HPC FOR NUCLEAR STOCKPILE STEWARDSHIP

CS 455

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INTRODUCTION

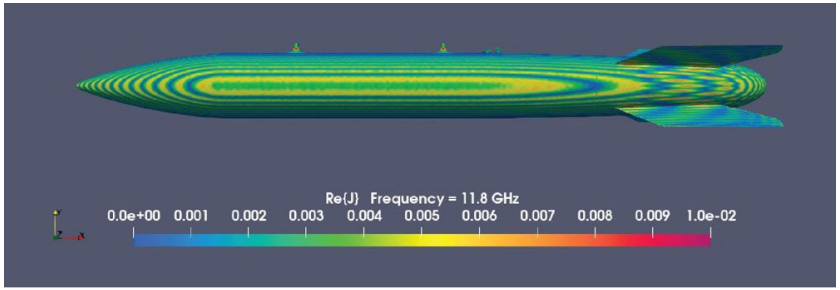
- National Defense Authorization Act 1994 - Nuclear stockpile stewardship program started
- Maintain nuclear weapons' safety, security, and reliability without conducting physical tests
- Predicting and detecting problems by analyzing the effects of changes on warhead safety and performance

Stockpile Stewardship Program. Nevada National Security Site (NNSS). URL: https://nnss.gov/mission /stockpile-stewardship-program/

FULL 3-D SIMULATIONS

To model entire weapon systems to assess performance under detonation conditions

ASCI White machine : IBM's commercial **512 node** computer cluster - **8,192 processors**, **6TB Memory**, **160TB Storage**, consumed 3 MW of electricity, theoretical processing speed of **12.3 teraFLOPS**

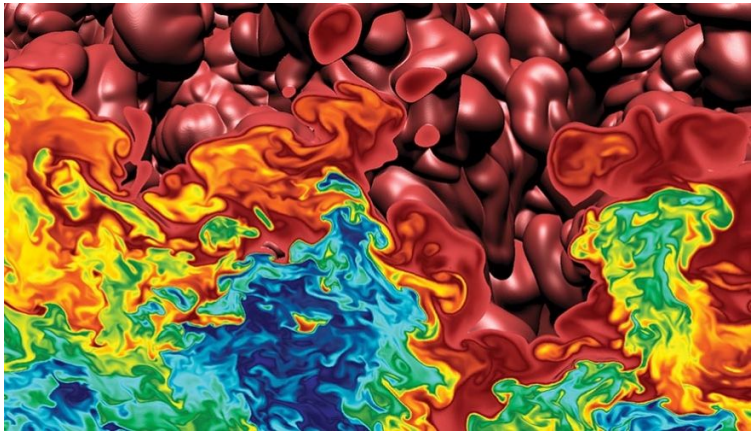


Simulation of an 11.8 GHz current on the exterior of a virtual mesh object (the entry points and internal components are omitted from this simulation) (Image: Sandia National Laboratories)

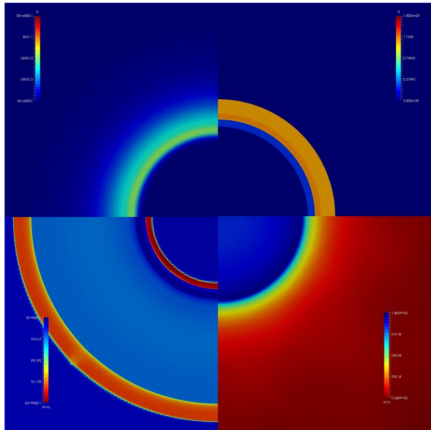
Lawrence Livermore National Laboratory and Los Alamos National Laboratory. Livermore, Los Alamos labs complete first 3-D simulation of full-system nuclear weapon. 2002. URL: https://www.llnl.gov/article/28761/livermore-los-alamos-labs-complete-first-3-d-simulation-full-system-nuclear-weapon

MULTI-PHYSICS MODELLING

Combines hydrodynamics, plasma physics, and material behavior under extreme conditions



BlueGene/L simulation of turbulent thermonuclear burning in a type Ia supernova.

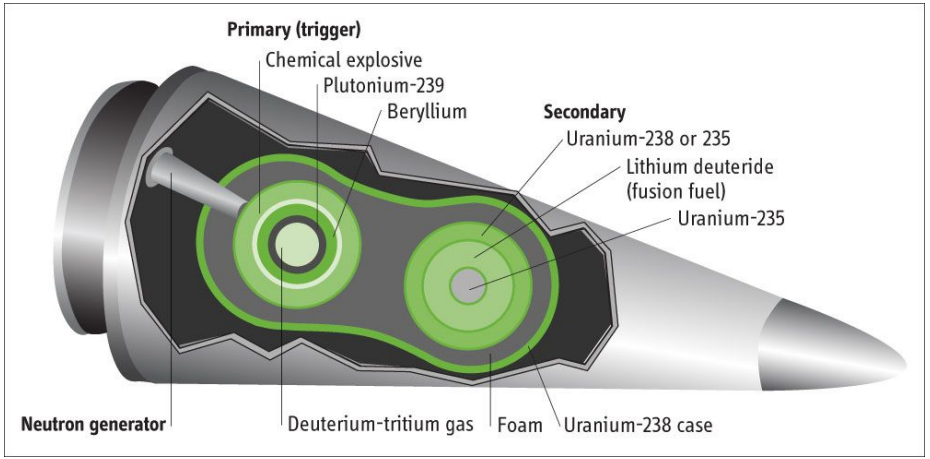


Upper right panel: a simplified inertial confinement fusion capsule as the simulation begins; 1.5 nanoseconds later (lower right), radiation energy impinges on the capsule, heating its material; the dense shell of the capsule (upper left) responds to this heating by expanding, with its inner edge moving inward and its outer edge outward; the capsule material's expansion causes either side of the expanding shell (lower left) to heat. (Image: Los Alamos National Laboratory.)

Aimee Hungerford and Ben Bergen, Multiphysics for the Masses, 2018, URL: https://deixismagazine.org/2018/11/multiphysics-for-the-masses/amp/

MATERIAL AGING STUDIES

Predict degradation of components using experimental data and simulations



EVOLUTION OF SUPERCOMPUTERS

RoadRunner (2008, 1 petaFLOP) and **BlueGene/L (2004, 280 TFlops)** enabled foundational 3D modeling of nuclear explosions.

EVOLUTION OF SUPERCOMPUTERS

Sequoia (20 petaFLOPS) and **Trinity (42 petaFLOPS)** supported higher-resolution studies of aging weapons.

EVOLUTION OF SUPERCOMPUTERS

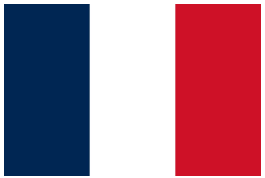
1.742 exaFLOPS (peak: 2.79 exaFLOPS), **El Capitan** is the world's fastest supercomputer as of 2025. Designed for the NNSA's Stockpile Stewardship Program, it enables high-resolution 3D simulations of nuclear weapon performance, aging effects, and modernization efforts.

COMPARATIVE ANALYSIS OF SIMULATION APPROACHES

United Kingdom

UK employs 3D modeling and hydrodynamics experiments (e.g., DARHT) to validate simulations. Relies on legacy nuclear test data and Focuses on warhead aging studies and modernization of the Trident system using HPC.

France



France uses robust device designs validated through reinterpretation of historical nuclear tests. Simulations focus on weaponization processes and aging effects, supplemented by experiments at laser facilities.

China

China conducts scenario-specific simulations, such as modeling high-altitude nuclear detonations (e.g.,radioactive cloud effects on satellites).

FUTURE DIRECTIONS - AI/ML INTEGRATION

- Cognitive simulation: Predicting material behavior under extreme conditions.
- Predictive maintenance: AI analyzes sensor data to reduce unscheduled downtime.
- Anomaly detection: Machine learning identifies aging trends in W80 battery efficiency.
- Workflow optimization: Cerebras' Wafer-Scale Engine accelerates AI/ML tasks in multi-physics simulations, improving throughput by 40x.

FUTURE DIRECTIONS - QUANTUM COMPUTING

- Sandia and Google solved specific neutron transport problems, in hours what classical systems require weeks to compute.
- LLNL's quantum algorithm simulates nuclear reaction rates (e.g., plutonium-240 decay) with 99.5% fidelity, addressing data gaps for aging studies.

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