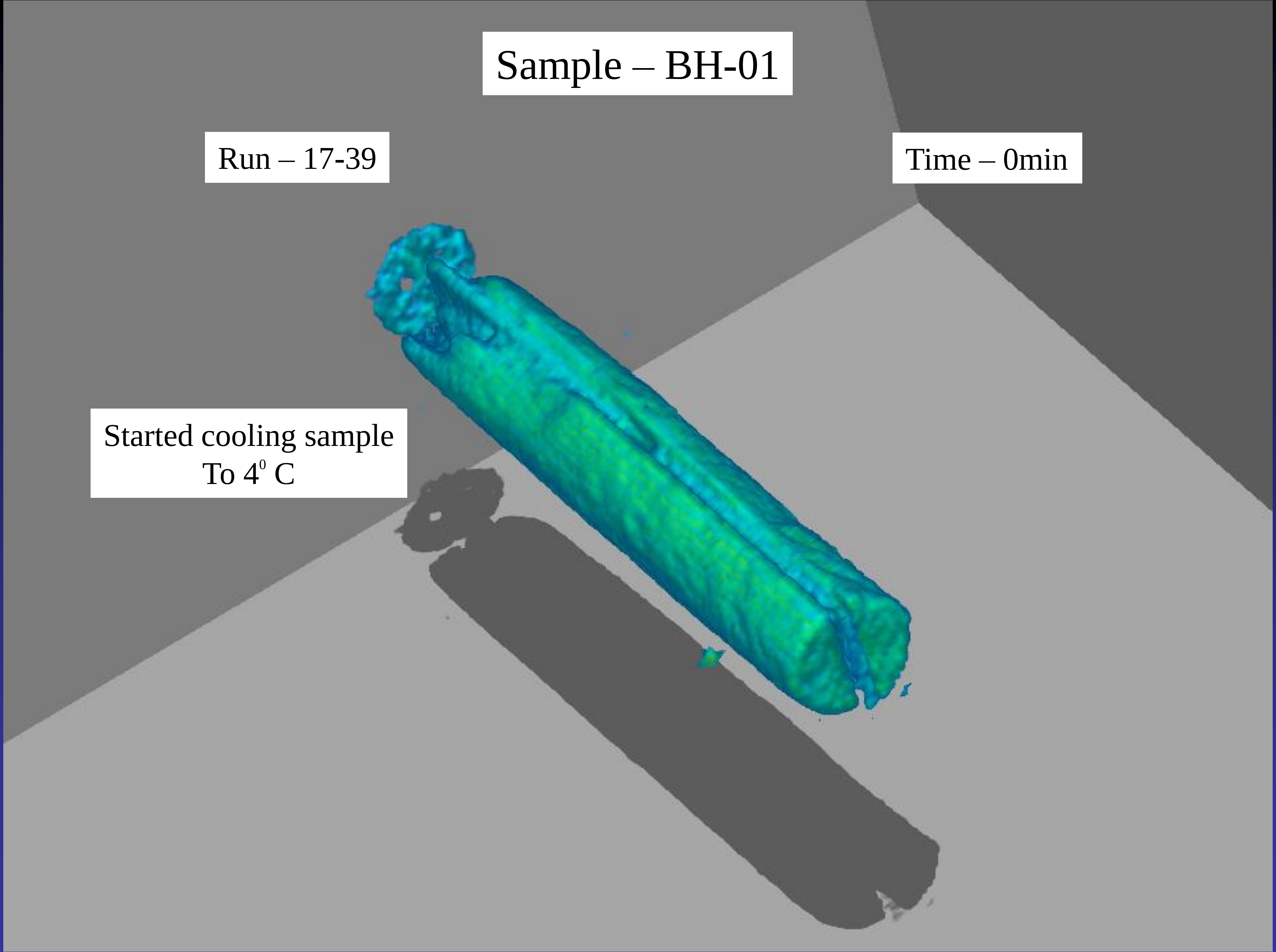
- Whole Core
- Longitudinal Cut With Machined Spacer to Simulate Open Fracture.

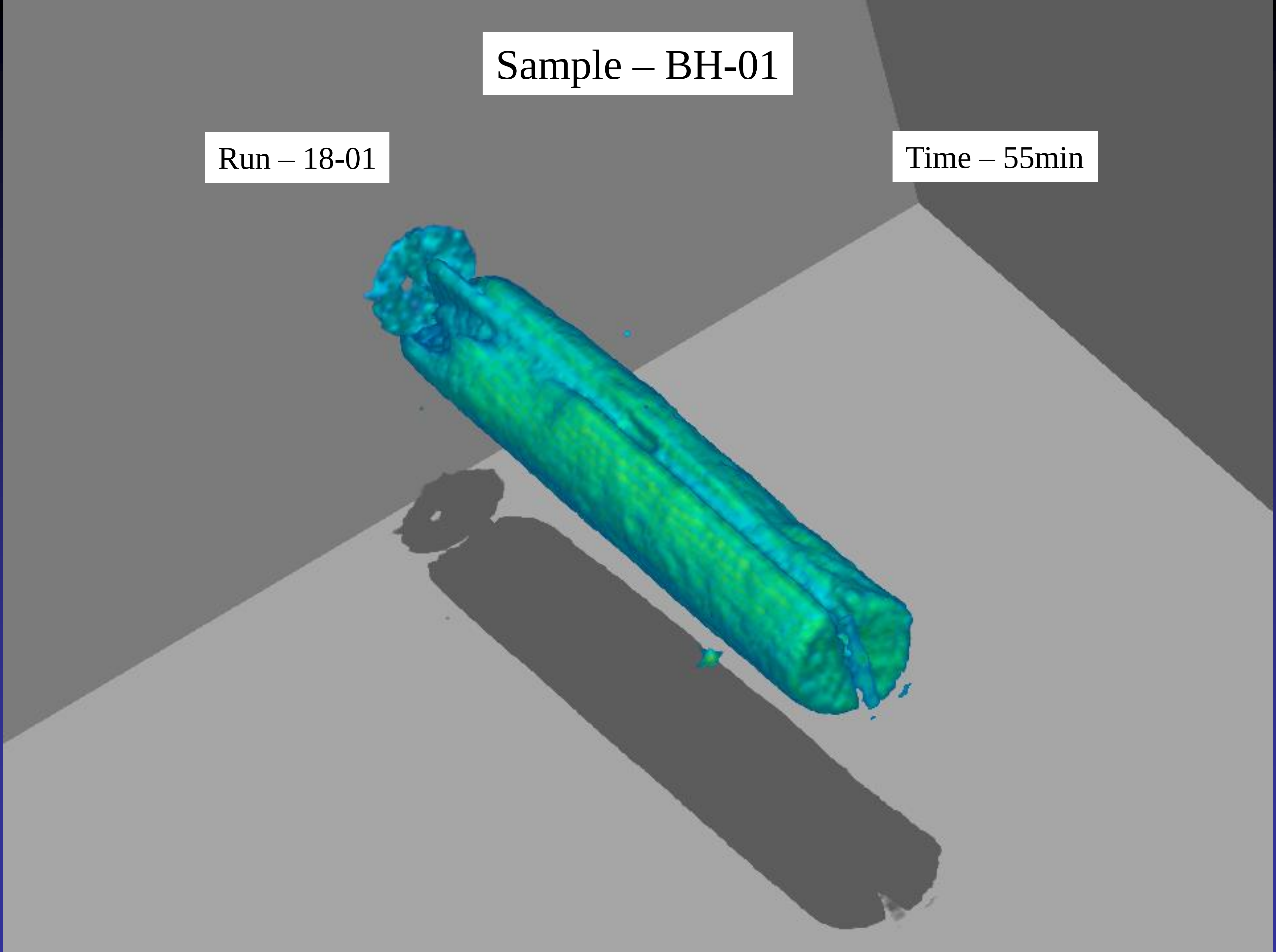


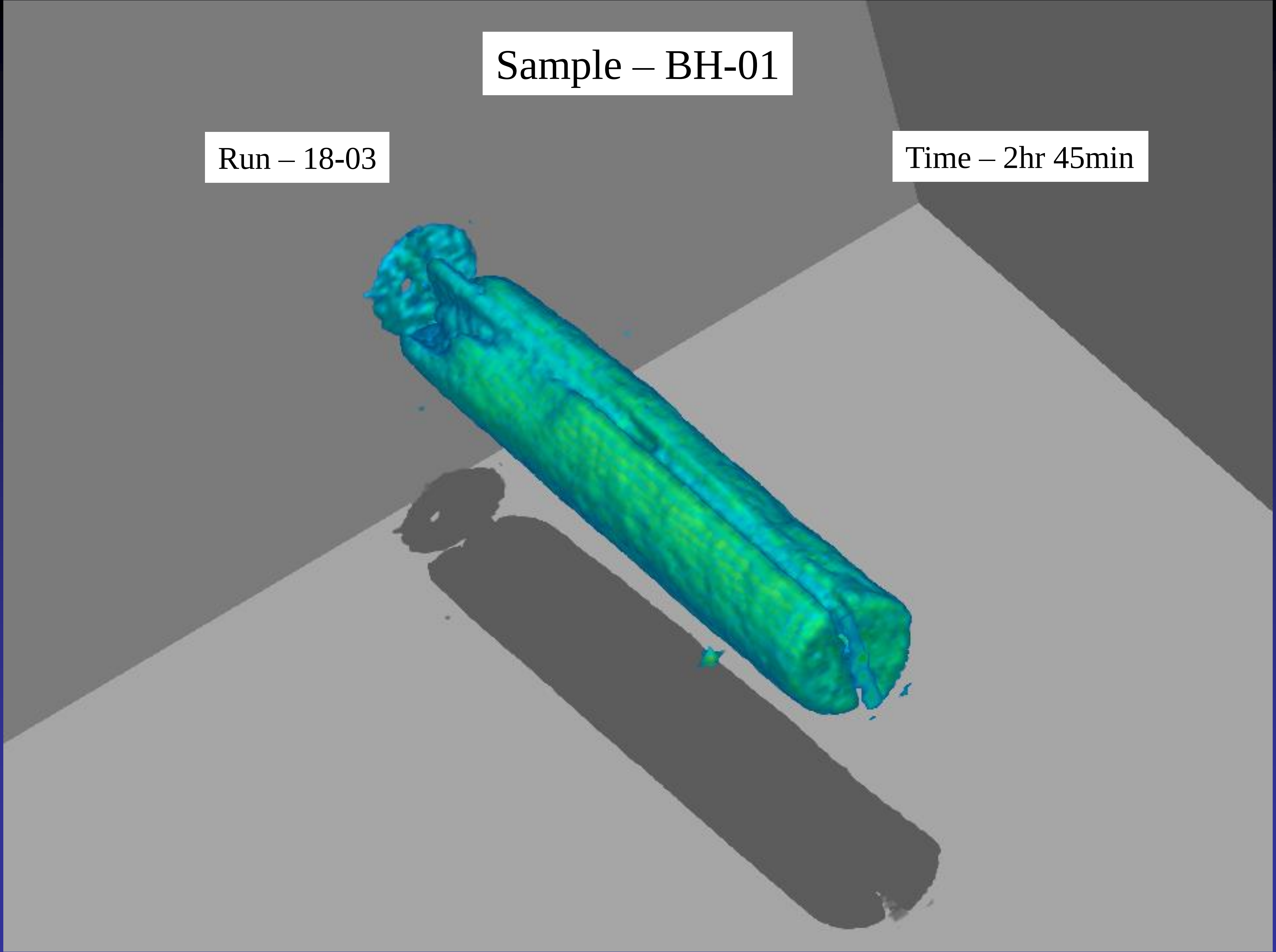




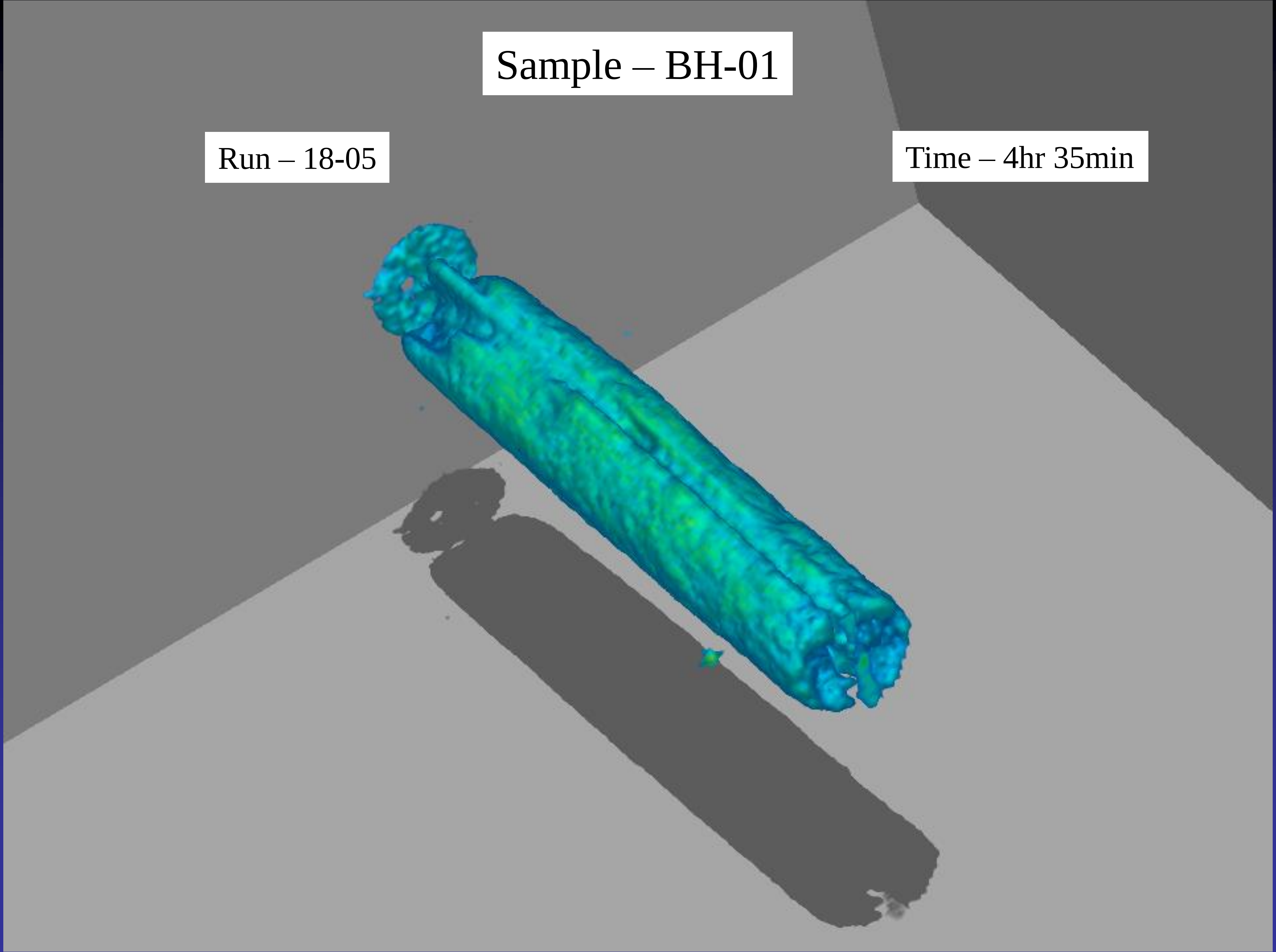
Sample – BH-01
Sample halves saturated
With methane and water
Middle space saturated
With methane

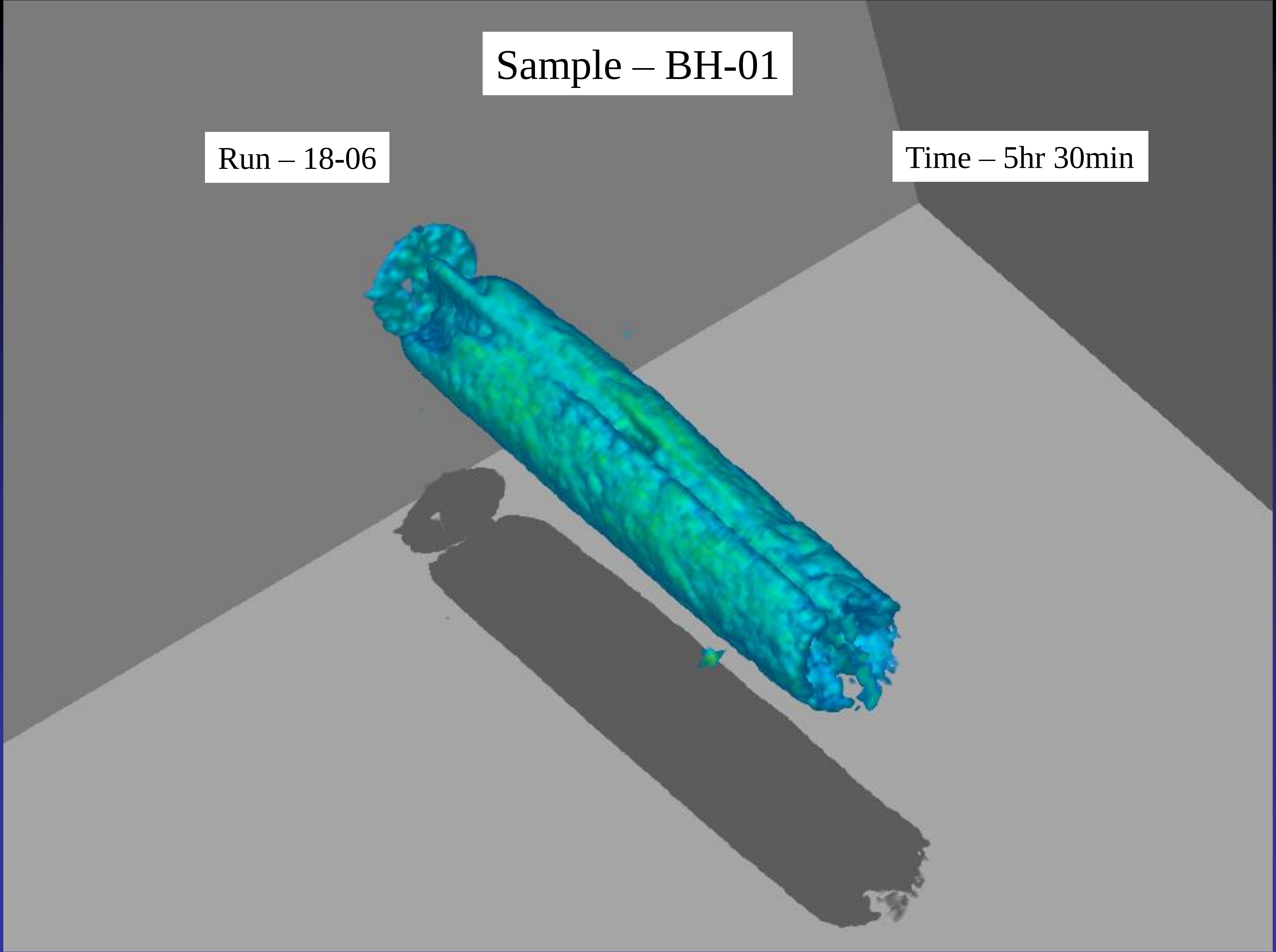

Sample – BH-01
Run – 17-39
Time – 0min
Started cooling sample
To 4^0 C

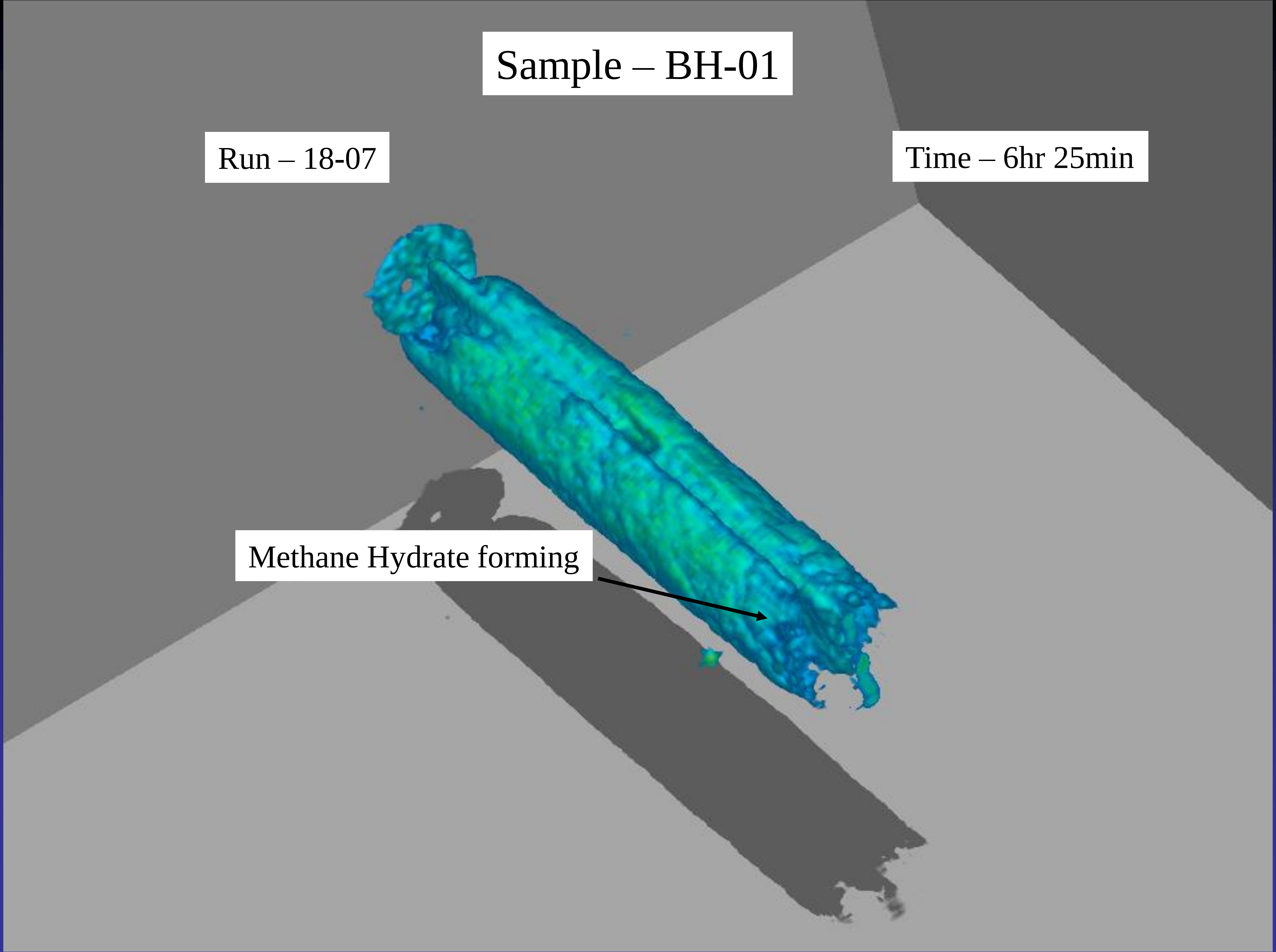

Sample – BH-01
Run – 18-01
Time – 55min

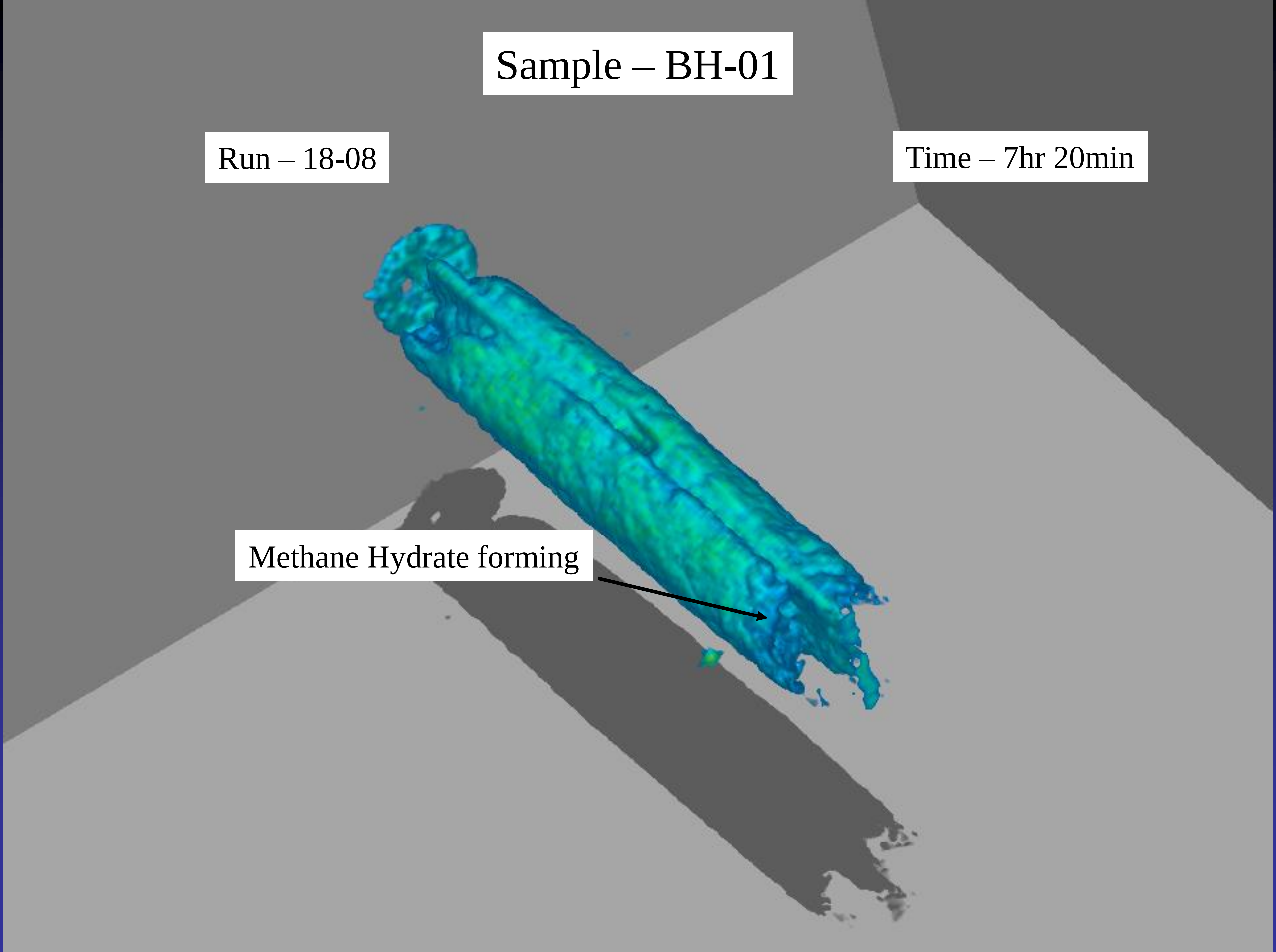


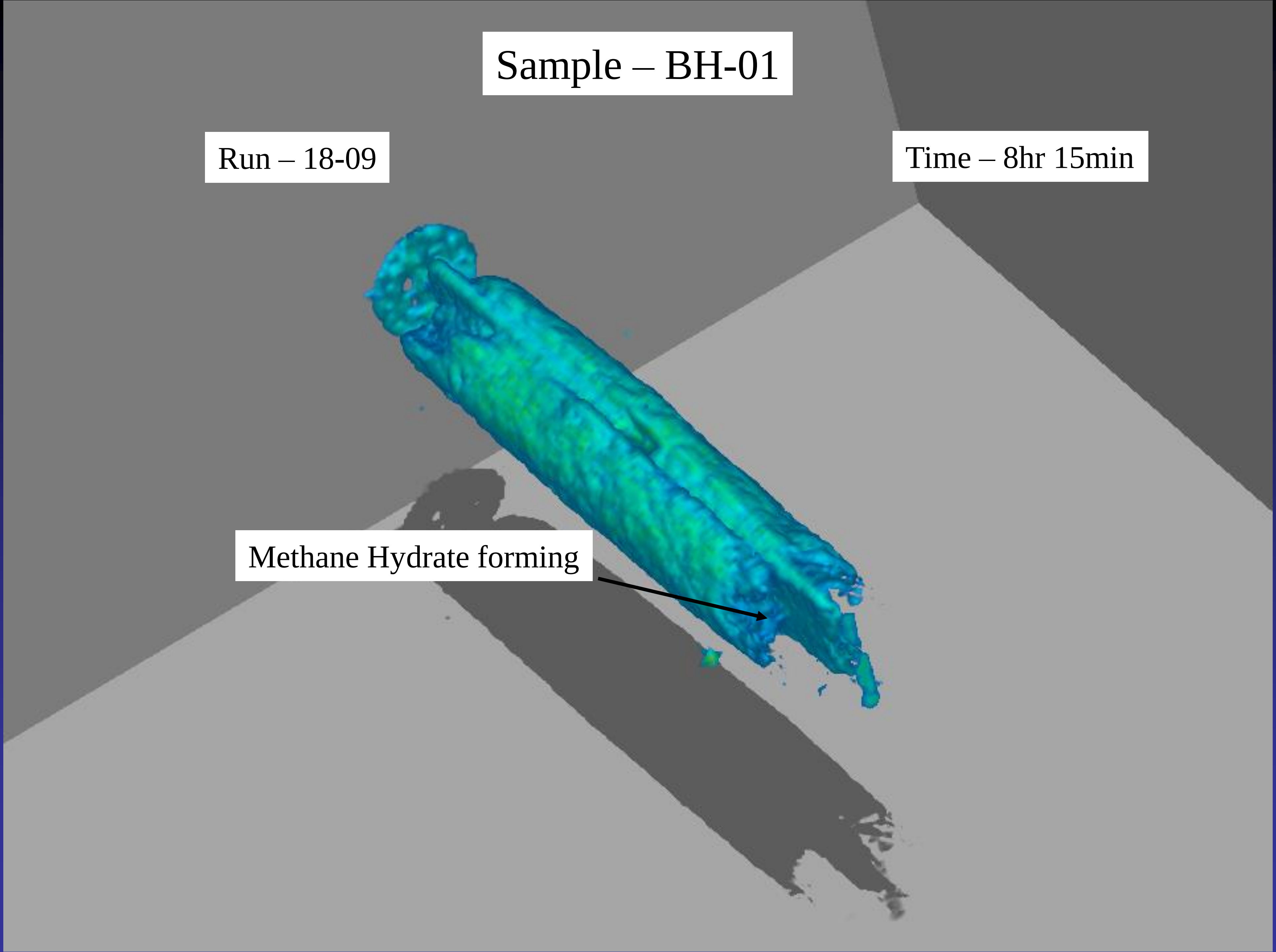
Sample – BH-01
Run – 18-03
Time – 2hr 45min

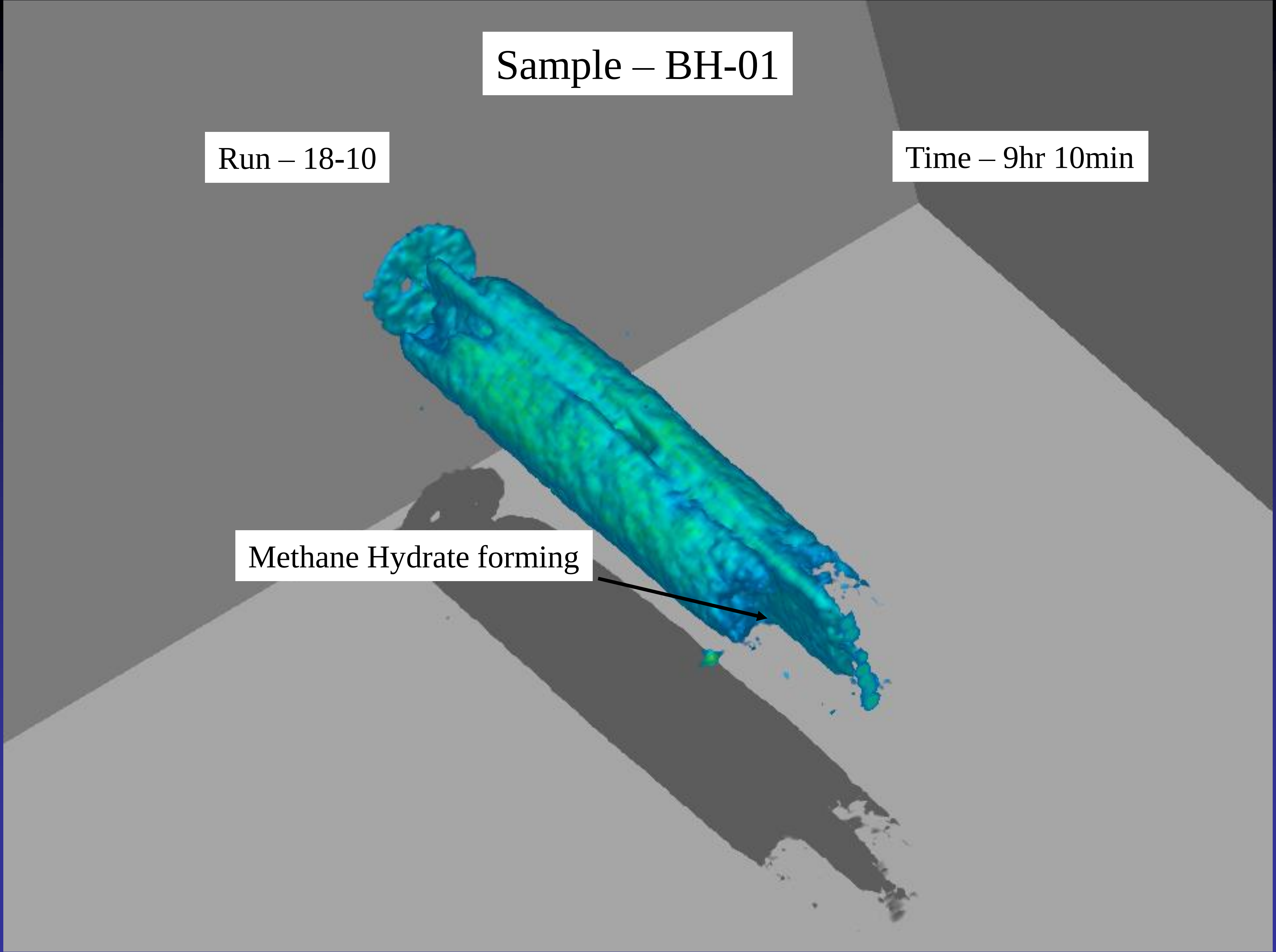

Sample – BH-01
Run – 18-05
Time – 4hr 35min

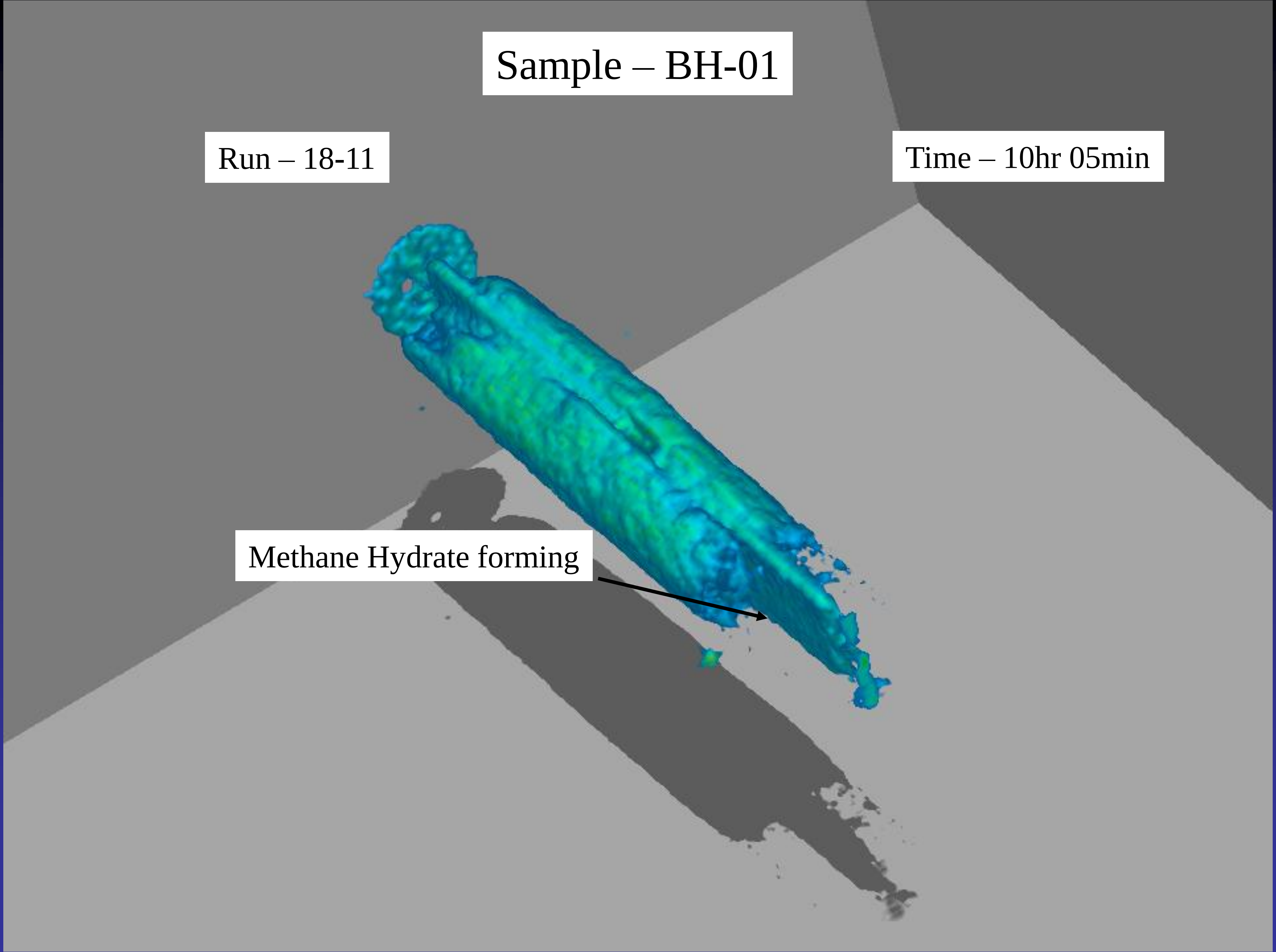

Sample – BH-01
Run – 18-06
Time – 5hr 30min

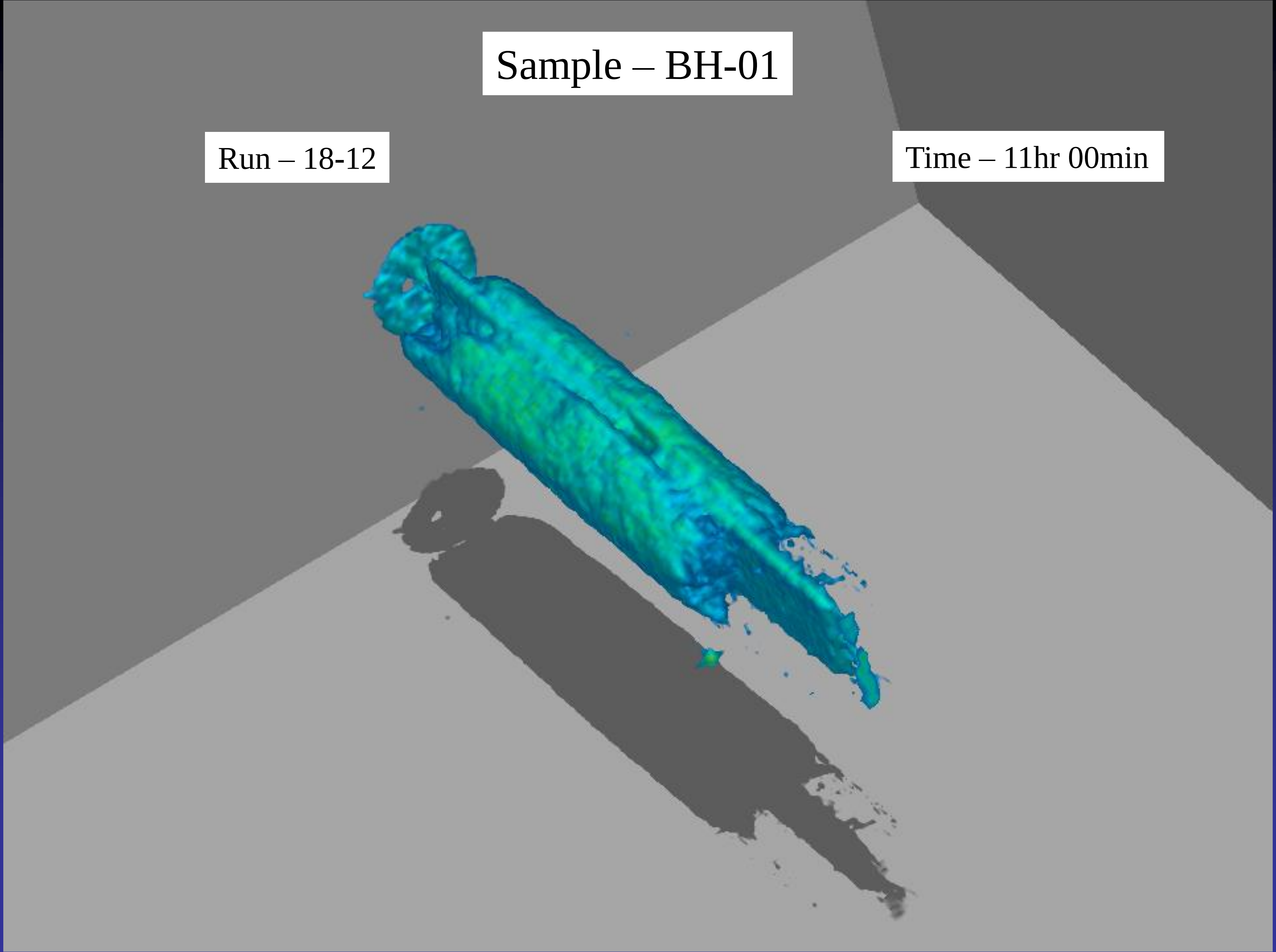

Sample – BH-01
Run – 18-07
Time – 6hr 25min
Methane Hydrate forming

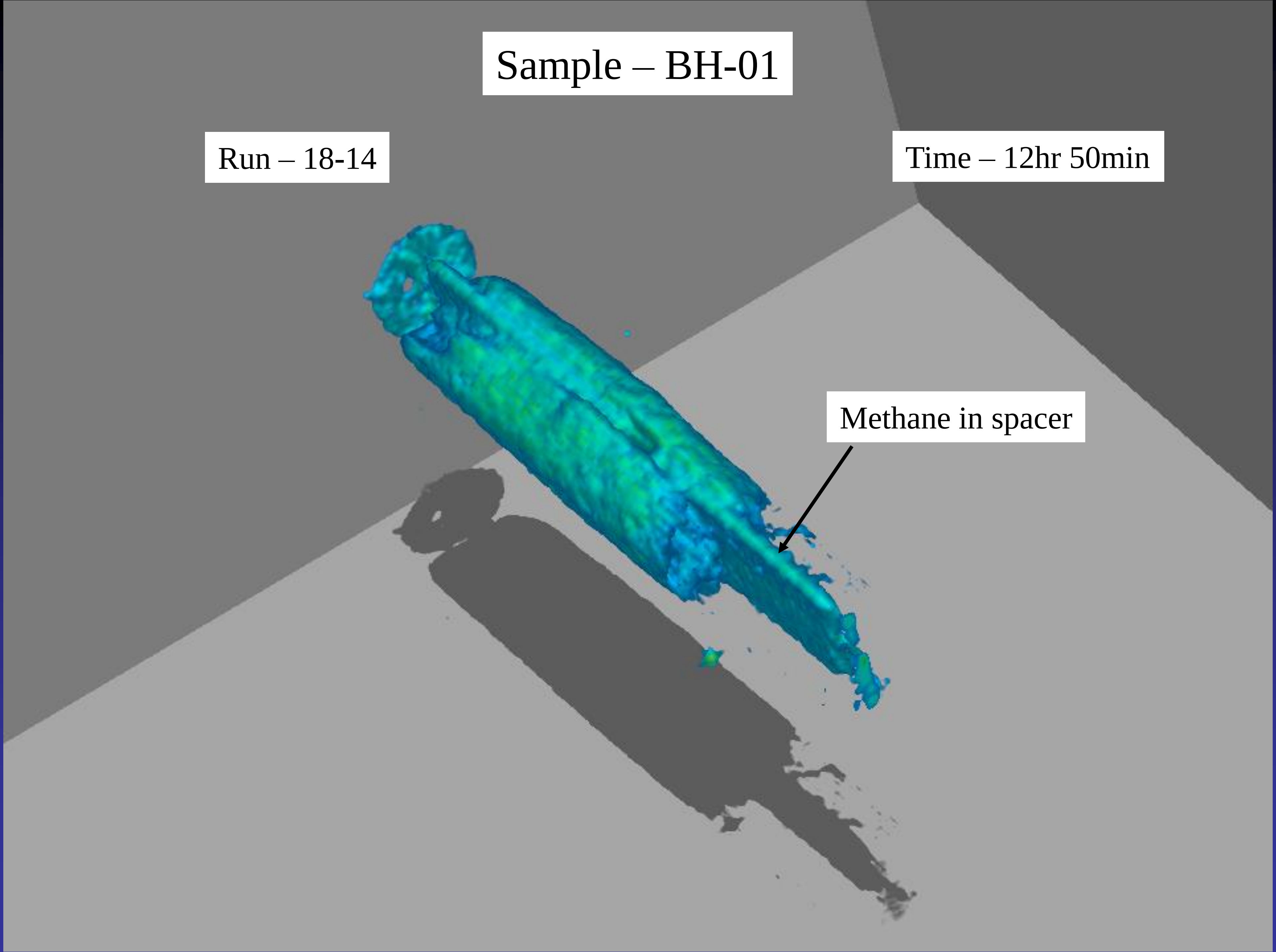

Sample – BH-01
Run – 18-08
Time – 7hr 20min
Methane Hydrate forming

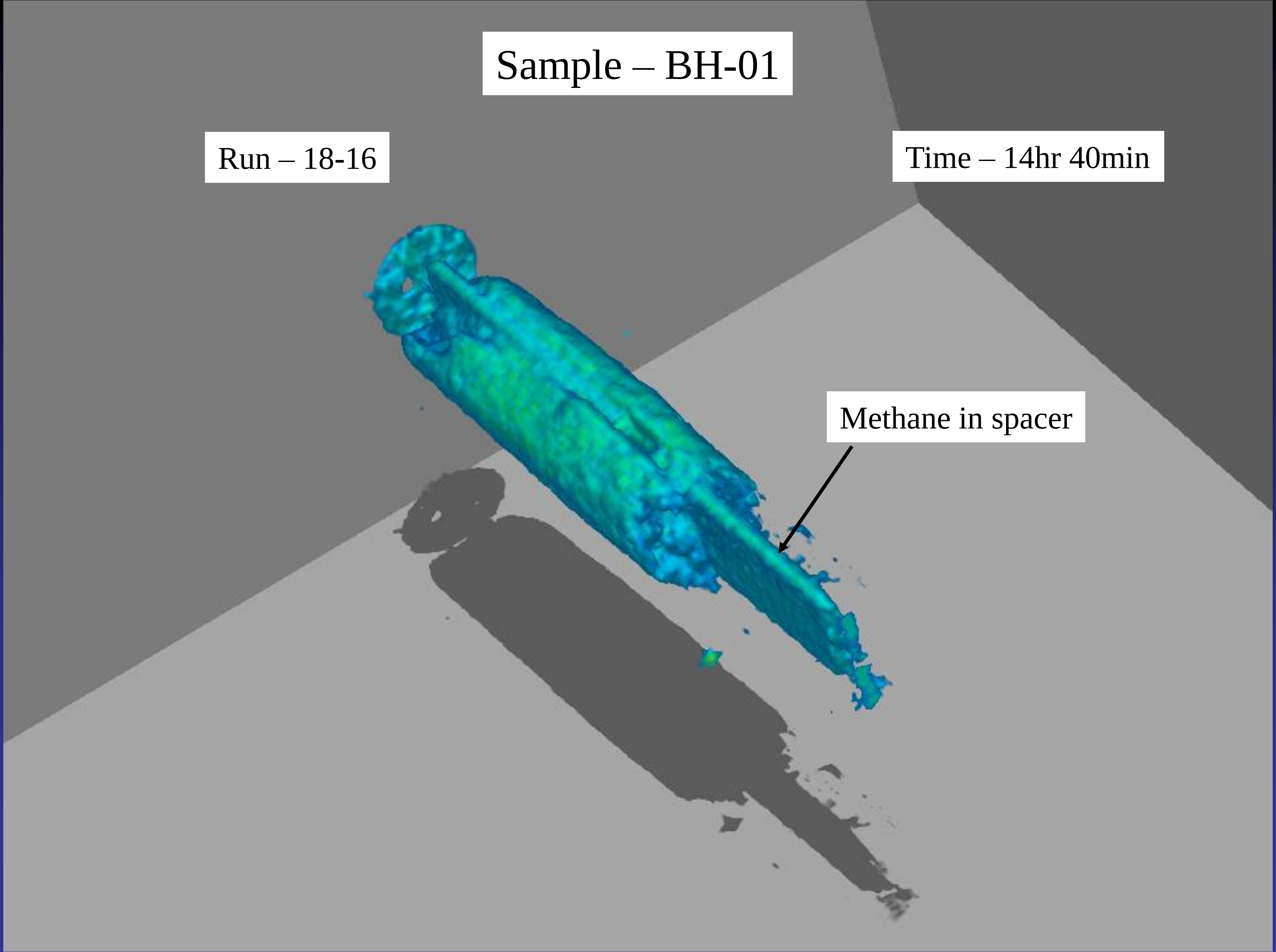

Sample – BH-01
Run – 18-09
Time – 8hr 15min
Methane Hydrate forming

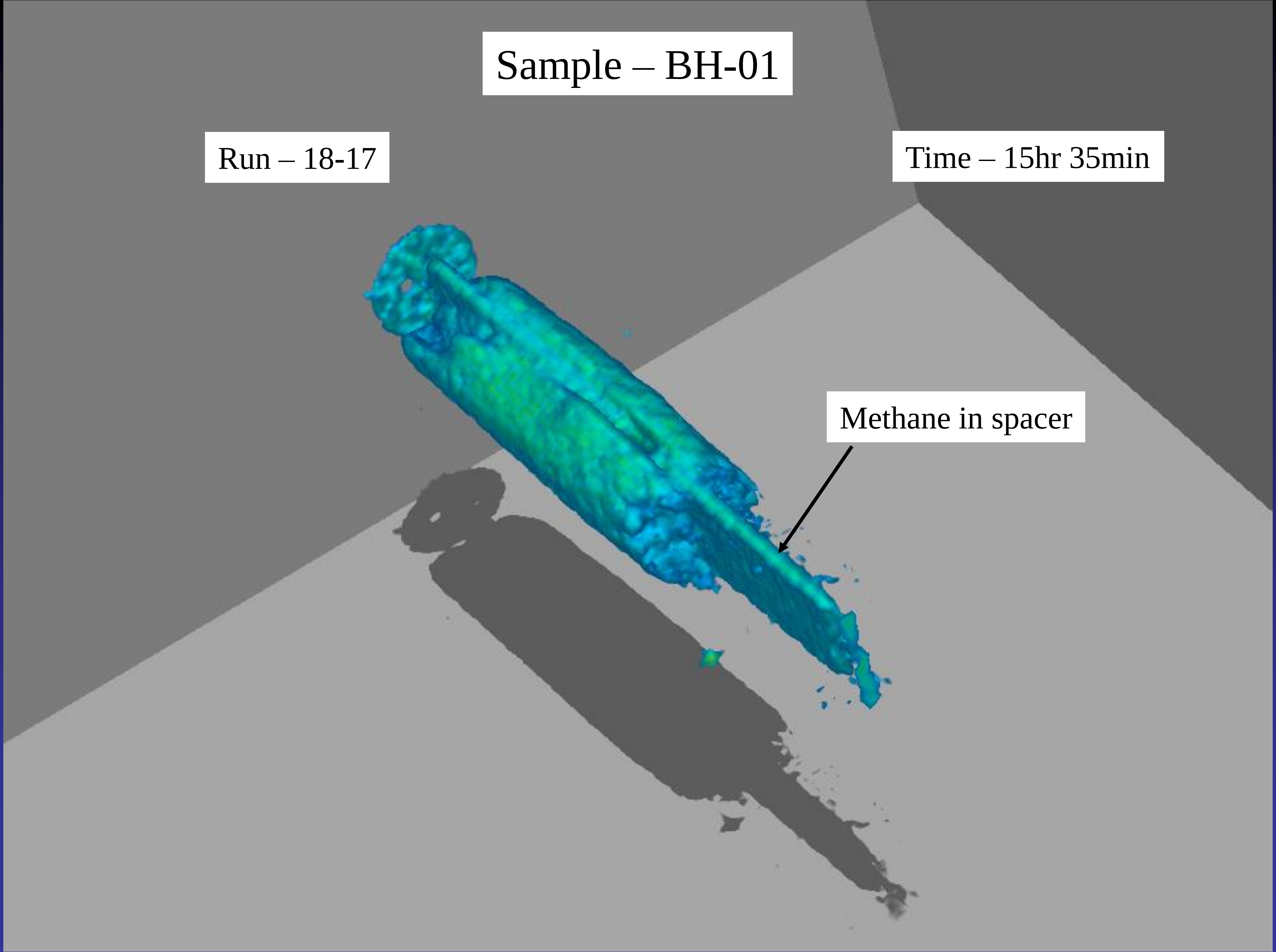

Sample – BH-01
Run – 18-10
Time – 9hr 10min
Methane Hydrate forming

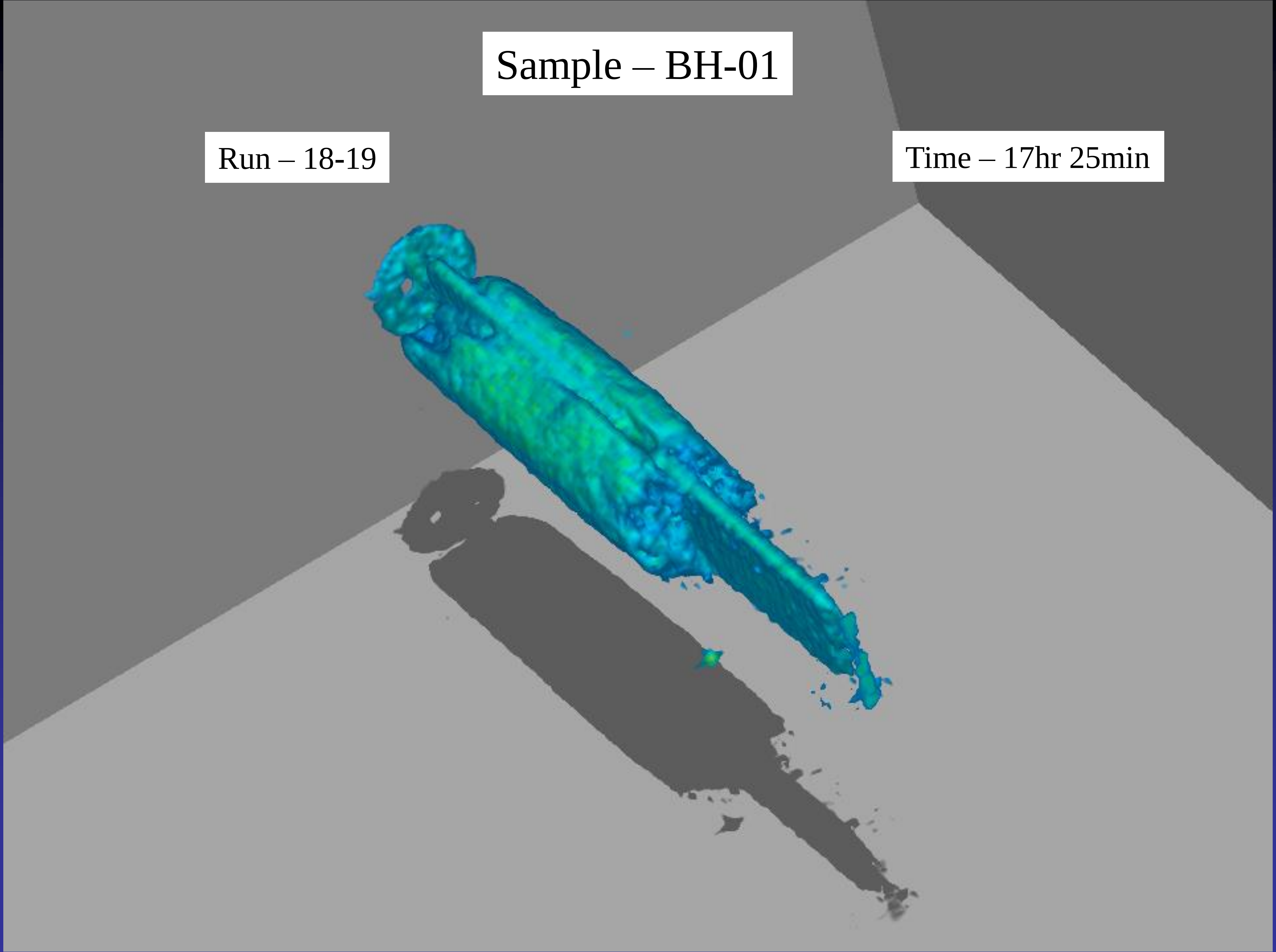

Sample – BH-01
Run – 18-11
Time – 10hr 05min
Methane Hydrate forming

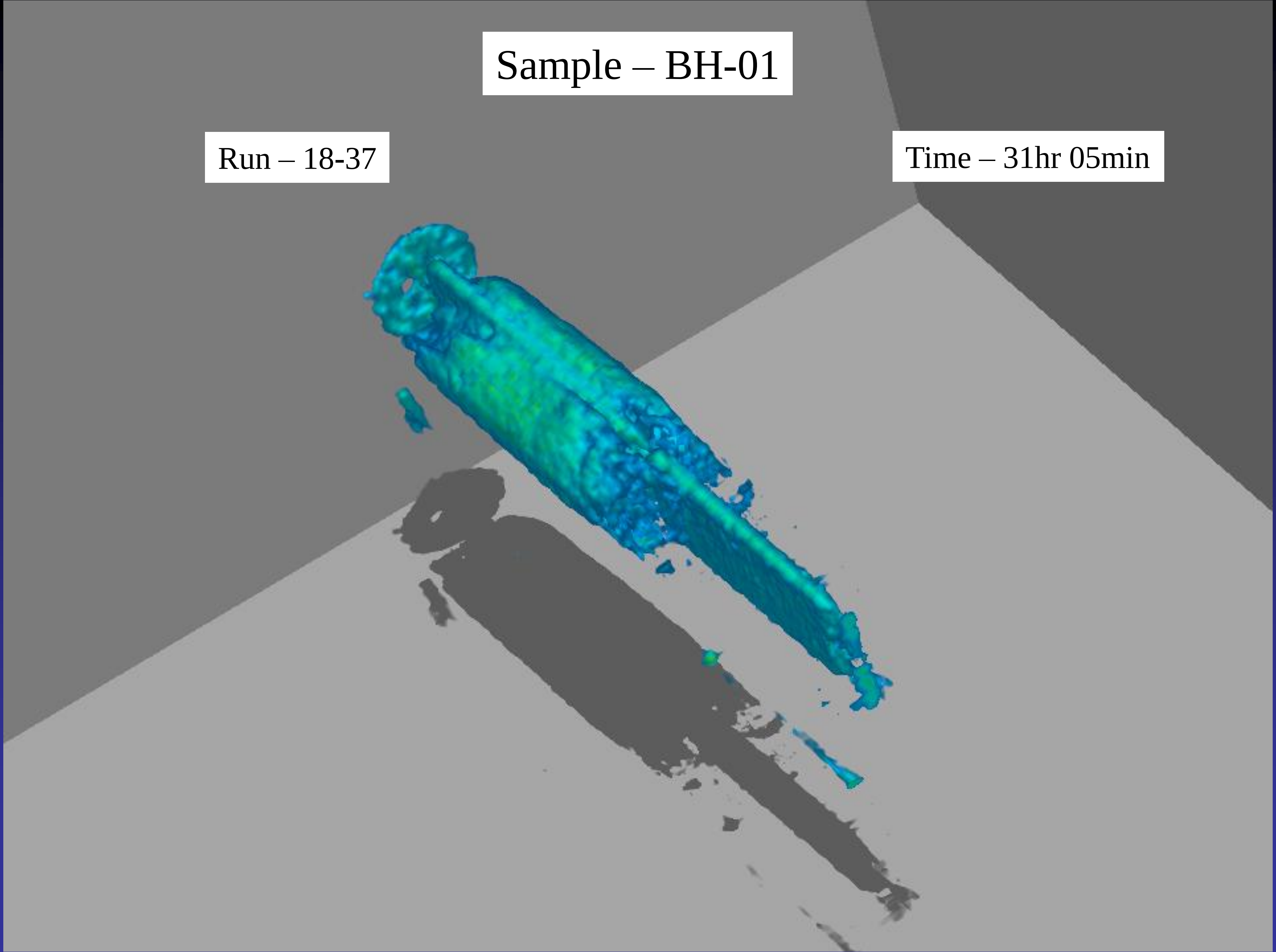

Sample – BH-01
Run – 18-12
Time – 11hr 00min

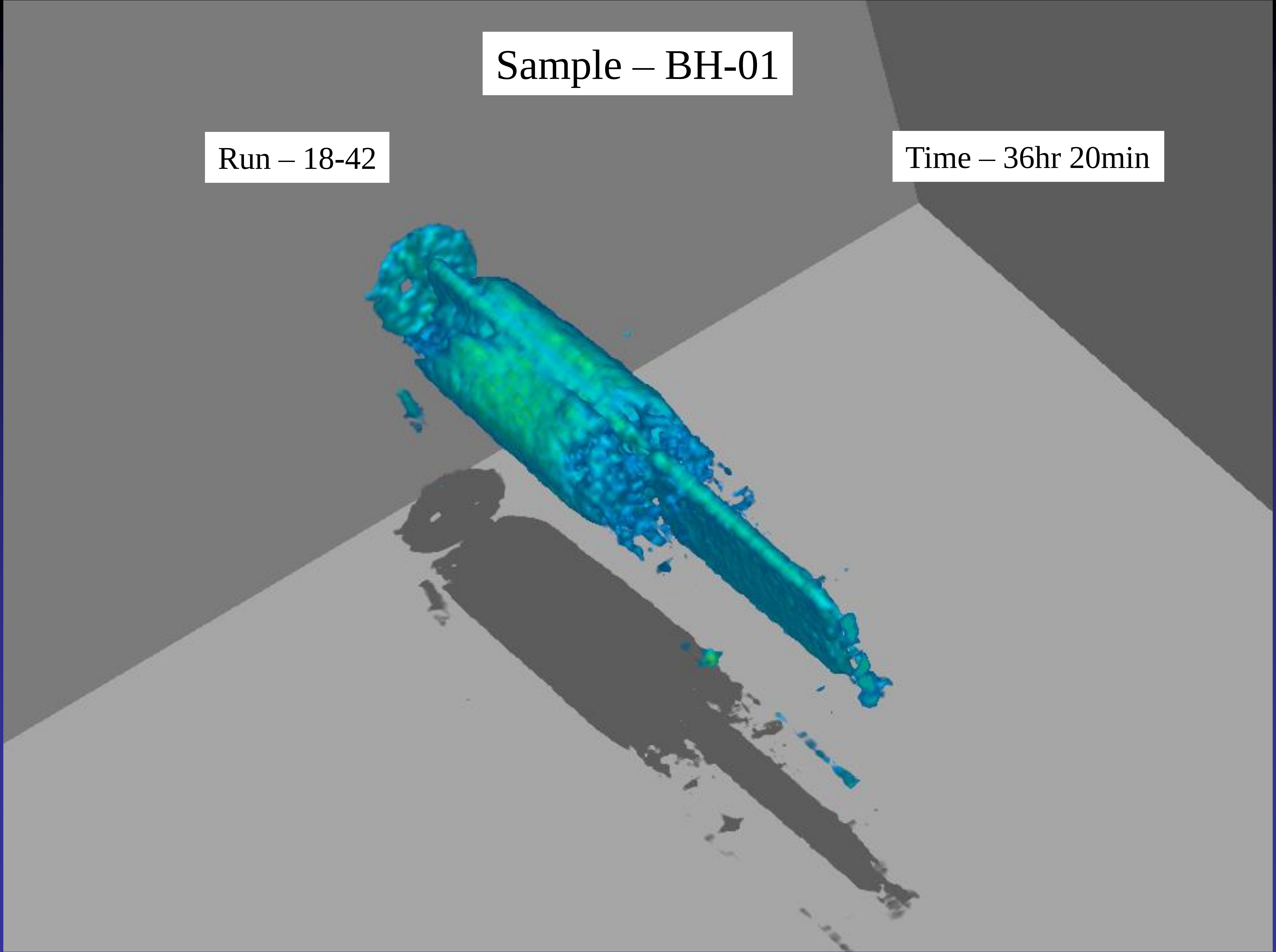

Sample – BH-01
Run – 18-14
Time – 12hr 50min
Methane in spacer


Sample – BH-01
Run – 18-16
Time – 14hr 40min
Methane in spacer


Sample – BH-01
Run – 18-17
Time – 15hr 35min
Methane in spacer


Sample – BH-01
Run – 18-19
Time – 17hr 25min

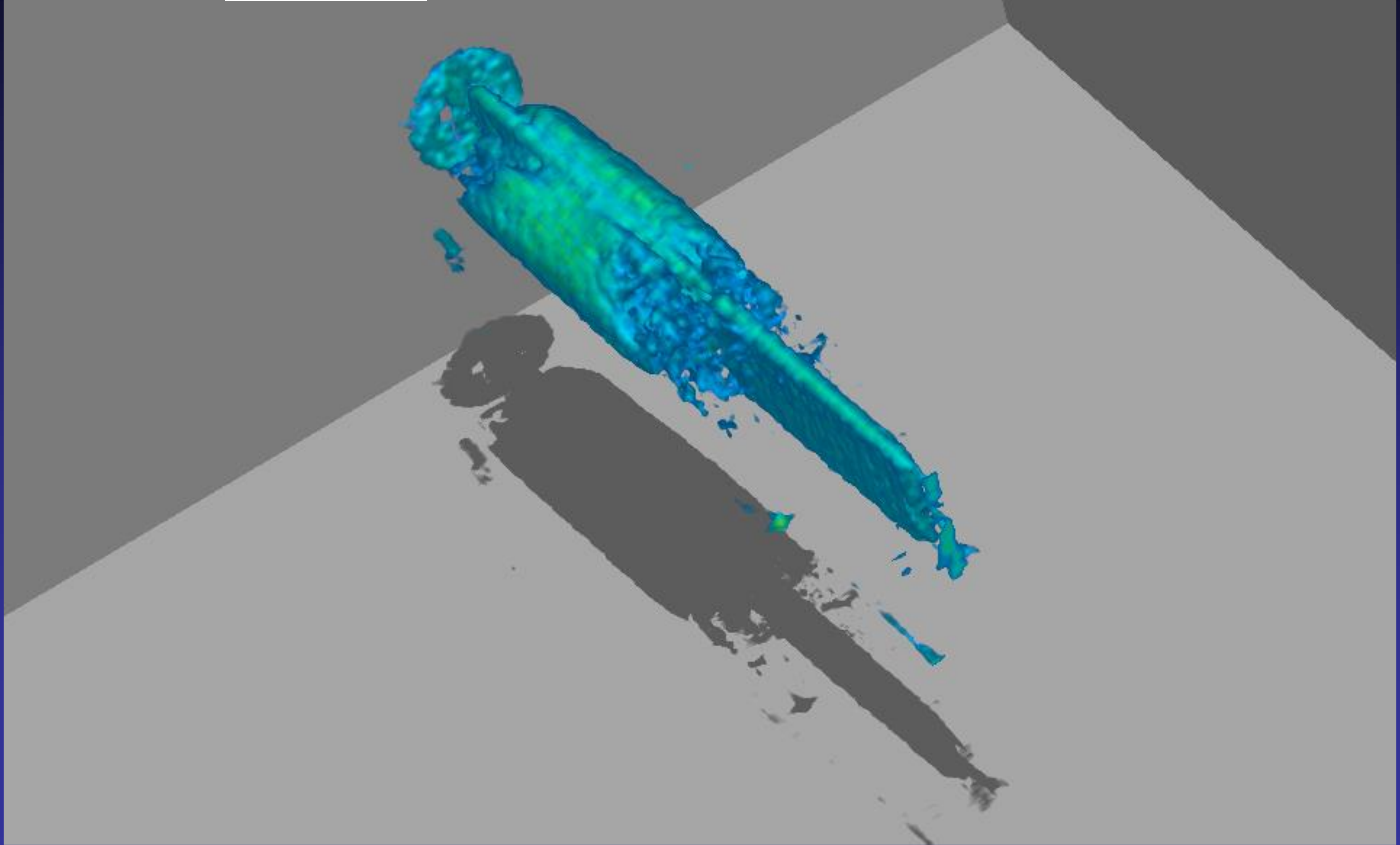

Sample – BH-01
Run – 18-37
Time – 31hr 05min

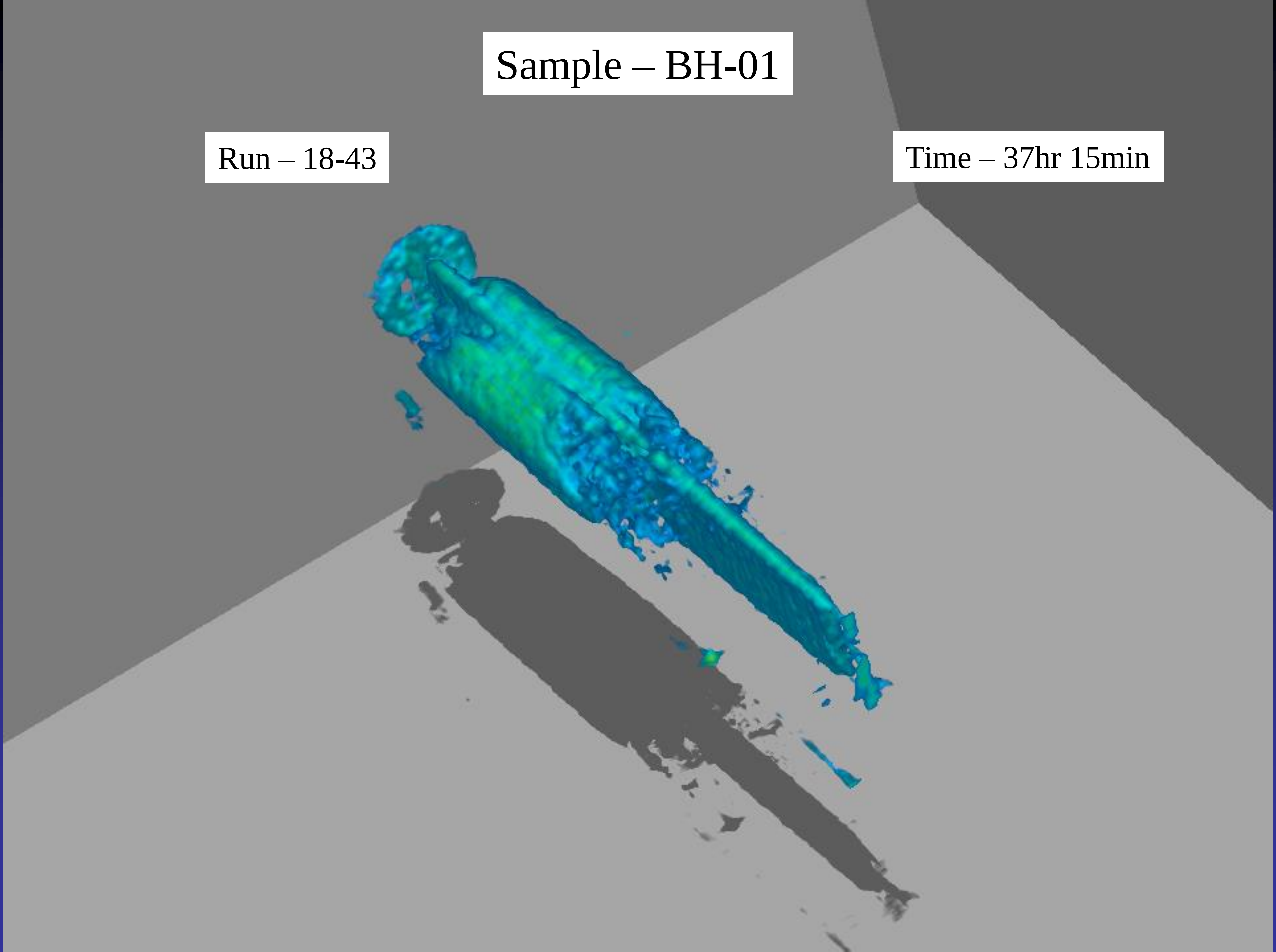

Sample – BH-01
Run – 18-42
Time – 36hr 20min

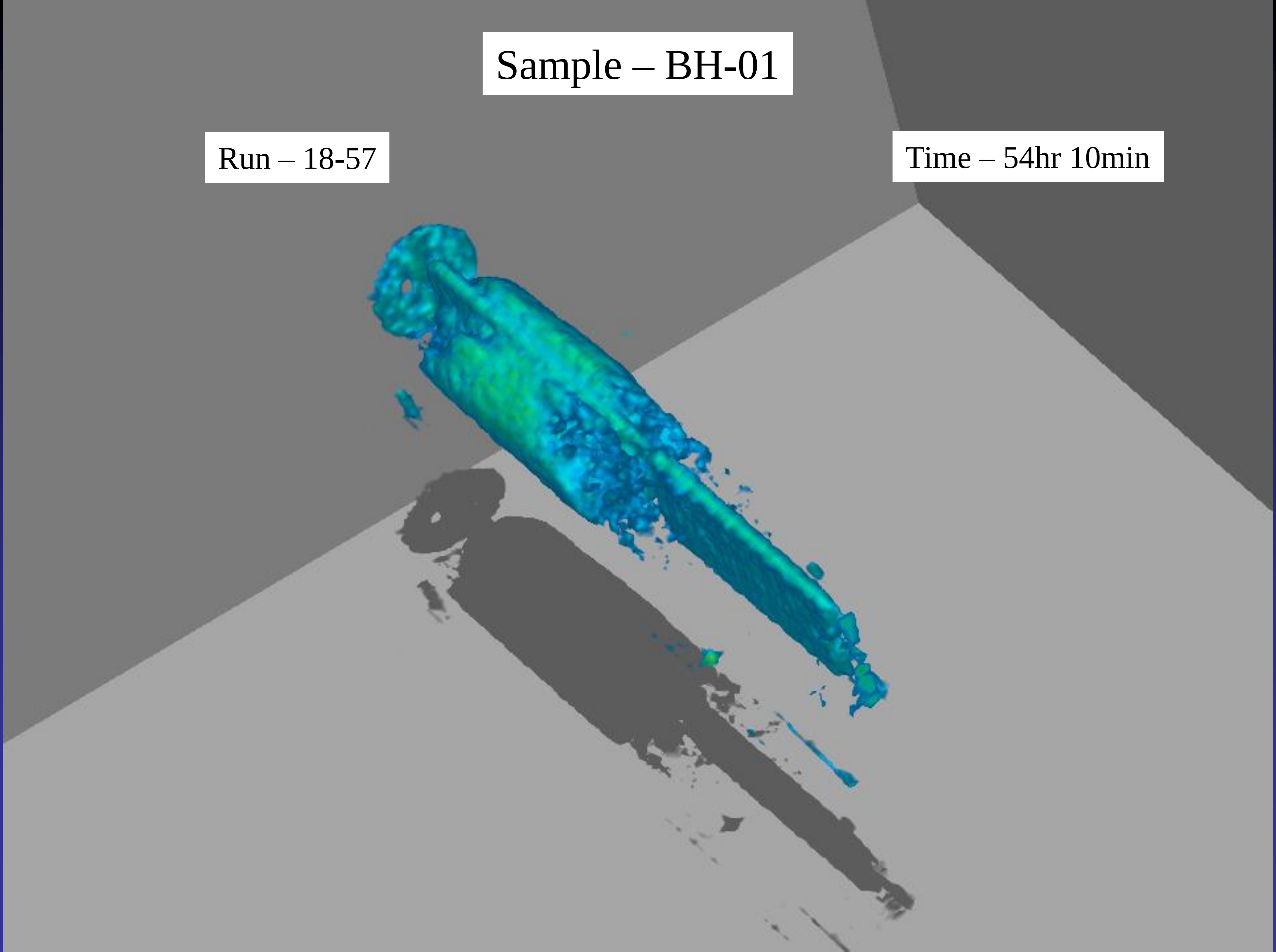
Sample – BH-01

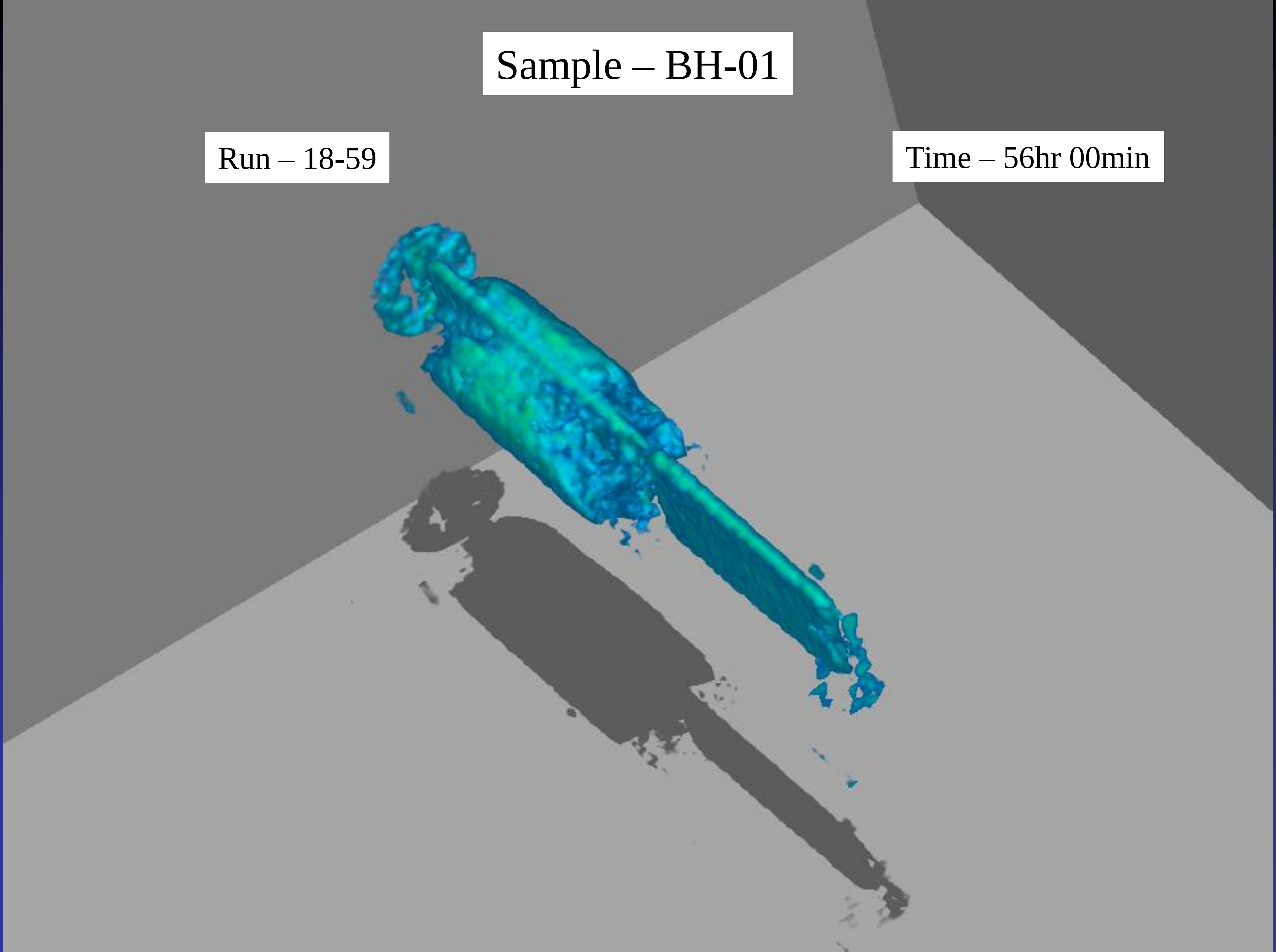
Run – 18-43

Time – 37hr 15min



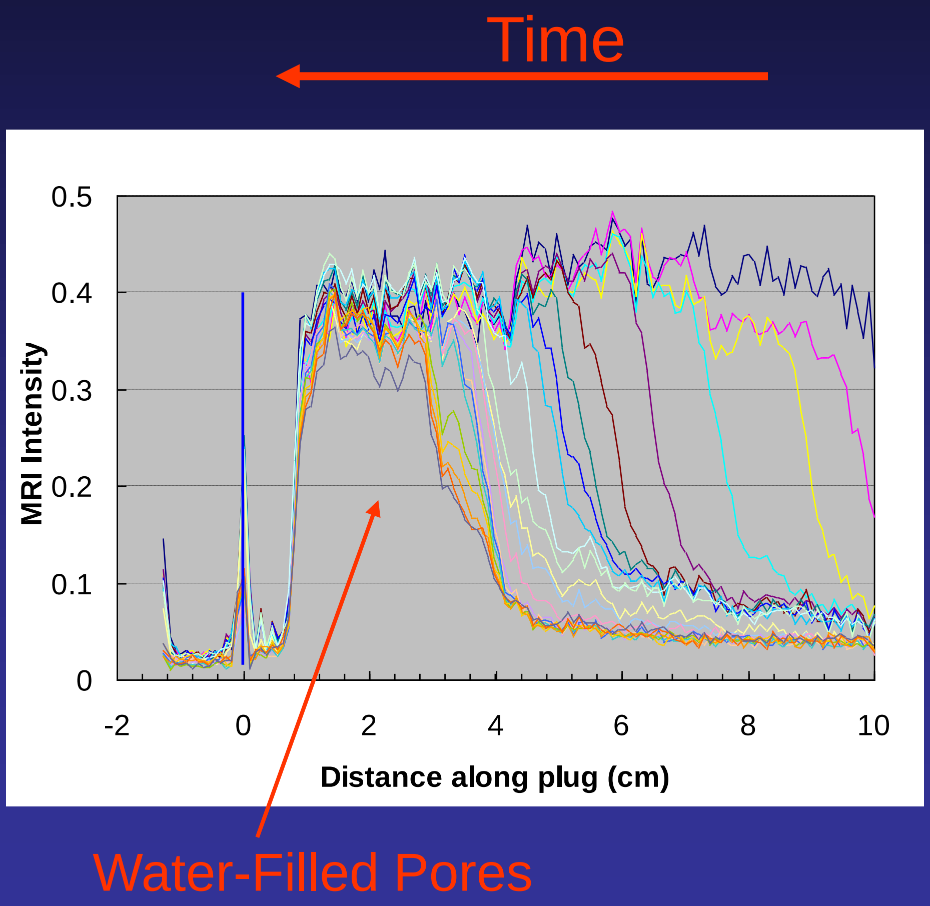

Sample – BH-01
Run – 18-43
Time – 37hr 15min


Sample – BH-01
Run – 18-57
Time – 54hr 10min


Sample – BH-01
Run – 18-59
Time – 56hr 00min

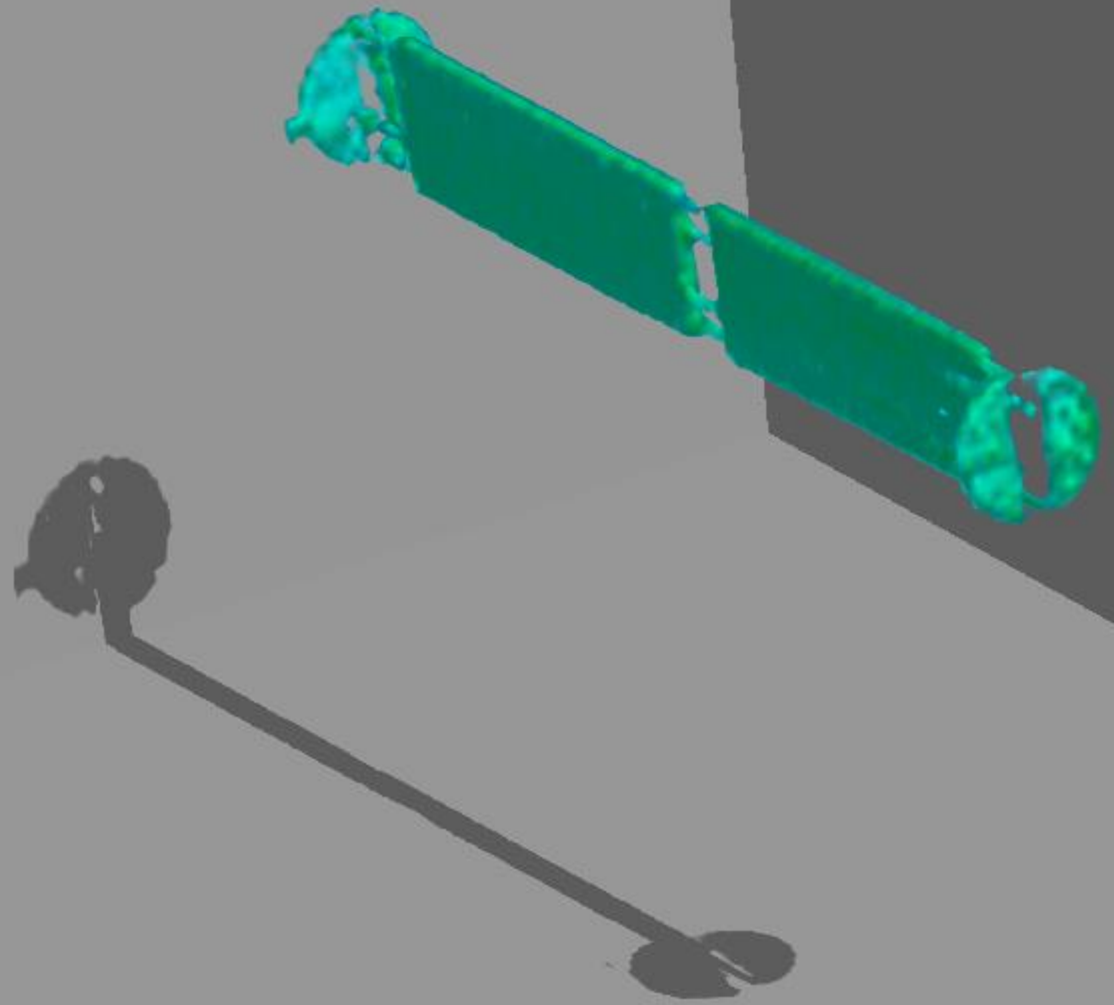
Progress of Hydrate Front

- Longitudinal Profile in Core – 5 mm from Fracture.
- Approximately 35 Hours, ~ Equal Time Increments.
- Hydrate Growth Slows with Time.



0.0 hrs

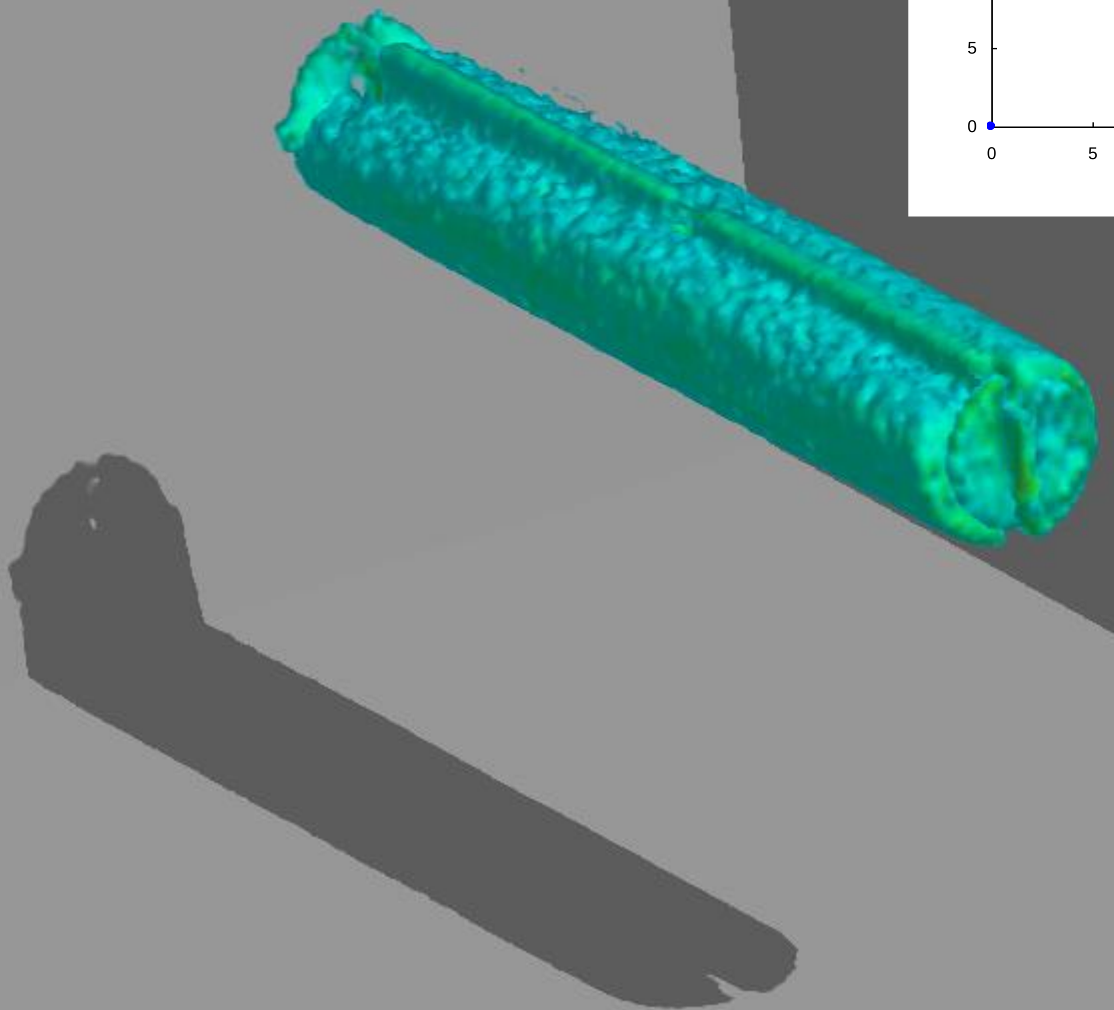
Methane in Spacer

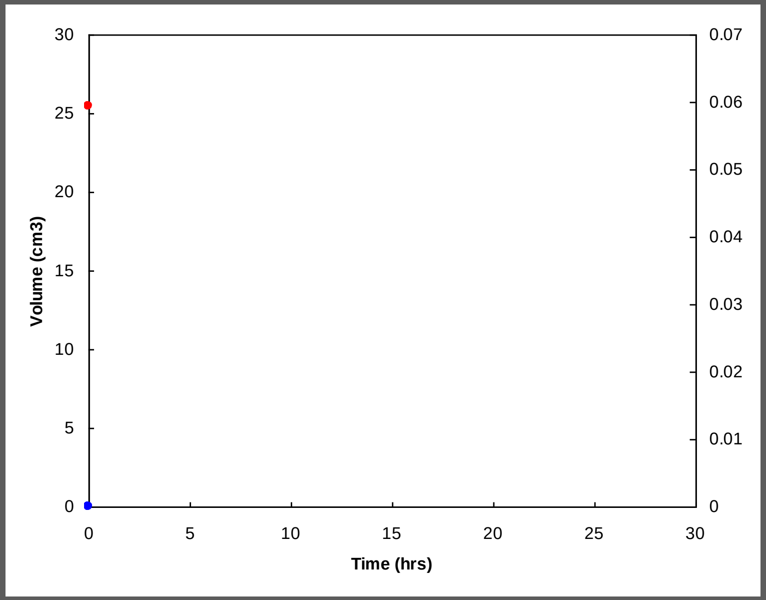


33-07

0.0 hrs

Sw=0.5 + Methane

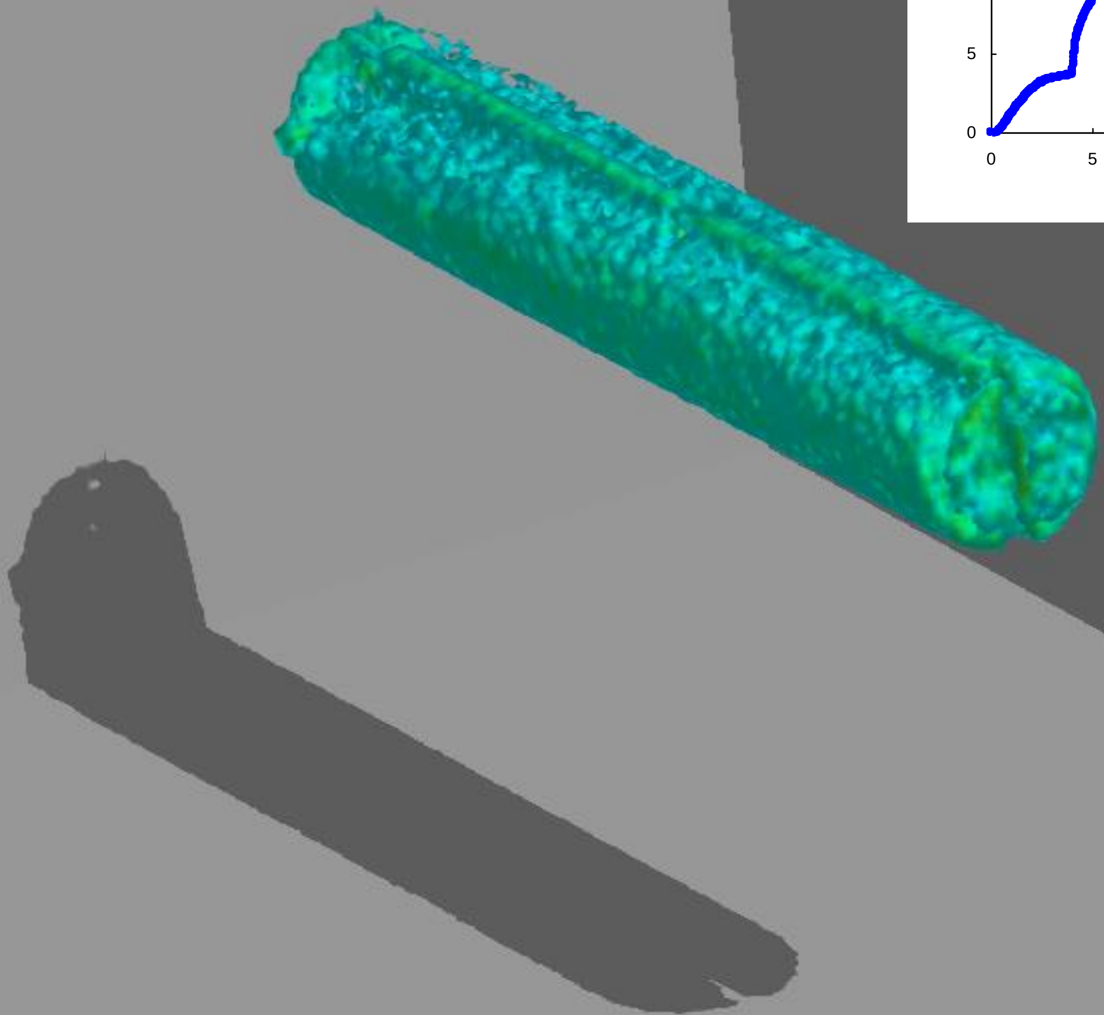


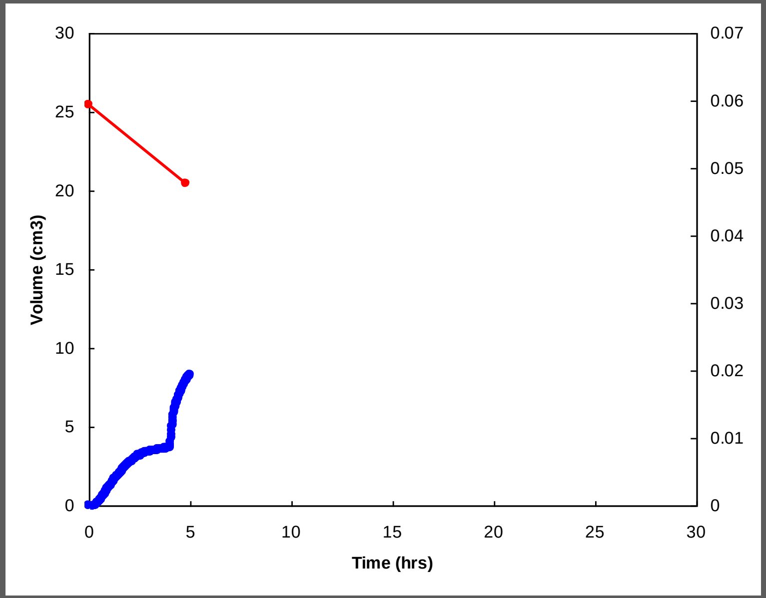


33a-01

5.0 hrs

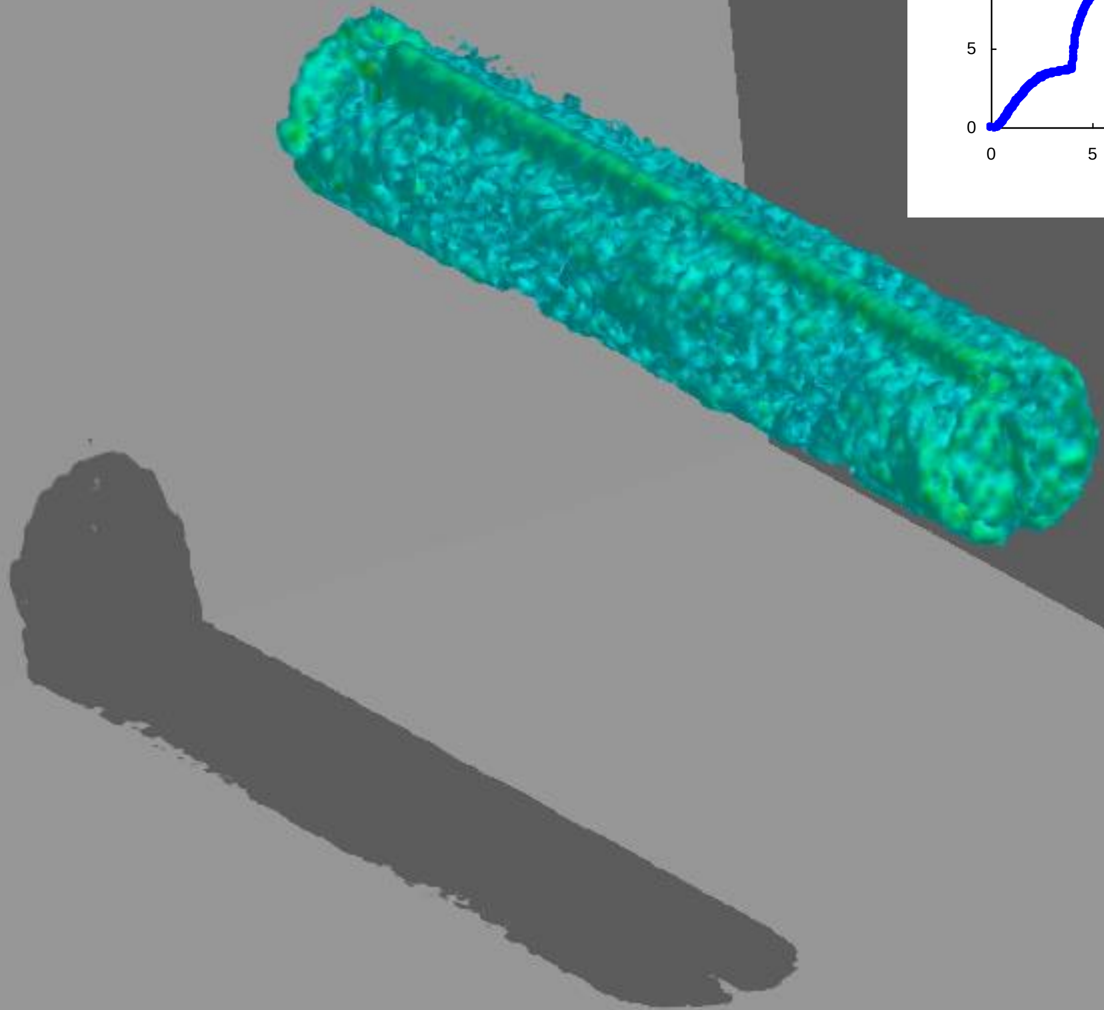
Cooling Starts

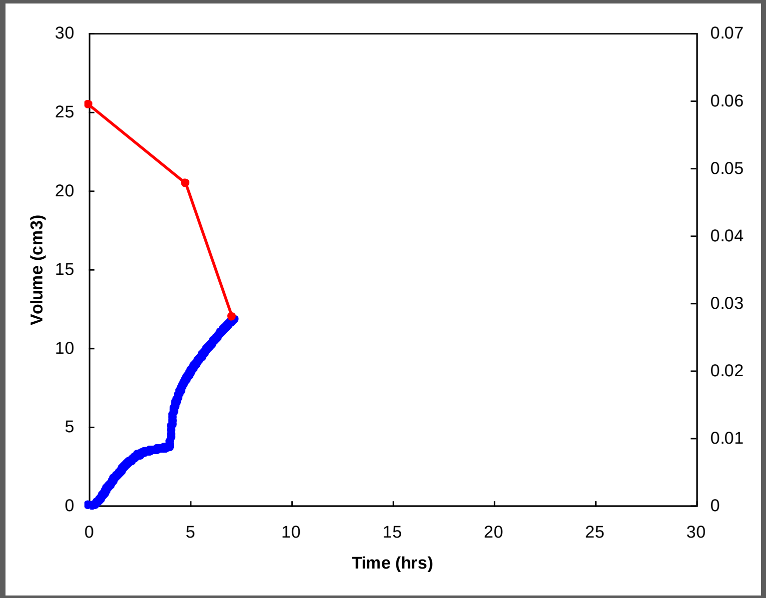




33c-01

7.2 hrs

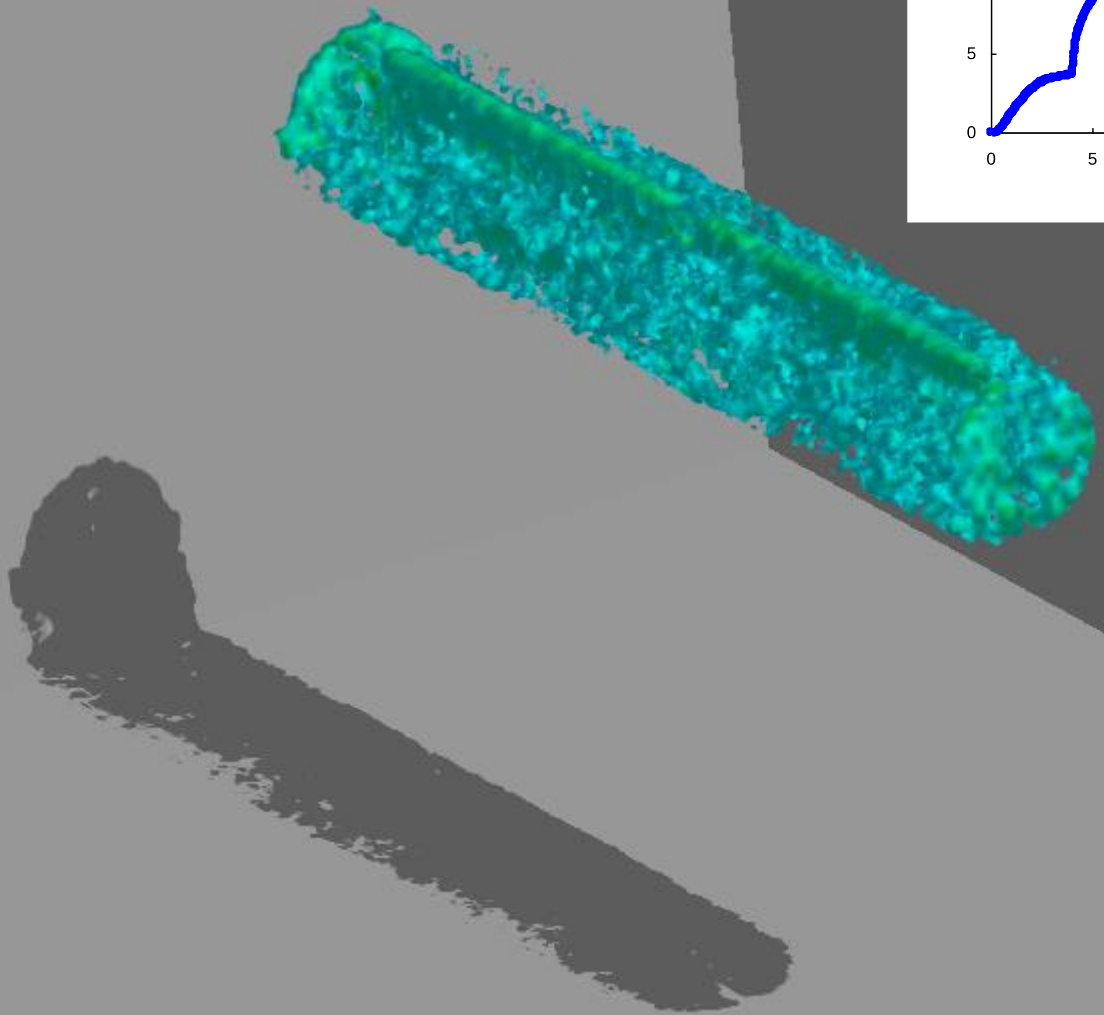


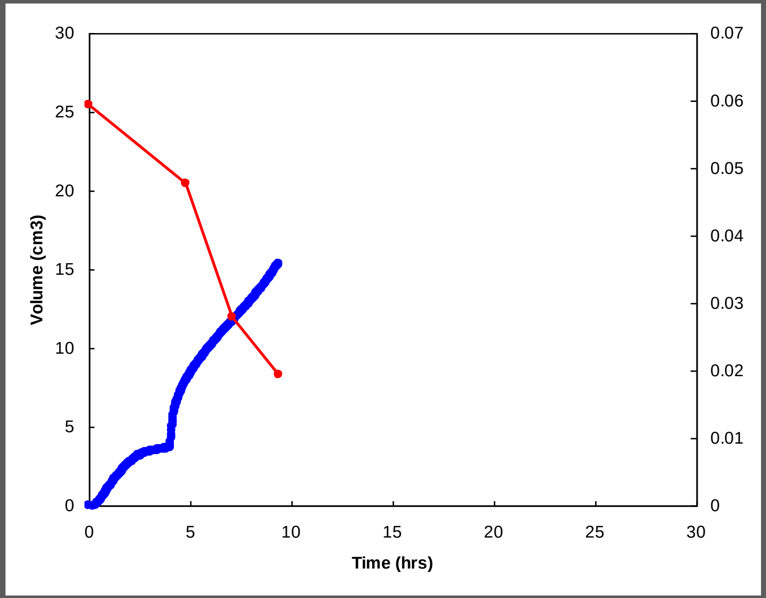


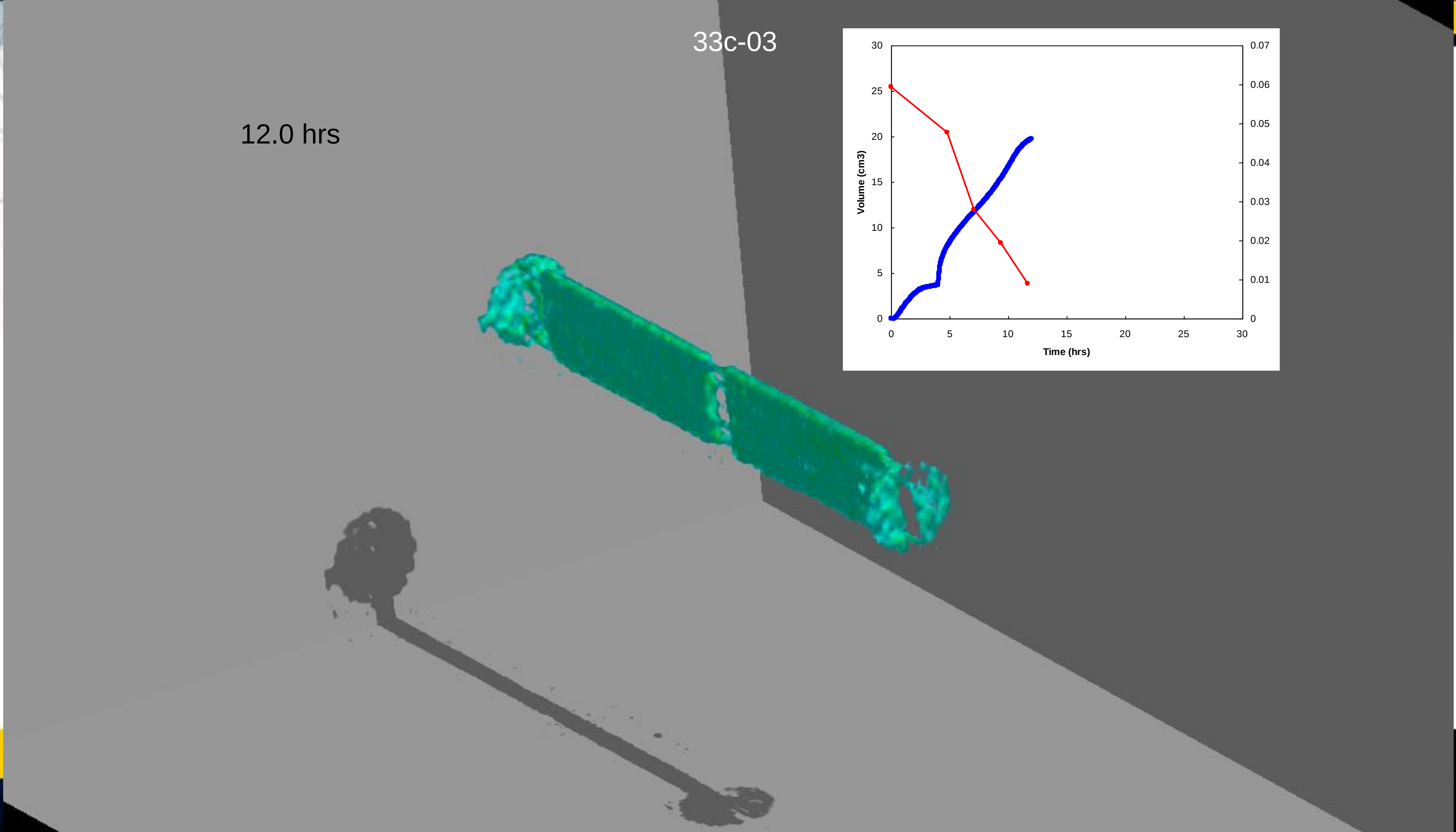
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

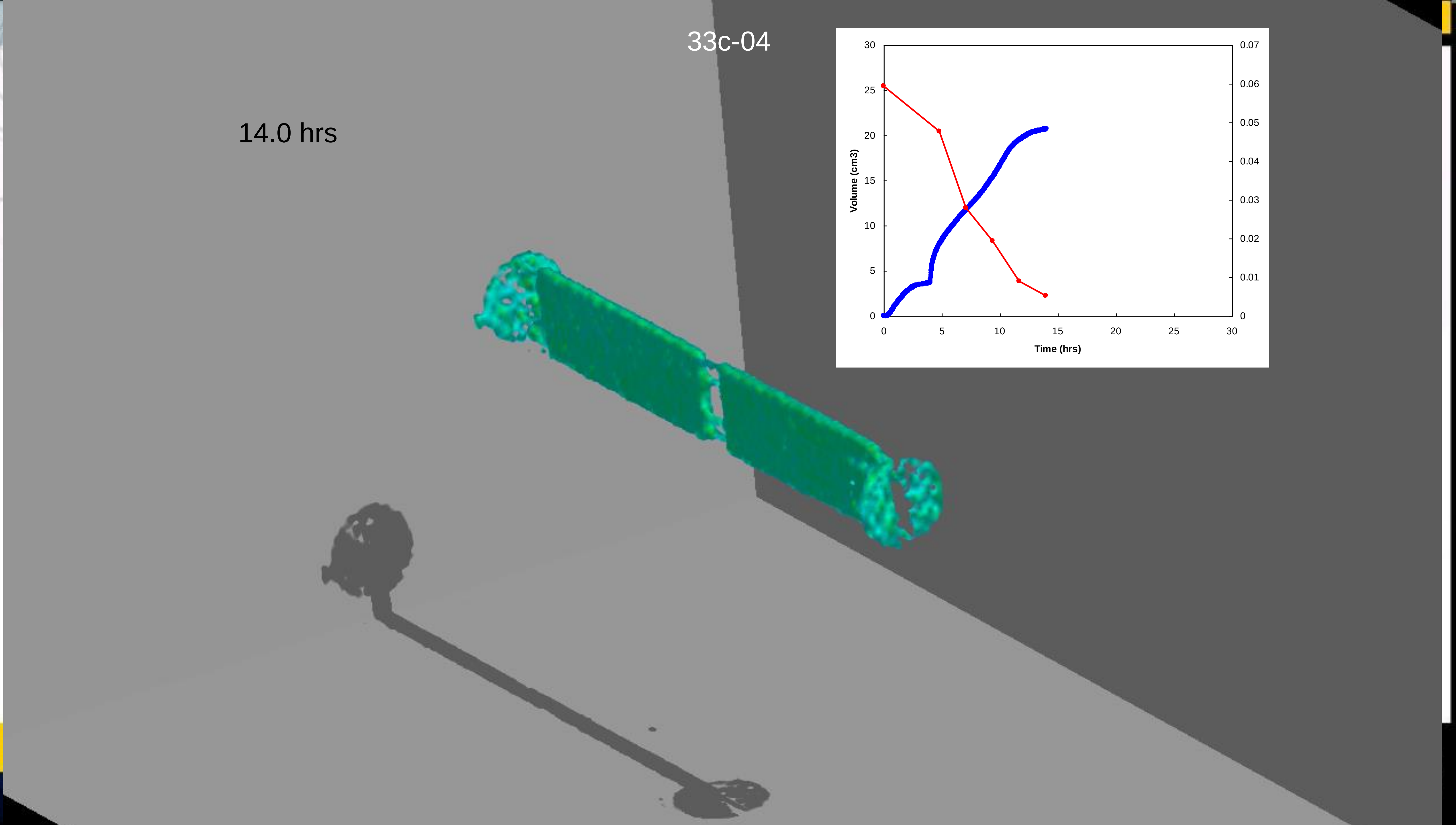
33c-02

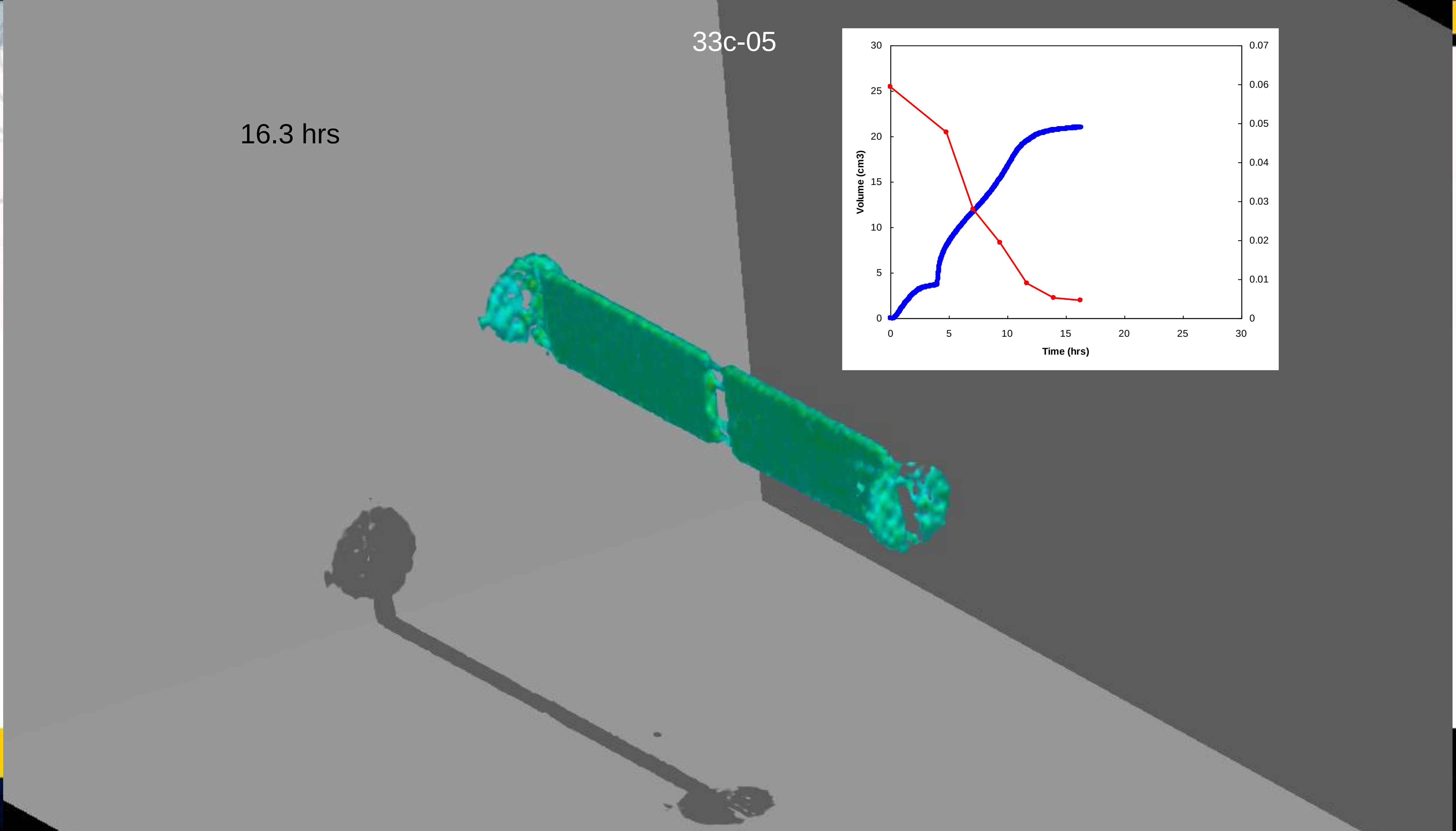
9.4 hrs





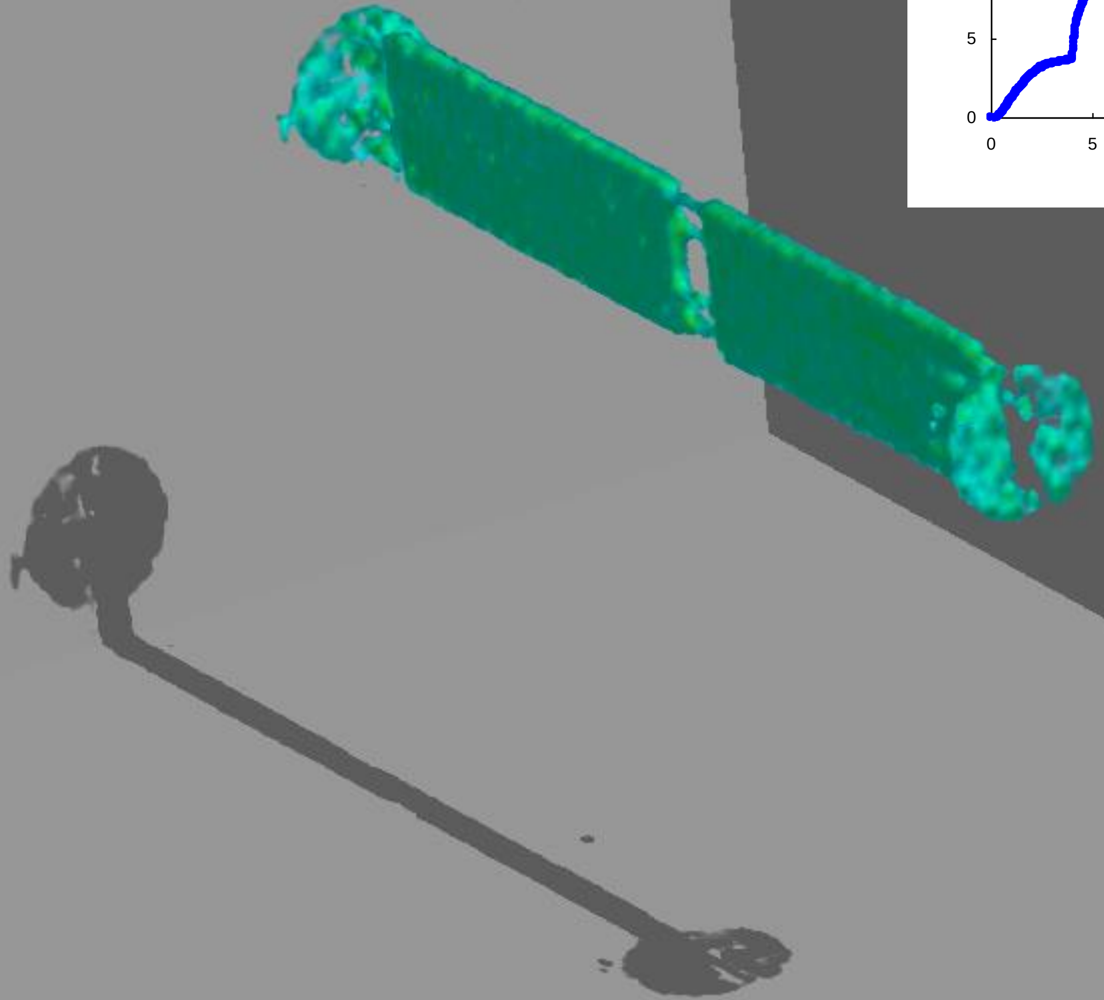

33c-03
12.0 hrs
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

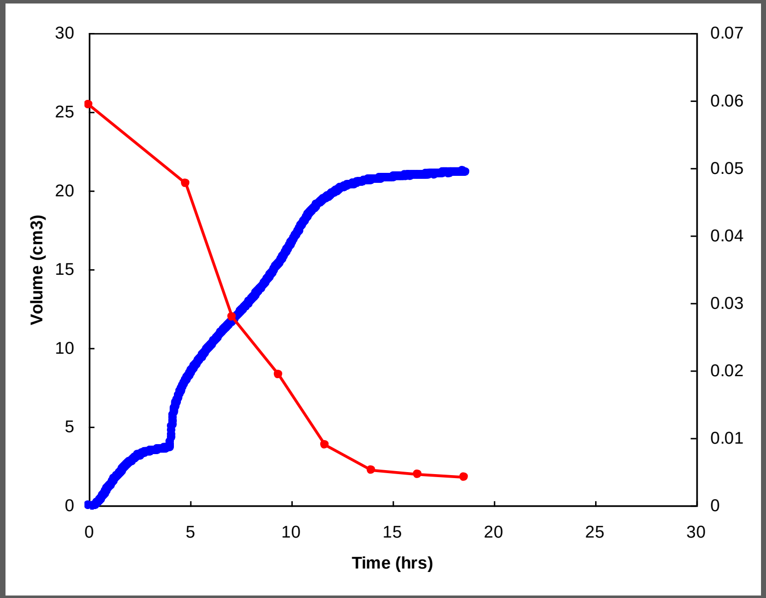

33c-04
14.0 hrs
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07


33c-05
16.3 hrs
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

33c-06

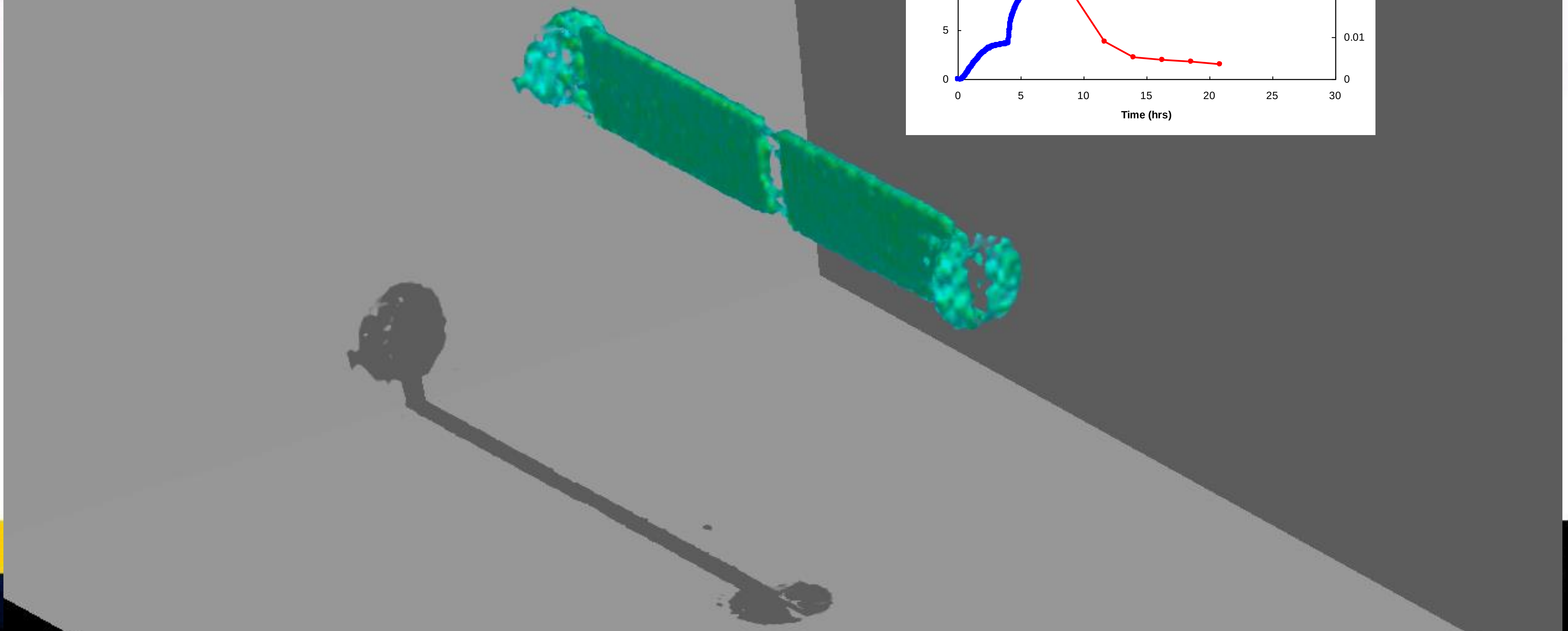
18.6 hrs

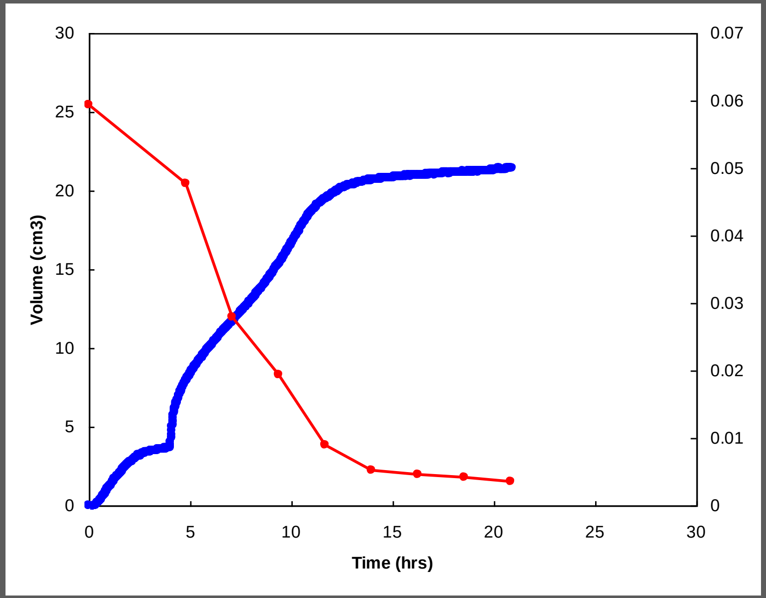


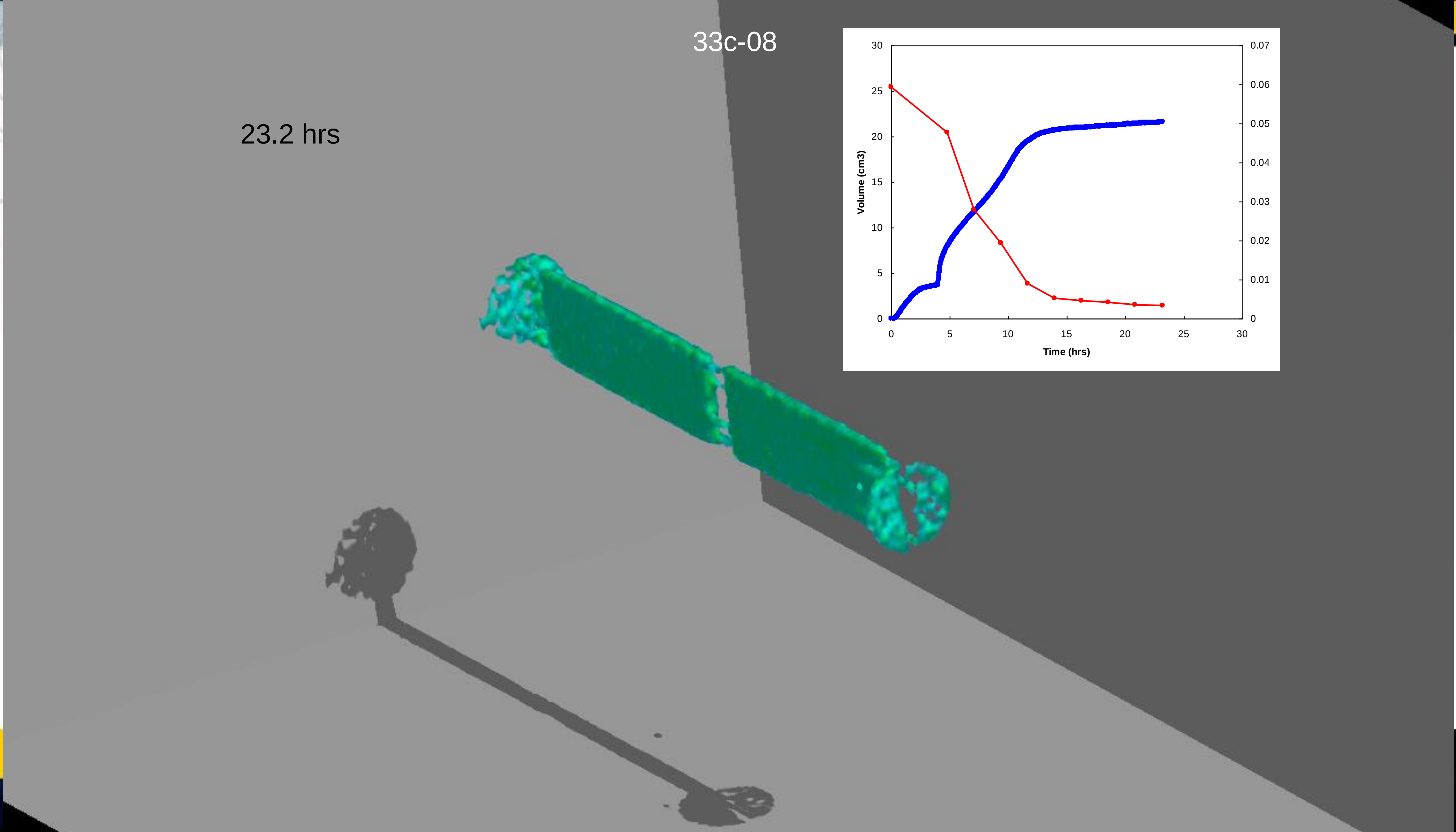


33c-07

20.9 hrs

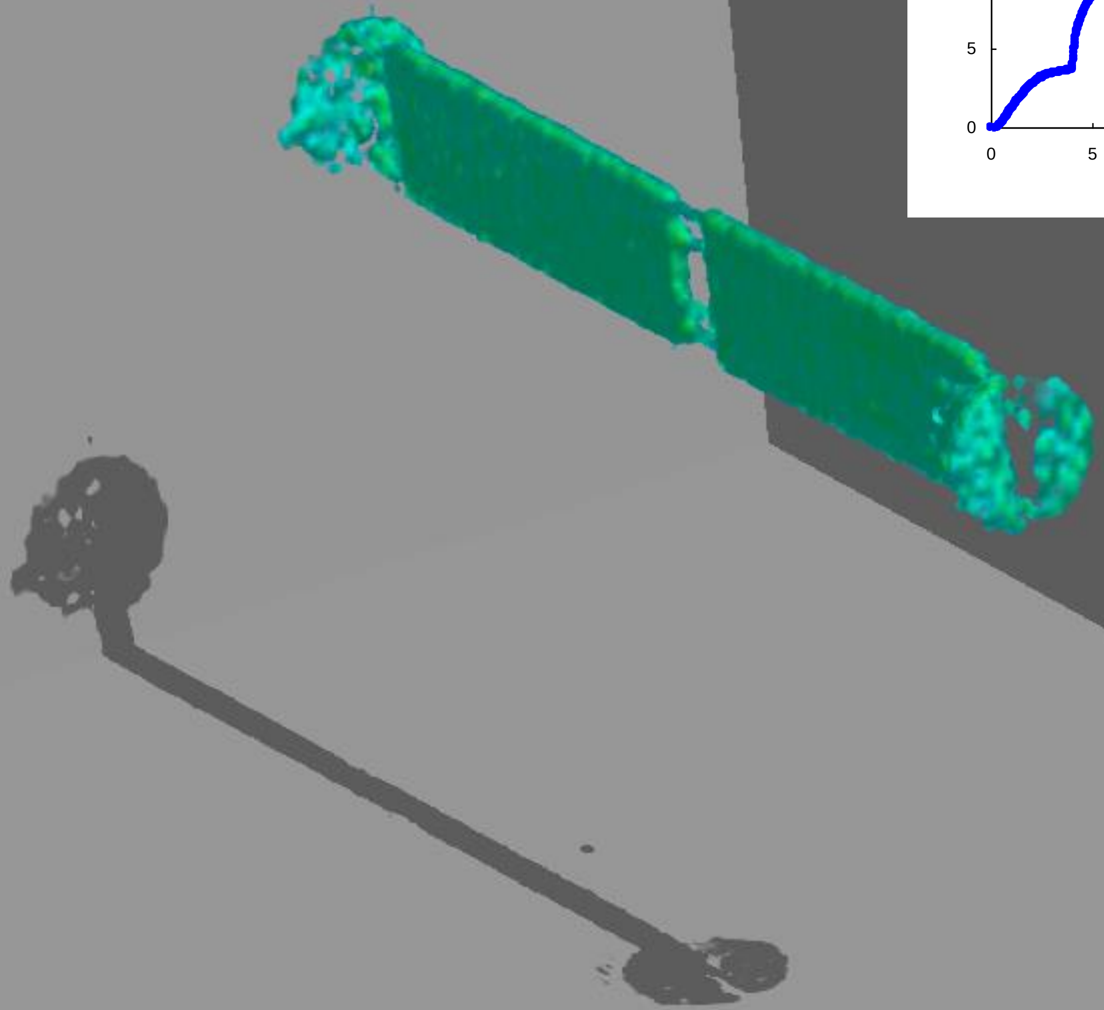


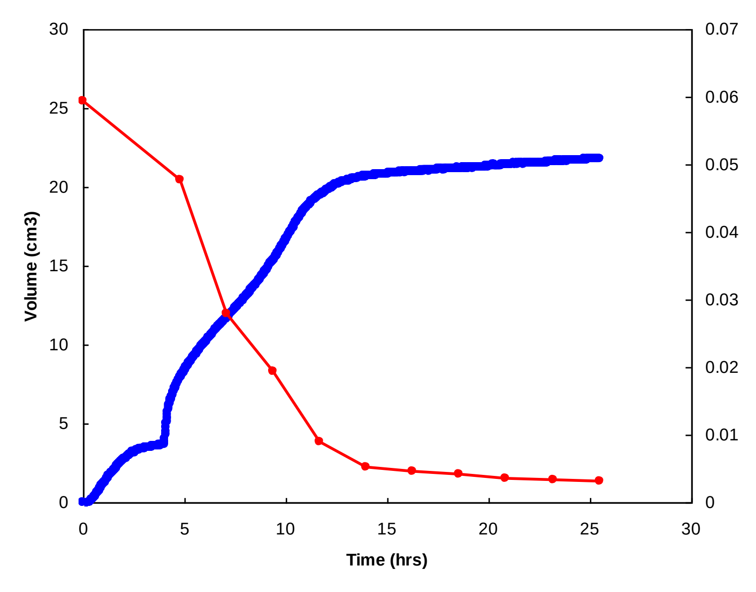


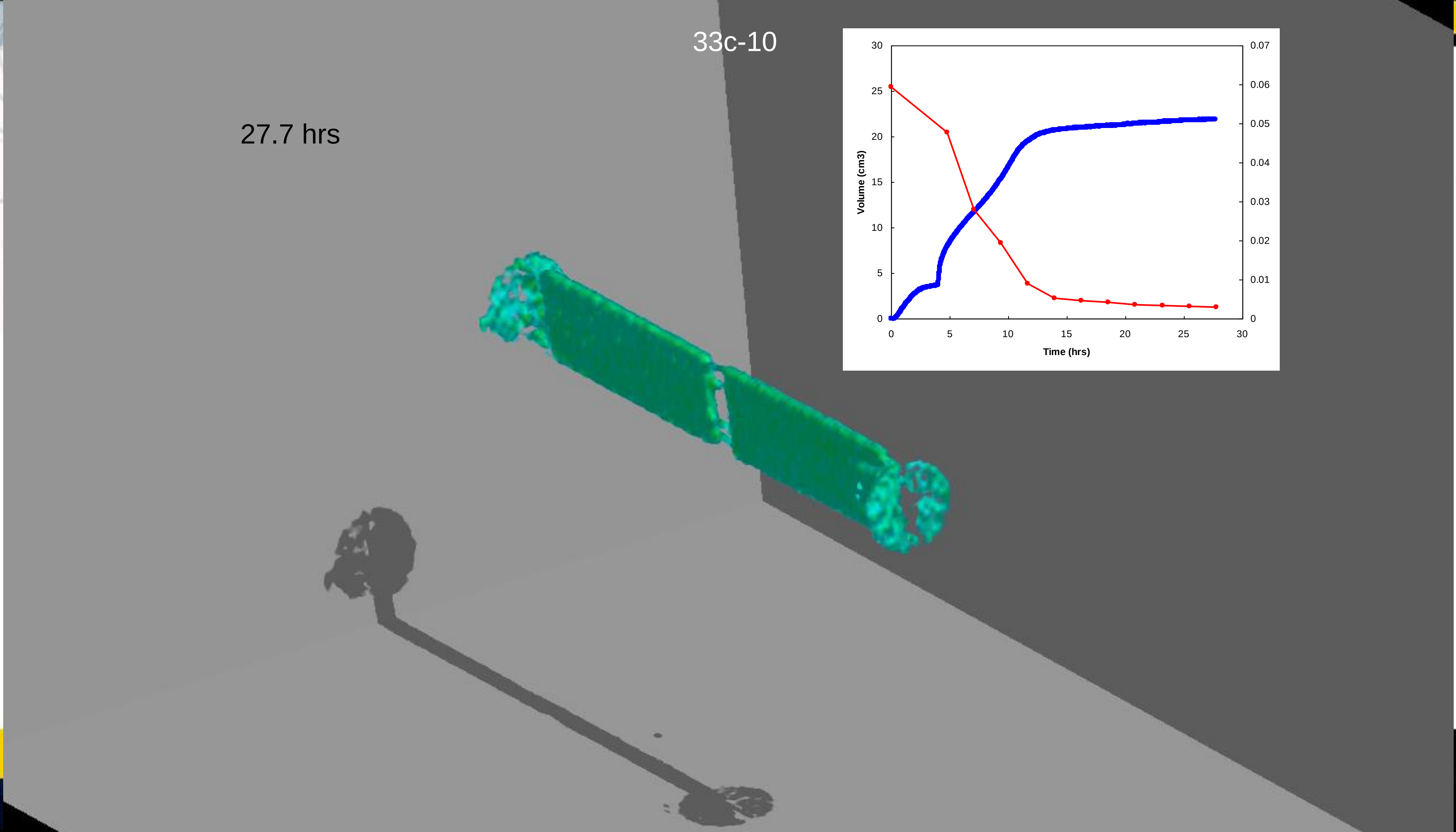

33c-08
23.2 hrs
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

33c-09

25.5 hrs

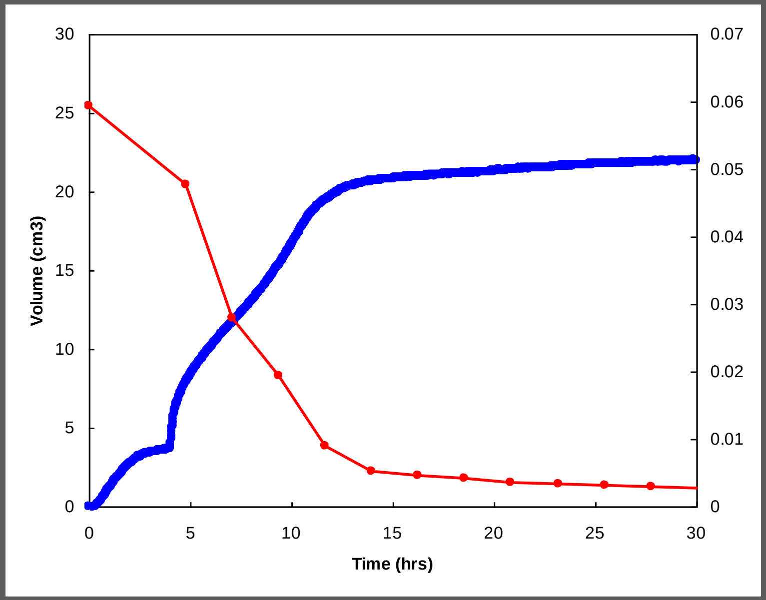




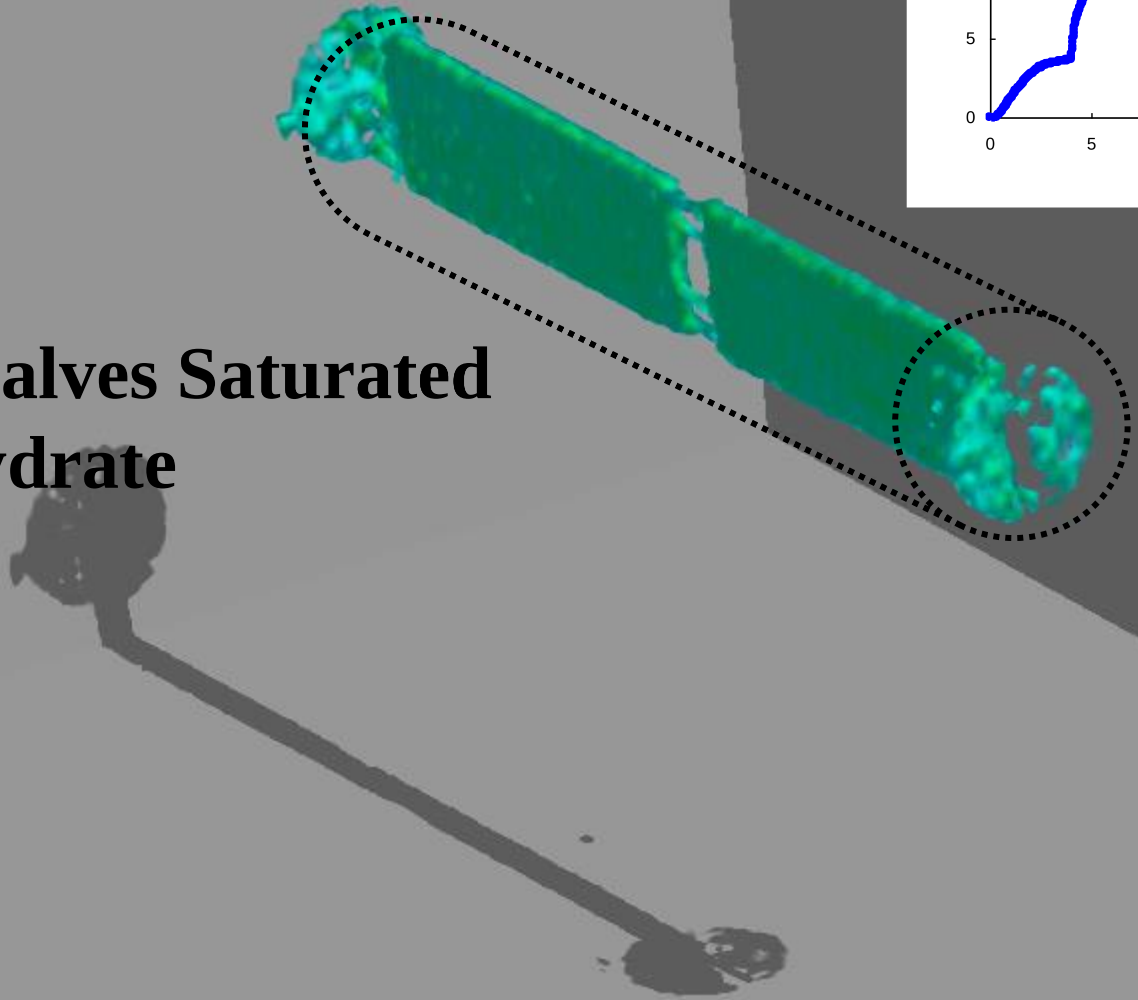


33c-10
27.7 hrs
Volume (cm3)
Time (hrs)
0
5
10
15
20
25
30
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07

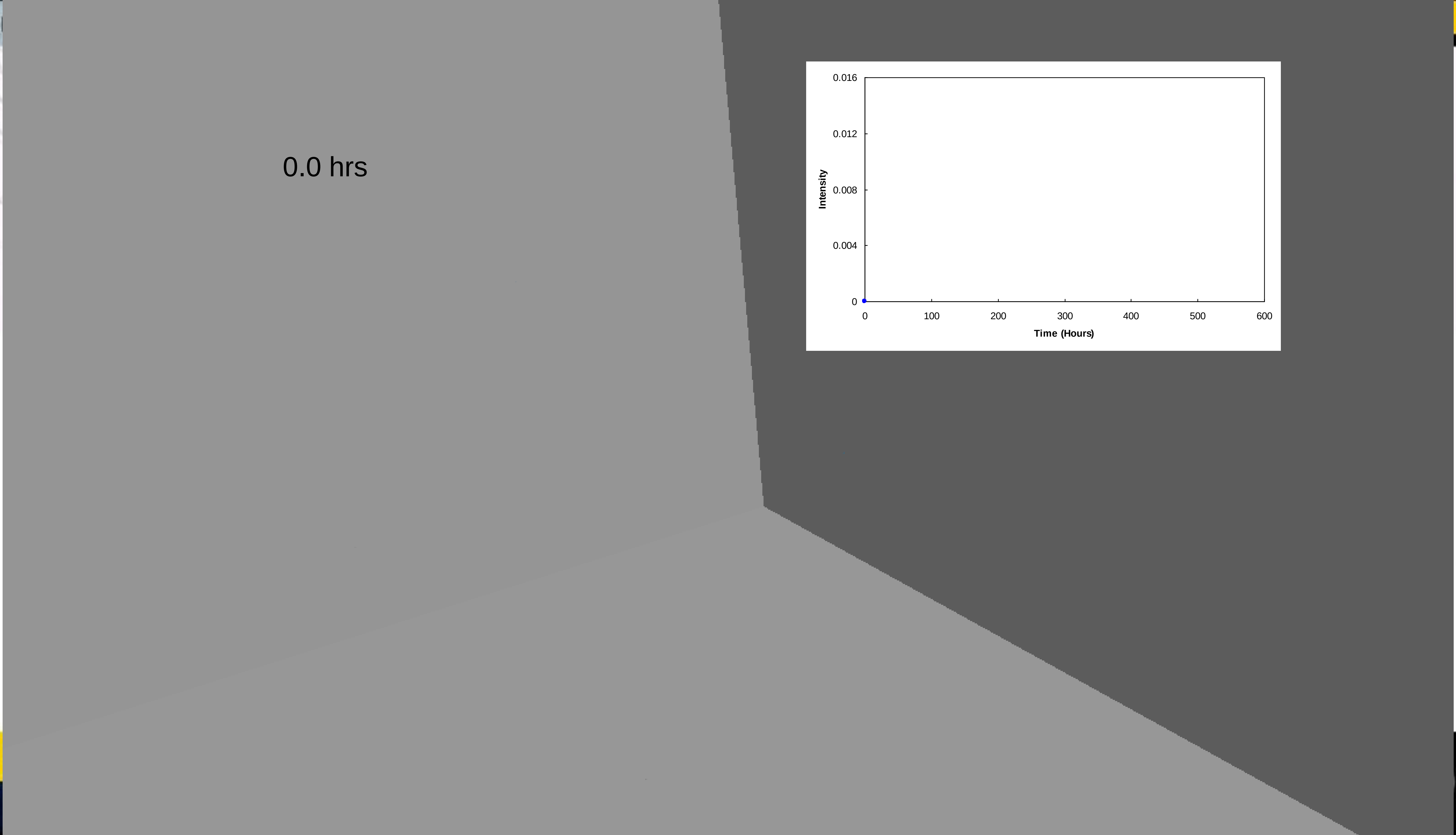
33c-11



30.0 hrs



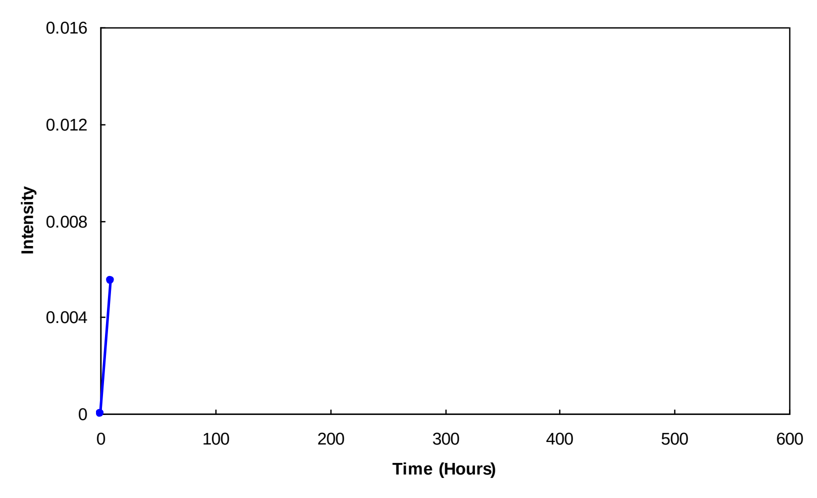
Core Halves Saturated with hydrate



0.0 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

34a-01

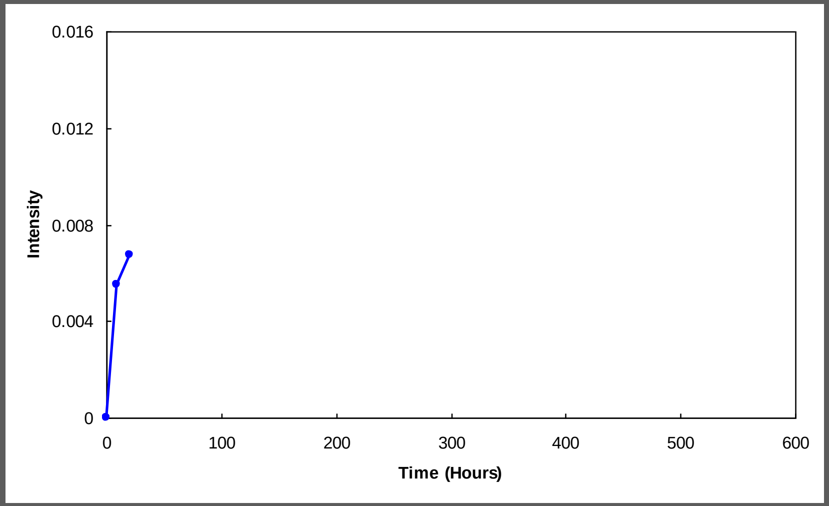
9.1 hrs



0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

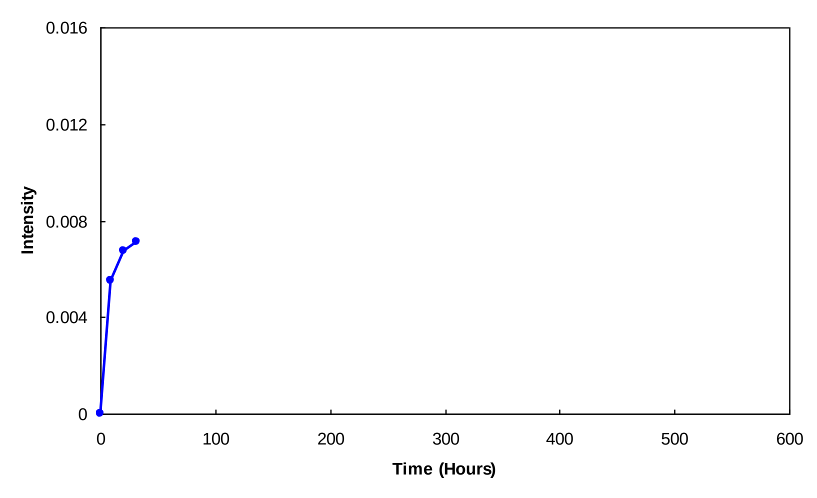
34b-01

20.6 hrs



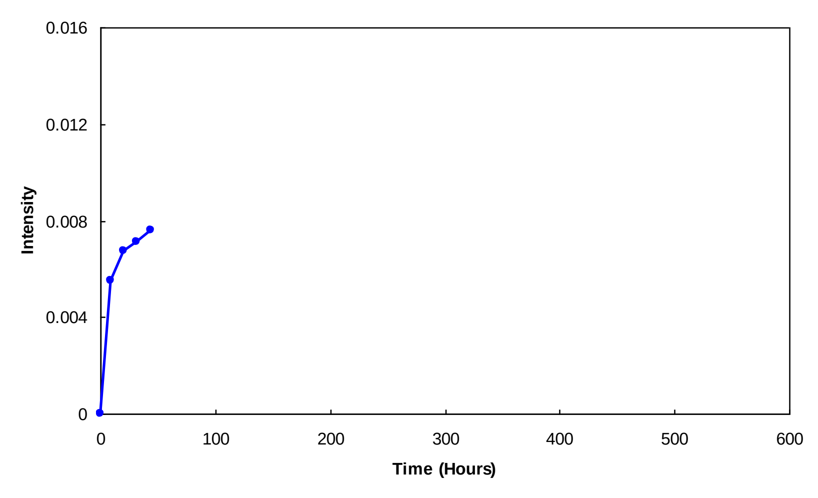
34b-02

32.0 hrs



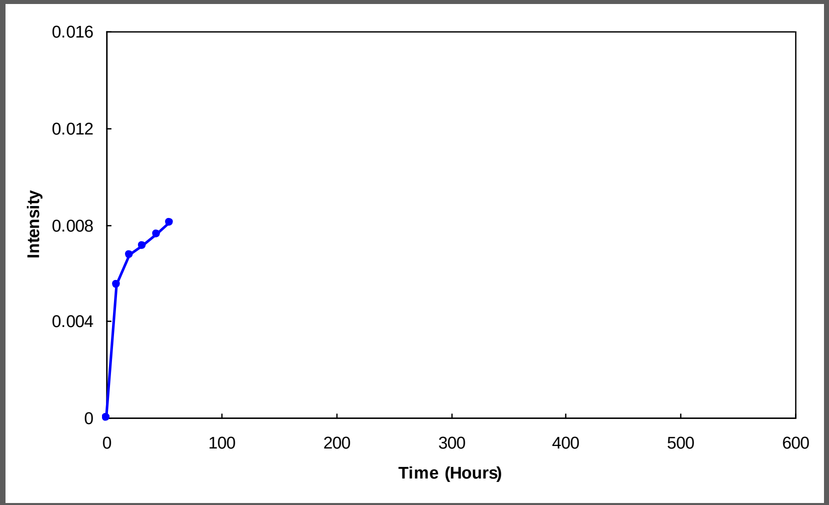
34b-03

43.4 hrs

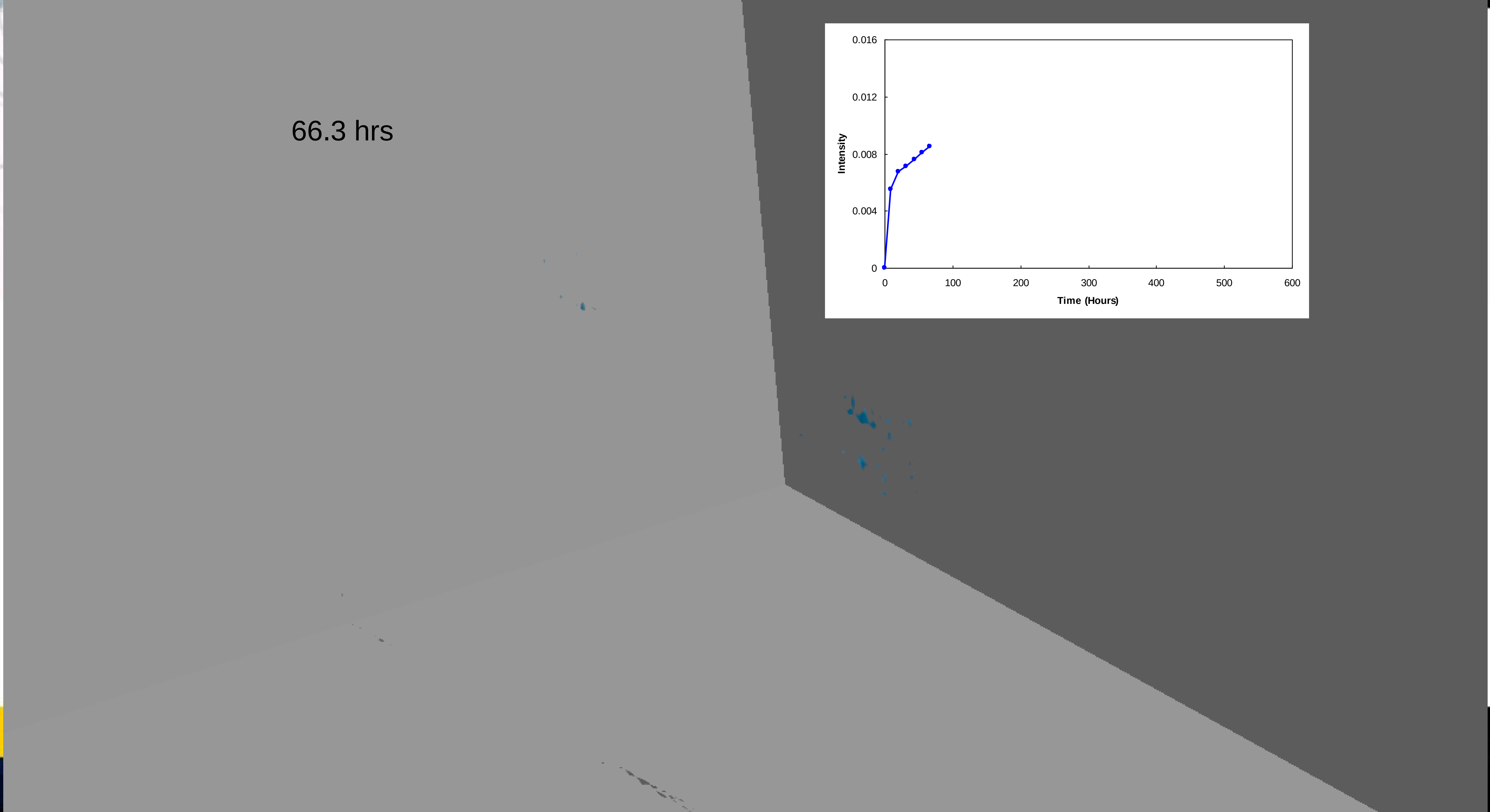


34b-04

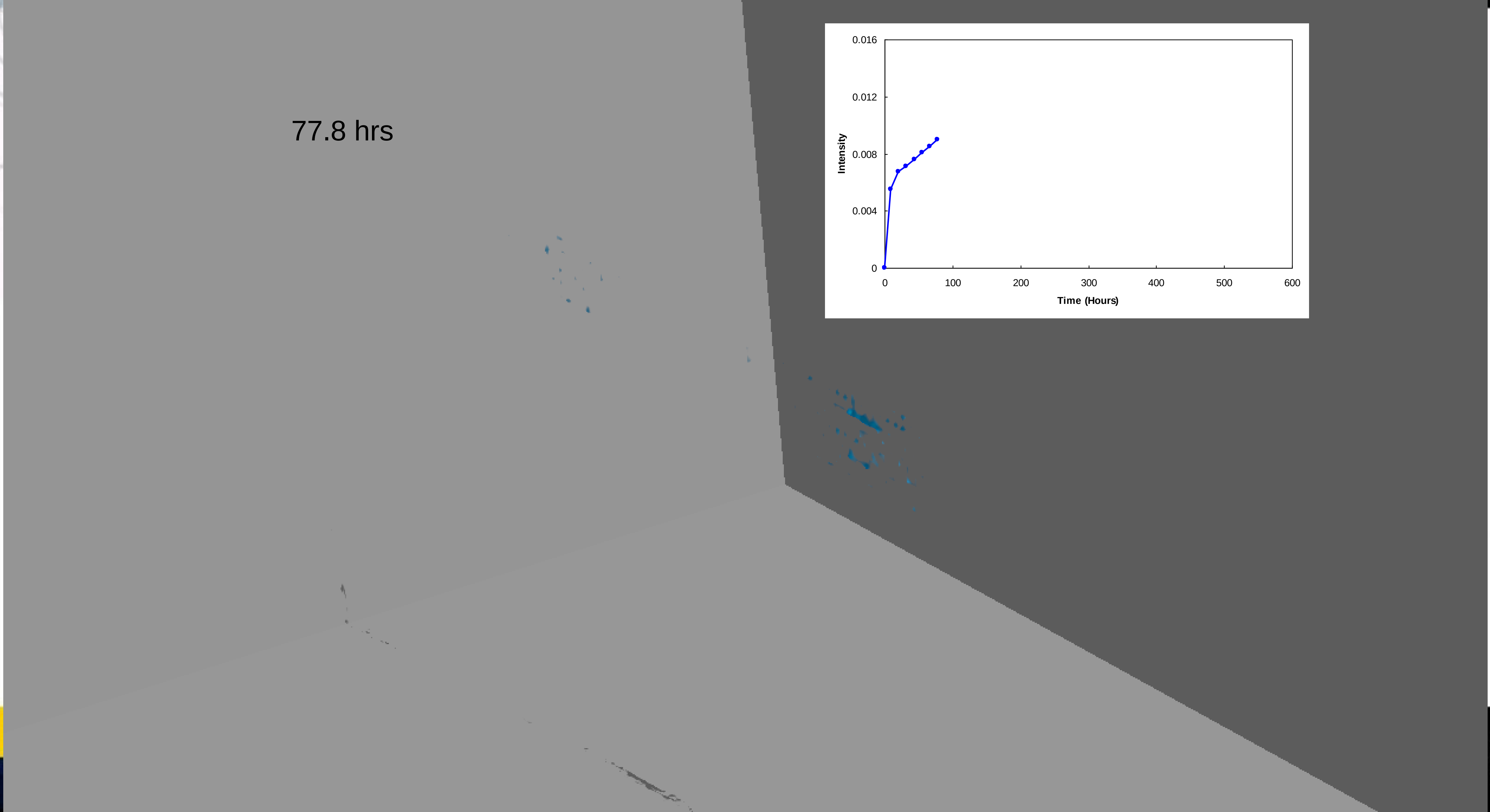
54.9 hrs

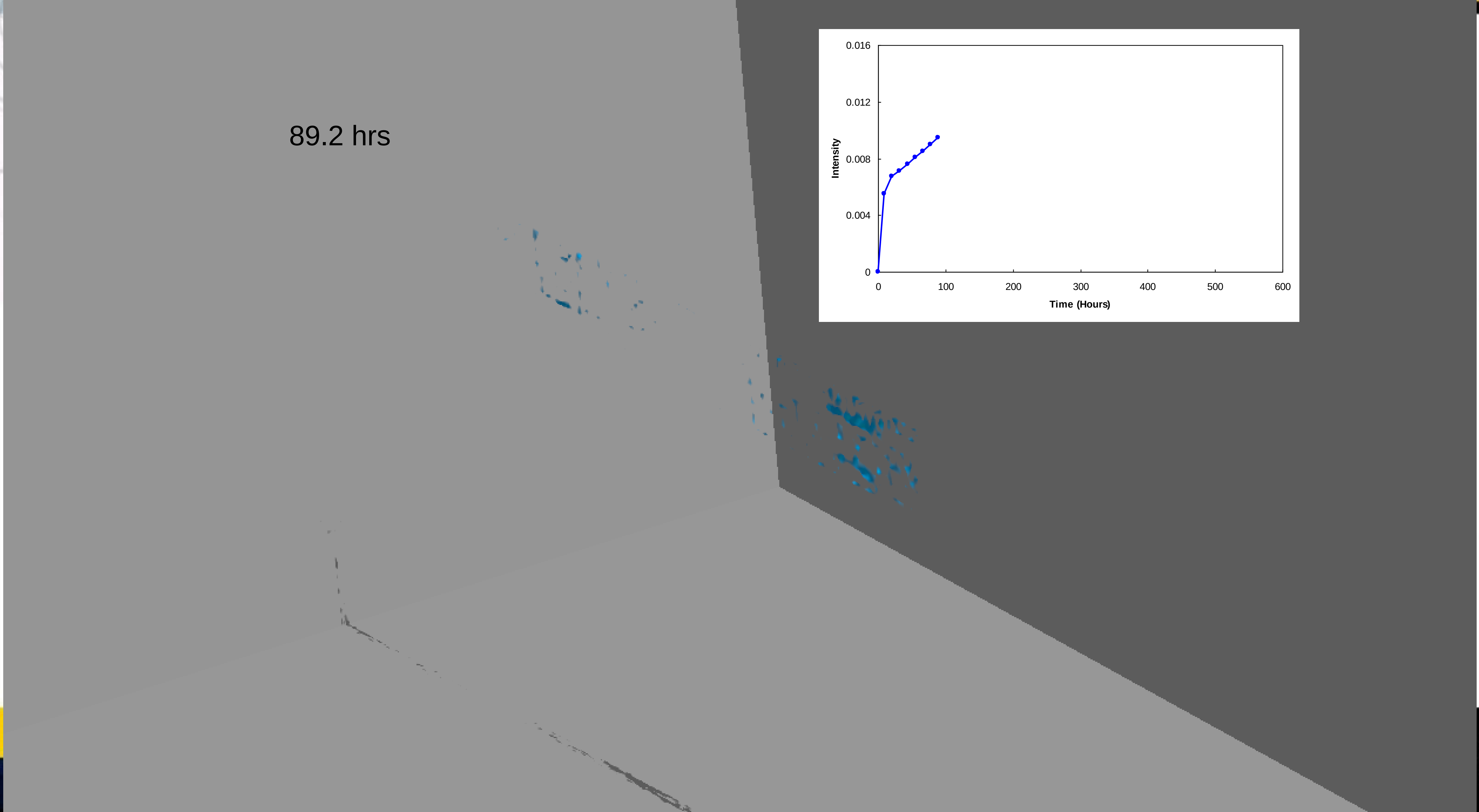


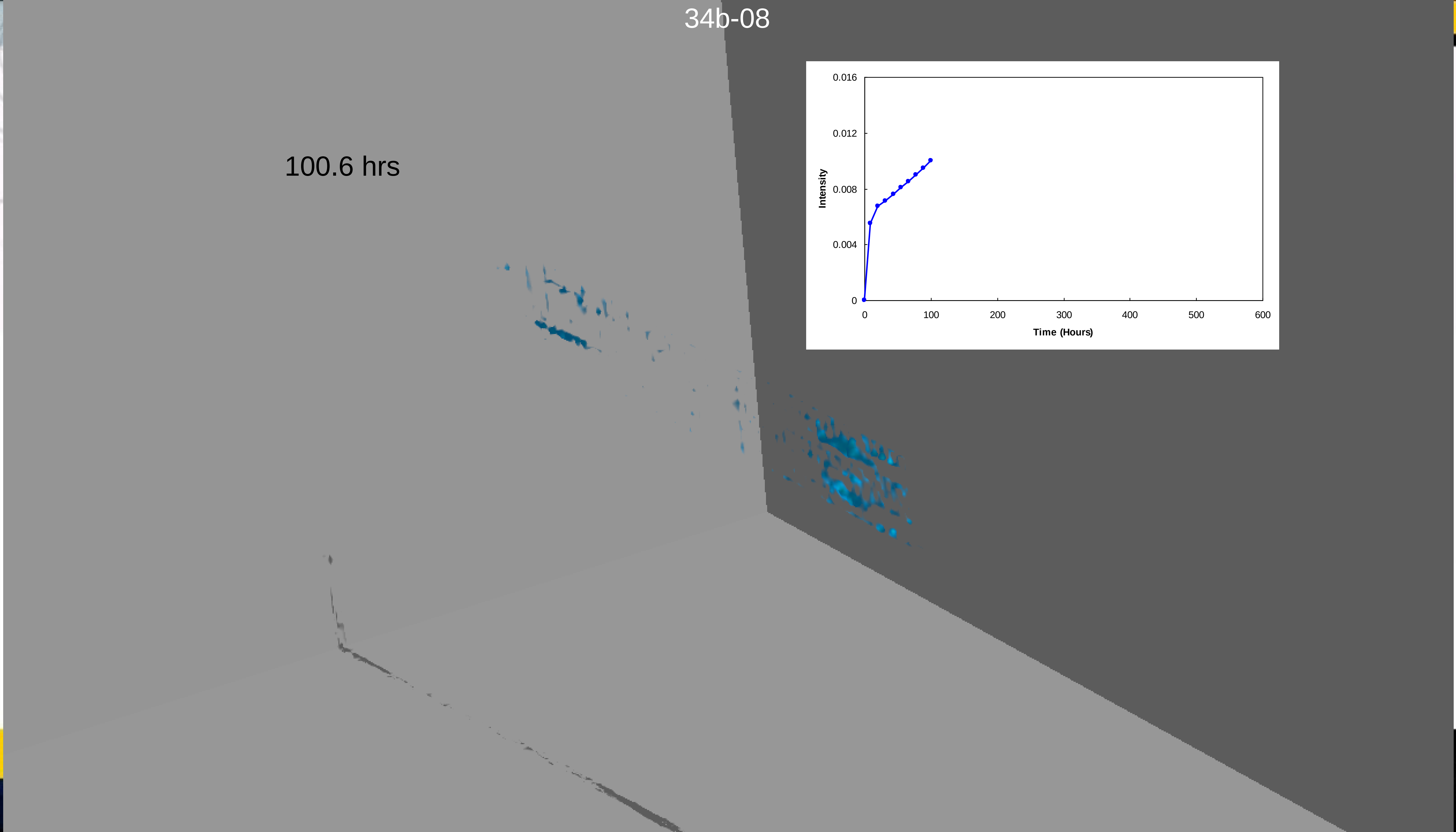
34b-05


66.3 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

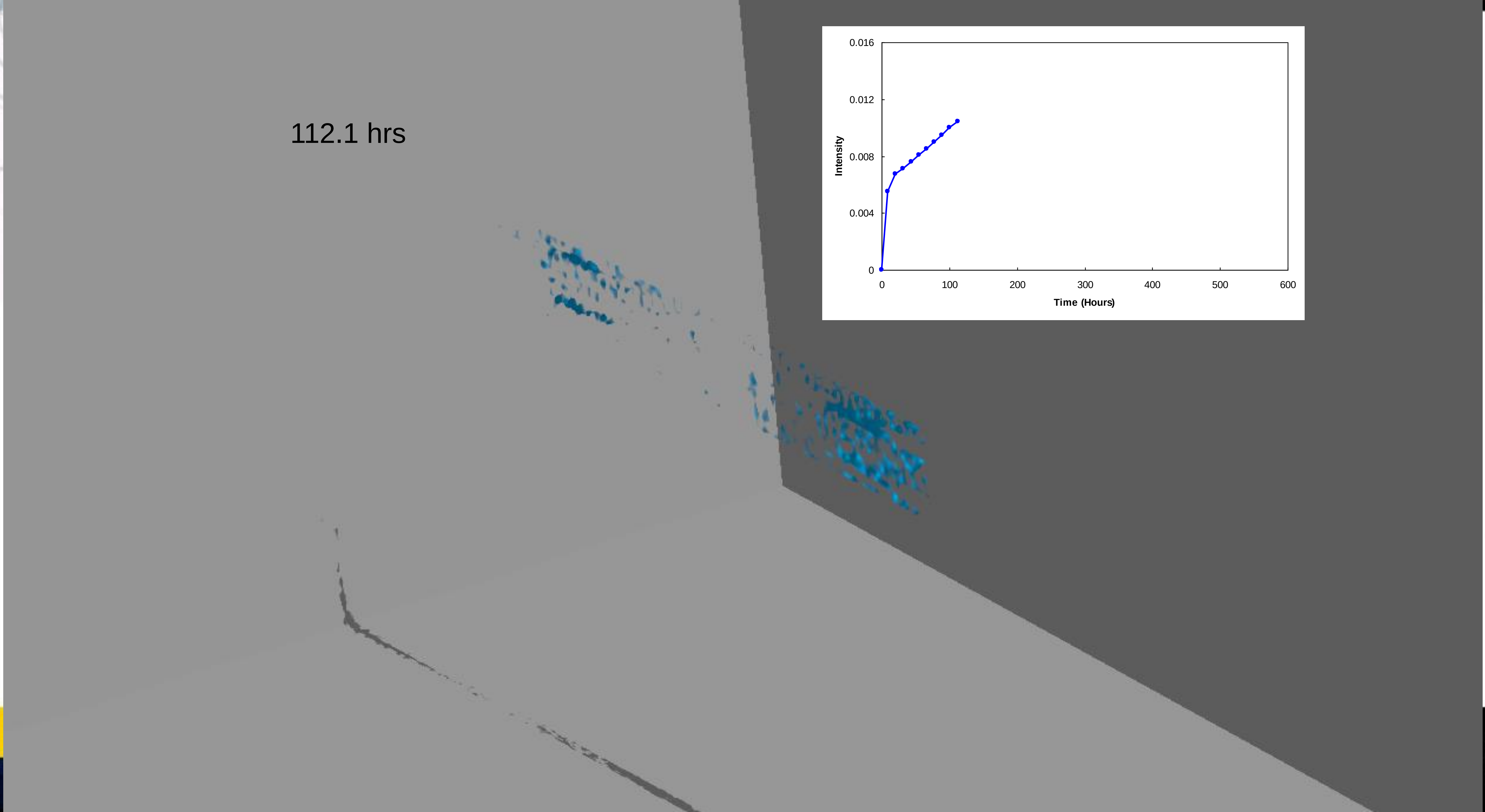
34b-06


77.8 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)


89.2 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

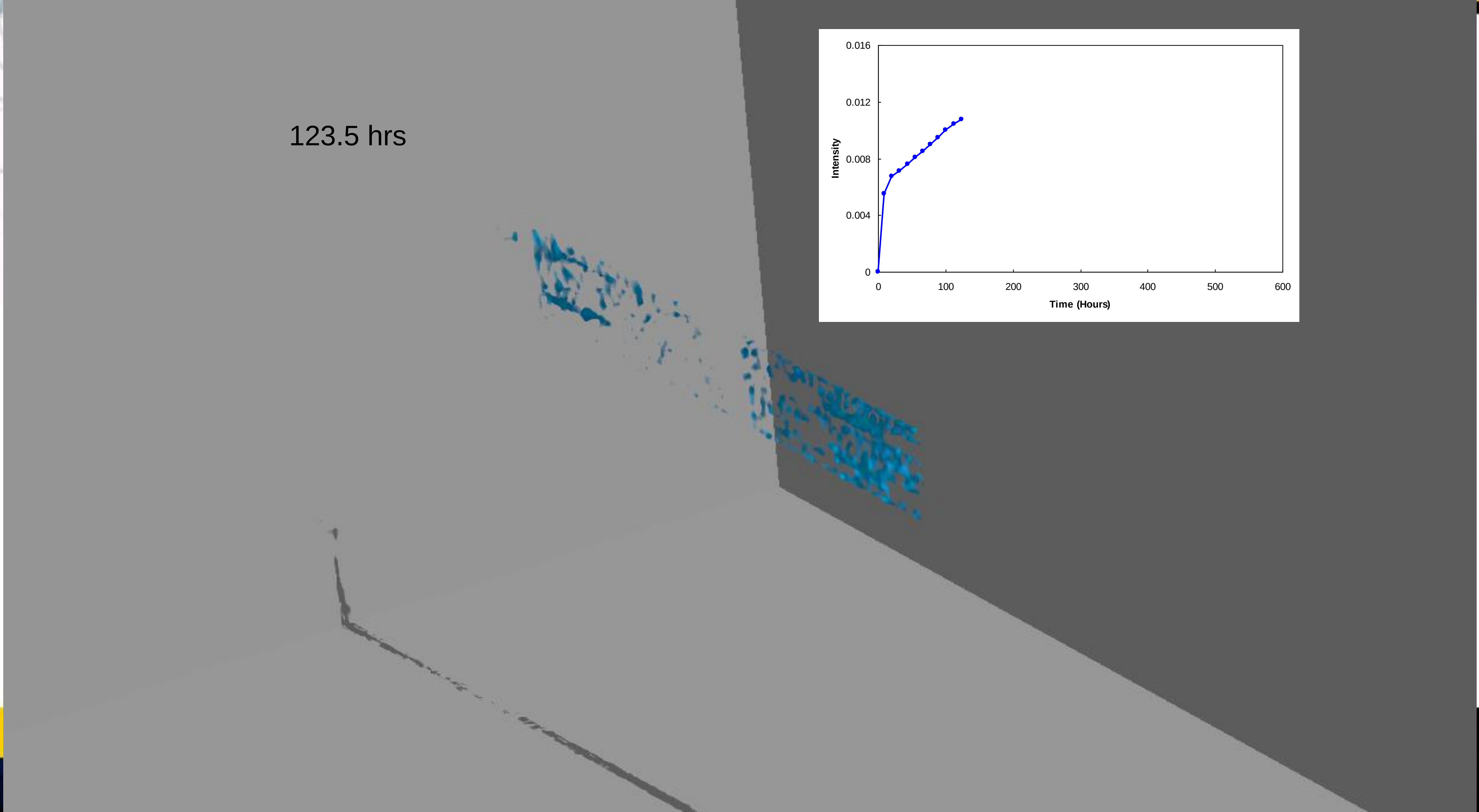

34b-08
100.6 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

34b-09

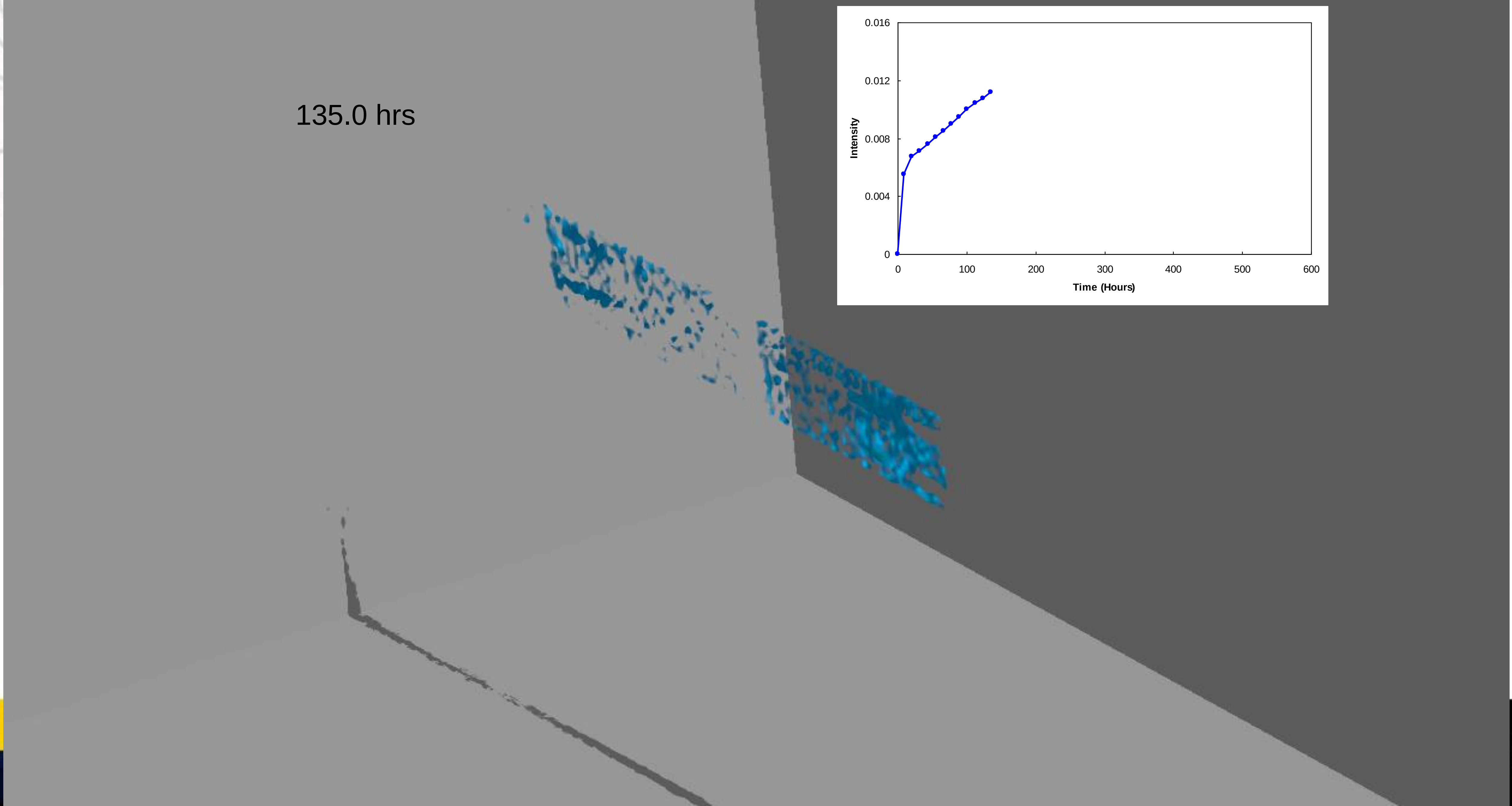


112.1 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

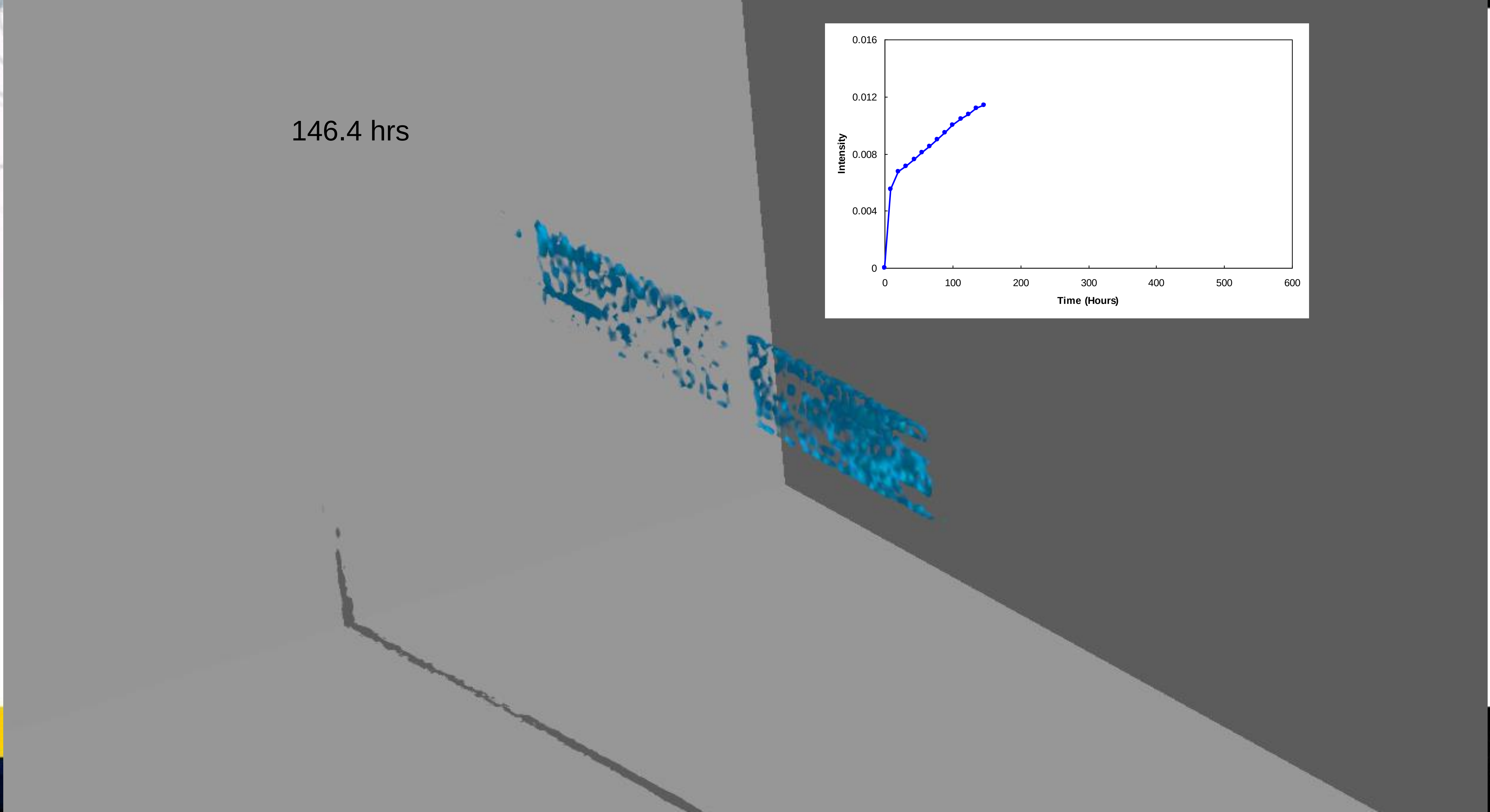
34b-10


123.5 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

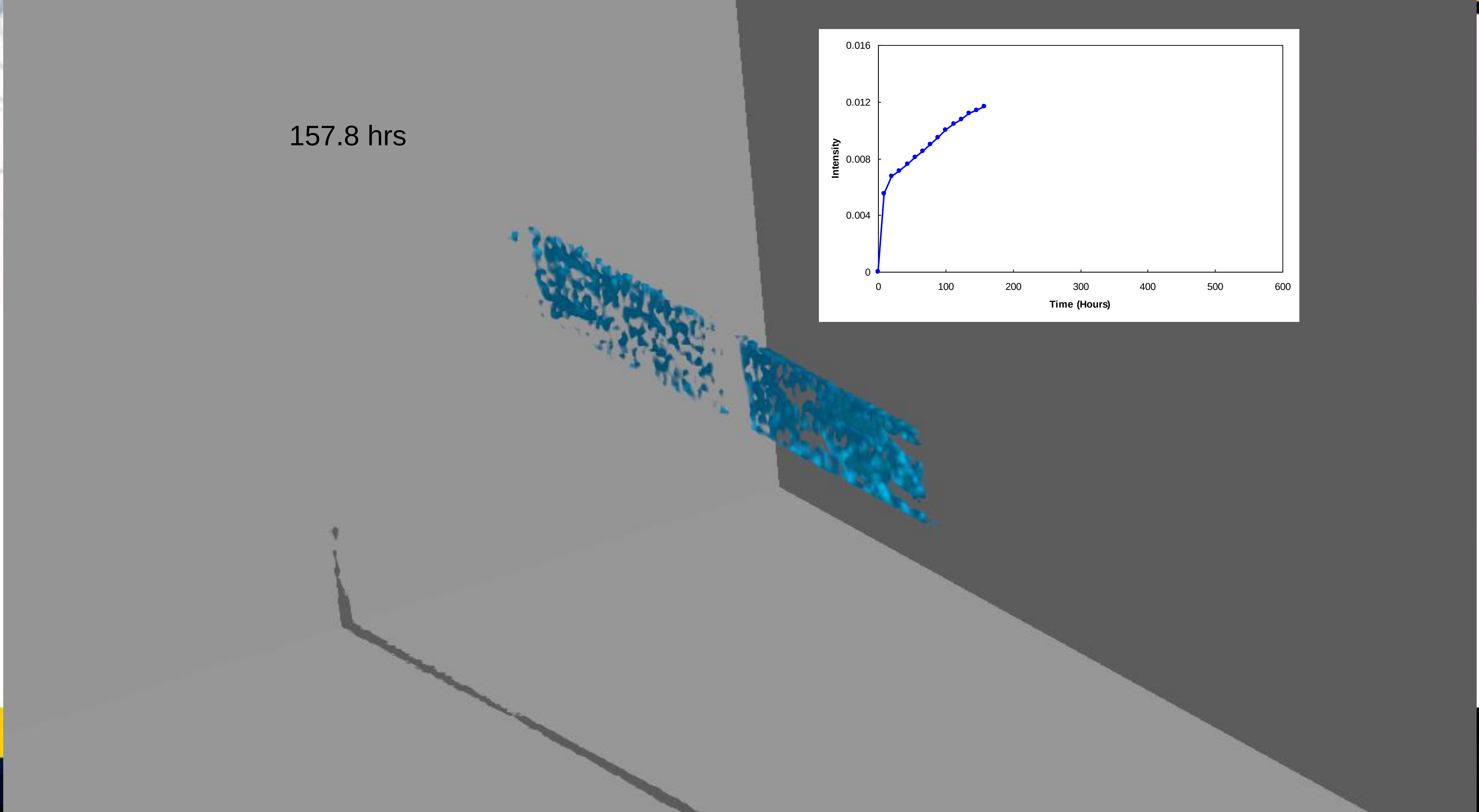
34b-11


135.0 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

34b-12

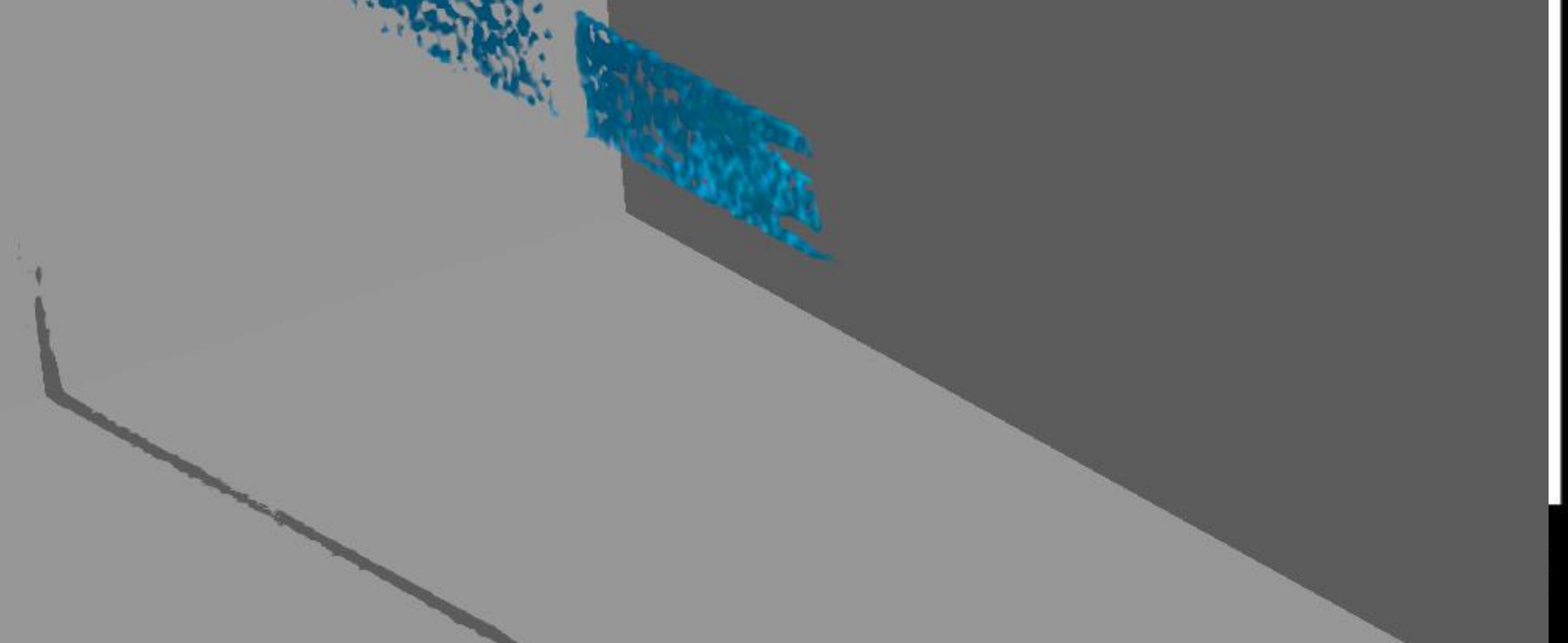

146.4 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

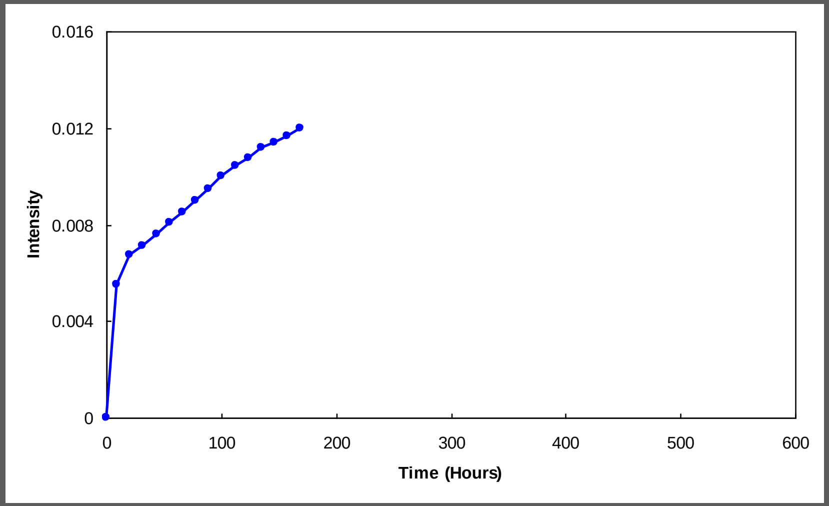
34b-13


157.8 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

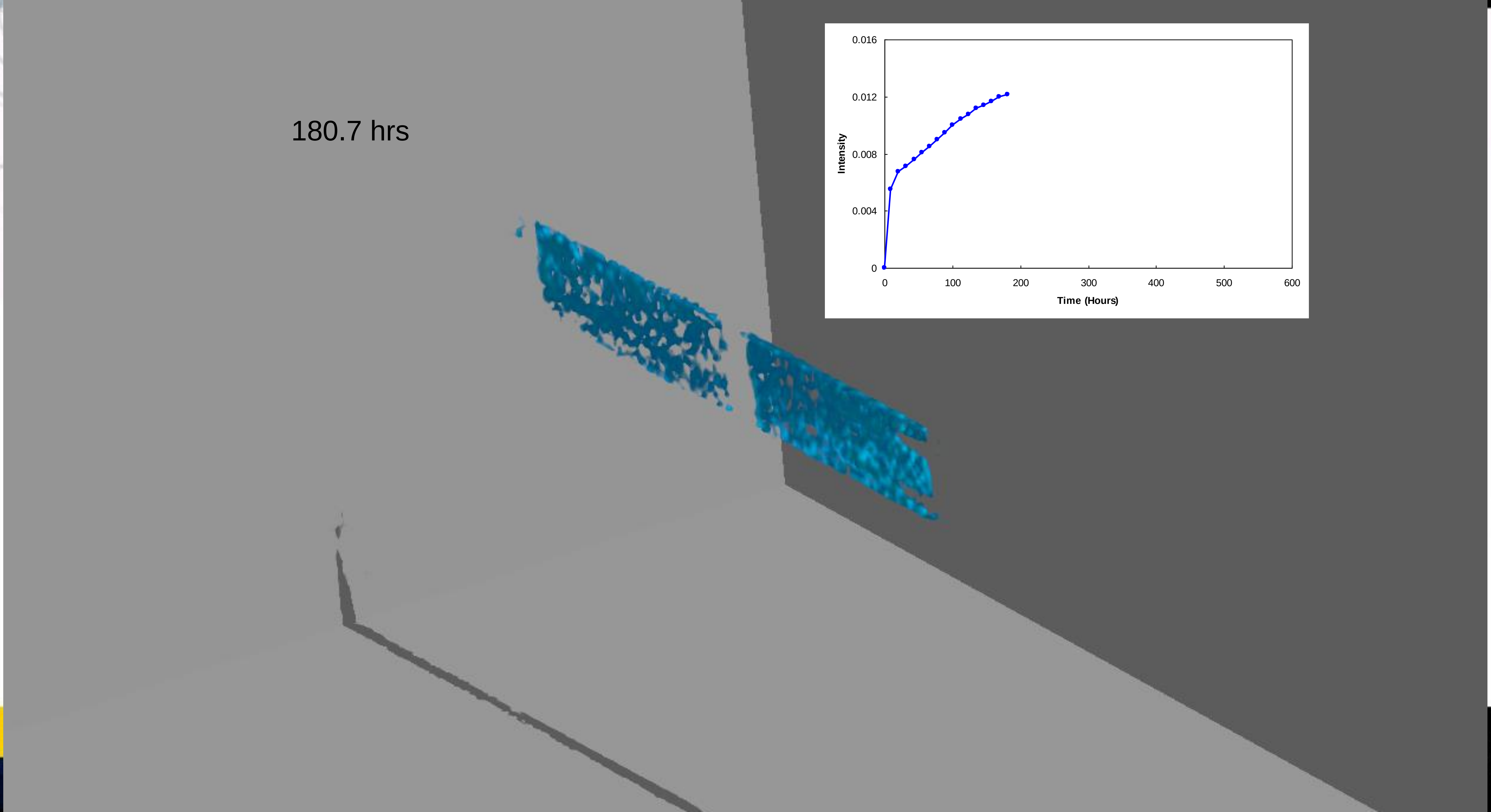
34b-14

169.3 hrs

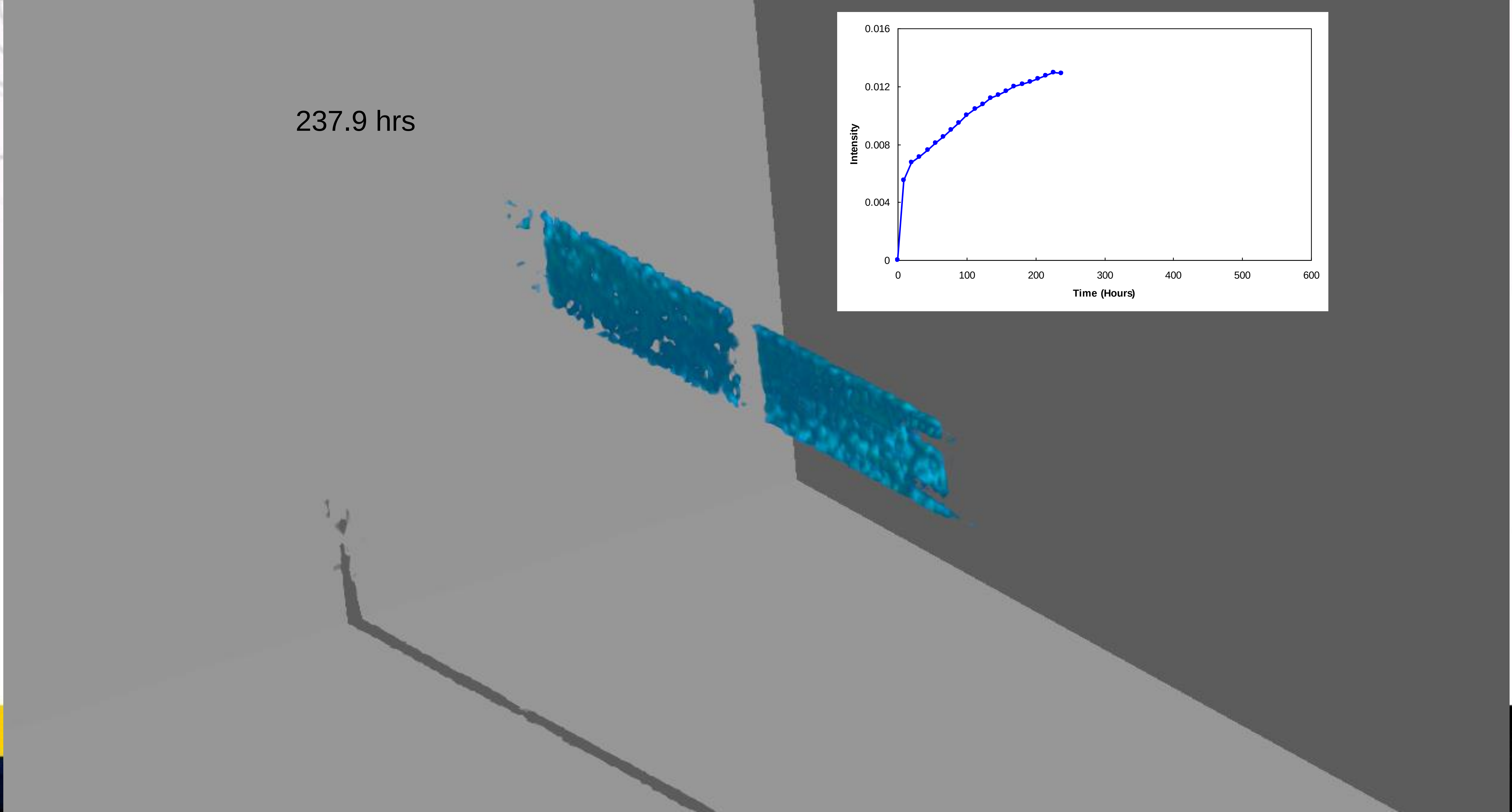




34b-15

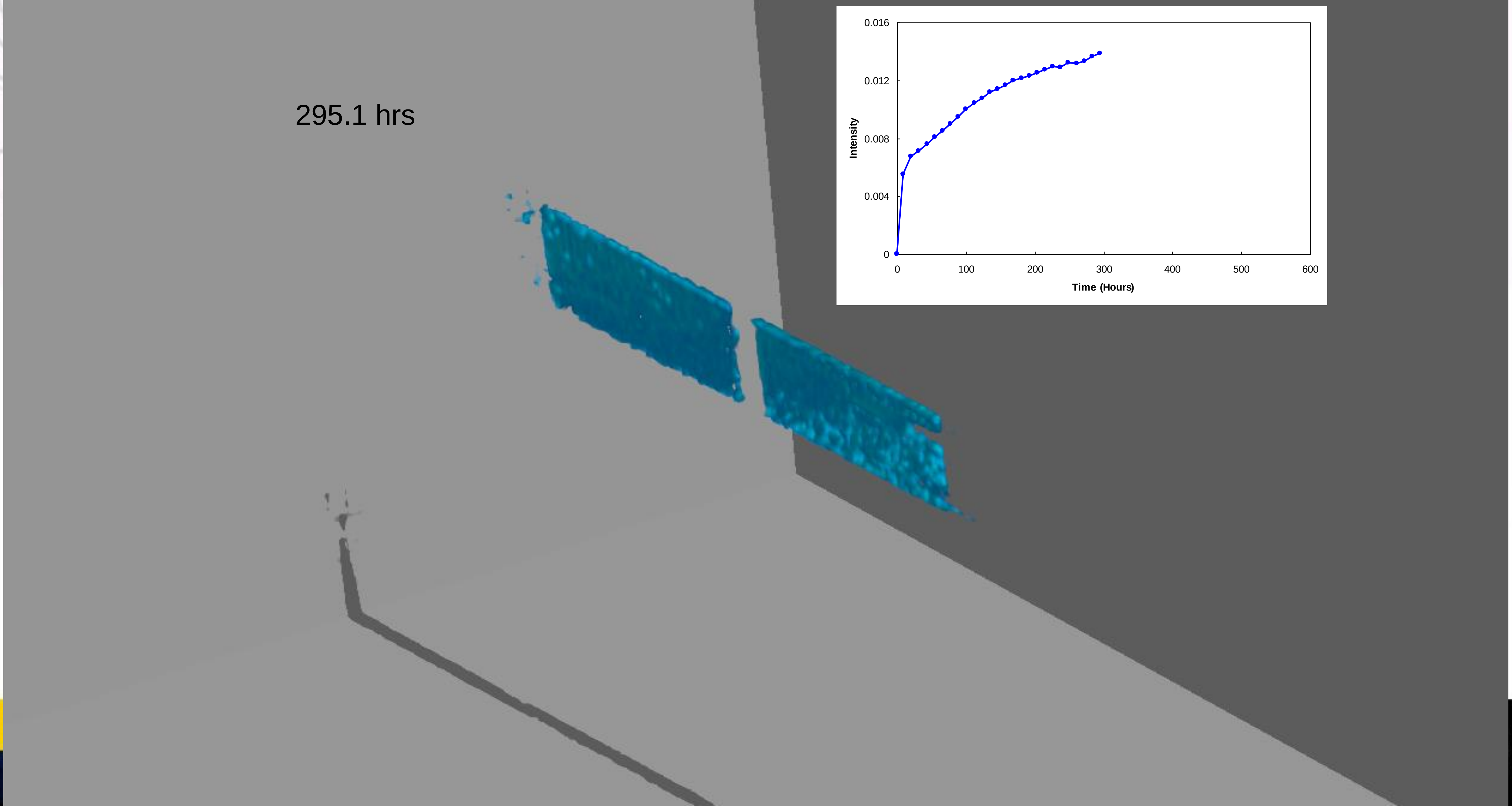

180.7 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

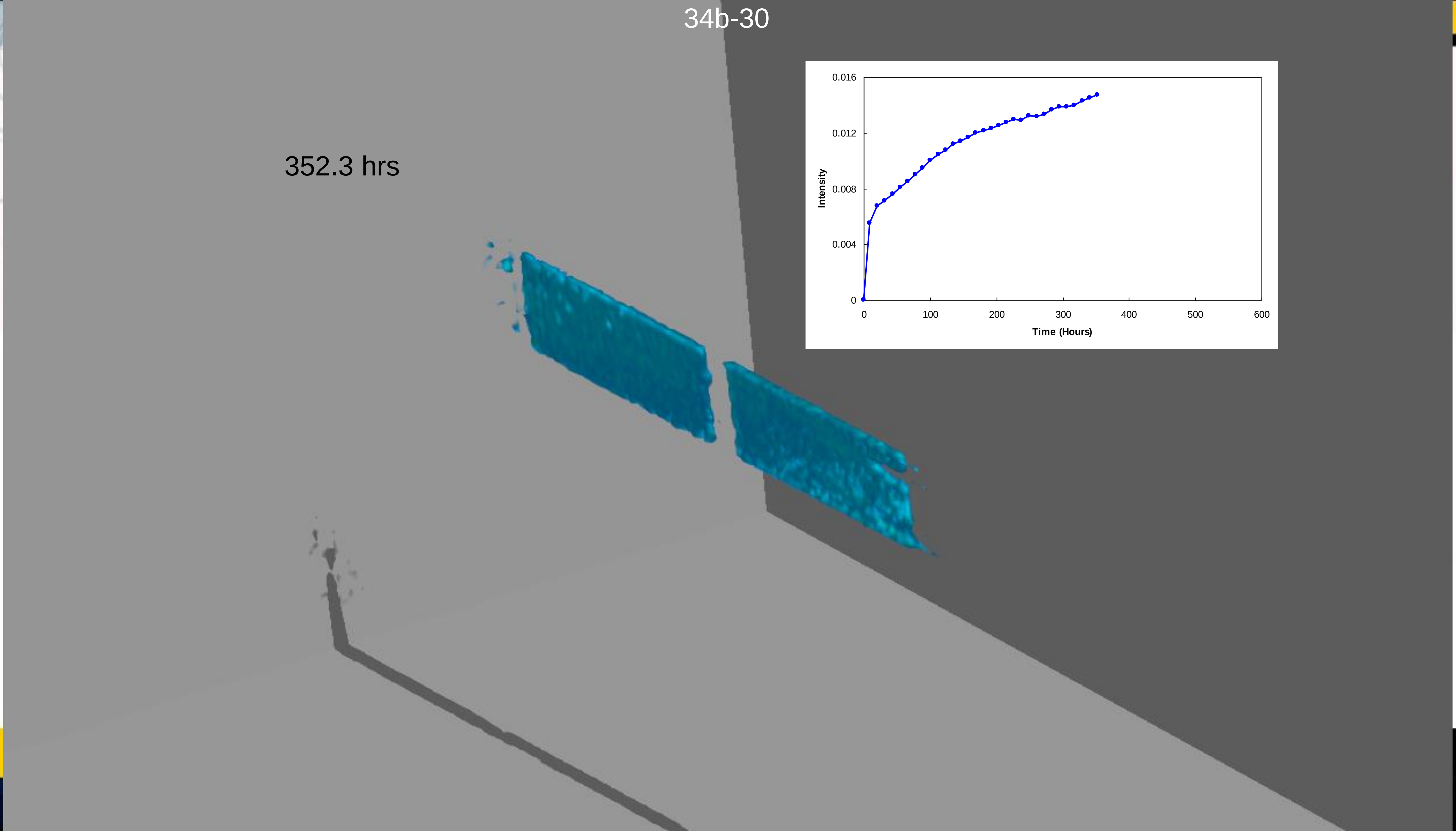
34b-20


237.9 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

34b-25

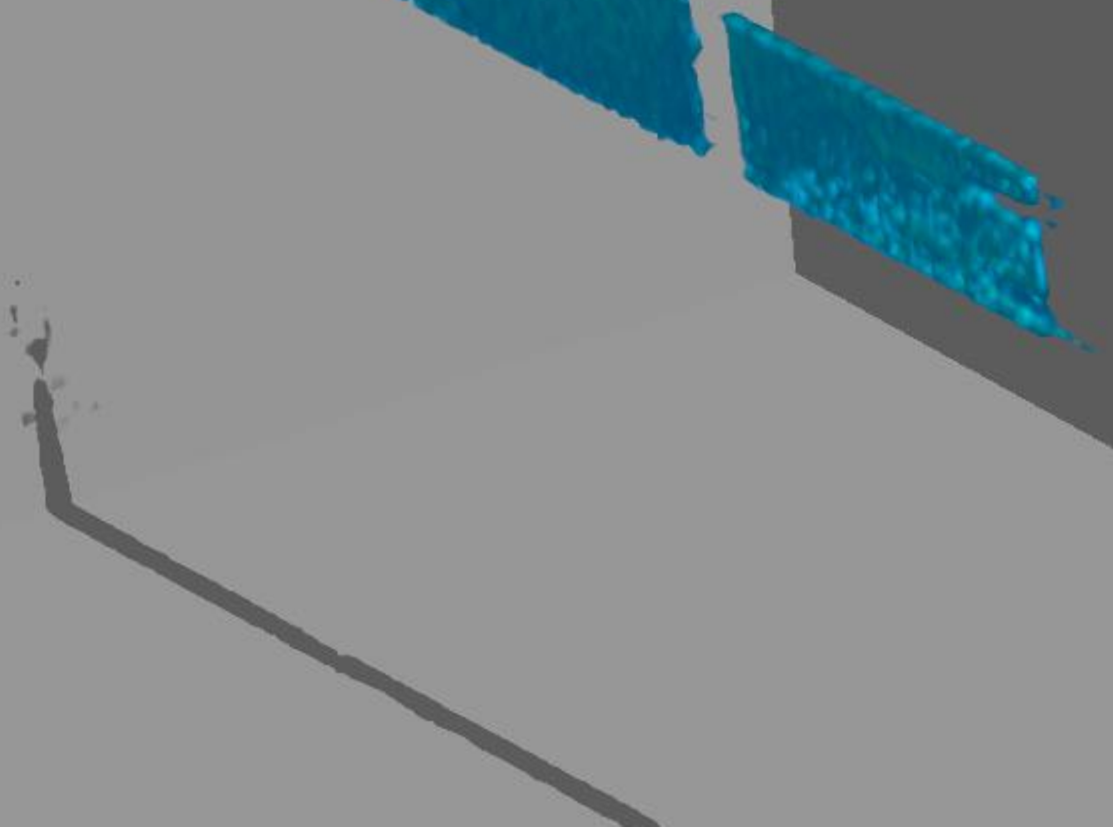
295.1 hrs

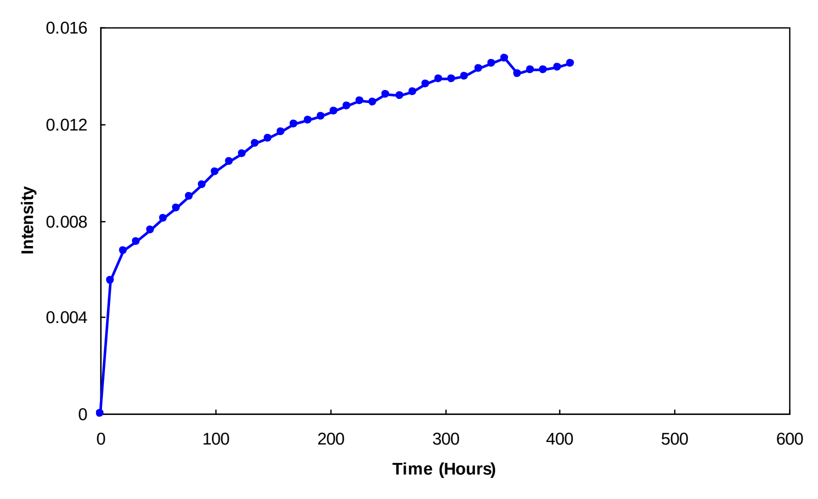



34b-30
352.3 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)

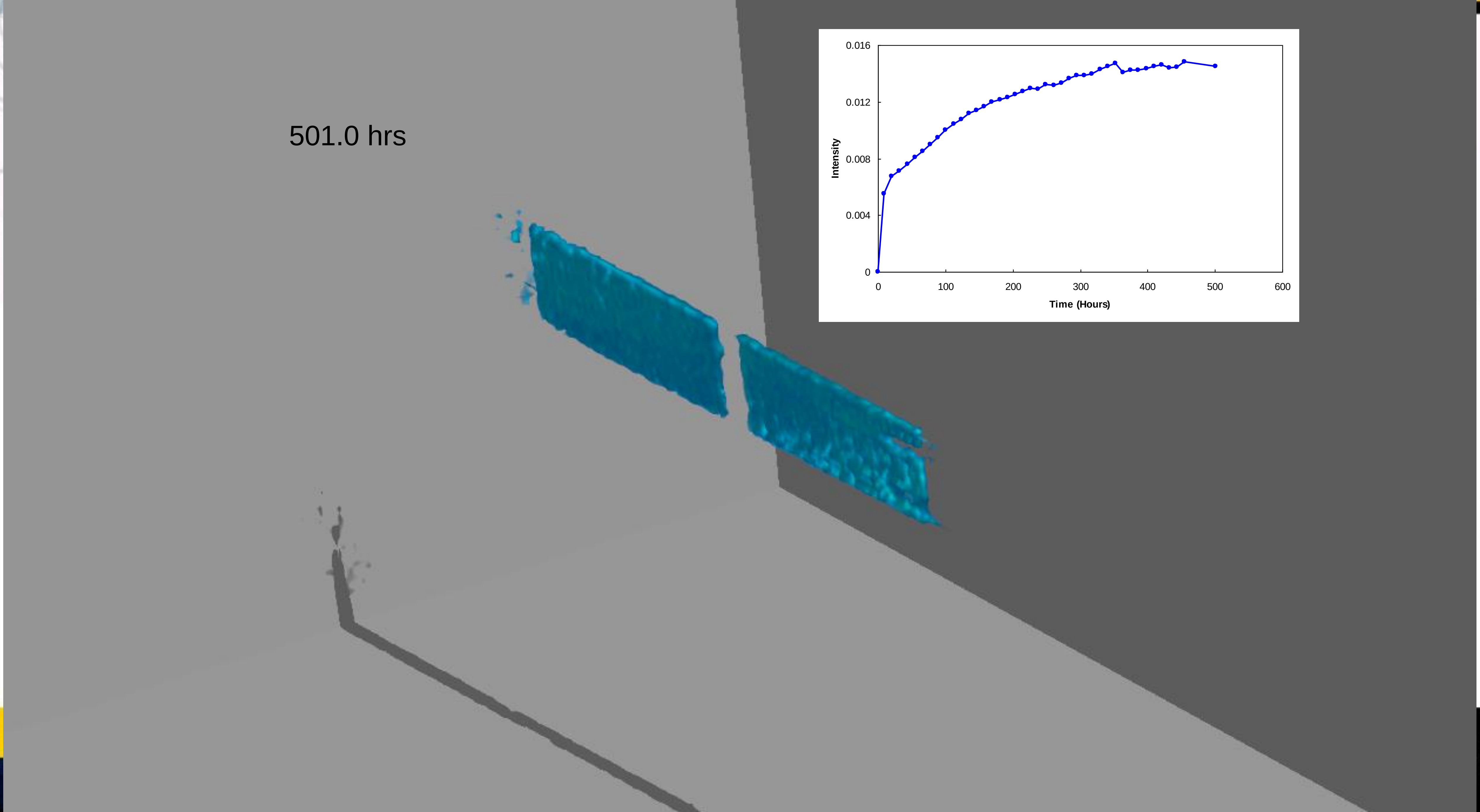
34b-35

409.5 hrs

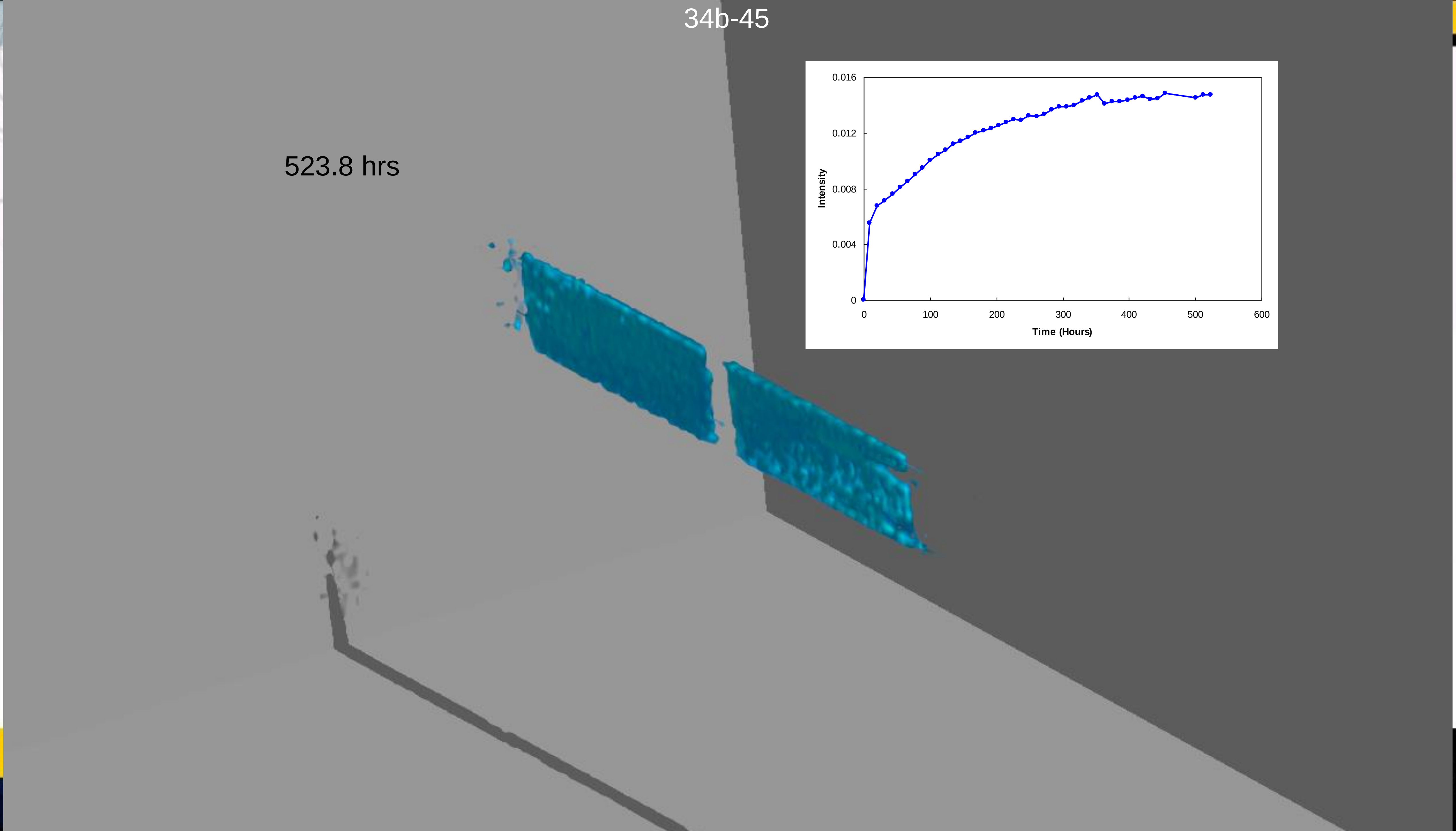




34b-40

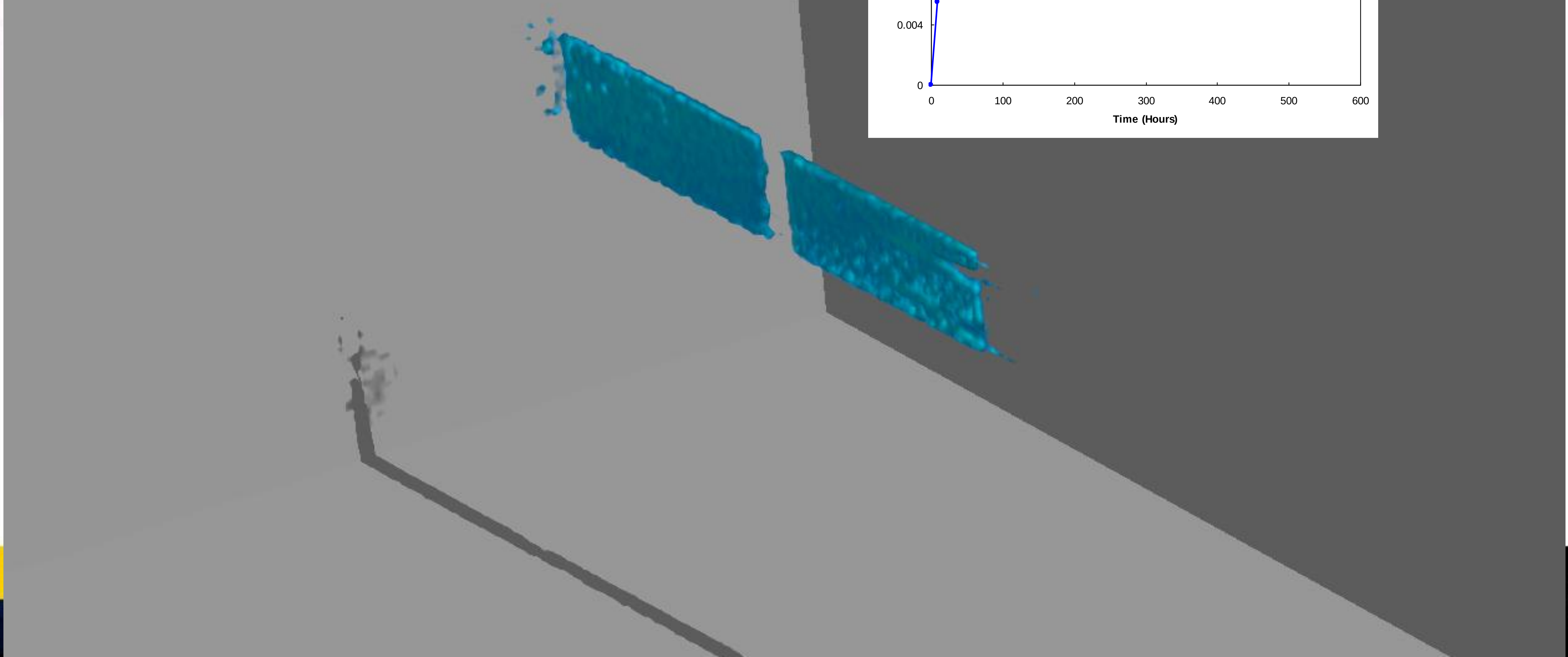


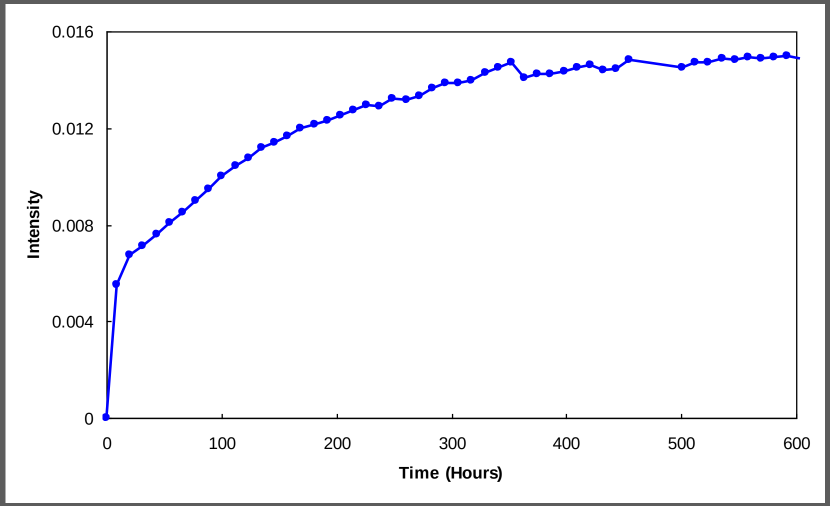
501.0 hrs
Intensity
0.016
0.012
0.008
0.004
0
0
100
200
300
400
500
600
Time (Hours)


34b-45
523.8 hrs
0.016
0.012
0.008
0.004
0
Intensity
0
100
200
300
400
500
600
Time (Hours)

34b-52

603.9 hrs





Scientific Conclusions

- MRI Provides Unique Dynamic Data of Hydrate Formation and Production Consistent with Conventional Results.
- CO_2 Exchange for CH_4 in Hydrates Is Rapid and Efficient.
- No Free Water Observed During Exchange Process.
- Sufficient Permeability Remains During Hydrate Formation and Subsequent Production.

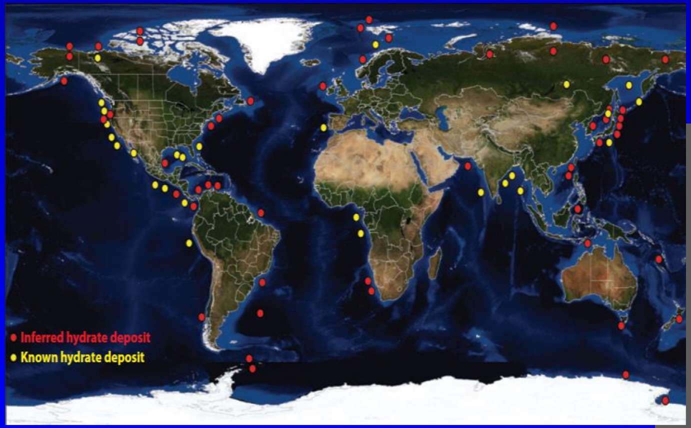
CO_2 Storage in Hydrate Reservoirs with Associated Spontaneous Natural Gas Production

Arne Graue and Bjørn Kvamme, Dept. of Physics, University of Bergen, NORWAY
Funding: ConocoPhillips, Statoil and The Research Council of Norway

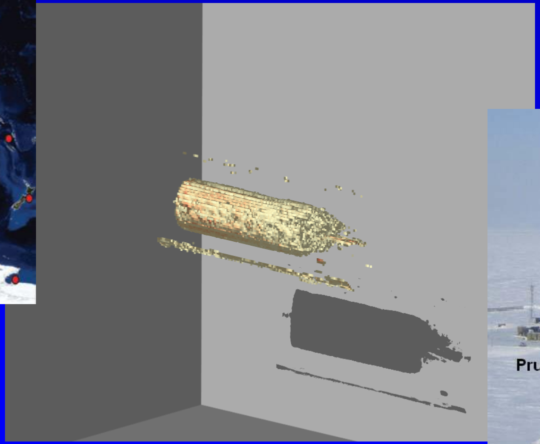
Objectives:

Experimentally and theorethically determine spontaneous methane production when hydrate is exposed to CO2; with the purpose of CO2 sequestration.

Methane hydrate reservoirs



In-Situ **imaging (MRI) of hydrate formation**



Methane production by CO2 injection in field test in Alaska 2012

Alaska Field Injection Test 2011-2012

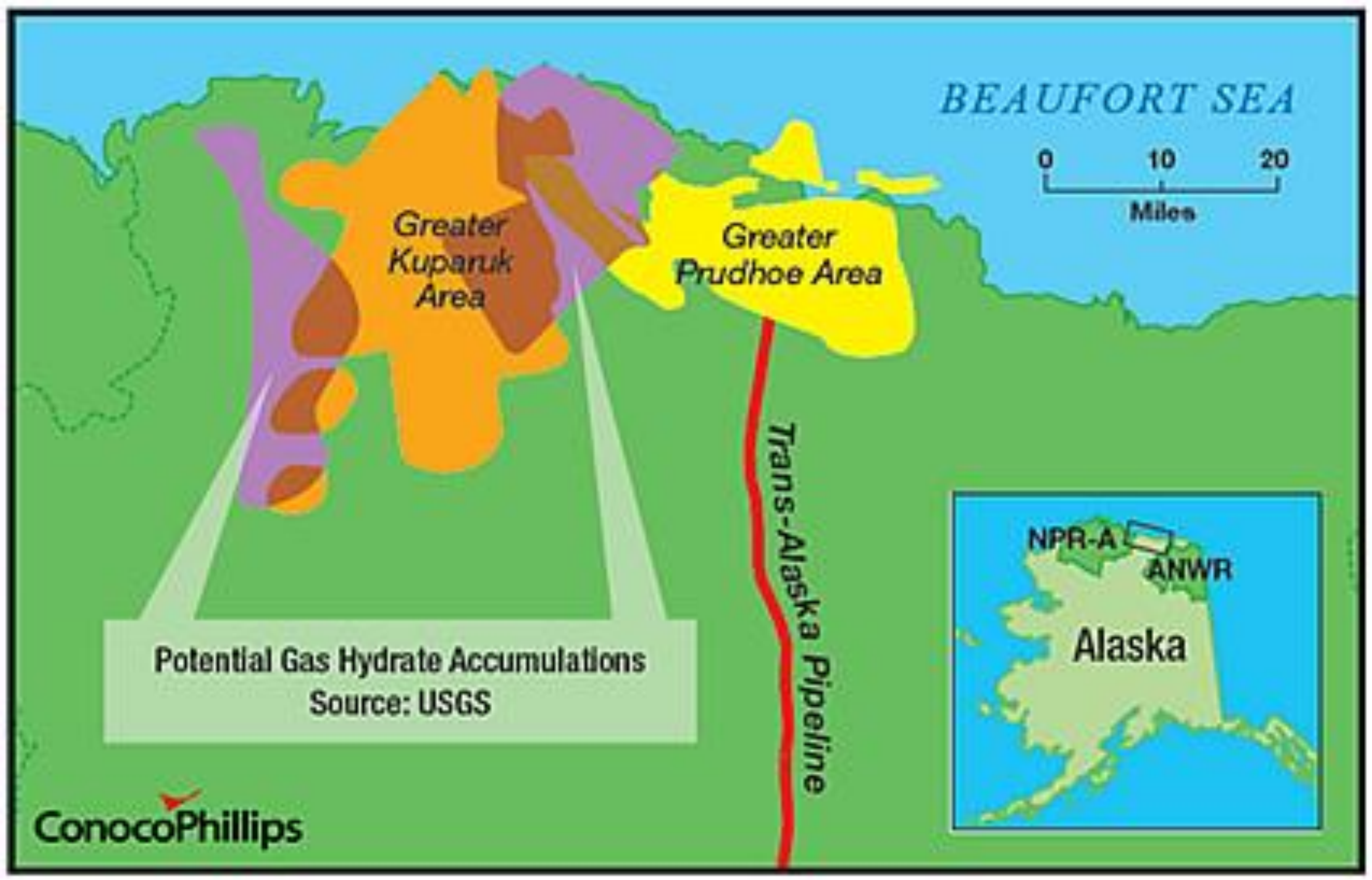
- **ConocoPhillips, USDOE and JOGMEC**
- **US$ 11.6 mill funding from US DOE, total cost ca. US$30mill**
- **CO_2 injection**

Summary of Field Test (Injection Test)

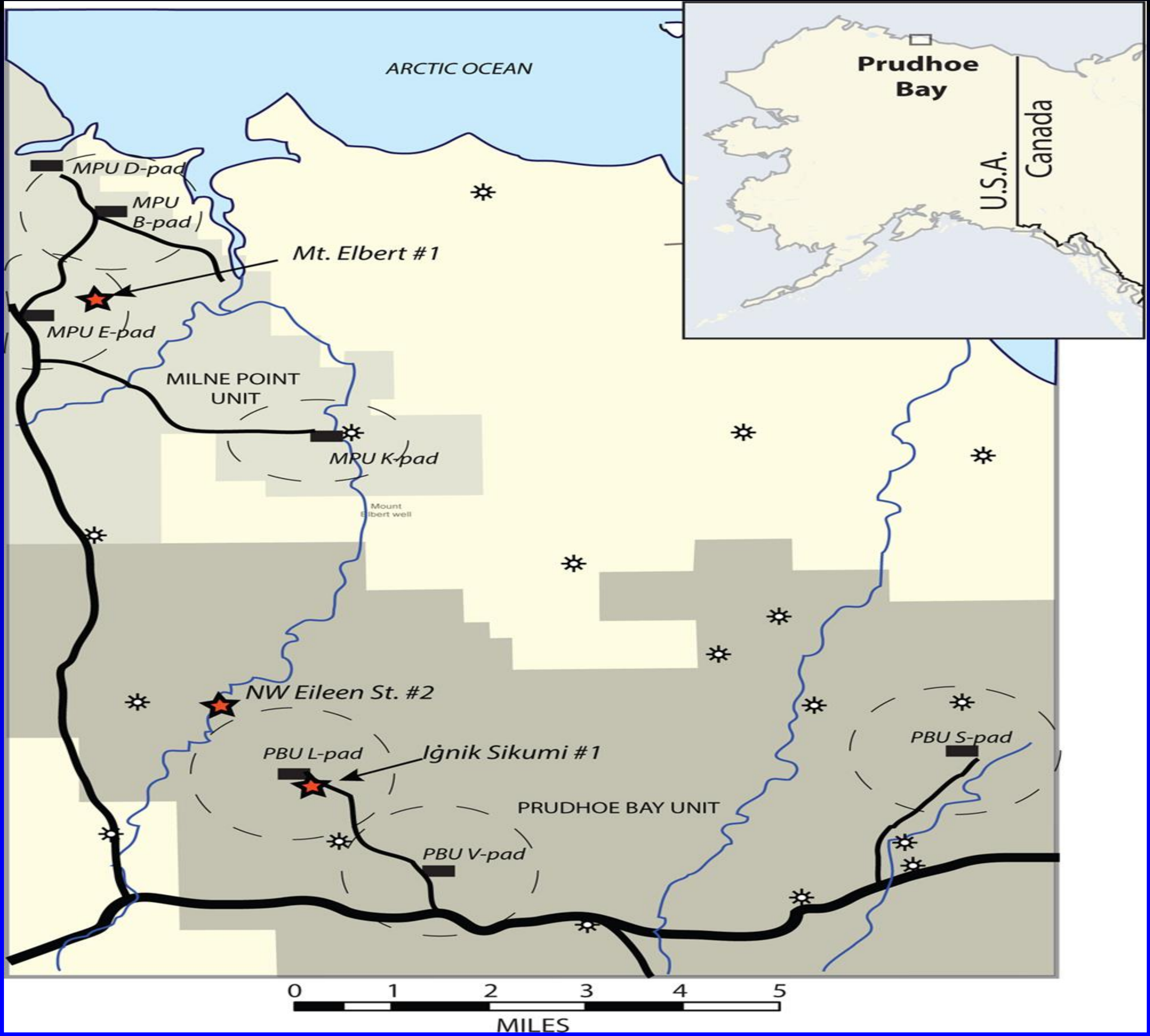
Schedule:

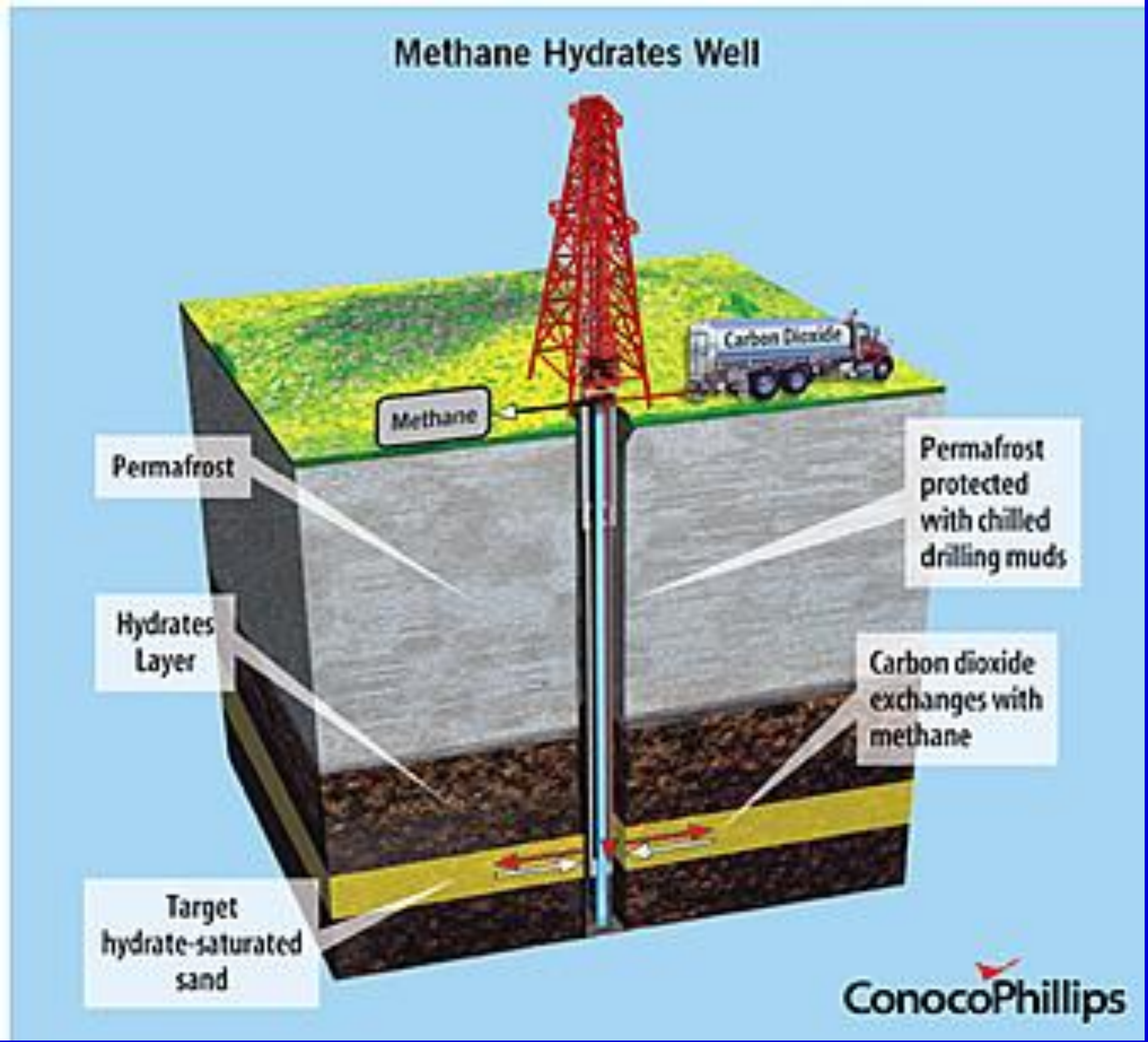
Apr. 2011:	**Drilling test well (Complete)**
Nov. 2011:	**Finalizing parameters for the field test**
Jan.-Apr. 2012:	**Field test**

Location：	**Prudhoe Bay operating unit in Alaska, USA**
Operator：	**ConocoPhillips Company (COP), through its wholly owned subsidiary, ConocoPhillips Alaska, Inc.**
Investors：	**The United States Department of Energy（DOE） JOGMEC; Japan Oil, Gas and Metals National Corp.**

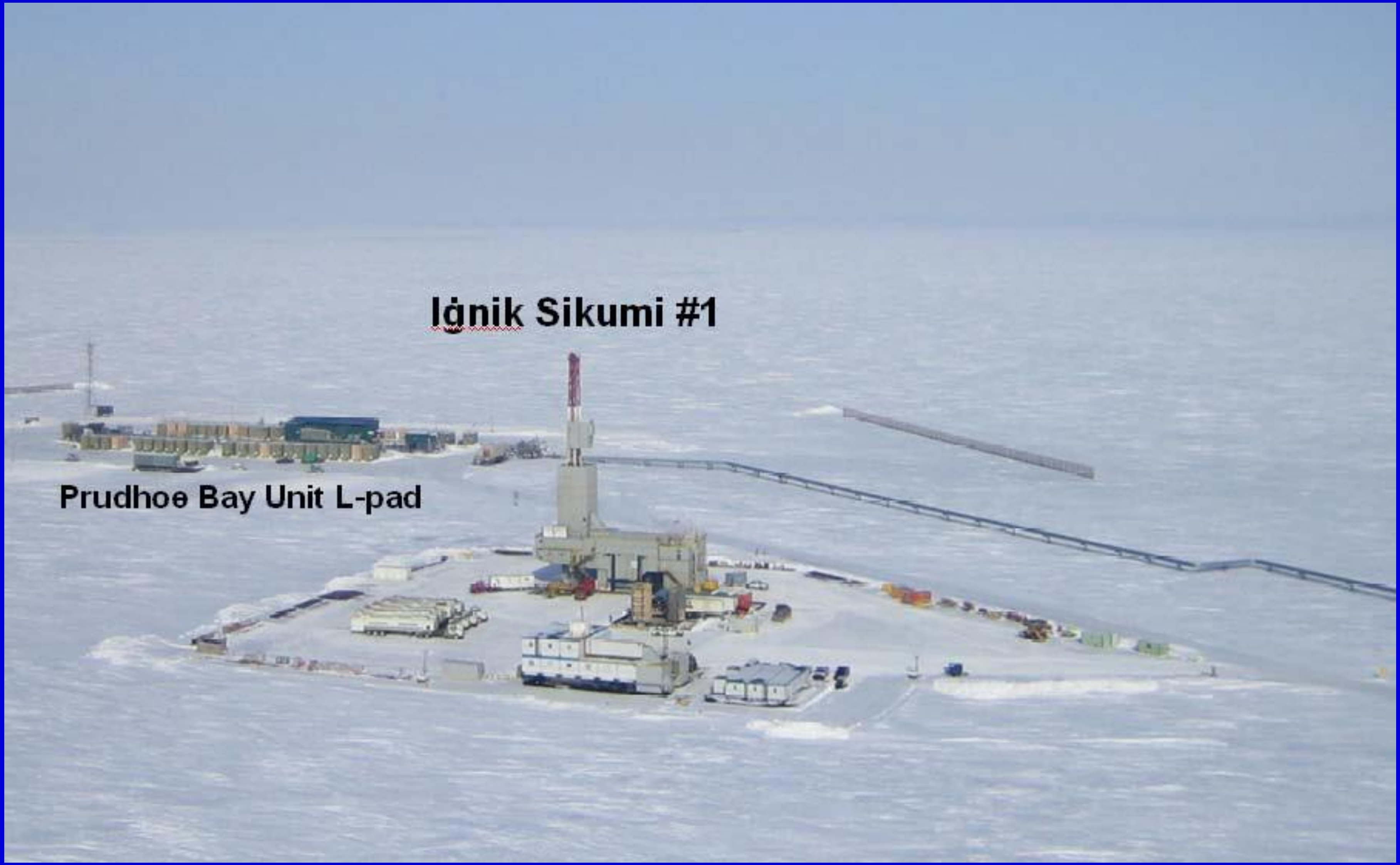


BEAUFORT SEA
0
10
20
Miles
Greater Kuparuk Area
Greater Prudhoe Area
Trans-Alaska Pipeline
Potential Gas Hydrate Accumulations
Source: USGS
NPR-A
ANWR
Alaska
ConocoPhillips

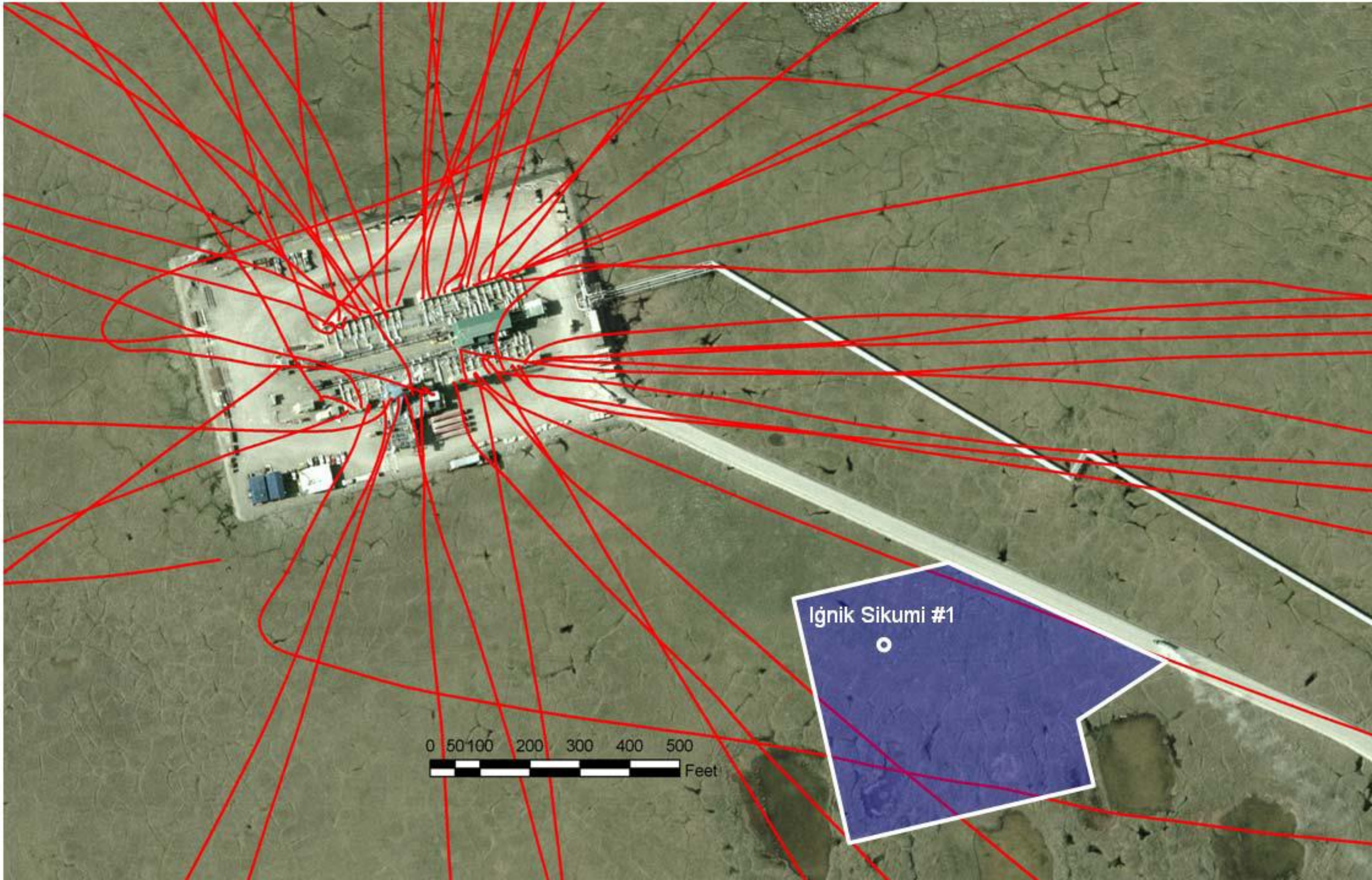

ARCTIC OCEAN
Prudhoe Bay
U.S.A.
Canada
MPU D-pad
MPU B-pad
Mt. Elbert #1
MPU E-pad
MILNE POINT UNIT
MPU K-pad
NW Eileen St. #2
PBU L-pad
Iġnik Sikumi #1
PBU S-pad
PRUDHOE BAY UNIT
PBU V-pad
0
1
2
3
4
5
MILES



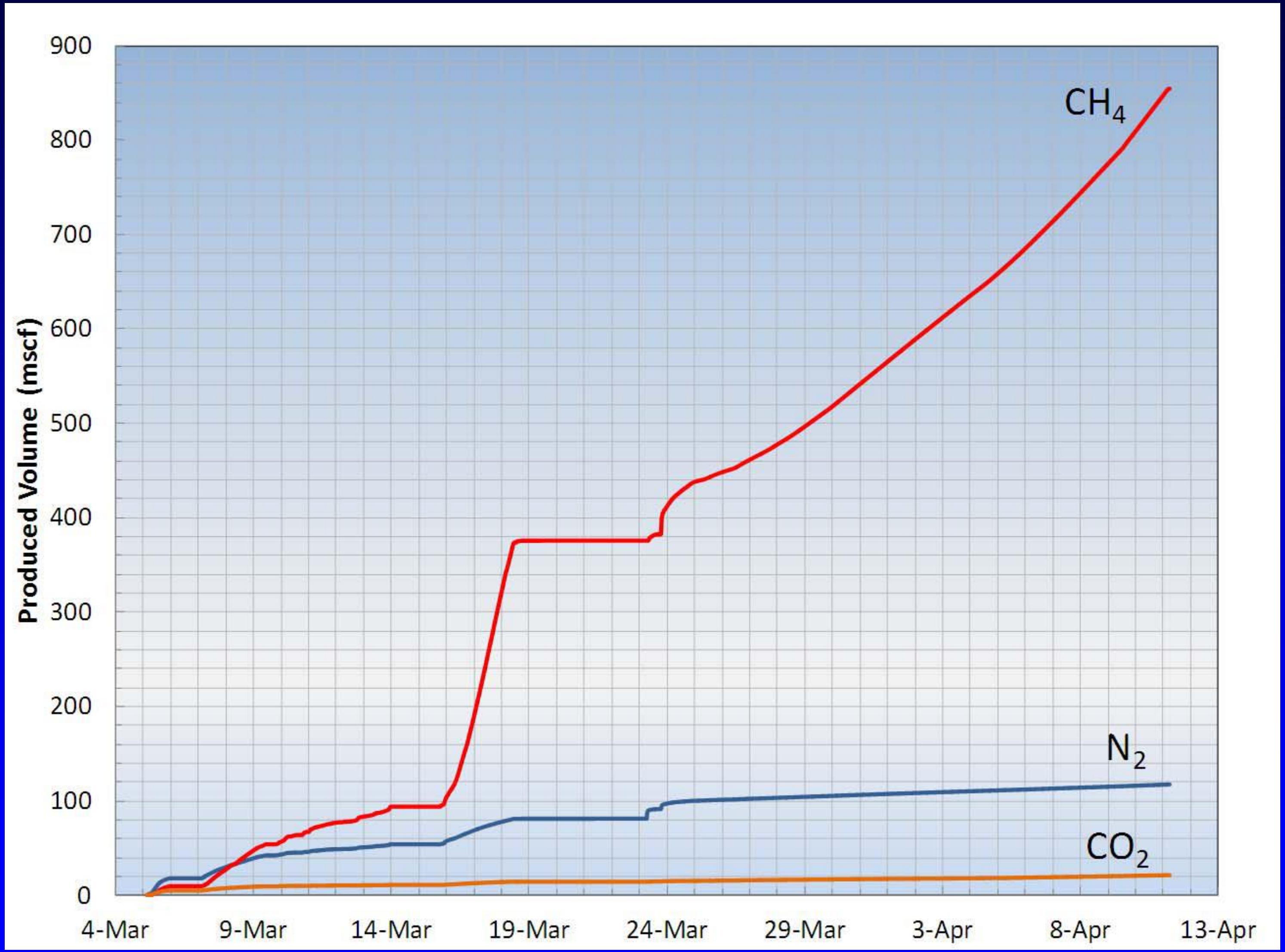
Methane Hydrates Well
Carbon Dioxide
Methane
Permafrost
Permafrost protected with chilled drilling muds
Hydrates Layer
Carbon dioxide exchanges with methane
Target hydrate-saturated sand
ConocoPhillips


Iġnik Sikumi #1
Prudhoe Bay Unit L-pad

Department o



Gas Production from the Field Test



Iġnik Sikumi #1 Flowback/Drawdown: Gas composition

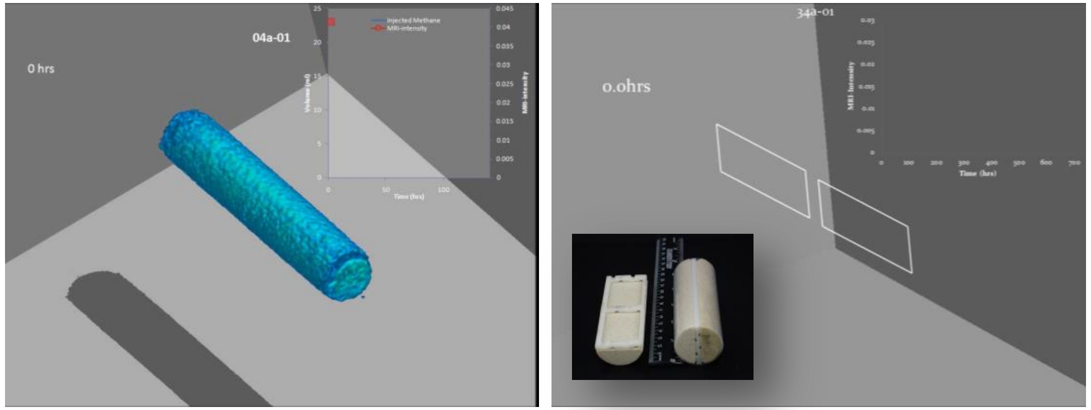
Conclusions on Industry Collaboration

- Mutually beneficial
- Students exposed to experienced senior petroleum experts
- Access to advanced and expensive equipment
- Leveraged research
- Provides qualified candidates for Norway and the oil industry
- Recruitment of national students

Energy for the Future
Gas Production WITH CO_2 Storage in Hydrates

Energy bound in hydrates **is more than combined energy** in conventional oil, gas and coal reserves

UiB Laboratory Verification of Technology

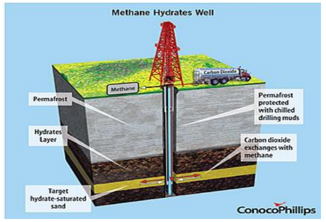


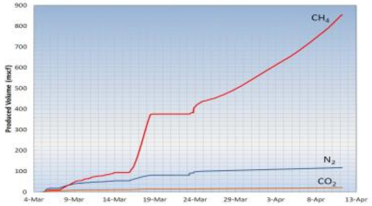
Field Verification of UiB Technology

"*While this is just the beginning, this research could potentially yield significant new supplies of natural gas.*"
U.S. Energy Secretary Steven Chu, May 2nd 2012

< 10 year

US $30 mill





DOE, ConocoPhillips and JOGMEC at the Iġnik Sikumi test site, Alaska

What are Methane Hydrates?

Methane hydrates are ice-like structures with natural gas trapped inside, and are found both onshore and offshore along nearly every continental shelf in the world.

Excerpt from U.S. Energy Secretary Steven Chu's statement

…to conduct a test of natural gas extraction from methane hydrate **using a unique production technology, developed through laboratory collaboration between the University of Bergen, Norway**… [D]emonstrated that this mixture could **promote the production of natural gas**. Ongoing analyses of the extensive datasets acquired at the field site will be needed to determine the **efficiency of simultaneous CO_2 storage in the reservoirs**.

Summary

Use of CO_2 as a commodity:

Business Case for CO_2 Storage:

- **CO_2 EOR**
- **Integrated EOR (IEOR) with Foam: *Carbon Negative Oil Production***
- **Exploitation of Hydrate Energy: *Carbon Neutral Gas Production***

Way Forward

New technologies ready for industrial scale implementation:

- **Onshore in Permian Basin, USA (80% CO_2EOR, EOR target 137Bbbl)**
- **Offshore Opportunities: NCS, Middle East, Asia, Africa and Brazil**
- **International Whole Value Chain CCUS Collaboration Offshore**

Thank you!