Webinar: **Practical Applications of STAR-CCM+ on Mars**

Parthiv Shah, ATA Engineering

September 5th 2018

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What We Do

ATA Engineering’s **high-value engineering services** help solve the most challenging product design challenges

Aerospace

Robotics & Controls

Themed Entertainment

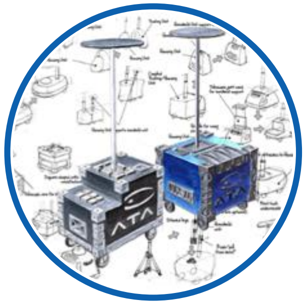
Defense

Industrial & Mining Equipment

Consumer Products

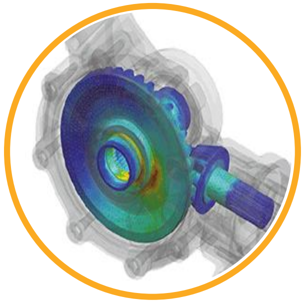
Our Services

We provide our customers with **complete, integrated solutions**



Design

From initial concept development to detailed structural design



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Comprehensive structural, fluid, acoustic, and thermal analysis services

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ATA is a value-added reseller for **Siemens PLM Software**

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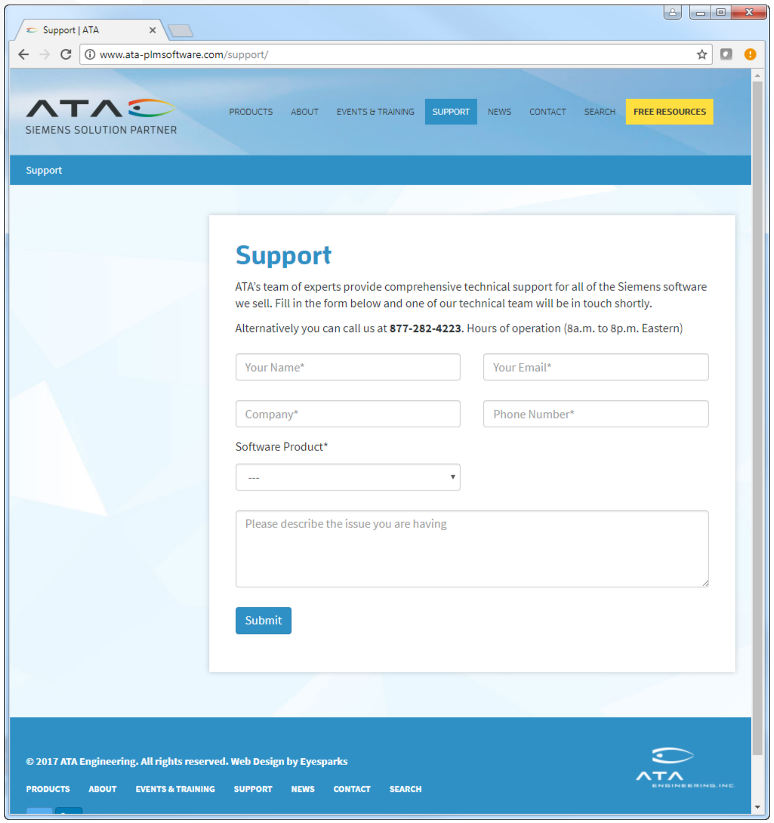

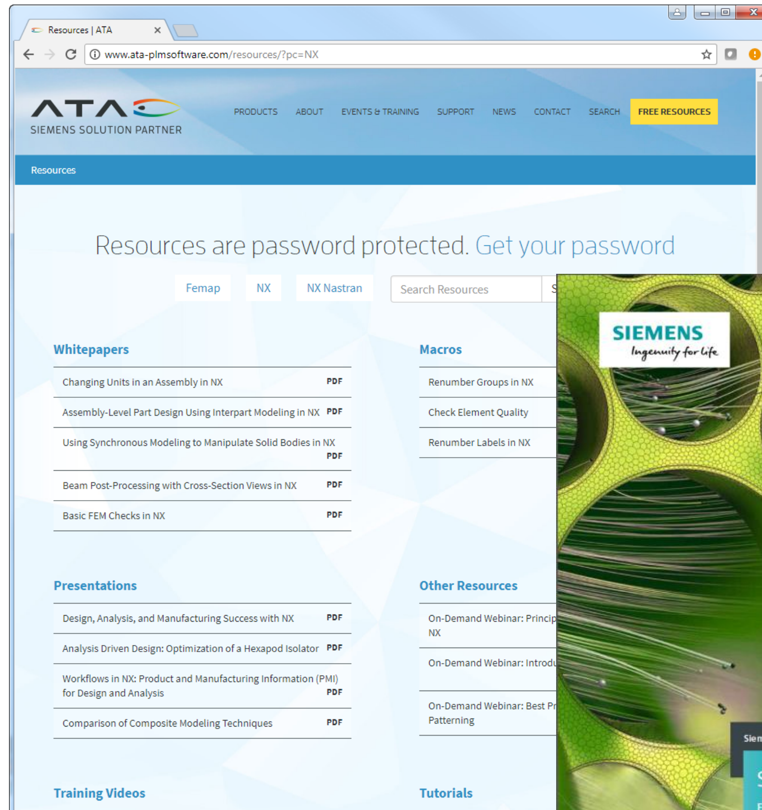

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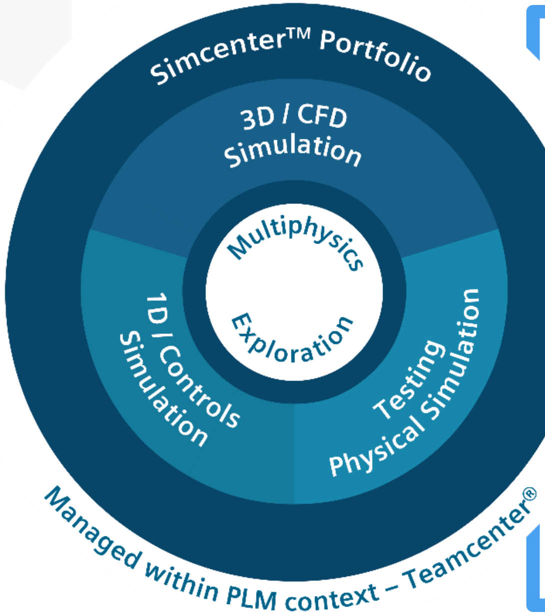
STAR-CCM+

Part of the Simcenter Portfolio for Predictive Engineering Analytics



- **Realism at each stage of development** by combining multiphysics, multi-disciplinary and systems simulation and test
- **Innovative designs** with multidisciplinary design exploration, and data analytics
- **Best practices, collaboration and long-term knowledge** with Teamcenter for simulation and data management in the context of the overall PLM system.

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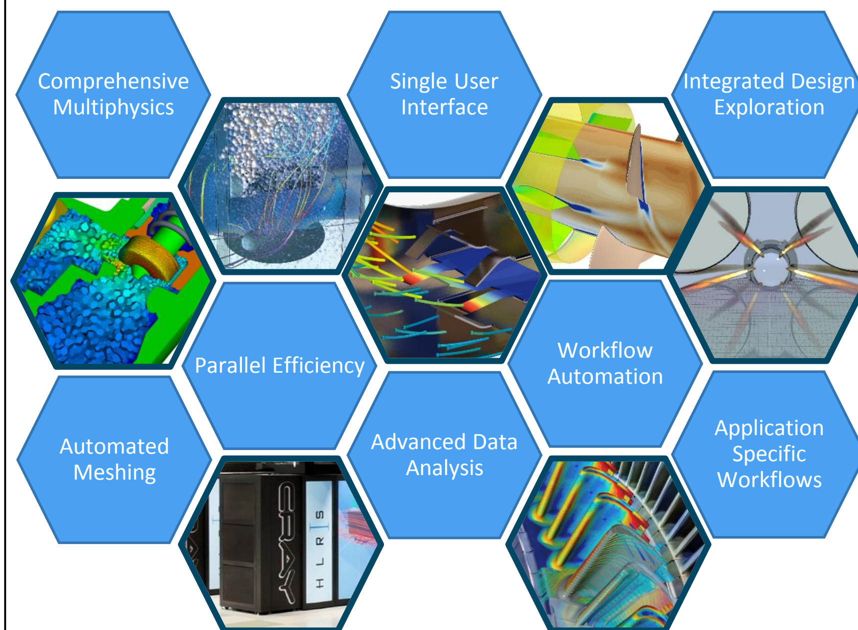
STAR-CCM+

An integrated multiphysics solution for the digital product

STAR-CCM+®

Engineer Innovation



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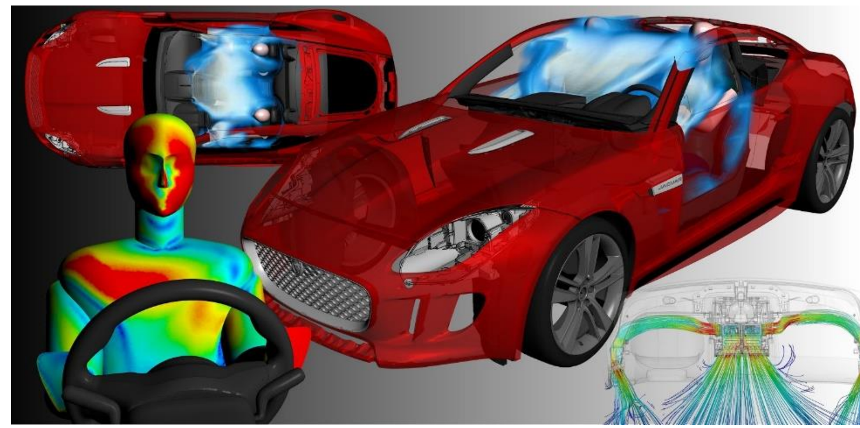

"Prototypes at JLR can be very expensive. If we can save a prototype, the software pays for itself. For systems such as the defrost system, we no longer build any prototypes apart from the final model. We rely totally on STAR-CCM+ to design the system"
Karamjit Sandhu, Jaguar Land Rover Limited

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Realism	Productivity	Efficiency	Innovation	Responsiveness	Success
with multiphysics	with streamlined workflows and automation	with HPC	with design exploration	with cutting-edge technologies	with customer support

Engineer Innovation

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Realism with multiphysics

- Integrated multiphysics from a single user interface
  - Improved accuracy by taking into account a greater range of interconnected physical phenomena
  - Built on a backbone of state-of-the-art, industry leading CFD capabilities
- Both finite element and finite volume approaches
  - No need to compromise
  - Choose the scheme appropriate to the physics
- Integration with CAE tools to expand simulation scope
  - Flexibility to us the right tool for the job
  - Loose and fully coupled co-simulation with 1D & 3D software solutions

"We've been able to deepen our analysis and drive engine designs faster and more effectively with the same resources as before"
Jeff Schlautman, General Motors

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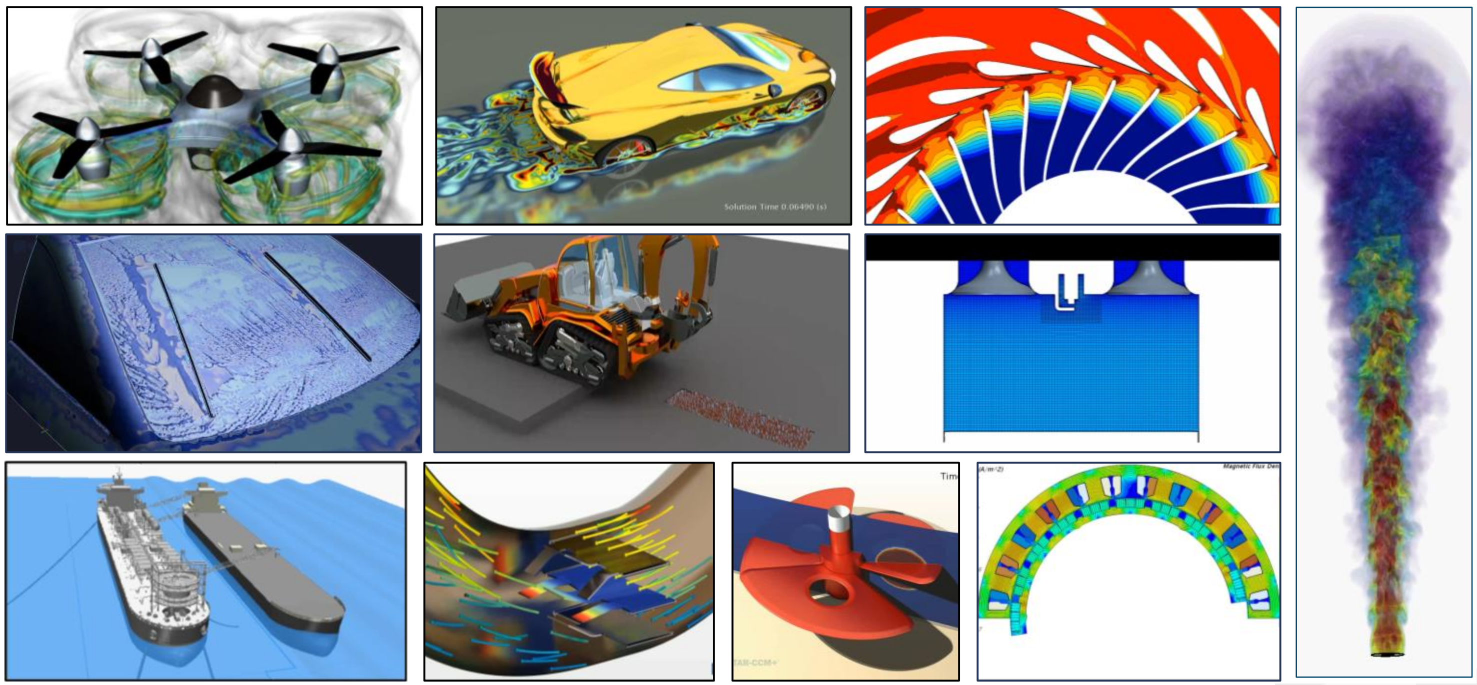
Realism with multiphysics

- Fluid dynamics
- Multiphase flows
- Reacting flows
- Solid mechanics
- Particle flows
- Rheology
- Electrochemistry
- Electromagnetics
- Aero-acoustics
- Fluid-structure interaction
- Conjugate heat transfer



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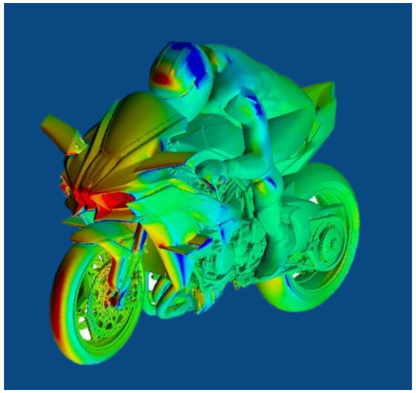
Productivity with streamlined workflows and automation

- Designed with automation in mind
  - Seamless process from geometry to results
  - Consistent, robust and repeatable workflows
  - Ensuring best practice with simulation templates
- No compromise between usability and functionality
  - Easy to learn and use even for advanced configurations and physics
- Single, flexible yet powerful scripting language
  - Automate the complete workflow with Java
  - Customize your experience with user designed panels
  - Use Simulation assistants for step by step processes



"Compared to before, now we can simulate several dozen cases in a reduced time. Thanks to this, the number of actual prototypes being turned out has also been reduced, making an extremely valuable contribution to lowering cost and man-hours alike."
Eiji Ihara, Kawasaki Heavy Industries Ltd.

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Efficiency with HPC

- STAR-CCM+ ensures computational resources are utilized with maximum efficiency
    - Solvers that scale to hundreds of thousands of cores
    - Parallel meshing reducing turnaround time and enabling mesh generation on clusters
- Unique licensing options to ensure software cost doesn't limit hardware utilization
    - Core count independent Power Sessions
    - Usage based Power-on-Demand for cloud deployment and burst capacity requirements
    - Flexible Power Tokens enabling design exploration

"Being able to use the POD licensing scheme and run simulations on a cloud has been a tremendous help for us in terms of productivity."
Mio Suzuki,Trek Bicycle Corporation

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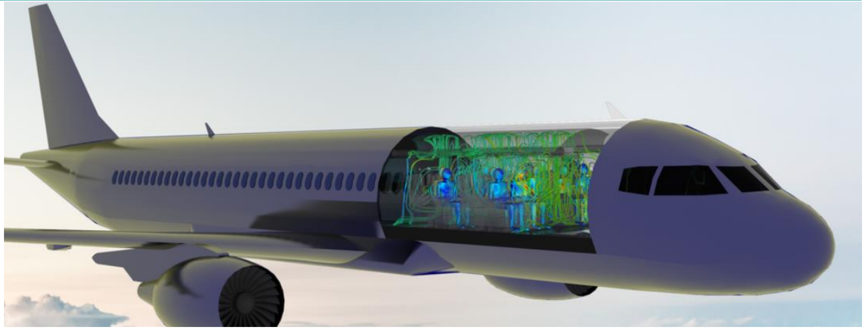
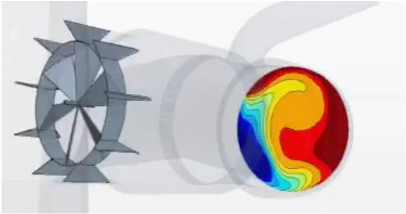
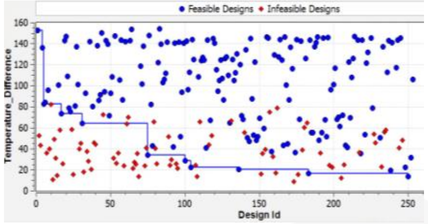
Innovation with design exploration



- Built-in design exploration and optimization
  - Easy to use with a familiar experience
  - Comprehensive range of exploration options
  - Gain insight into product behaviour and parameter influence with unique post-processing options
- Design Manager
  - Facilitating parametric analysis
  - No additional license required to enable sweeps
- Design manager with STAR-Innovate add-on
  - Explore entire design space and find better designs
  - Automatic search using embedded HEEDS technology
- Flexible license scheme to deploy design exploration





"With design exploration in STAR-CCM+ we learned what makes a good design and how to improve the performance of the system"
Andreas Ruch, ECS Analyst, Airbus

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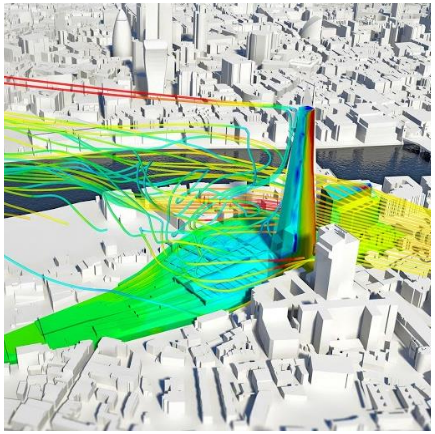
Responsiveness with cutting-edge technologies

- Three major releases a year:
  - Delivering state-of-the-art technologies
  - Includes over 100 new features and enhancements with each release
- Collaboration with customers to satisfy immediate simulation needs
  - IdeaStorm for collecting, voting, and commenting on new feature requests
- Partnering with our users to anticipate simulation trends allowing them to stay ahead of their competition
  - A proven track record of technological innovation since first release in 2006



With regular releases, new features are always being introduced into the code, which enables us to produce more accurate simulations quicker
James Bertwistle, WSP

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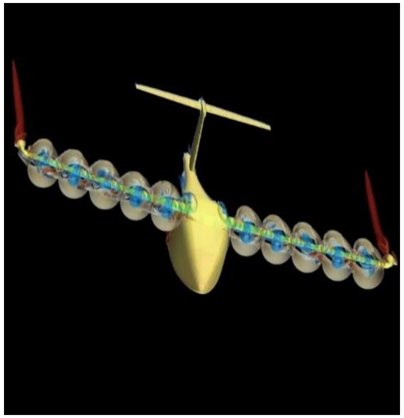
Success with customer support

- A team of global experts to ensure our customer's success
- Dedicated support to provide help every step of the way
  - Working closely with users to gain an in depth knowledge of their processes and requirements
  - Providing immediate solutions to your simulation challenges
- A customer portal, available 24/7
  - Access to a huge library of knowledge base articles
  - Track support queries and download software
  - Chat to support engineers and engage with the STAR-CCM+ user community



"Support from the engineers at Siemens PLM is great. It's really nice to be able to call up an expert with a question, and they make you their first priority and help you be successful."
Alex Stoll, Aeronautical Engineer, Joby Aviation

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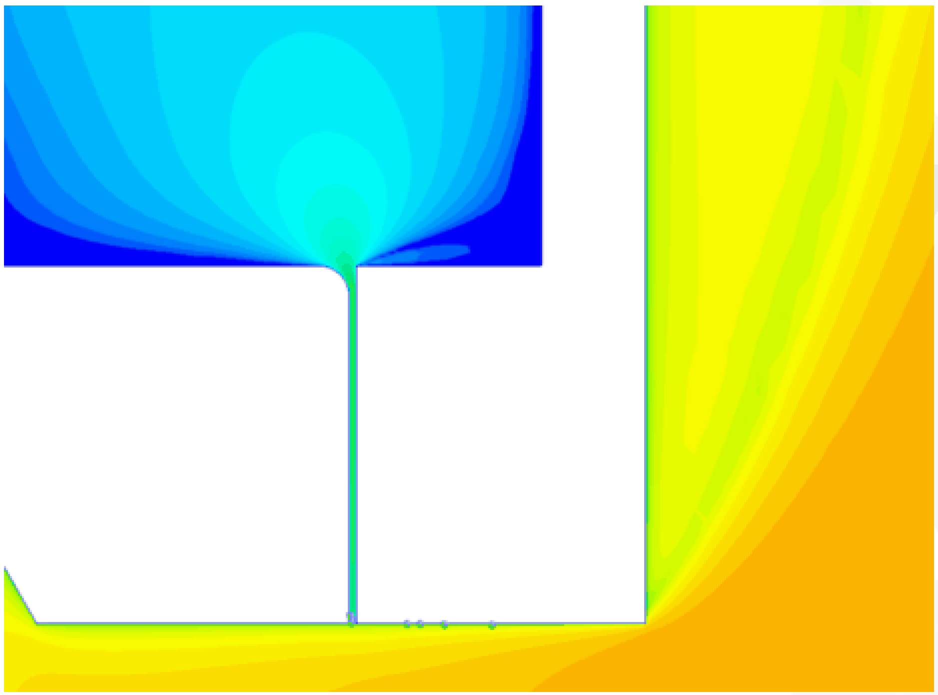

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Presentation Outline

- Introduction
- Mars 2020 – Fluid Mechanical Particle Barrier (FMPB)
  - Mission overview
  - FMPB Operational Principle
  - Role of CFD in FMPB Design / Validation
- Summary and Conclusions

Today's Presentation is Based on Material in the Public Domain

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The viscous Fluid Mechanical Particle Barrier for the prevention of sample contamination on the Mars 2020 mission

CrossMark

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Executive Summary

- Mars2020 Mission (https://mars.jpl.nasa.gov/mars2020/)
  - Acquire, encapsulate and cache samples of martial material for _possible (future mission) return to Earth_
  - Samples must be kept clean of terrestrial organisms that may adhere to the rover and/or on other abiological particles
- A key contamination prevention feature of sample tubes is a viscous Fluid Mechanical Particle Barrier (FMPB)
  - Thin annular orifice which limits penetration of contaminant particles by viscous resistance in fully developed (laminar) flow
- CFD used to support demonstration of FMPB principles under different external wind scenarios, including rarest, high speed Martian dust devils

Mars 2020 Mission Overview

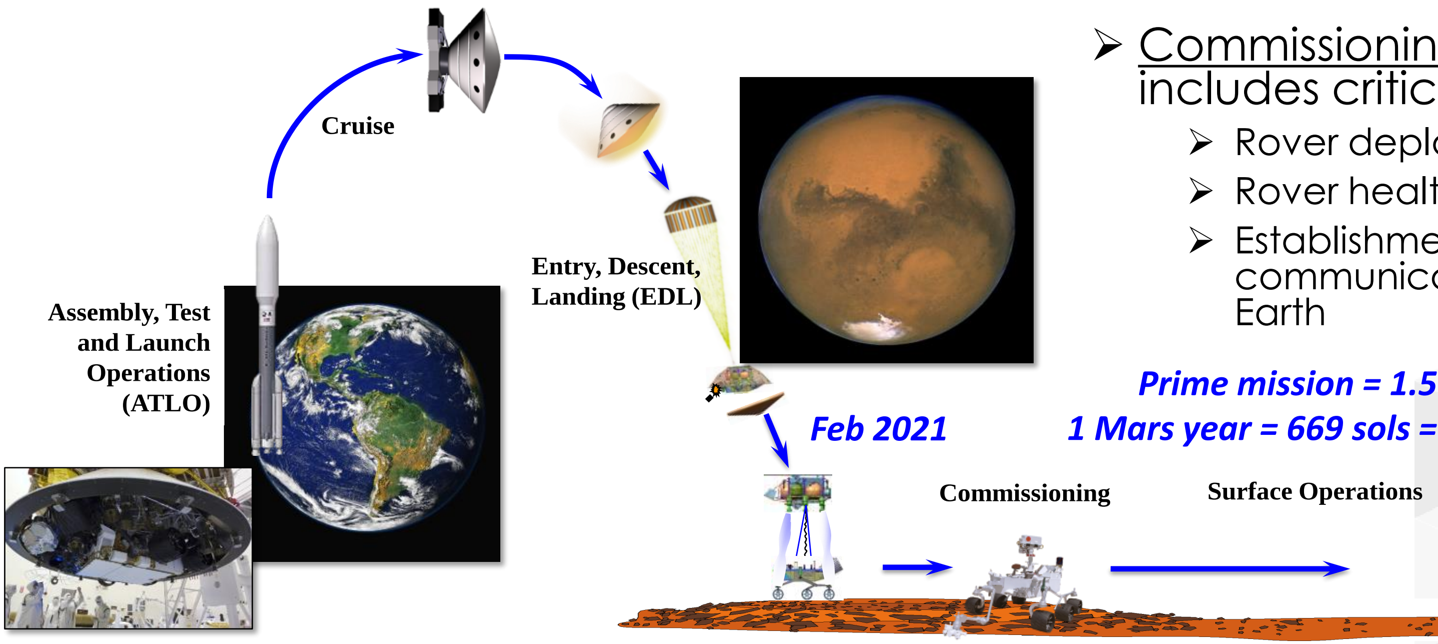
Part of NASA Mars Exploration Program
(https://mars.jpl.nasa.gov/mars2020/)

- Primary science goals
  - Characterize processes that formed and modified geologic record within a selected exploration area
  - Perform astrobiologically relevant investigations on geologic materials at landing site
  - Assemble documented, cached samples for possible future return to Earth
- Leverages proven design and technology of Curiosity rover that landed in 2012
- Acquisition, encapsulation and caching of samples is new, and subject to stringent contamination requirements
  - Terrestrial particles can carry biological signatures. Therefore, prevention of contamination is a critical objective

From Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68 and https://mars.jpl.nasa.gov/mars2020/

Mars 2020 Mission Overview

- Planned launch window: 16 July – 4 August 2020
- After LV separation, ~7 month cruise to Mars
  - Rover enclosed in aeroshell during cruise
- Cruise stage separates from EDL system just before Martian atmospheric entry and plunges through atmosphere uncontrolled
- Remaining EDL system undergoes controlled activity sequence leading to rover touchdown



Jul/Aug 2020

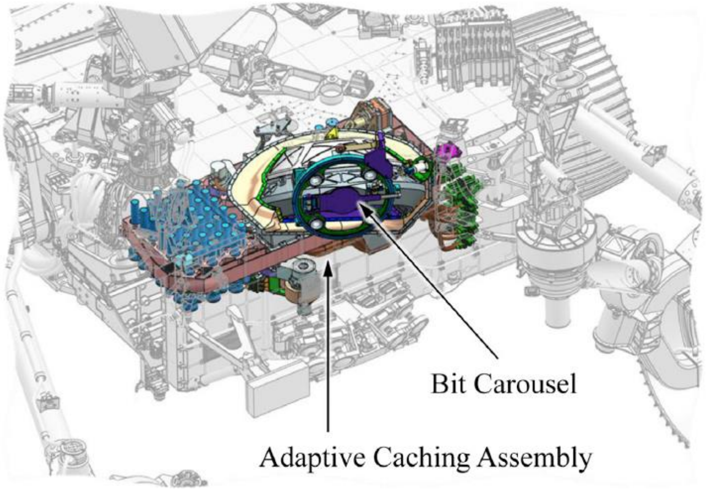
- <u>Commissioning</u> includes critical:
  - Rover deployments
  - Rover health checks
  - Establishment of communication w/ Earth

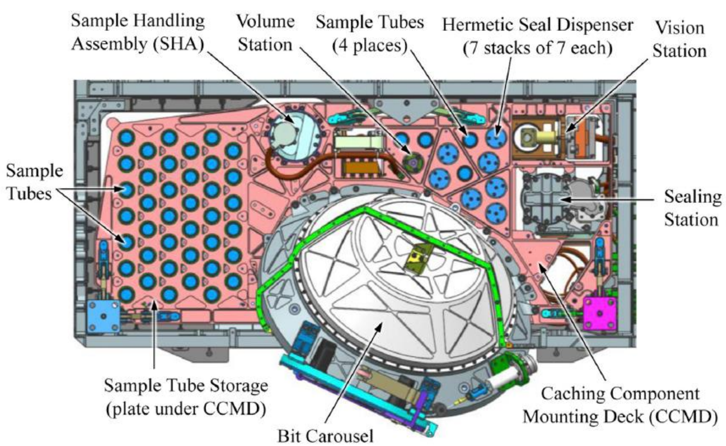
Prime mission = 1.5 Mars year

1 Mars year = 669 sols = 687 Earth days

From Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68 and https://mars.jpl.nasa.gov/mars2020/ (Courtesy NASA/JPL-Caltech)

Mars 2020 Sample Caching System (SCS) and Adaptive Caching Assembly (ACA)





- SCS:
  - Robotic arm
  - Turret
  - ACA
- ACA = hardware to inspect, encapsulate and drop samples onto Martian surface
  - Bit carousel
  - Sample tube storage (STS) assy.
  - Seal dispenser assy.
  - Sample handling assy. (SHA)
  - Volume assessment station
  - Vision assessment station
  - Tube warming station
  - Sealing/sample tube drop-off station

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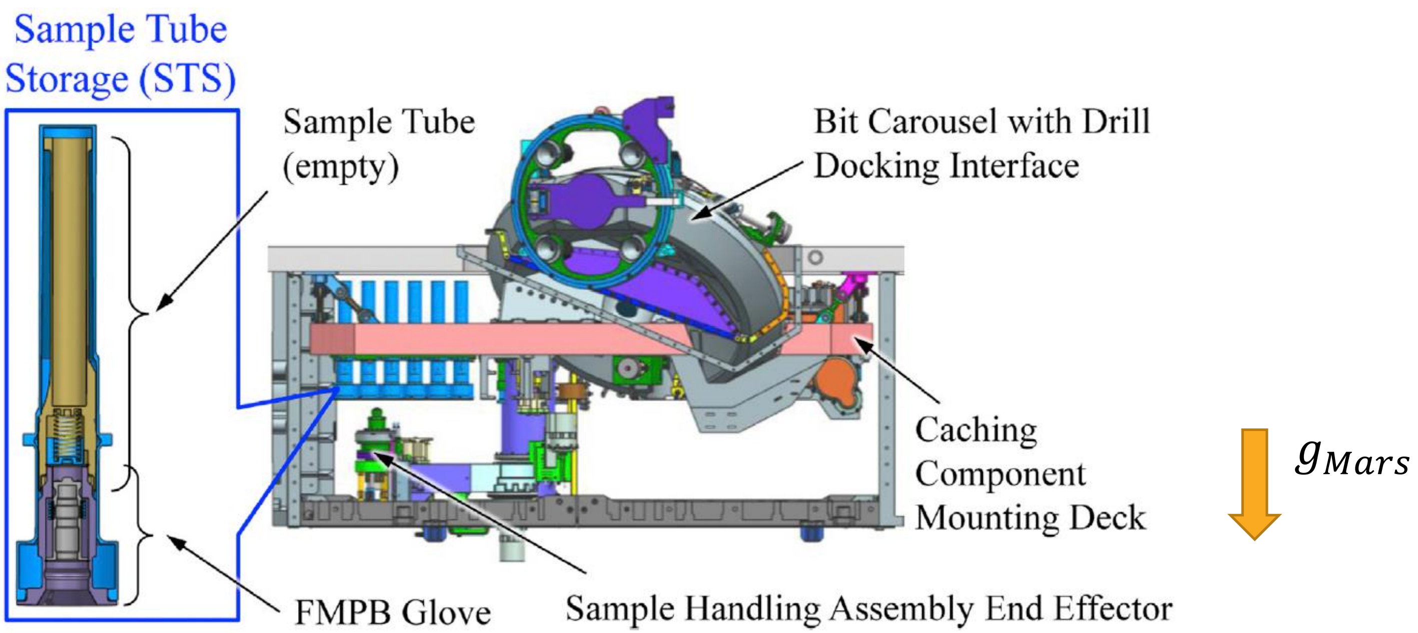
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

Fluid Mechanical Particle Barrier (FMPB) within STS

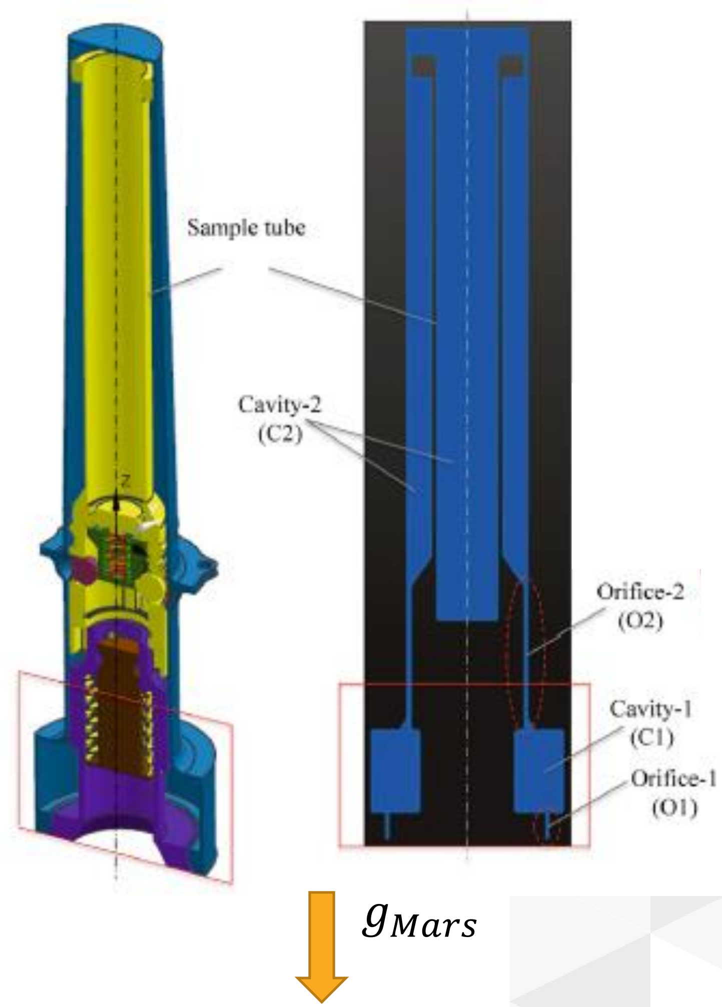
- Upon landing, top deck vent and ACA belly plan deploy, introducing airflow to remove molecular contaminants from outgassing hardware
- Additionally, bit carousel doors open
  - Doors sealed before landing to prevent particulate transport
- STS contains sterilized sample tubes and seals protected by FMPB glove



Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

FMPB Operational Principles

- Positive pressure between external environment and tubes results in a net inflow which may lead to particle penetration
  - Additionally, local flow nonuniformities (e.g., turbulence) may allow instantaneous penetration
- Fluid viscosity retards flow through thin annular Orifice-1 (O1) that separates tube and external environment
- Orifice must be sized to ensure that
  - "Large" particles of O(orifice gap=R_0-r_0) prevented from penetrating orifice
  - "Small" particles penetrate no farther than Cavity-1 (C1) over characteristic "filling" time, so they eventually fall under influence of gravity



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Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

Multi-fidelity Technical Approach Used to Substantiate FMPB Design

- Development of a first-principles analytical model of fluid and particle dynamics (NASA/JPL)
- 2-D and 3-D CFD simulations (ATA Engineering, Inc.) for validation of analytical model and assessment of scenarios too challenging for idealized models
- Laboratory water tunnel testing (NASA/JPL)

Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

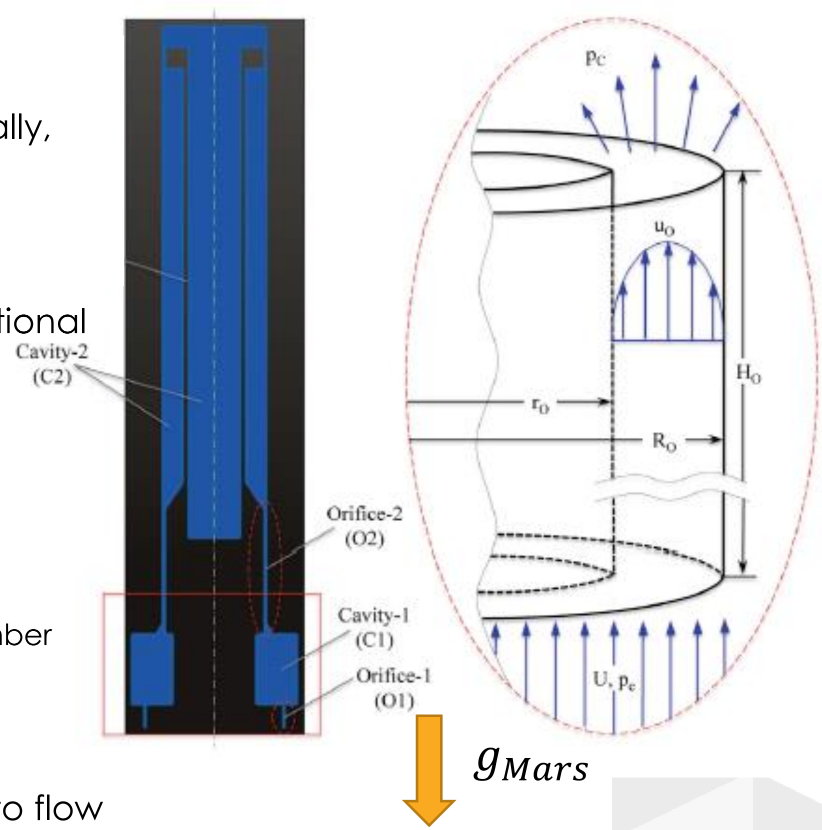
First-principles 1-D fluid dynamics model (NASA/JPL)

Fluid dynamics

- Flow modeled as a network of two orifice-cavity (O-C) pairs in series
- Each orifice (O) presents a flow resistance due to locally, fully-developed Poiseuille flow
  - Volumetric flow rate proportional to driving pressure
- Rate of change of pressure in each cavity (C) proportional to net mass addition
  - Mass addition can be related back to driving pressure
- Final form of 1-D model is a pair of 1st order ODE's for chamber pressures p_c:

$$\dot{\mathbf{p}}_C = A\mathbf{p}_C + \mathbf{b}.$$

  - Coefficient matrices *A* and *b* comprise orifice and chamber geometry parameters, as well as atmospheric boundary conditions



- Solution of $p_c(t)$ is given below and is easily relatable to flow velocity by Poisseuille's law.

$$\mathbf{p}_C(t) = \mathbf{p}_C^H(t)\left\{\mathbf{c} + \int_0^t \left[\mathbf{p}_C^H(s)\right]^{-1}\mathbf{b}(s)ds\right\}$$

Homogeneous solution *Integration constant found from IC's*

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Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

First-principles particle dynamics model (NASA/JPL)

- Once flow velocity known, particle trajectory determined using Newton's second law
  - Aerodynamic force given by Stokes' drag, corrected for particle Reynolds number and slip (Knudsen number ≳0.1) effects

- Particle dynamics dominated by gravity (F_g) vs. drag (F_D) as other forces* found to be negligible

- Additionally, particle interactions with walls are conservatively neglected

$$m_p \frac{d\dot{\mathbf{z}}_p}{dt} = \mathbf{F}_D + \underbrace{\cancel{\mathbf{F}_P}}_{\sim 0} + \underbrace{\cancel{\mathbf{F}_M}}_{\sim 0} + \underbrace{\cancel{\mathbf{F}_B}}_{\sim 0} + \mathbf{F}_g$$

*inertial force due to virtual mass (F_M), Basset force (F_B), & pressure gradient, or Froude-Krylov force (F_P)

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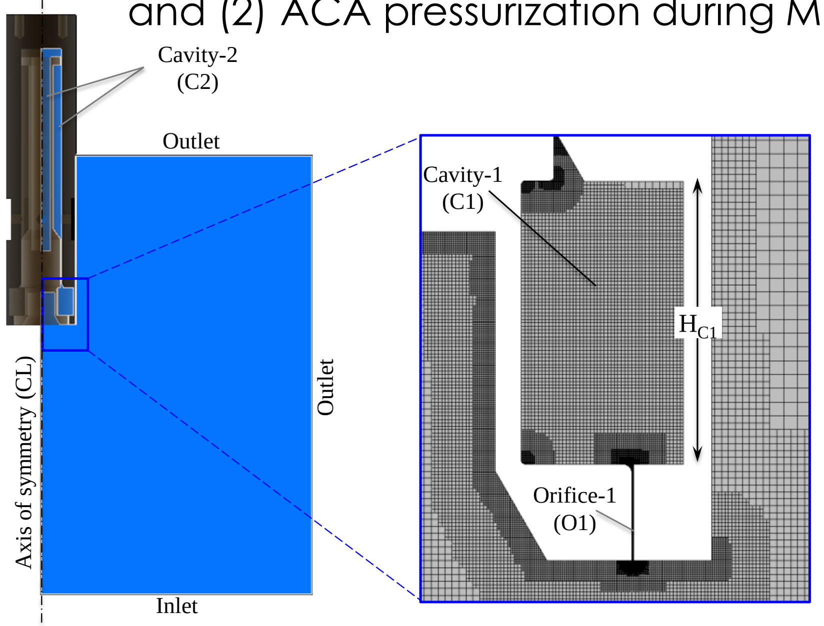
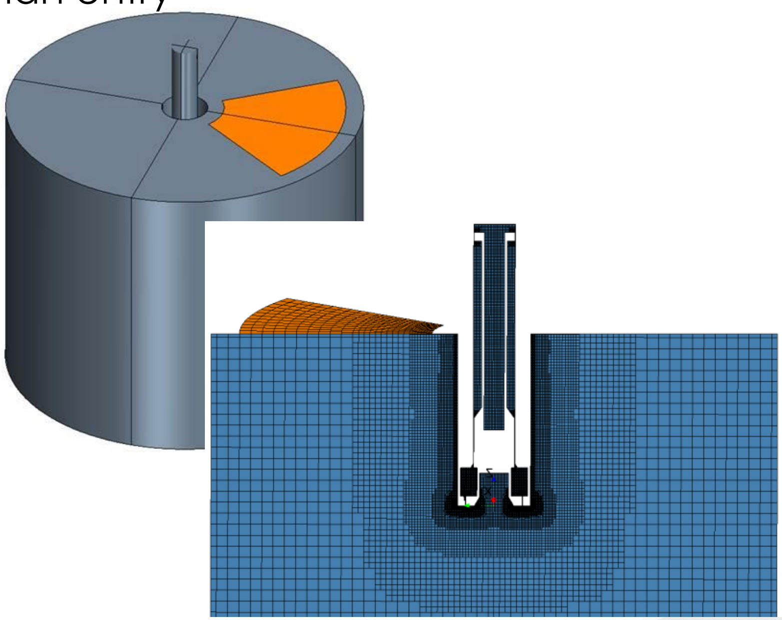
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

FMPB CFD Simulations Using STAR-CCM+

2-D and 3-D Flowfield simulations (ATA Engineering, Inc.)

- Time-accurate, low Mach, segregated flow model with ideal gas assumption for Martian atmosphere (CO_2)
- No-slip, viscous boundary on all walls
- One-way coupled Lagrangian framework for particle dynamics
- Hexahedral-dominant, Trimmer meshes (3-D model was an axisymmetric replication of a 2-D mesh)
- Two types of unsteady BC's: (1): direct flow from ambient Martian winds, and (2) ACA pressurization during Martian entry

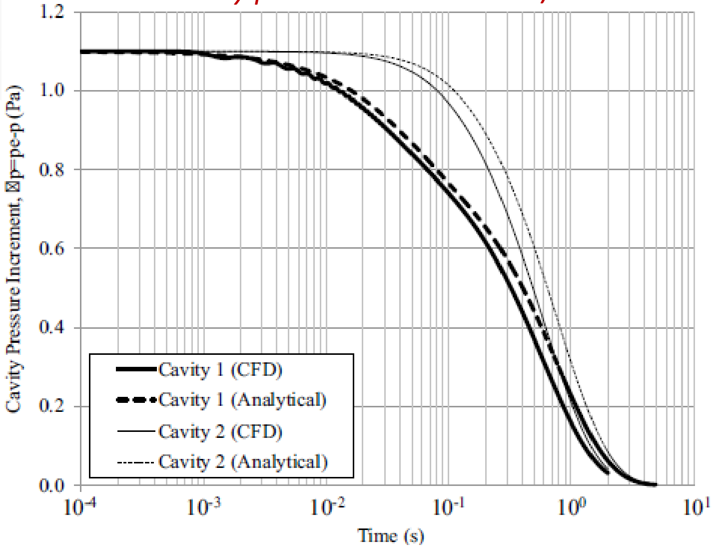




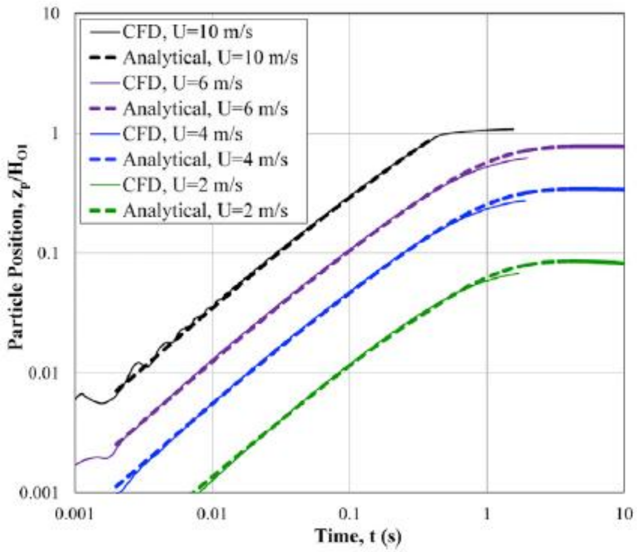
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68
Images from CFD simulations performed by ATA Engineering using STAR-CCM+

CFD Successfully Validated 1-D Analytical Model

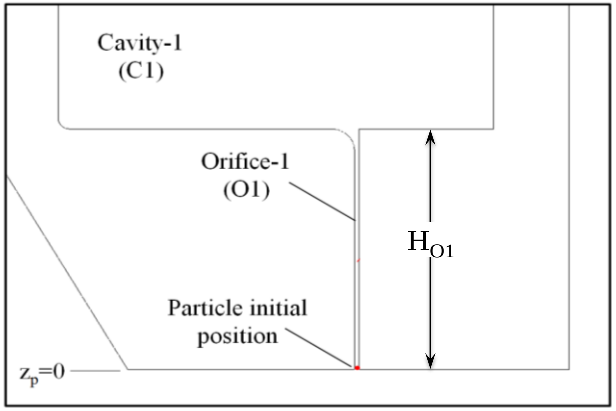
Cavity pressurization at 10 m/s



0.3 μm particle vertical (z) position vs. time trajectory



- ➢ Good agreement of cavity pressurization and 0.3 μm particle* position time histories at different velocities



** biological particles of concern for M2020 are 0.3 μm or larger*

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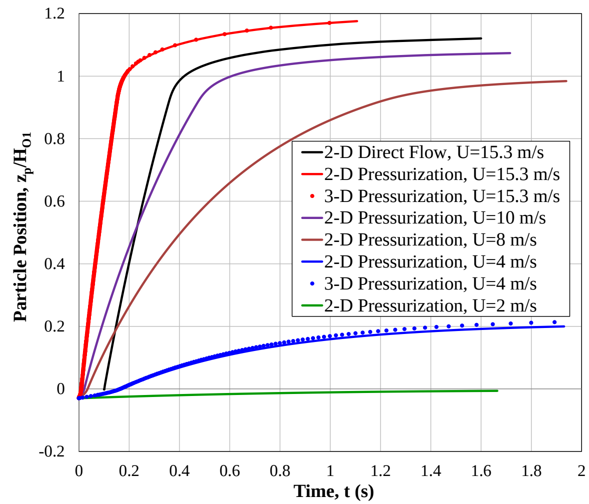
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68
CFD results generated by ATA Engineering using STAR-CCM+

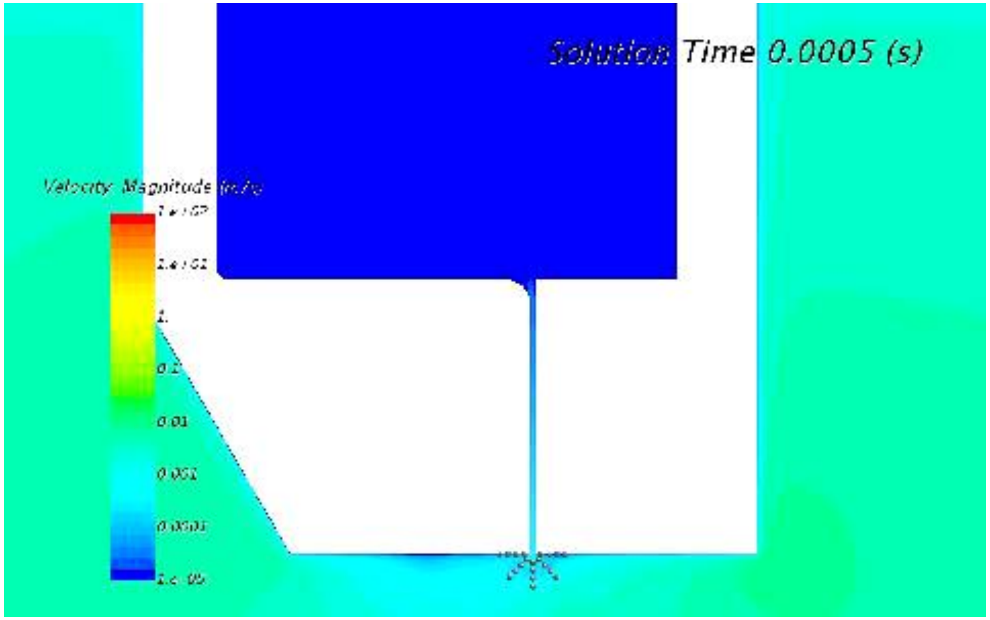
FMPB: STAR-CCM+ Lagrangian Particle Tracking

(ATA Engineering, Inc.)

- Release of particles near O1 demonstrates FMPB operational principle in pressurization and direct flow scenarios
- Under Martian gravity, particles that penetrate C1 cannot approach O2 or C2/sample tubes



Direct flow at 15.3 m/s



Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68
CFD results generated by ATA Engineering using STAR-CCM+

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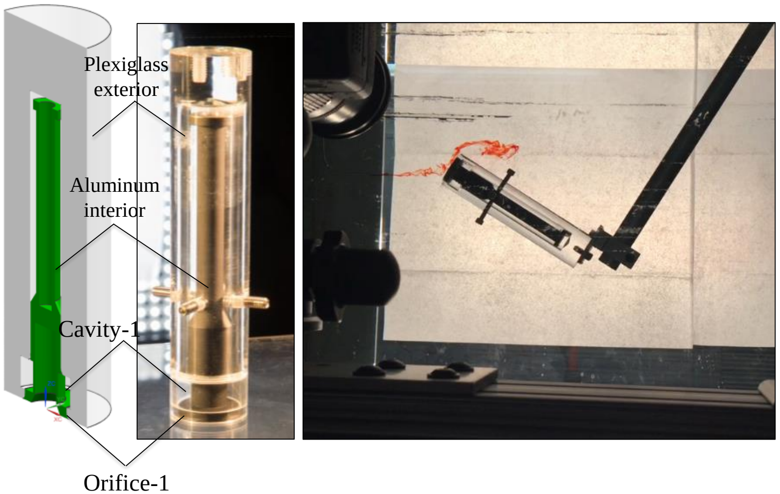
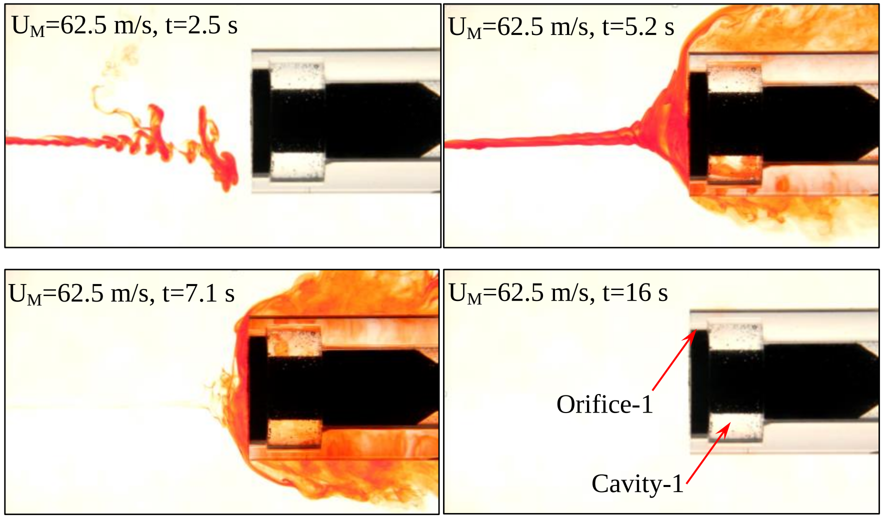
FMPB: Confirmation through Laboratory Testing (NASA/JPL)

Performed at Free Surface Water Tunnel, Caltech

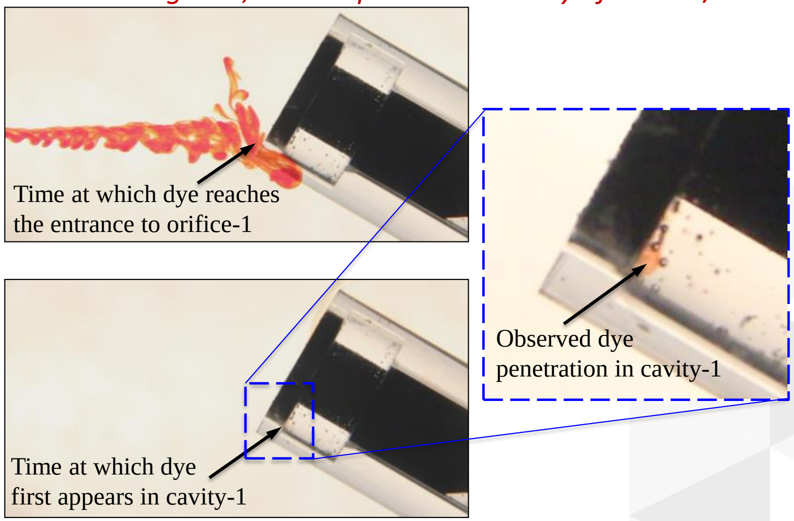
- Goal: determine whether flow asymmetries (e.g., AoA) lead to noticeable penetration
- Water tunnel testing can match Reynolds number but not particle Stokes number
- Therefore, dye flow penetration used as surrogate for particle penetration
- Short dye injections demonstrate no penetration at zero AoA, and penetration time scale at high AoA (e.g. 30 deg) infers orifice flow speed for Mars equivalent velocity of 62.5 m/s



Zero AoA, Mars equivalent velocity of 62.5 m/s



30 deg AoA, Mars equivalent velocity of 62.5 m/s



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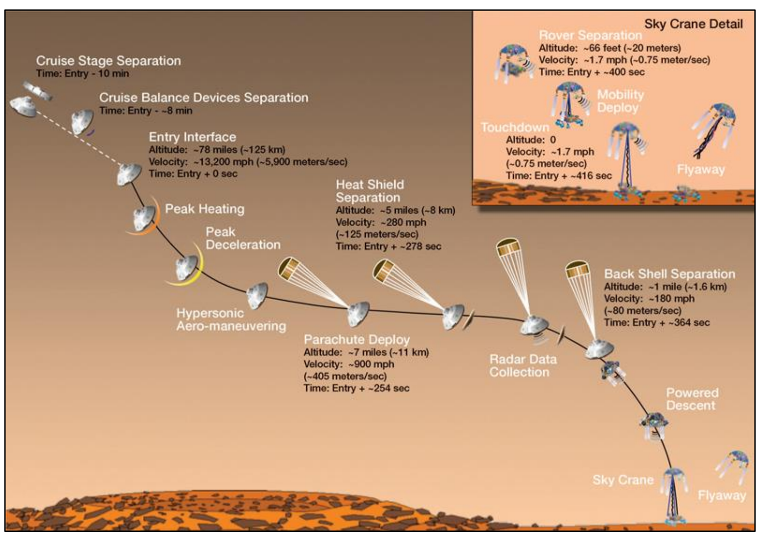
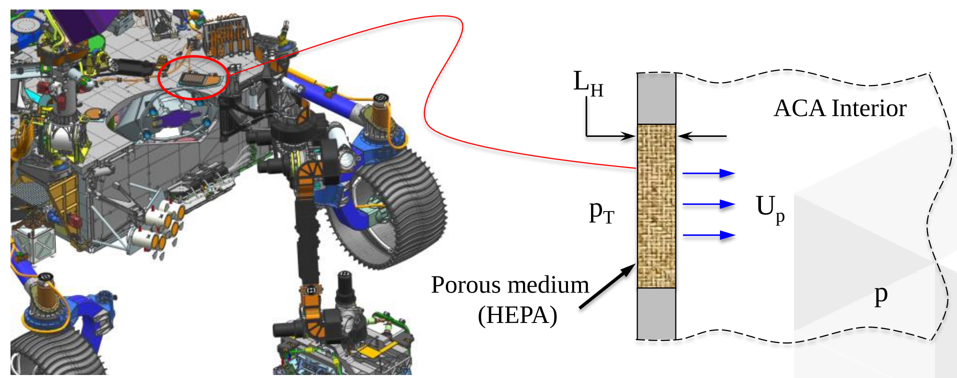
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

FMPB Performance During Mission

- First non-negligible flow ingestion may occur during EDL
  - From Entry Interface through heatshield separation some pressurization occurs, though ACA interior separated from exterior Martian gas by HEPA
  - Analysis of HEPA delta pressure and equivalent flow speeds suggests local flow speeds in ACA are well below worst case CFD simulations



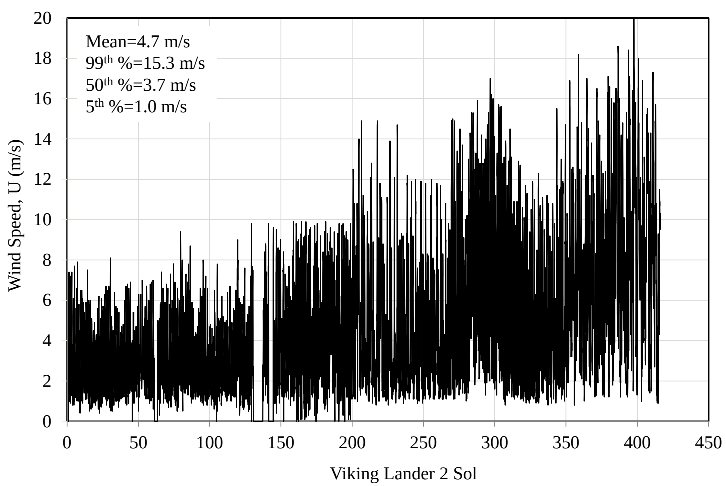


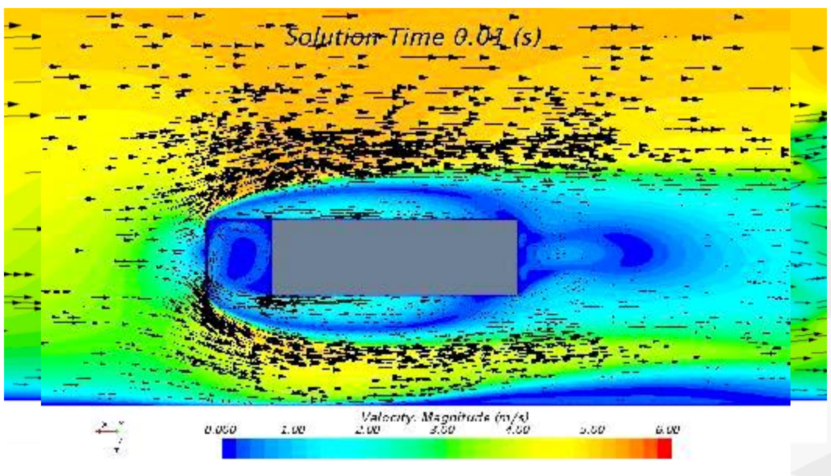
Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68, (Courtesy NASA/JPL-Caltech)

FMPB Performance During Mission

Rover surface operations

- Rover commissioning phase begins upon landing, when ACA "belly pan" is dropped to allow molecular contaminant ventilation
- Expected Martian winds assessed using 1976 Viking Lander 2 data
- 3-D Large eddy simulation in STAR-CCM+ used to predict local flow speeds in Martian boundary layer
  - Highly defeatured model of rover cavity used to represent ACA open cavity
  - Numerical probes used to compute turbulent flow statistics
  - Results demonstrate mean speeds below values used in particle penetration CFD studies

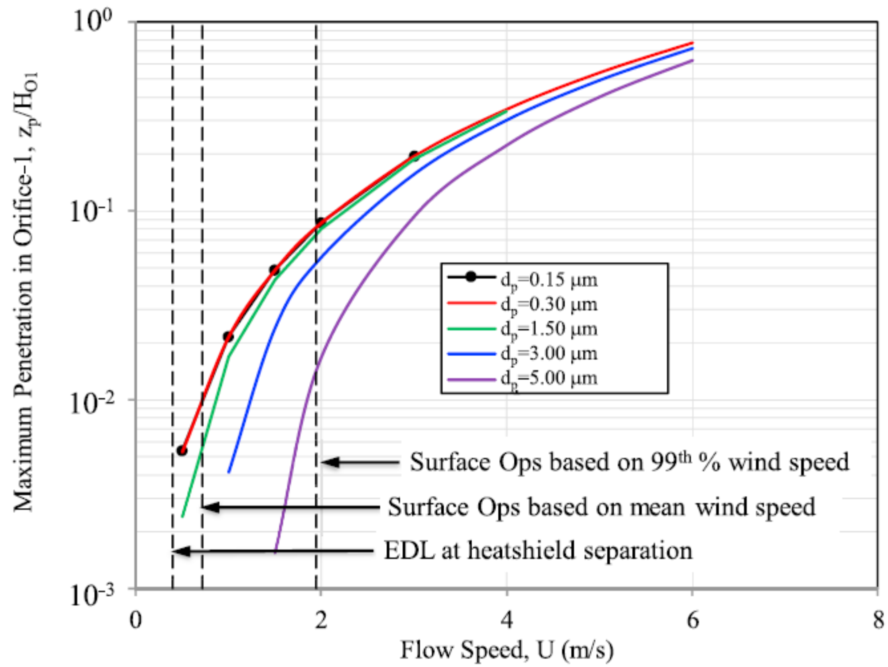




Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68
CFD results generated by ATA Engineering using STAR-CCM+

FMPB: Conclusions

- M2020 mission leverages proven design of MSL/Curiosity, though, caching Martian material samples creates unique contaminant requirements
- Using CFD, FMPB shown to prevent contamination by viscous flow resistance
- First principles analytical model was verified using CFD (STAR-CCM+) and wind tunnel testing, and demonstrated limited particle penetration under worst wind scenario (99th % nominal Martian wind speed (15.3 m/s))



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Images adapted from Mikellides et al., *Planetary and Space Science* 142 (2017) 53-68

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