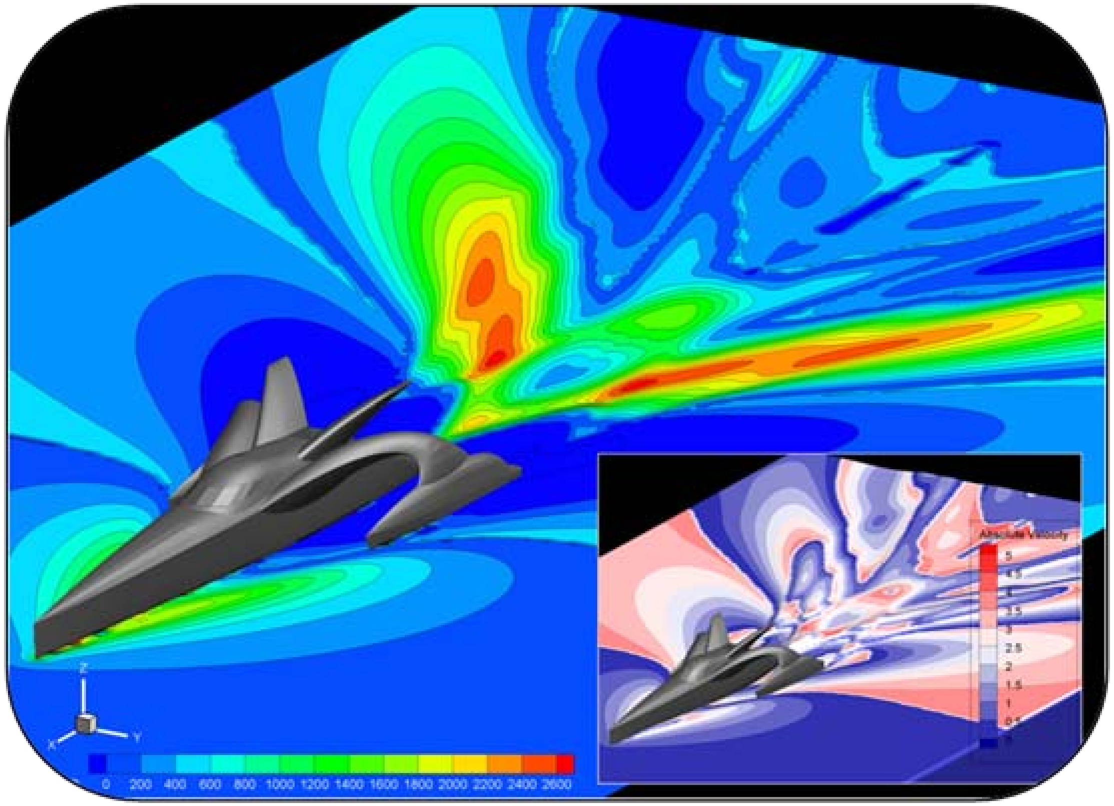
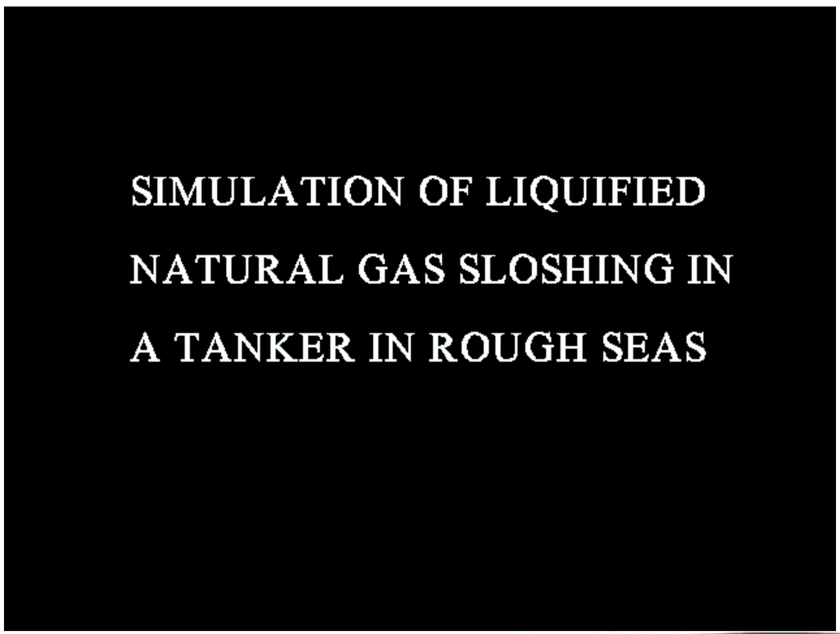
摇晃 和 稳定

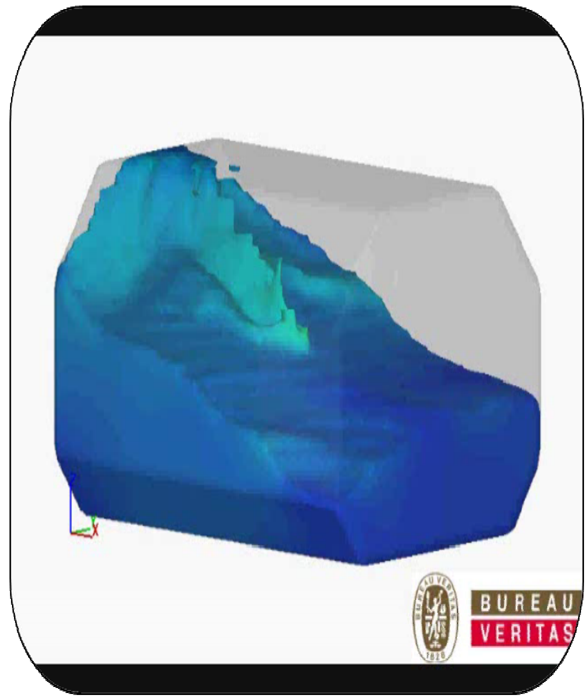

Z
Y
X
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600

装载摇晃动力分析(non-inertial frame)

在全球行驶的水面船舰其装载的摇晃是影响行驶稳定度的重要因素. 船舰会因波浪摇动船身产生可观的内部装载摇晃压力. 摇晃力对船体稳定及内部结构都会有影响.

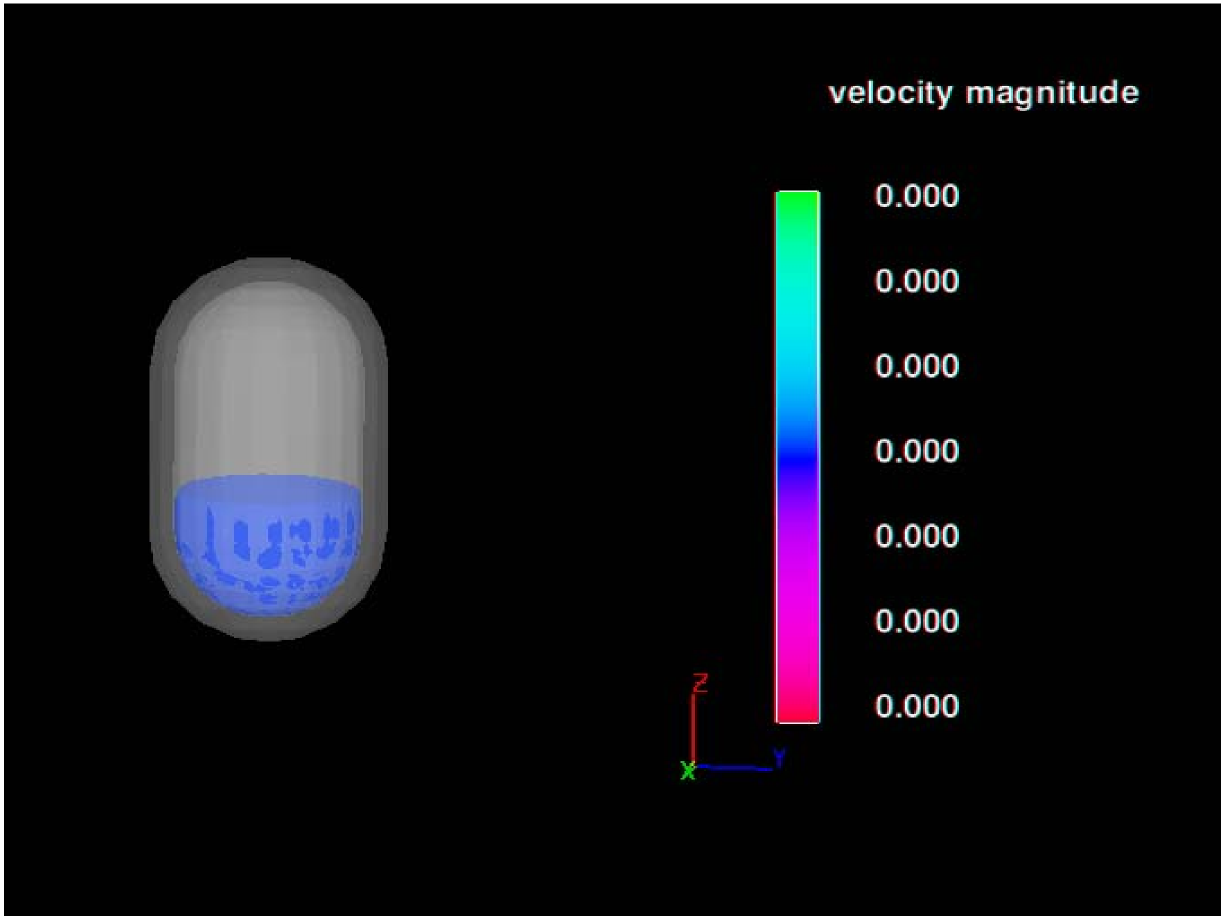
FLOW-3D 的非惯性面模组能够轻易的精准模拟复杂的运动以模拟装载液摇晃的动力分析.



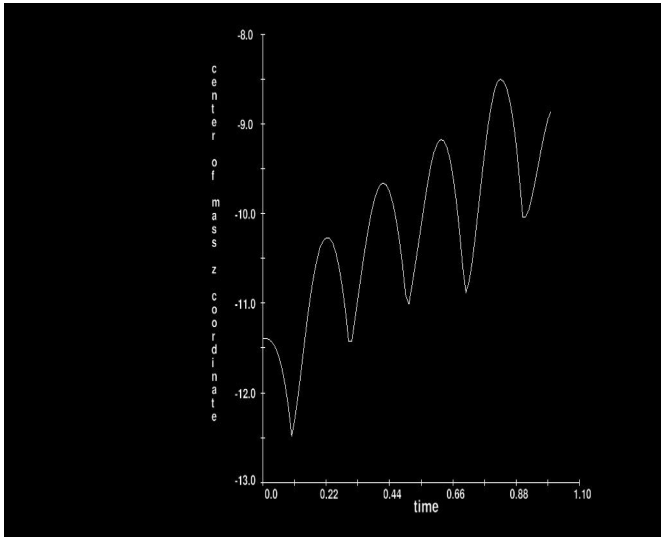


Sloshing animation courtesy of Bureau Veritas.

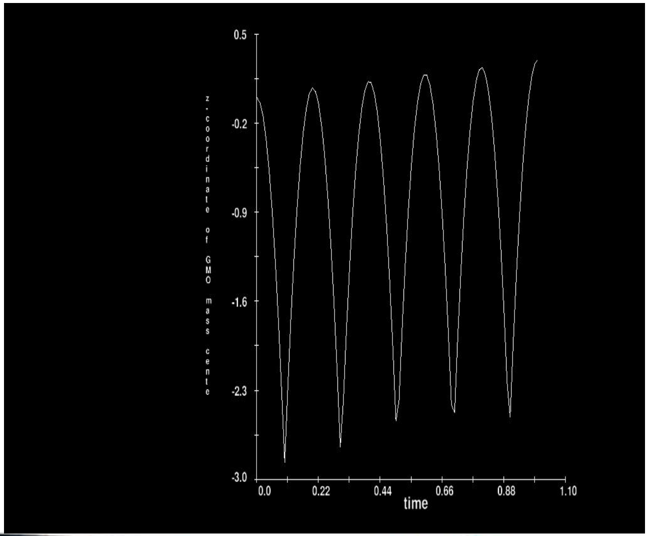
Sloshing with GMO (流固耦合)



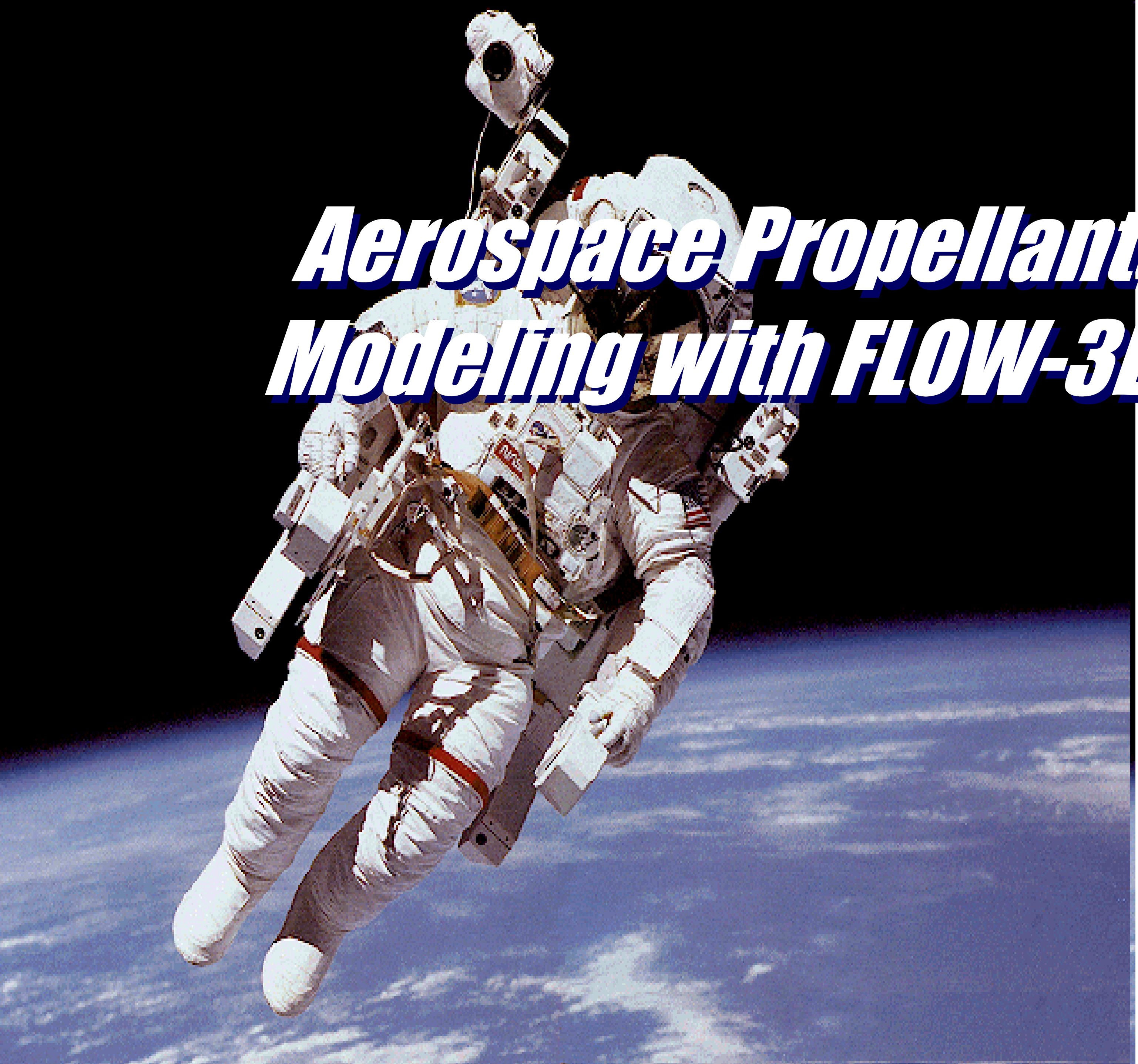
装载液重心曲线



载体重心曲线



Aerospace Propellant Modeling with FLOW-3D



Contents

- 推进燃料系统管理问题
- FLOW-3D 应用案例
- 结论

推进燃料系统管理问题

推进燃料系统管理问题

分为六类 ：

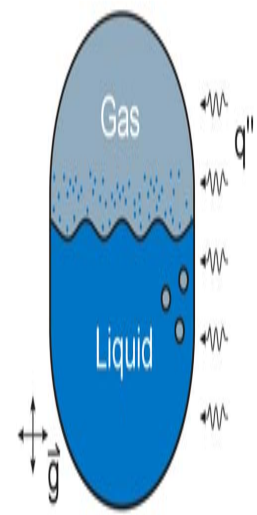
- **动力推升时的晃动**
  - 关注载具稳定的控制
  - 平缓的自由液面 及 可忽略的表面张力
  - 与地面情况相同的自然对流
  - 横向晃动波 及 环型档板
  - 适用摇摆晃动模型
- **低重力及严重晃动**
  - 关注载具稳定的控制
  - 产生严重晃动
  - 表面张力会影响液体位置
  - 阶段分离, 交会, 对接, 再入境, 与着陆动力学
- **旋转加速的晃动**
  - 关注载具稳定的控制
  - 旋转时的稳定控制
  - 热控转动
  - 粘性边界层效应
- **液体燃料的供应**
  - 关注液态燃料控制
  - 防止漩涡及抑制气化燃料的进入
  - 毛细液体的取用
  - 質譜測量與水平的遙感
  - 高 低重力环境
- **阀及管道内的流动**
  - 阀内流动状况及压降
  - 空化
  - 瞬态流動力学
  - 监控屏幕
- **热效应**
  - 关注压力控制及热动力
  - 低溫蒸發和变化性加熱及加速環境的增压
  - 液體和氣體的熱分層
  - 热致动效应
  - 損耗崩潰
  - CFM 硬件 (TVS, spray bar, jet mixers)

此报告的重点

低温流体模型

低温流体模型需具备几项特性以精准表现其热动力及流体动力行为.

- 同时解决液相及气相的控制方程式
- 各流体和储槽间的热传
- 浮力效应
- 变动的外部加热及加速
- 低重力下的表面张力效应
- 在不可凝结组件内的多种损耗性气体
- 介面动力及晃动分析
- 热动力流通系统次模型



General Cryogenic Tank Schematic

FLOW-3D has all of these required features for multiphase cryogenic CFD.

以CFD-为依据的低温系统设计

计算流体动力分析为低温流体系统提供许多利基. 然而, 著手设计前要仔细的量化验证.

- 减少或消除地面测试
- 减少或消除太空实验
- 提升太空设计 的执行
  - 使用实尺寸的流体及环境; 不会有动态缩尺测试的误差
  - 快速评估设计 及 参数的特徵化
  - 可降低各种为促进安全的假设方案评估的成本
- 降低设计周期及生命周期成本
- 比以实验为依据的方法提供更多负担得起的太空探测计画

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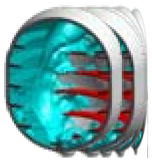
vs.



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Many CFD simulations can be run for less than the cost of a physical test

CFD-based cryogenic design processes, once validated, lead to both lower cost & higher performing space hardware.

所需太空计划

NASA 的太空探测计画是一直使用低温推进燃料系统于地面出发，著陆 及 升空.

- **液态氢 (LH_2) 液态氧 (LO_2), & 液态甲烷 (LCH_4) 流体**
- **低温流体管理系统需控制压力及温度.**
- **贮存期可达6个月.**
- **太空中微重力环境 (1E-7 g to 1E-2 g)**
- **在月球(0.17 g)或火星 (0.38 g) 的少重力状态**

NASA's LSAM Concept

NASA's Ares V Earth Departure Stage Concept

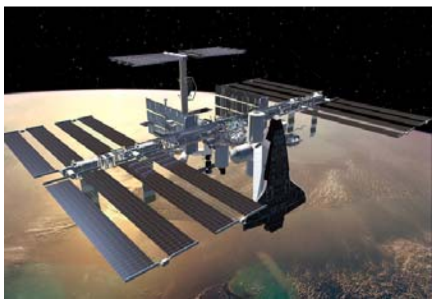
Accurate cryogenic modeling tools will aid development of NASA's space vehicles.

FLOW-3D Application Examples

部分波音公司计画及飞行载具是以 FLOW-3D 协助及支持

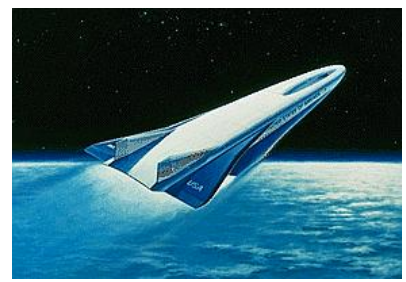
FLOW-3D 已有很长的历史在支持成功的飞行载具及计画上. 波音公司使用已超过 20 年.

Delta II


Space Station


Delta IV


Space Shuttle

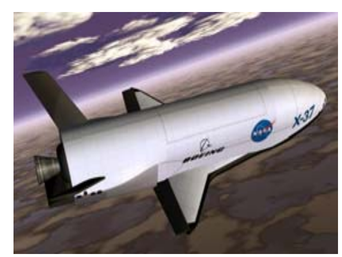

NASP

DC-X Lander


Commercial Aircraft



Commercial Satellites



X-37

FLOW-3D

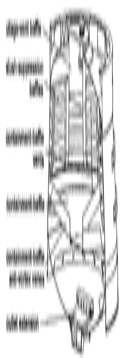
Sloshing & Stability

Example 1: DC-X Liquid Oxygen Slosh (1992)

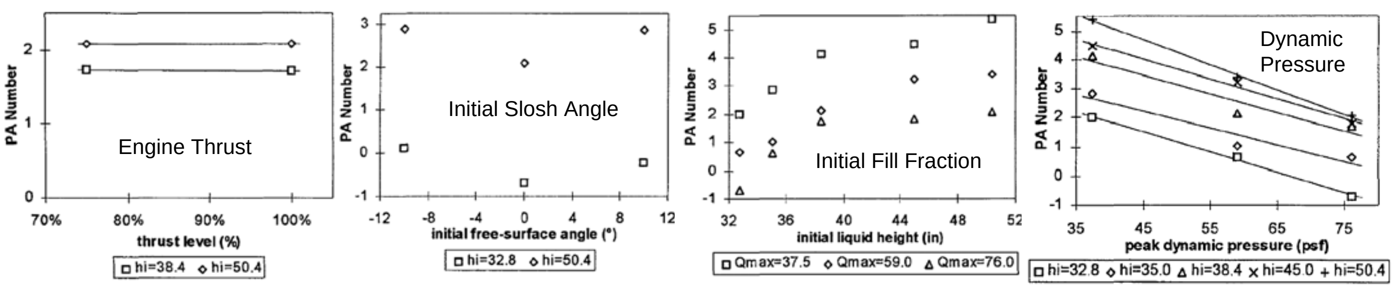
The DC-X 旋转运动推进燃料供应系统 的设计只是以 CFD 及 基本的工程原理.

- **FLOW-3D-为基础的 Navier-Stokes solver 暨源自Delta II & NASP的资料**
- **快速评估各种方案参数**
- **高精准 6-自由度晃动模拟**
- **减少或消除推进实验**

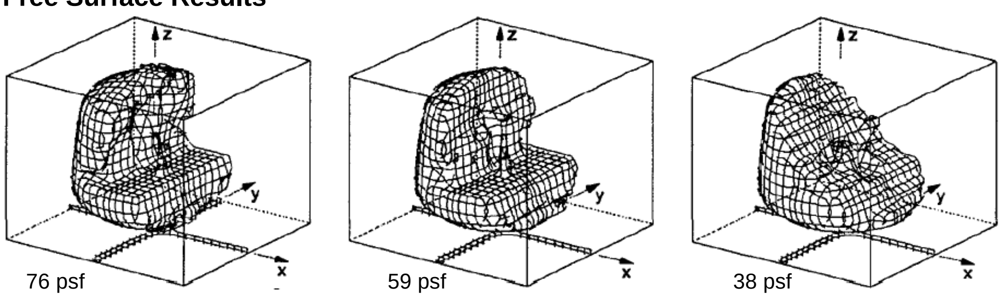
LO2 Tank Internal Design



Parametric Design Evaluation



Free Surface Results



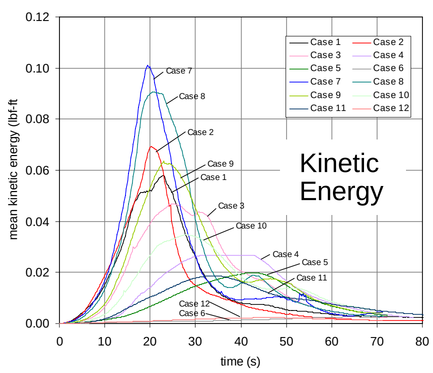
No testing was performed before successfully demonstrating the CFD-based design in flight in 1993

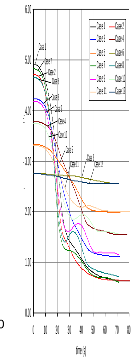
Reference: Grayson, G.D. and Cook, L.M., "Performance Characteristics of The DC-XA Liquid Oxygen Propellant Acquisition System," AIAA Paper 96-3081, July 1996.

Example 2: X-37 H2O2 Slosh (1999)

- **H2O2 于5英尺直径的隔层舱中的低重力晃动**
- **模拟各种任务方案以找出最差状况及最适设计**
- **及时的喷射推进决定于引擎重新启动前适当的推进燃料设定**

参数设计评估

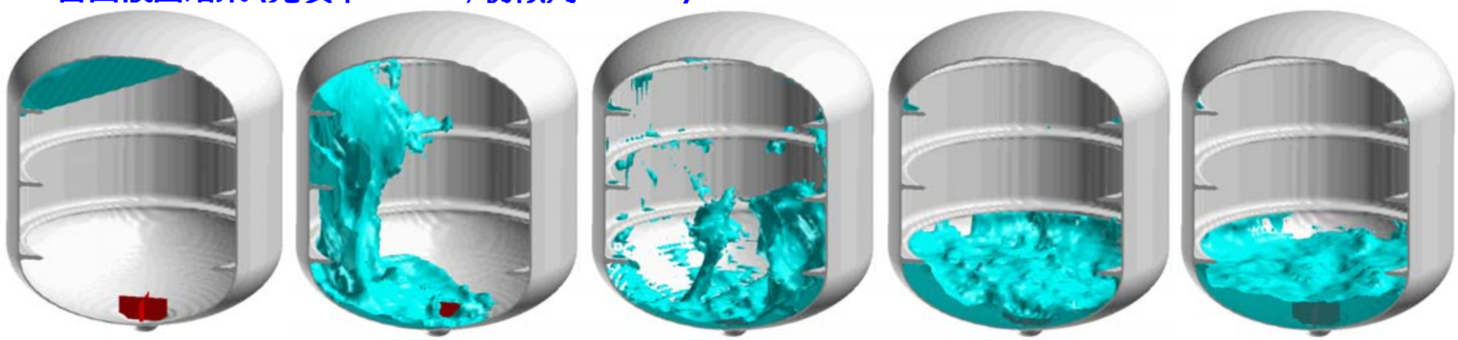




C.G.

自由液面结果 (充填率 = 10%, 初倾角 = 20°)

High Resolution Model



t=0 s t=20 s t=40 s t=60 s t=80 s

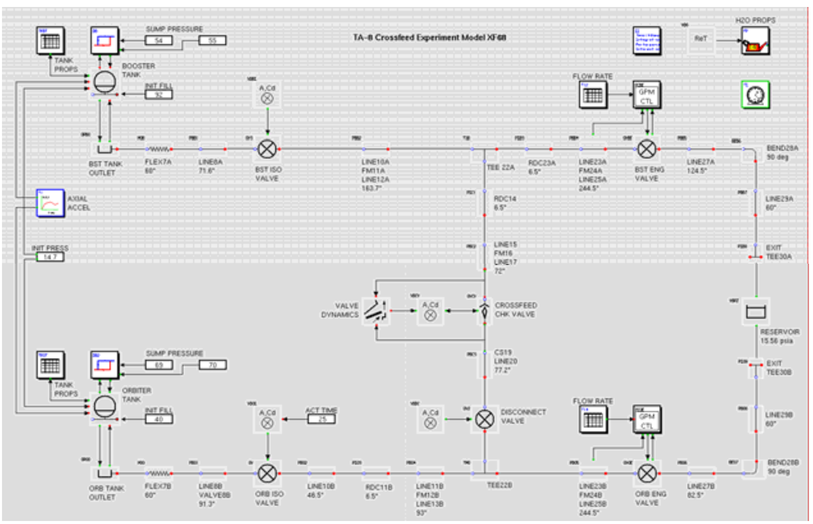
Consistent, parametric evaluations with validated CFD tools optimize space hardware designs without testing.

is used to

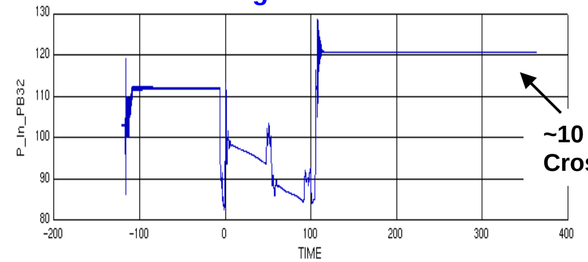
Example 3: Transient Flow Networks (2002)

- 瞬态流动网络问题是依据FLOW-3D的模拟数据以EASY5系统来解决.
- 依具 SLI & 777 数据模拟以解决water hammer 问题
- 第2代 RLV 的推进燃料交互供应系统以EASY5 模拟.

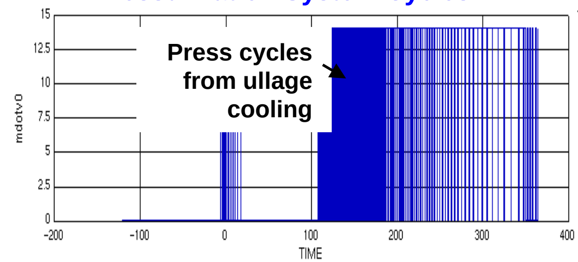
Model Schematic:



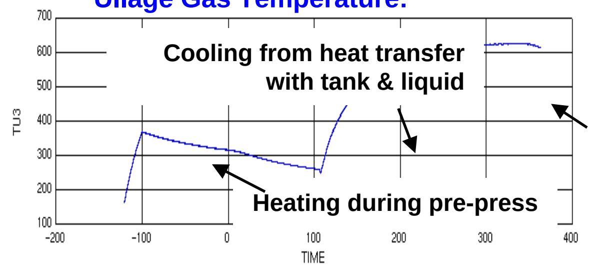
Pressure Surge at Check Valve:



Pressurization System Cycles:



Ullage Gas Temperature:



Water hammer in complex propellant systems is modeled accurately with combined EASY5 / FLOW-3D based transient flow network models.

Reference: Chandler, F.O., Grayson, G.D., and Mazurkivich, P., "The Importance of Detailed Component Simulations in the Feedsystem Development for a Two-Stage-to-Orbit Reusable Launch Vehicle," 41st AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, Paper 2005-4370, Tucson, Arizona, July 2005.

MHTB LN2 Tank Pressurization in Normal Gravity Operations Sequence (for Example 4)

模拟及物理实验都按照如下的相同操作程序.

1. ***初始条件***: **粗略的增压阶段,依据量测数据,找出精准的模拟所需的初始条件**
2. ***增压***: **在喷雾前, 燃料舱因为外部受热而产生的自我增压**
3. ***TVS 喷雾***: **TVS 喷雾杆作动以混合, 冷却, 及减压流体**
4. ***再增压***: **喷雾杆作动完后再自我增压**

Initial Condition	Pressurization	TVS Spray	Repressurization

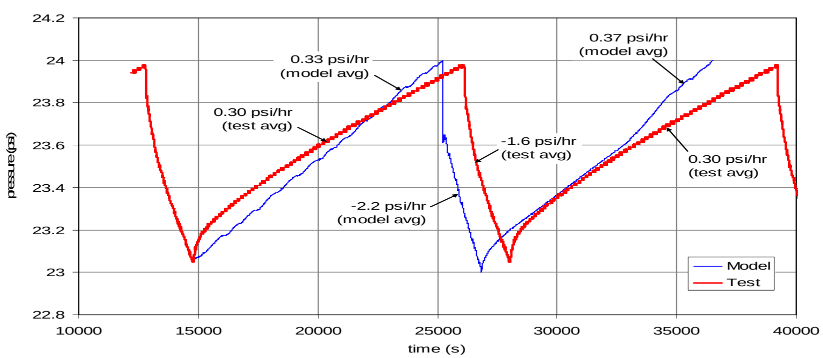
time →

Reference: Grayson, G.D., et al, "CFD Modeling of Helium Pressurant Effects on Cryogenic Tank Pressure Rise Rates in Normal Gravity," 43rd AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, Paper 2007-5524, Cincinnati, Ohio, July 2007.

Example 4: MHTB LN2 Tank Pressurization in Normal Gravity (2005)

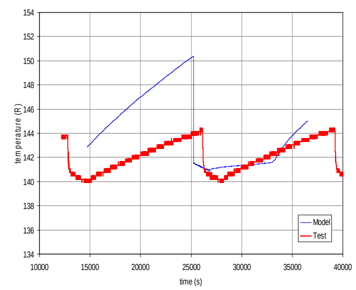
- 10 英尺直径 NASA MHTB 燃料舱
- LN2 以 He 加压的测试数据
- 估算热漏(heat leak)的边界条件

Pressure History

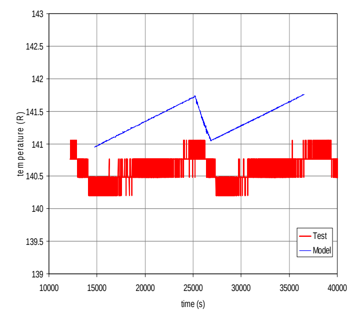


N2 pressurization rate predicted to within 10% for the first pressurization cycle and within 23% for the second cycle.

Gas Temperature History



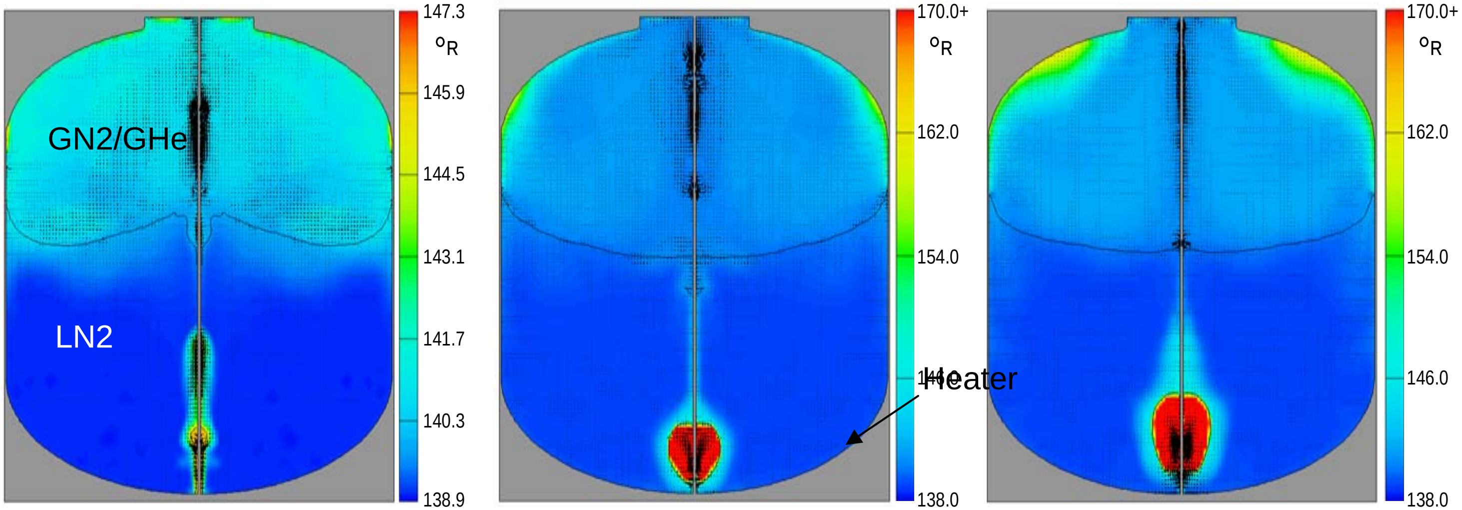
Liquid Temperature History



Reference: Grayson, G.D., et al, "CFD Modeling of Helium Pressurant Effects on Cryogenic Tank Pressure Rise Rates in Normal Gravity," 43rd AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, Paper 2007-5524, Cincinnati, Ohio, July 2007.

Example 5: MHTB LN2 Tank Pressurization in Low Gravity (2005)

温度分布及速度向量



a) t = 1280 s, Vmax = 0.14 ft/s
b) t = 2300 s, Vmax = 0.094 ft/s
c) t = 3160 s, Vmax = 0.085 ft/s

- 一个氧气气泡瞬间在加热器周围产生.
- 最初浮力促使气泡分离并快速上升扰动自由液面.

- 加热器周围气泡变得稳定并随时间变大
- 低重力加速 1E-5 g 不足以将气泡剥离

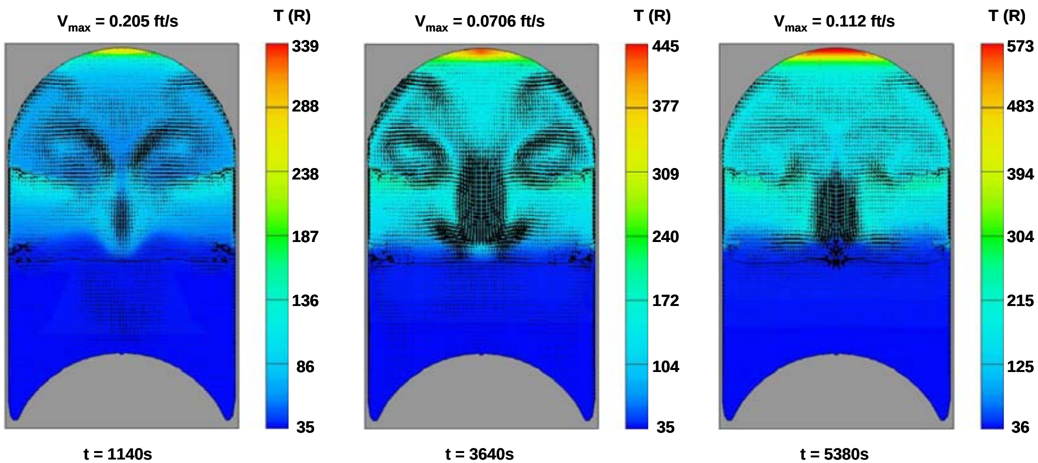
- 经过3160 秒 气泡仍持续变大.
- 有明显的热羽流(thermal plume)在气泡和加热器间产生.

The validated modeling techniques are applied to on-orbit conditions to estimate cryogenic space tank behavior.

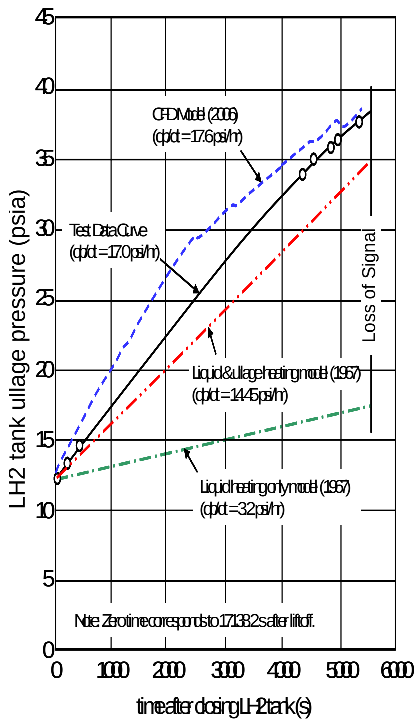
Reference: Grayson, G.D., “Low-Gravity Modeling of Cryogenic Spray Bar Tanks,” 2007 Space Cryogenics Workshop, Huntsville, Alabama, July 2007.

Example 6: S-IVB AS-203 Flight Experiment (2006)

- **S-IVB AS-203 LH2 实验 (1966) 以最近发展的多相流功能来模拟.**
- **增压预测误差小于 3.5%; 温度损耗预测小于6%.**
- **低重力下自然对流被证明对于大的低温舱有很大影响.**



Tank Pressure History Comparison

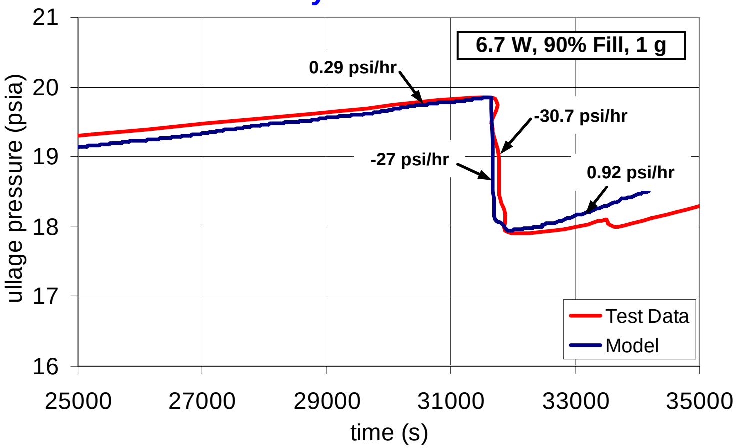


Confidence is gained in our cryogenic tank modeling techniques by experimental validation using Saturn S-IVB flight data.

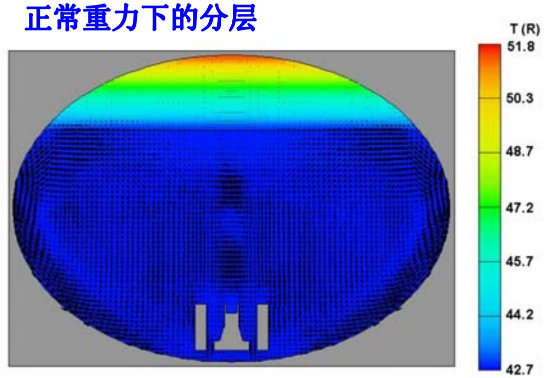
Example 7: STUSTD LH2 Tank Pressurization (2006)

- 71 立方英尺. 椭圆舱
- LH2 及 GH2 损耗
- 轴向喷射 TVS
- 1-g 下测试 及 低重力预测

Pressure History

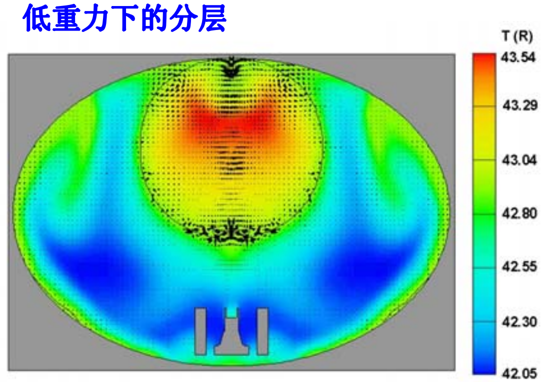


正常重力下的分层

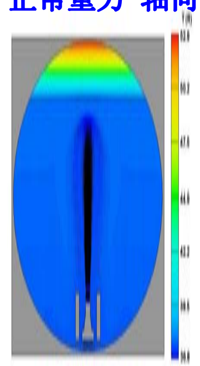


STUSTD 测试仪

低重力下的分层



正常重力 轴向喷射 TVS 操作



Predicted LH2 tank pressurization and TVS depressurization rates agree well with the STUSTD test data.

Reference: Lopez, A., Grayson, G., Chandler, F., Hastings, L. & Hedayat, A., “Cryogenic Pressure Control Modeling for Ellipsoidal Space Tanks in Reduced Gravity,” 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Paper 2008-5104, Hartford, CT, July 21-23, 2008.

Boeing's conclusions

- Considerable work has been done to develop accurate CFD tools for propellant modeling.
- Quantitative verification of FLOW-3D based models results has been achieved in many cases over the last 20 years.
- These validated modeling approaches continue to be used for flight vehicle design today.

We greatly thank Flow Science for the dedicated support to make a CFD-based design process possible for cryogenic fluid systems in aerospace.

Contact Us

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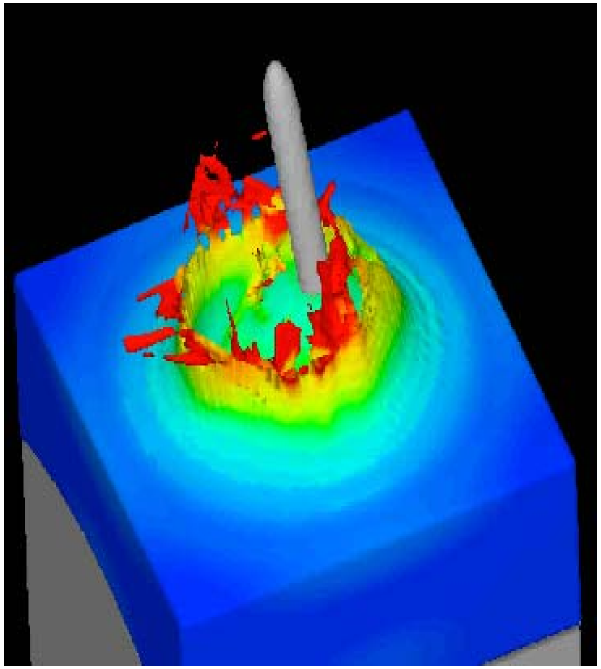
Phone: 021-31260876



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