Nuclear Criticality Safety Pioneer Panel: Lawrence Livermore National Laboratory History

Presented at the American Nuclear Society Summer Meeting
NCS Pioneers Panel Session
June 2017

LLNL-PRES-

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Lawrence Livermore National Laboratory

Panel Discussion Topics

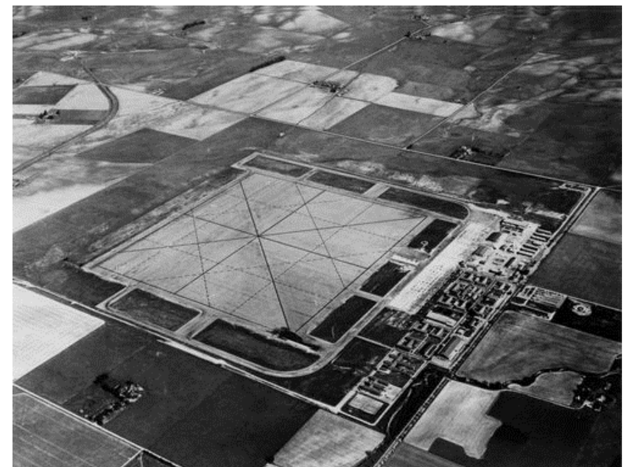
- Overview of Critical Experiment Programs and Reactors
- 1963 Criticality Accident
- Historical Perspective of Criticality Calculations
- History of the Nuclear Criticality Safety Office/Group/Division at LLNL

LLNL Criticality Experiments

- From 1952-late 1970's, LLNL performed thousands of critical and high-multiplication experiments
- Mainly supporting the weapons program, so many are classified
- 153 LLNL experimental configurations are included in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook

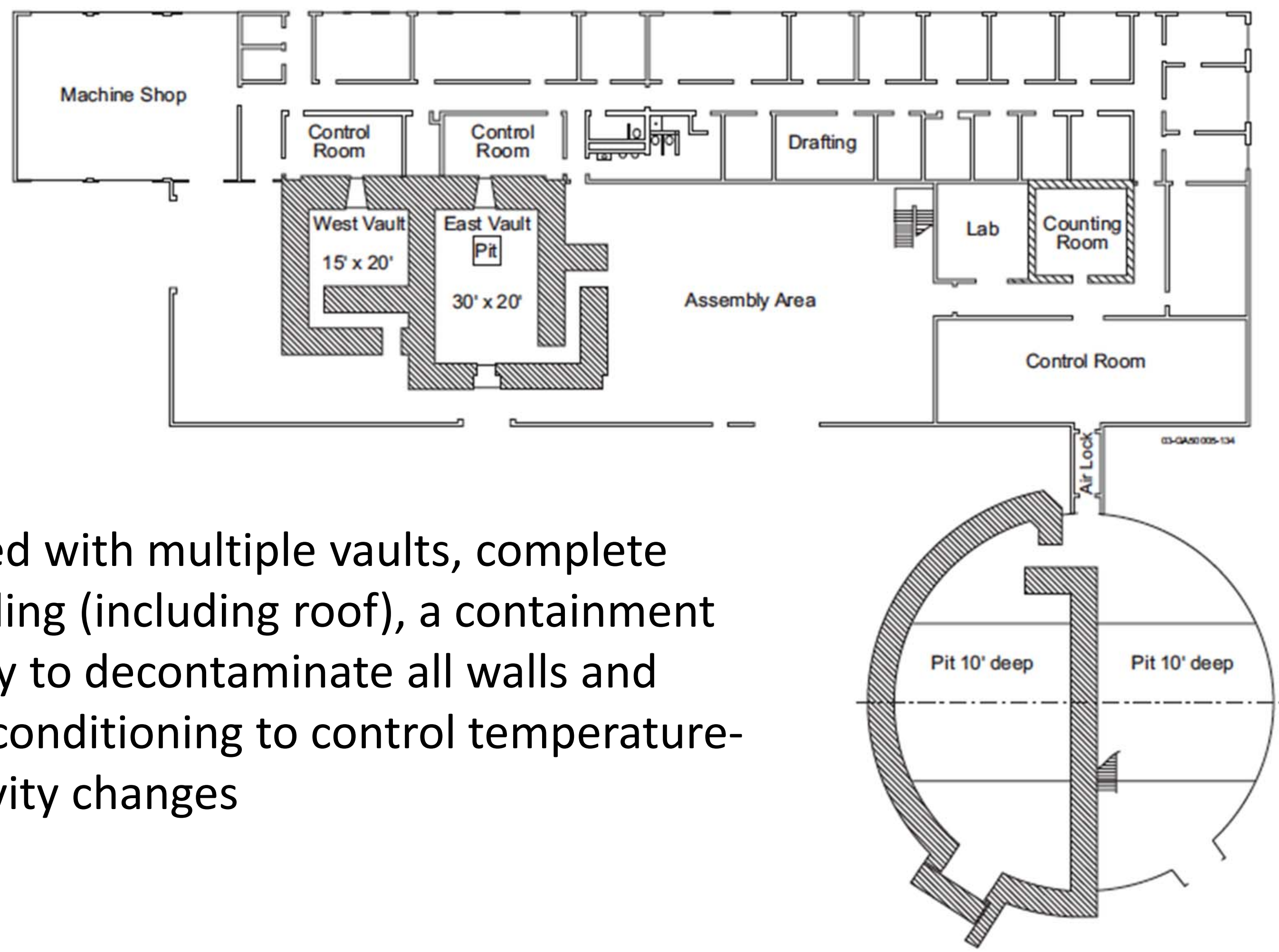
Early Experiments

- September 2, 1952- the first team of scientists and engineers arrived at the abandoned Livermore Naval Air Station
- First sub-critical experiments made in late 1952
  - Experiments conducted in a co-opted men's showering room
  - Most likely in the Bachelor Officer's Quarters
- In late 1952-1953
  - Some assemblies made in a shielded vault
  - Other assemblies made in an isolated area of the site with a remote control room located 1000 feet away



Courtesy of the Livermore Heritage Guild

New Critical Facility Purpose-Built in 1954



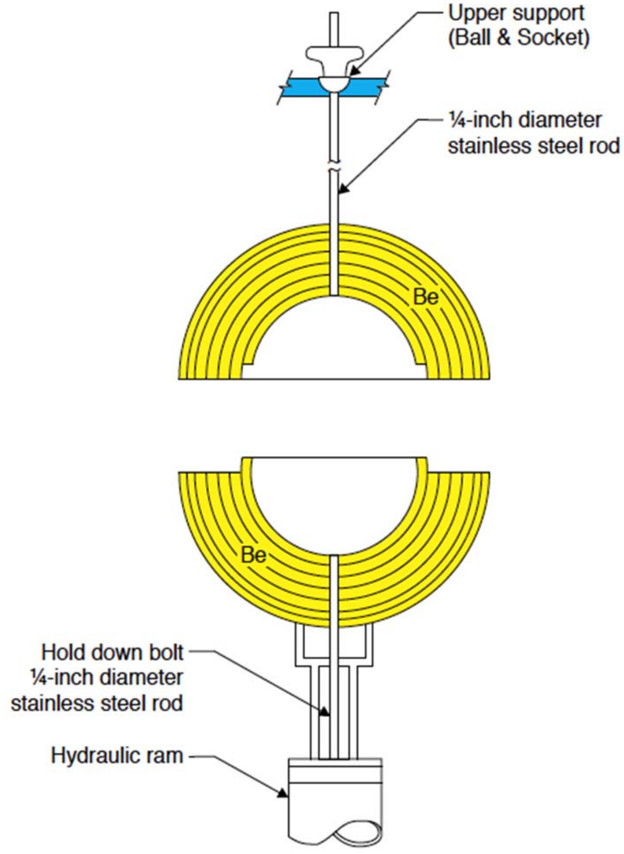
- Facility designed with multiple vaults, complete concrete shielding (including roof), a containment shell, the ability to decontaminate all walls and floors, and air conditioning to control temperature-induced reactivity changes

Nimbus Program

- 1958-1959 Experiments to determine the critical mass of HEU in spherical geometry as a function of reflector thickness
- Used a set of unclad HEU nesting shells and the Nimbus Vertical Lift Machine
- Evaluated by D. Heinrichs as HEU-MET-FAST-058 (Beryllium reflector)
- Eight of the Nimbus shells are currently in use in Hands-on Training as part of the TACS assembly

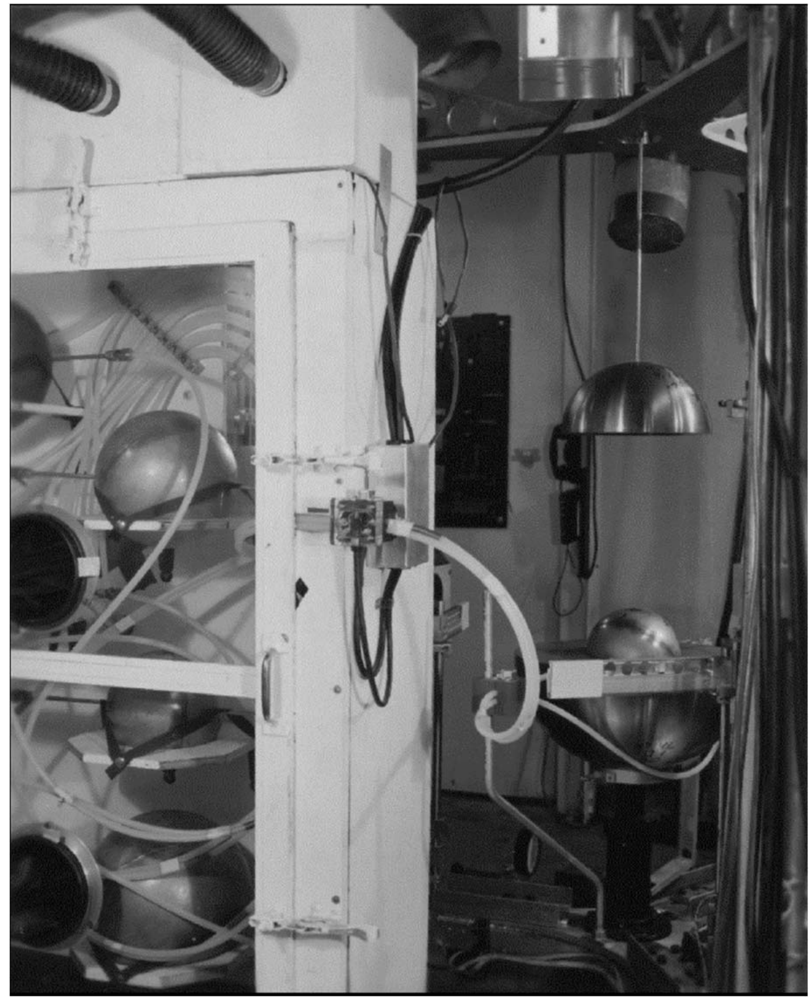
Medusa Program- Late 1950's

- Composite cores of plutonium and HEU surrounded by beryllium metal reflectors
- Used the Nimbus Vertical Lift Machine
- 23 mixed cores evaluated by R. Brewer as MIX-MET-FAST-007

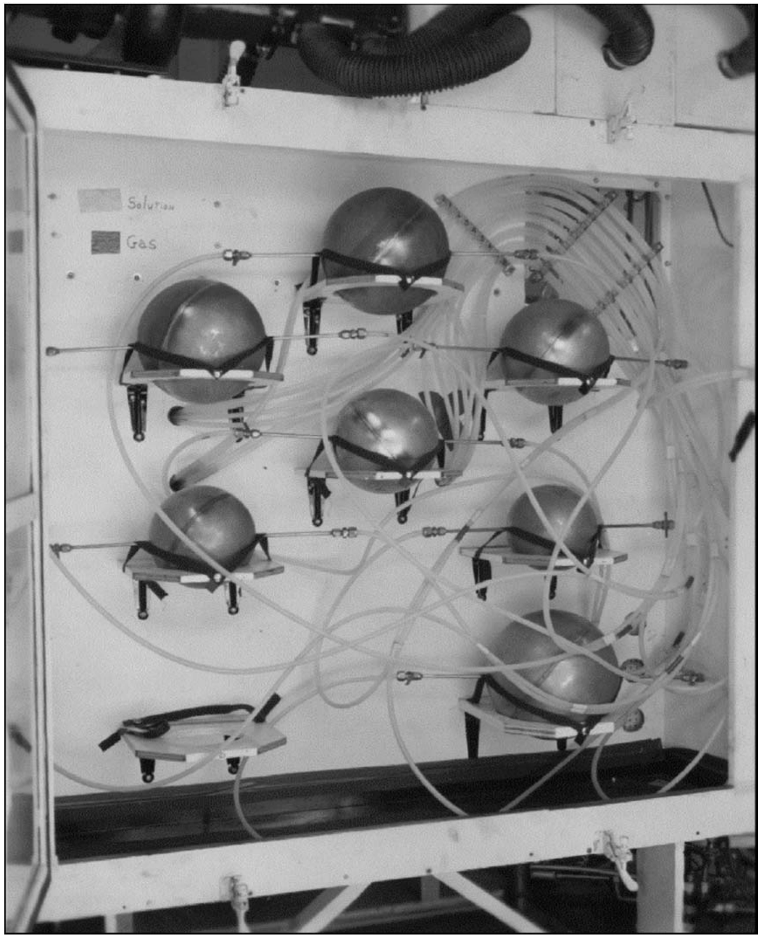


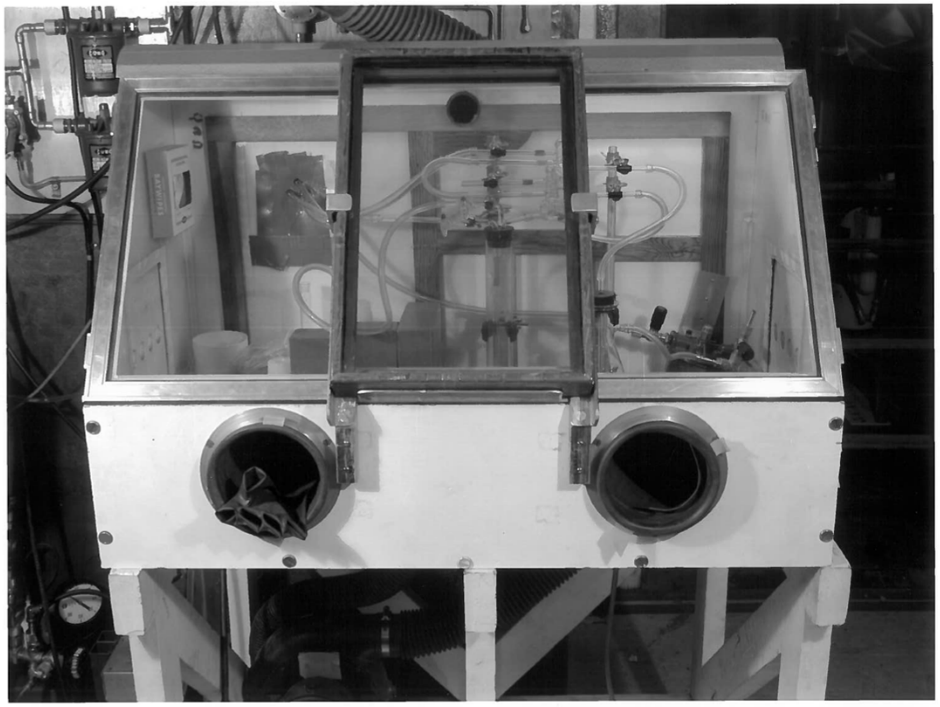
Falstaff Program Late 1950's

- Series of spherical critical experiments with Aqueous solutions of ^{233}U in the form of UO_2F_2 stabilized with 0.3% by weight of HF
- Stainless steel spherical vessels with radii of 7.87 to 12.45 cm with Be, CH_2, and composite reflectors
- Evaluated by D. Heinrichs as U233-SOL-THERM-011 and THERM-015 and U233-SOL-INTER-001
- Only source of intermediate 233U experiments and achieved lowest measured critical masses for ^{233}U



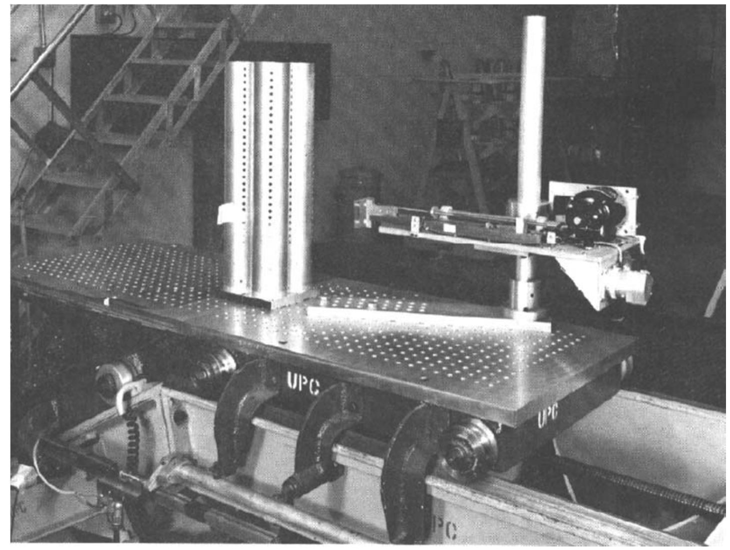
Falstaff Program Pictures

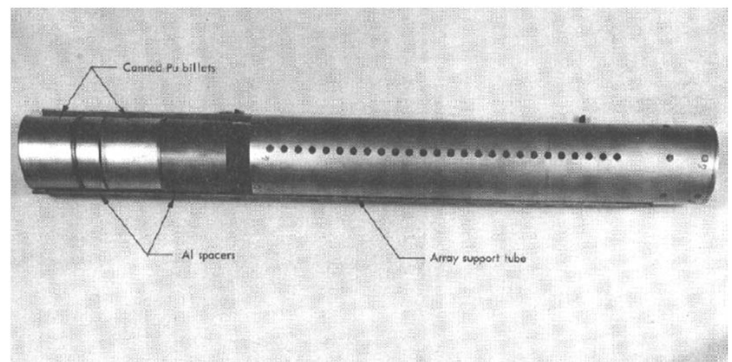




Plutonium Array Program

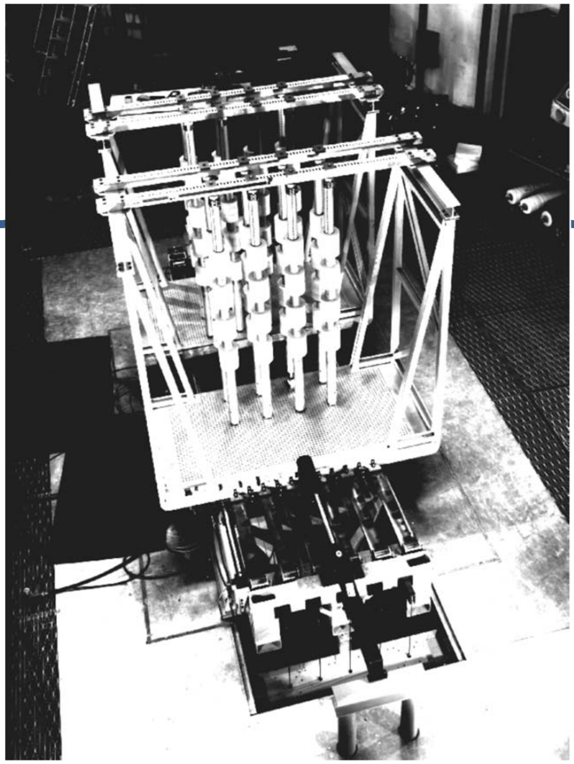
- Initiated in support of weapons program and code benchmarking
- 3 and 6 kg alpha Pu buttons arranged in close proximity for safe handling and storage arrangements
- Phase I started in 1964 and used the small horizontal split-table assembly located in the C-Vault of the criticality facility
- Evaluated by F. Trumble as PU-MET-FAST-003

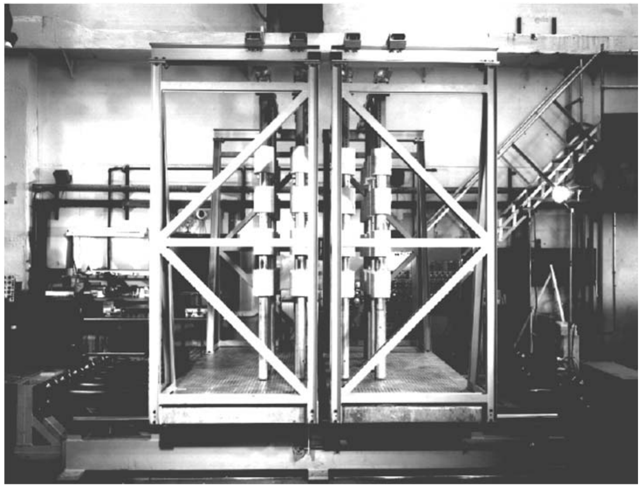




Plutonium Array Program

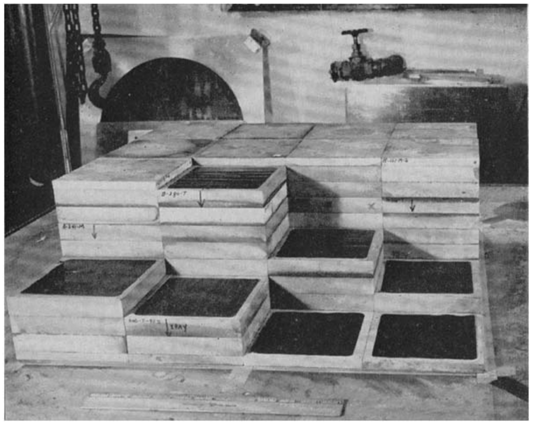
- Phase II used a much larger horizontal split table assembly machine for studies on much larger arrays
- Unmoderated button arrays, evaluated by J. Justice and F. Trumble as PU-MET-FAST-004
- Arrays moderated by mock high explosive, evaluated by J. Justice and F. Trumble as PU-MET-FAST-017
- Data from these experiments were used to design a new high-capacity vault for button storage at Hanford

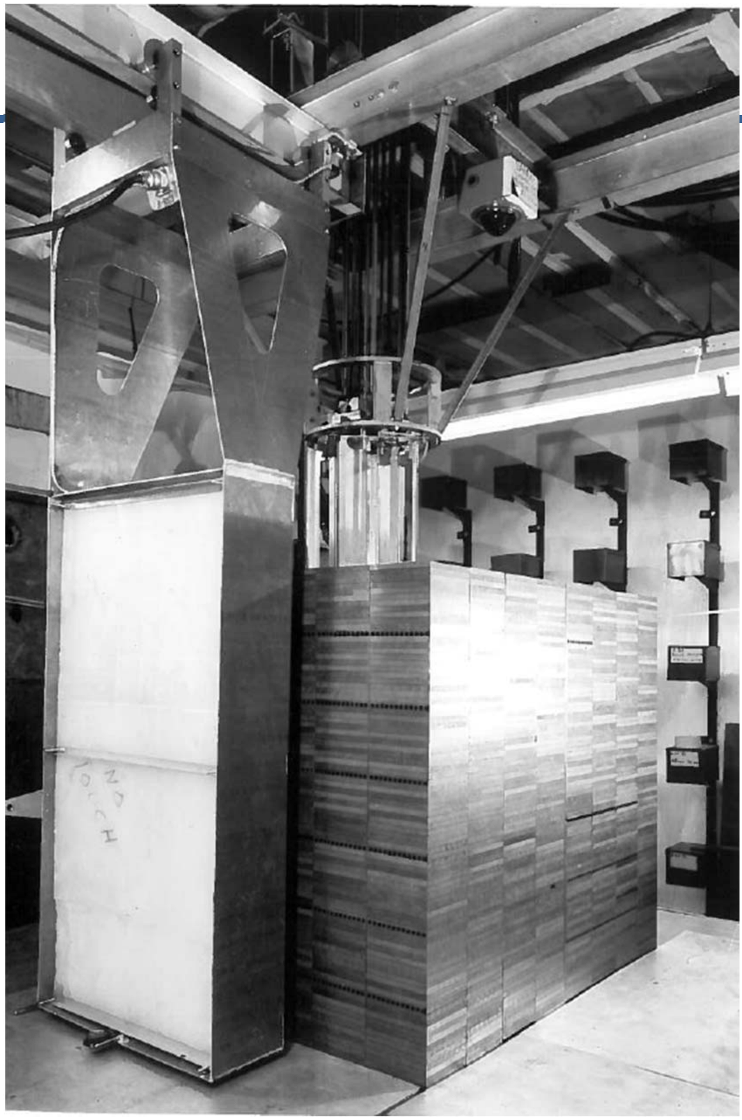




Uranium Foil Assemblies

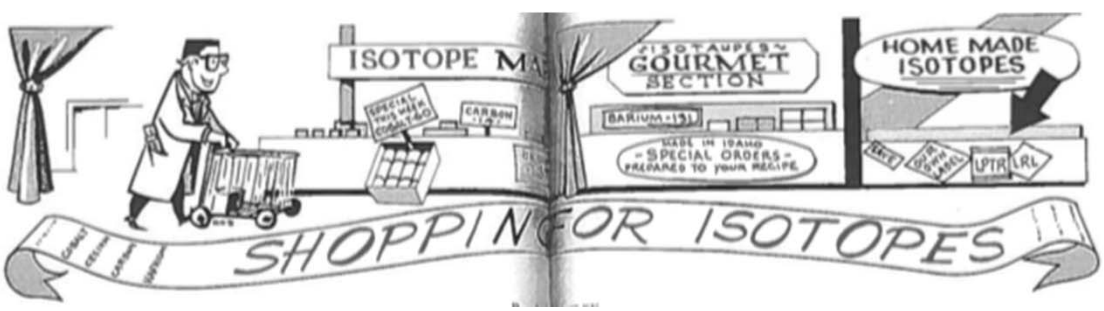
- HEU foils, 0.002” thick, 5.25” square, 16.15 g ^{235}U
- Puppy- D_2O moderation
- Spade- BeO/Be experiments conducted for space propulsion
- Snoopy- Graphite

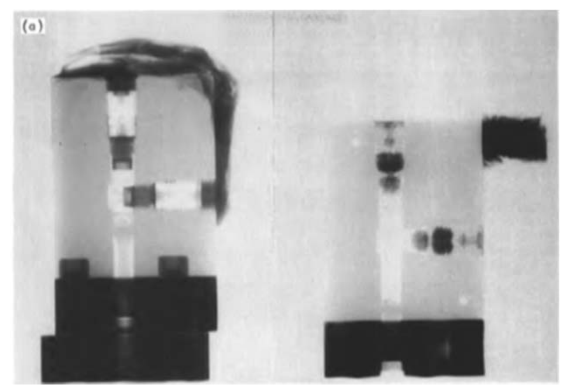




Livermore Pool Type Reactor (LPTR)

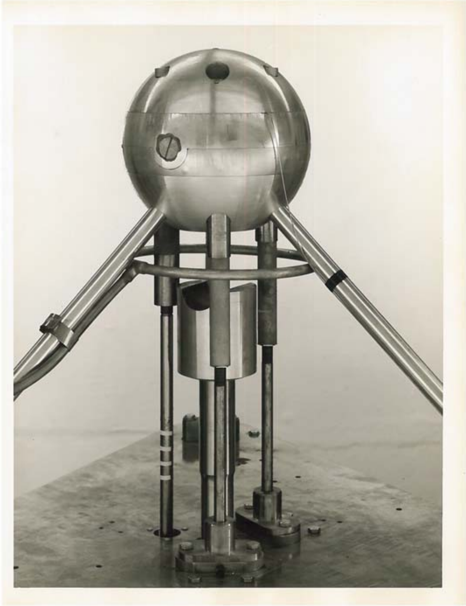
- Designed as a high-flux research reactor facility
- Materials Test Reactor type, 1 MW, later increased to 3 MW
- First critical on December 13, 1957, decommissioned in 1980
- 6 beam tubes, irradiation wells, neutron radiography facility, neutron activation for trace element analysis and isotope generation

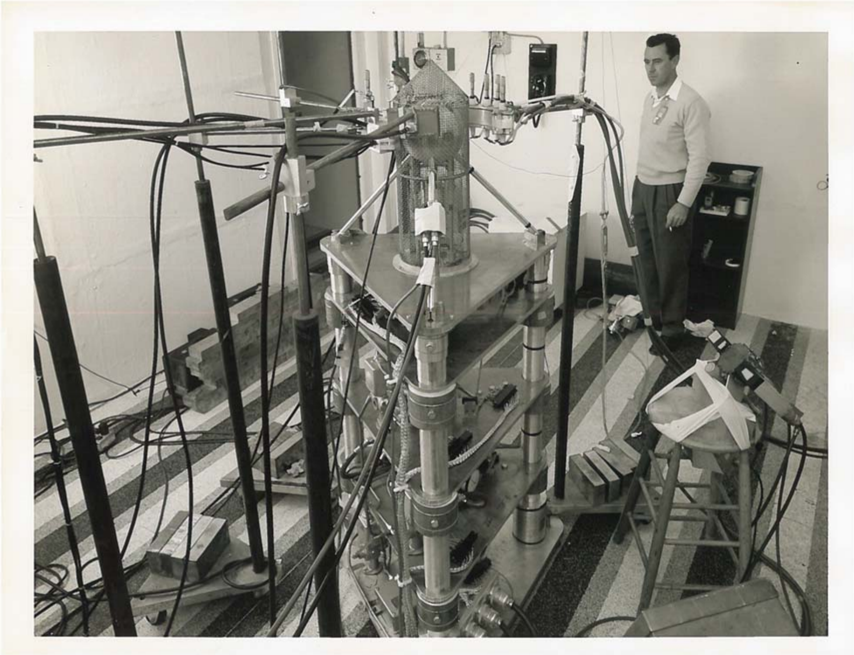




Kukla Reactor

- Located at the Livermore Critical Facility
- Sphere of 55 kg HEU
- Maximum burst yield of $2x10^6$ fissions
- Popular source of neutrons for radiation damage experiments
- All samples irradiated externally
- Need for larger neutron sources lead to Fran and Super Kukla reactors, both built at the Nevada Test Site





Nevada Test Site (NTS) Facilities

Fran Burst Reactor- 1962-1965

- Operated at NTS
- 63 kg of Oralloy (93.5% U235) in a cylindrical assembly with an internal annular void for samples

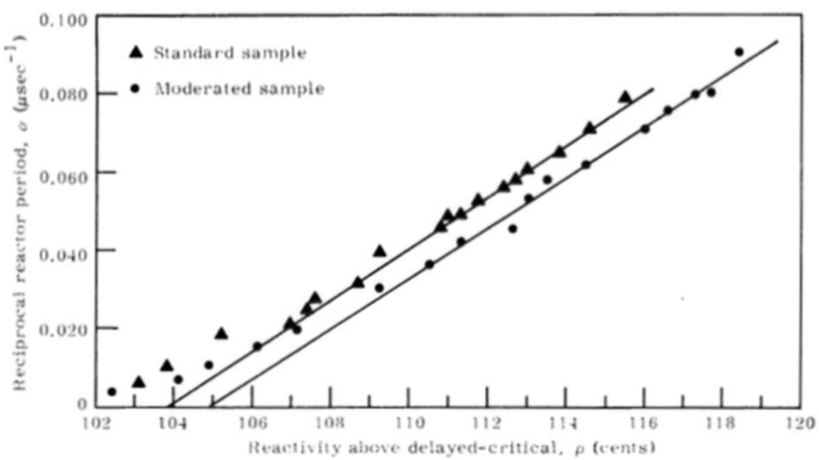
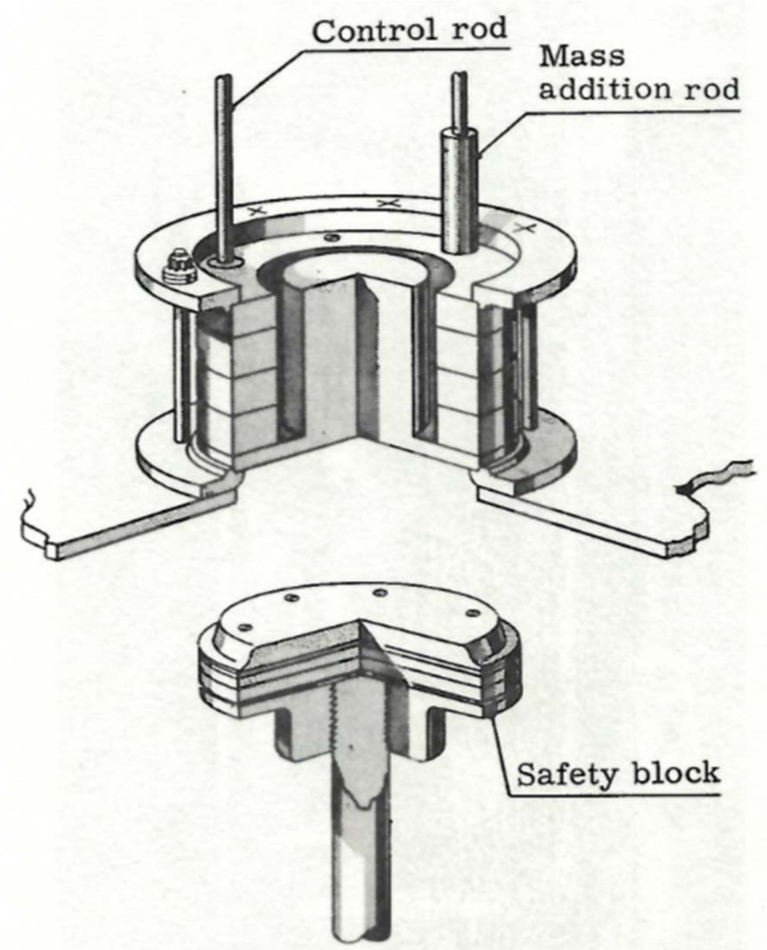


Fig. 1. Use of reactor period data to locate prompt-critical.

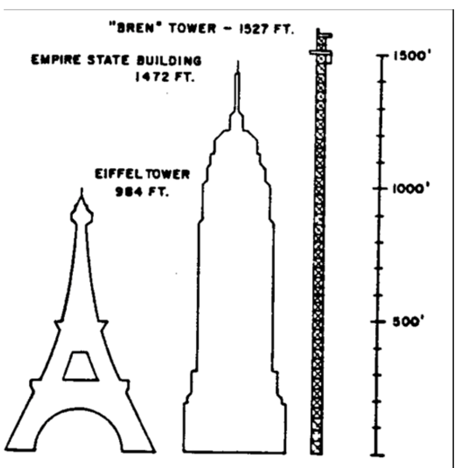


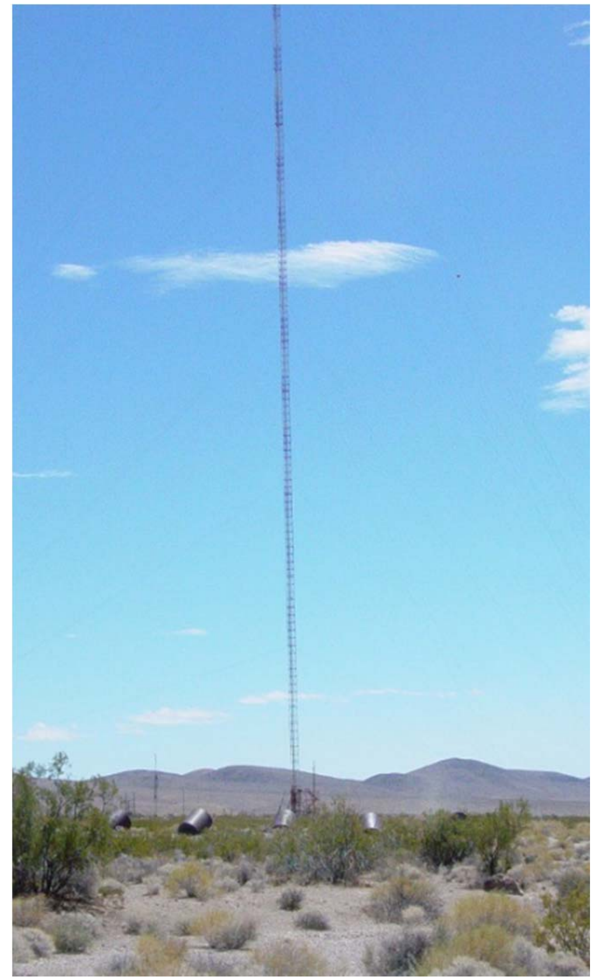
Super Kukla Burst Reactor- 1964-1979

- Operated in a bunker at the Nevada Test Site
- 4450 kg of U (20% enriched)
- Nickel-plated cylindrical reactor with 30" outer diameter
- Inner cavity for test materials measured 30" tall by 18" diameter
- Max burst: 3×10^{18} fissions

Bare Reactor Experiment, Nevada (BREN)

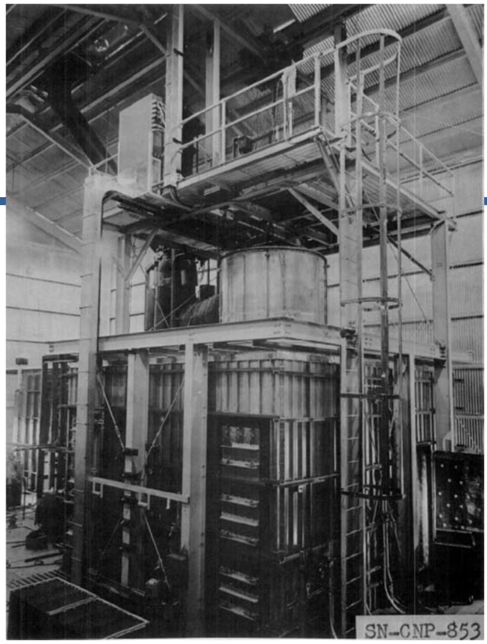
- Built in 1962 at NTS
- Designed to mimic the neutron and gamma radiation burst from Hiroshima
- BREN Tower was 1527 ft tall, which was the tallest free-standing structure west of the Mississippi
- Demolished in 2012



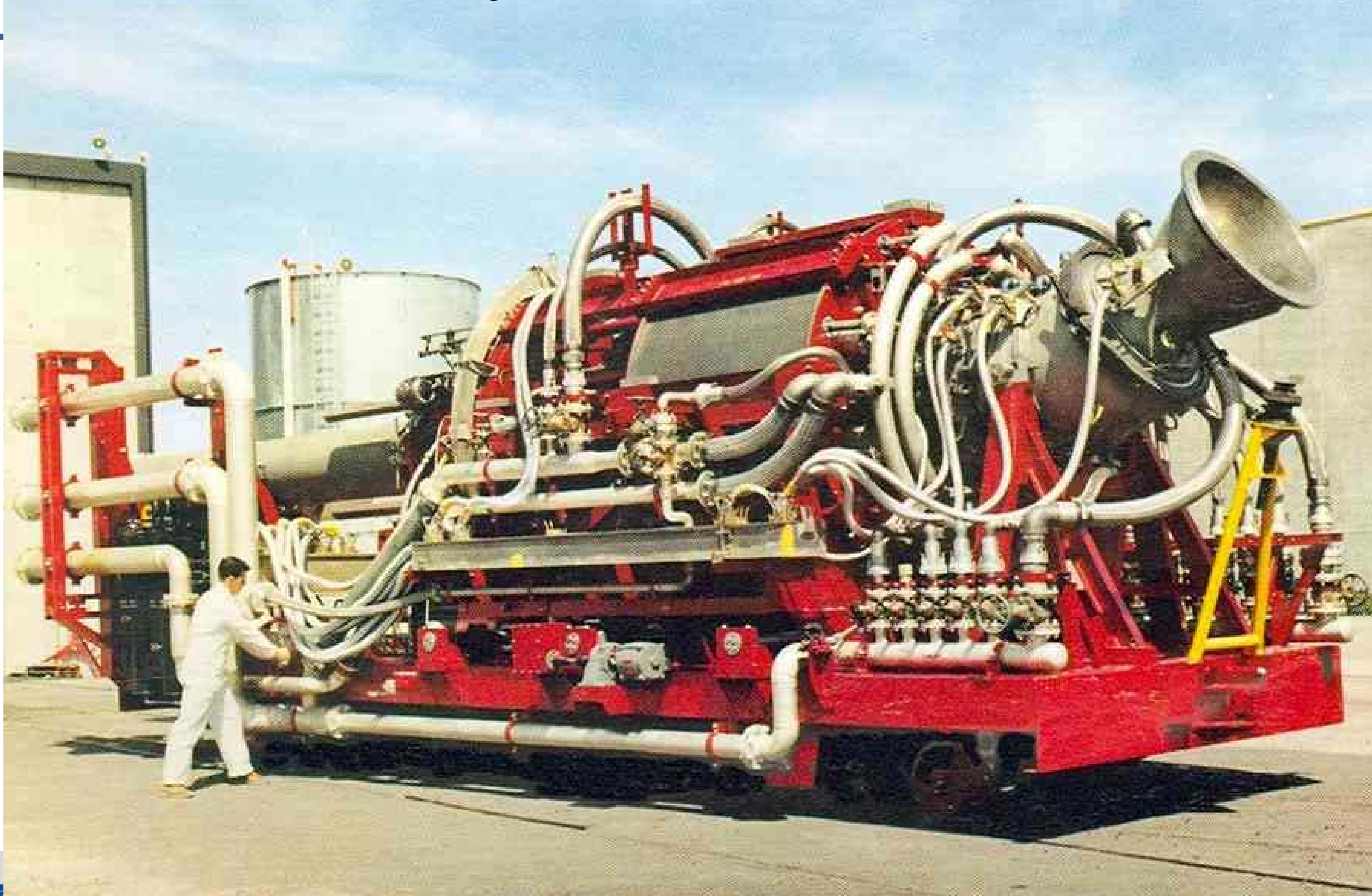


Hot Box Facility

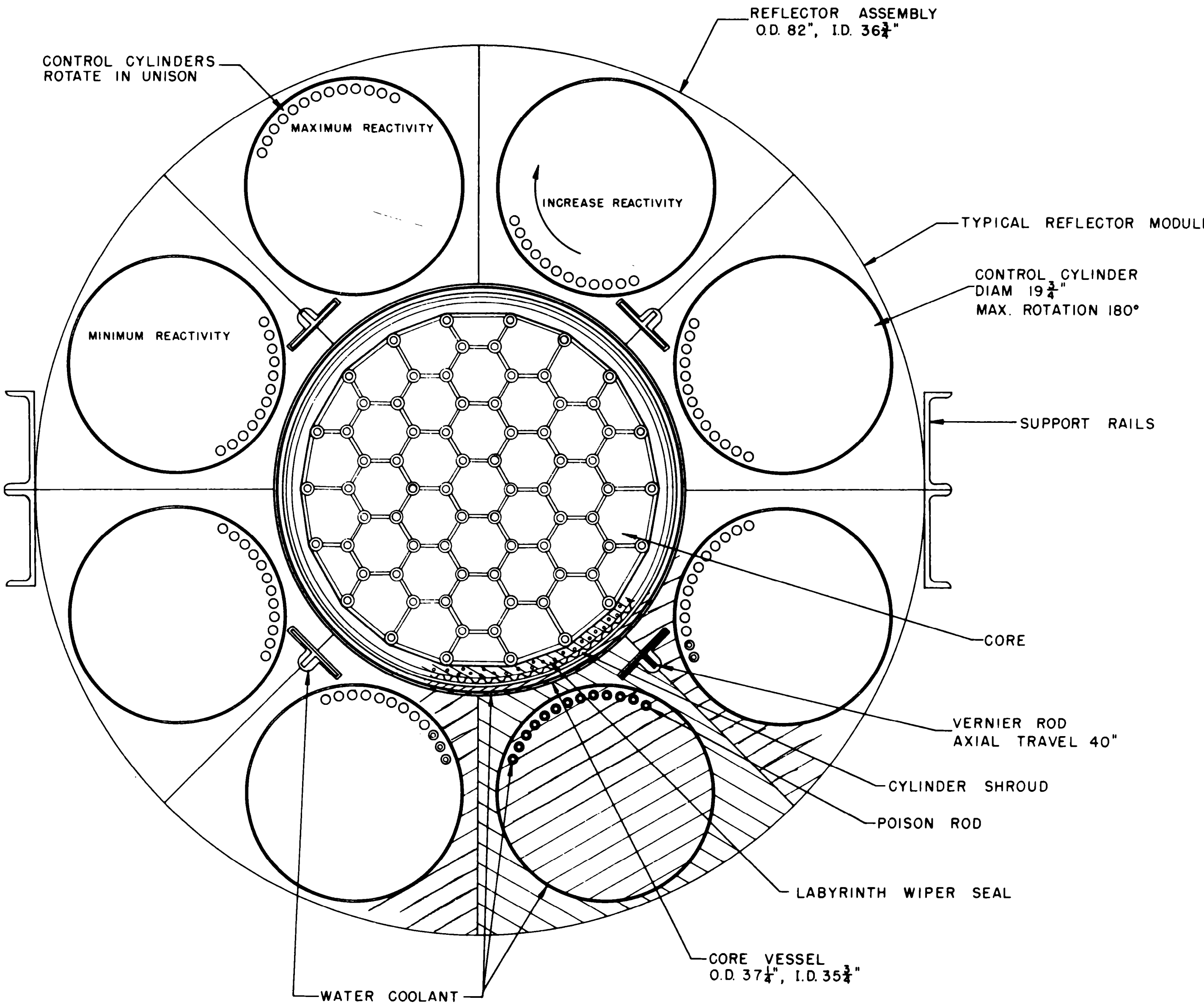
- Constructed at NTS in 1959
- Zero Power reactor facility consisting of HEU foils and moderator blocks up to 10ft by 10ft by 8 ft
- The entire assembly was inside an oven that circulated heated N_2 gas, allowing temperatures up to 1200 F
- Hot Box was designed to provide benchmark cases to validate computer codes at elevated temperatures
- Graphite and BeO moderated assemblies



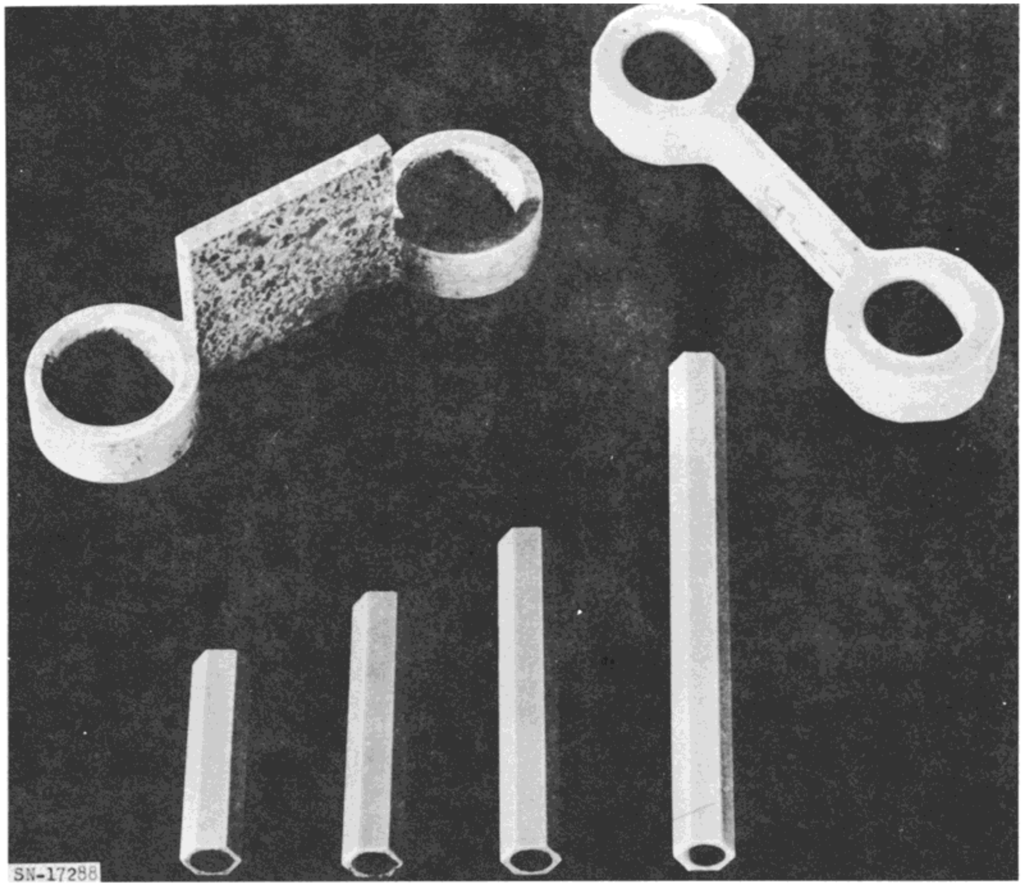
Tory II A Test Vehicle



Tory II A Reactor Cross Section



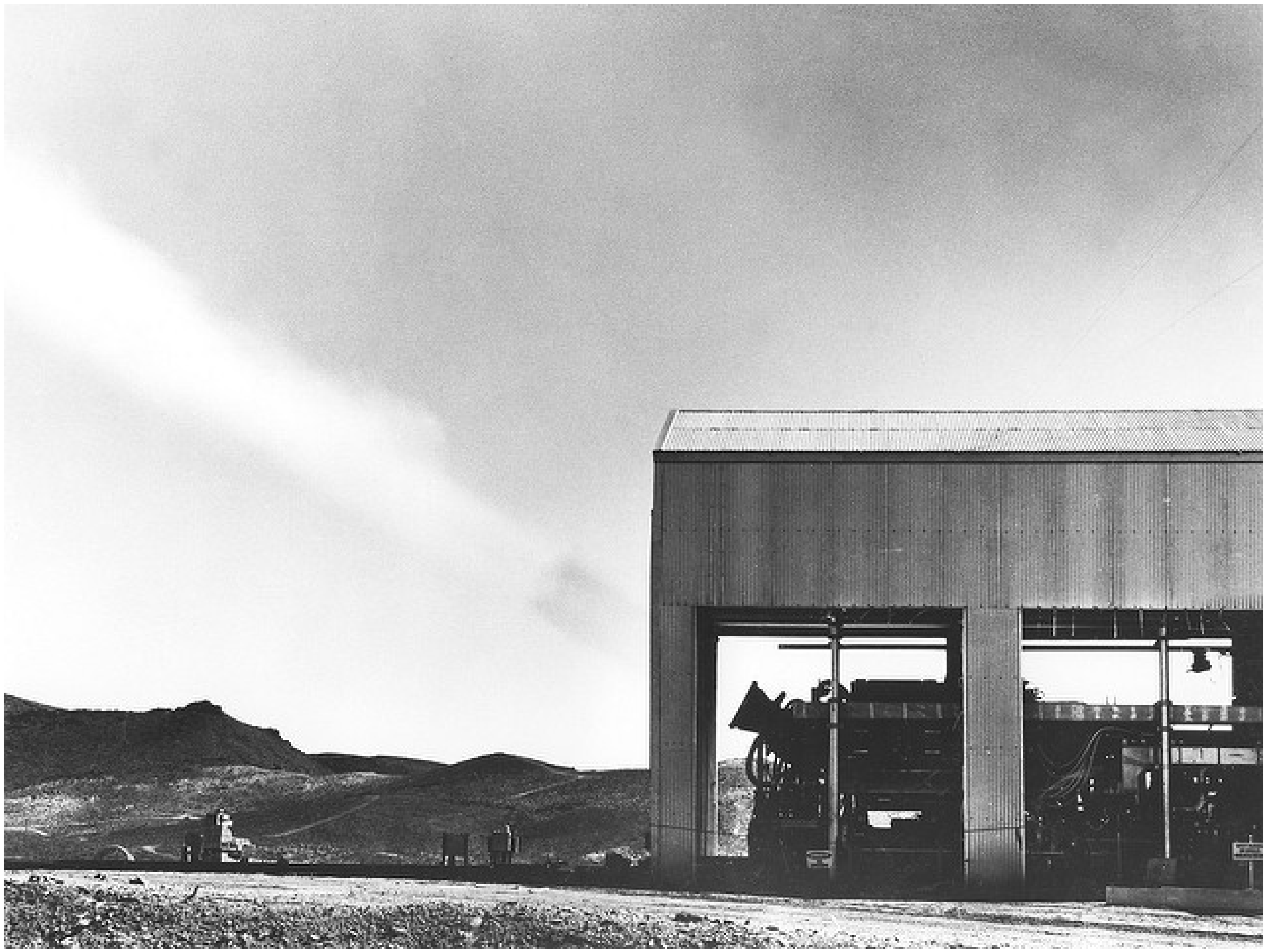
Tory II A Fuel Elements and Structural Links



Tory II C had similar components

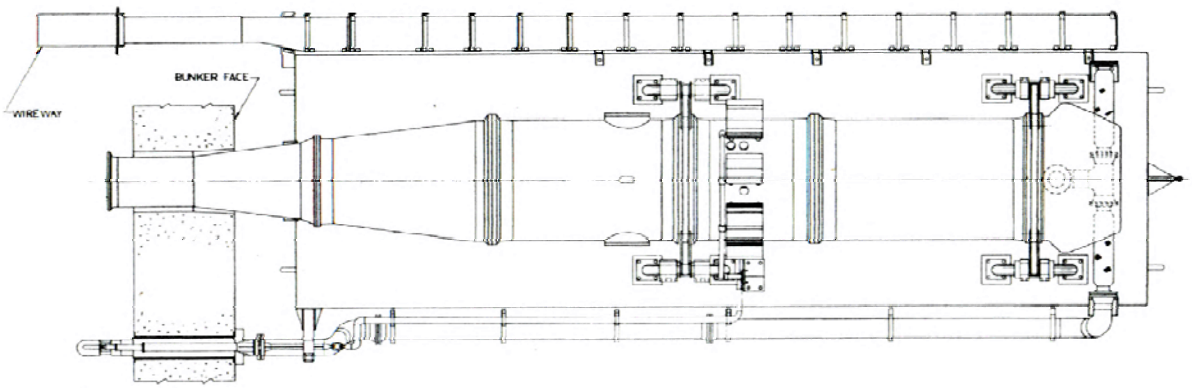
Fuel elements (Think of an ordinary pencil with a hole drilled through it).
Tory II C contained approximately 400,000 BeO fuel elements.

Tory IIA at Power

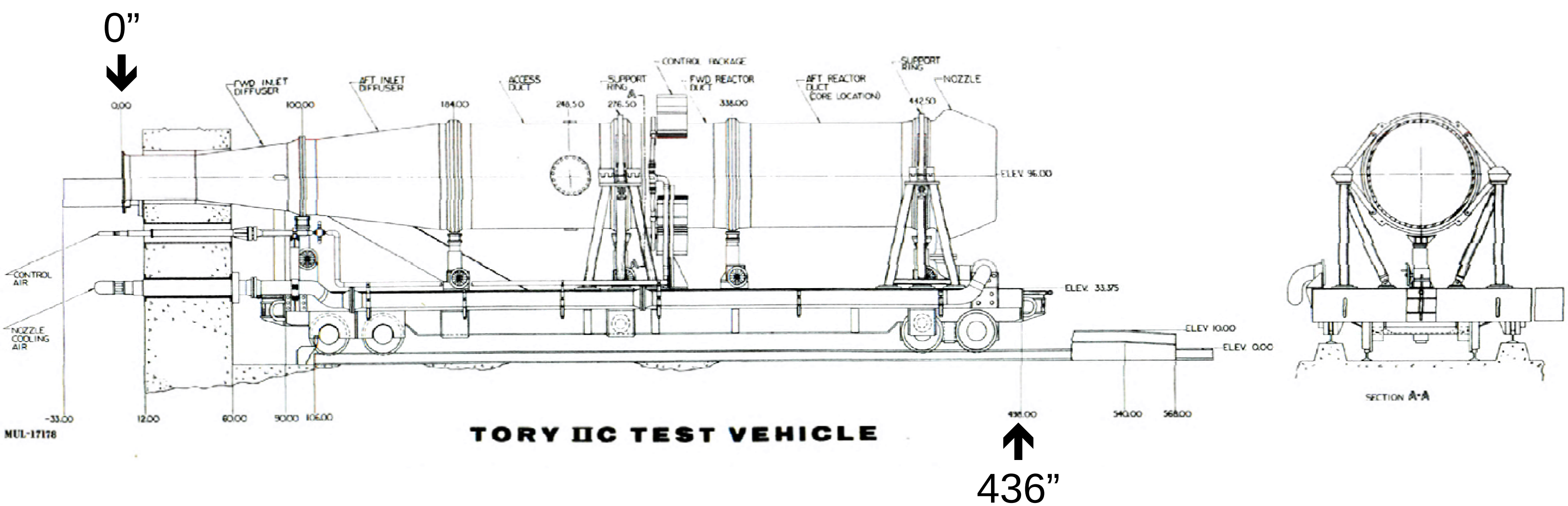


Tory II C Test Vehicle and Locomotive

Tory II C Test Vehicle and Assembly Building



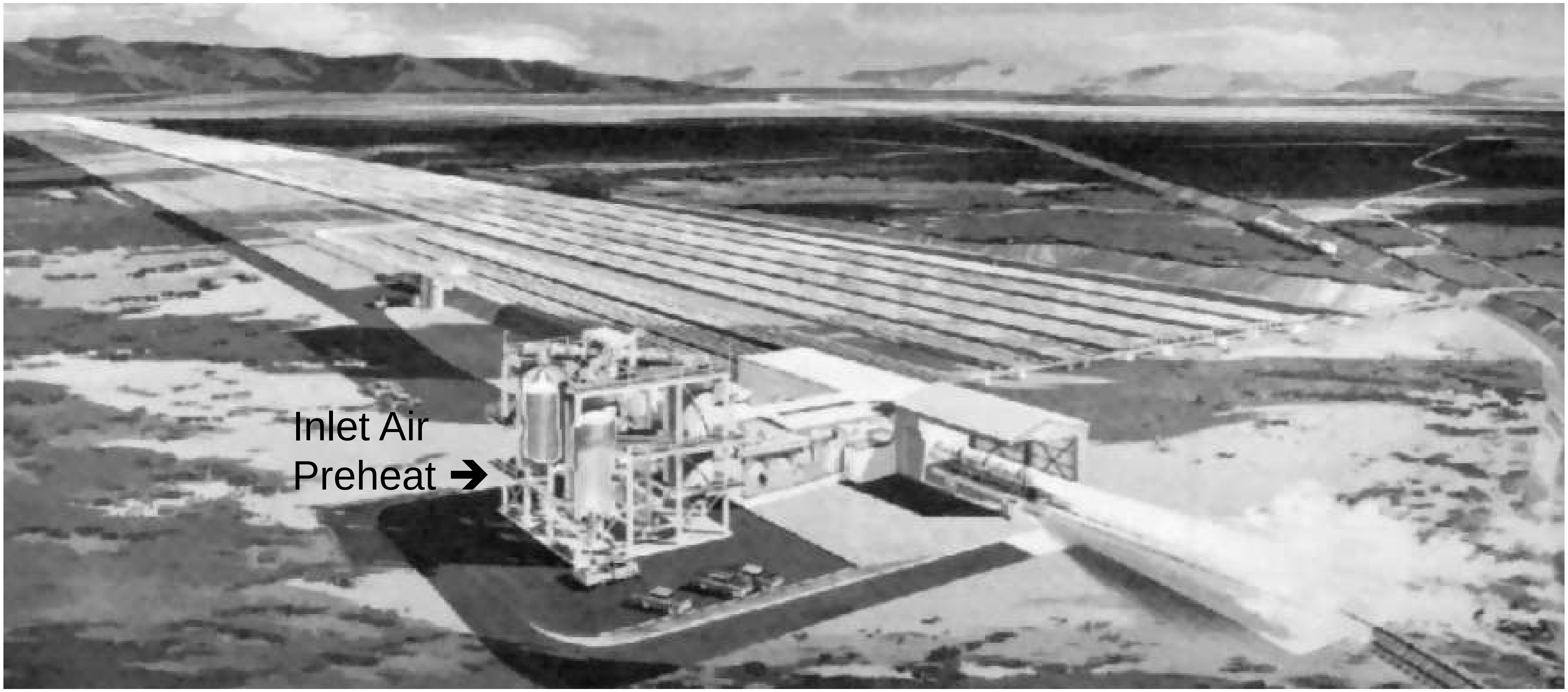
BUNKER FACE
WIREWAY



0”
FWD INLET DIFFUSER
AFT INLET DIFFUSER
ACCESS DUCT
SUPPORT RING
CONTROL PACKAGE
FWD REACTOR DUCT
AFT REACTOR DUCT (CORE LOCATION)
SUPPORT RING
NOZZLE
0.00
100.00
184.00
248.50
276.50
338.00
442.50
ELEV 96.00
ELEV 33.375
ELEV 10.00
ELEV 0.00
CONTROL AIR
NOZZLE COOLING AIR
-33.00
12.00
60.00
90.00
106.00
436.00
540.00
568.00
MUL-17178
TORY IIC TEST VEHICLE
SECTION A-A
436”

Aerial Photo of Pluto Test Site

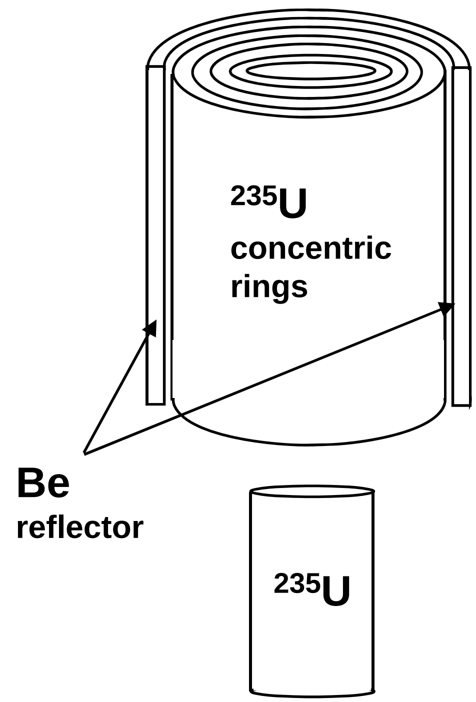
Pluto Test Site (Artist's Rendition)



The LLNL Criticality Accident

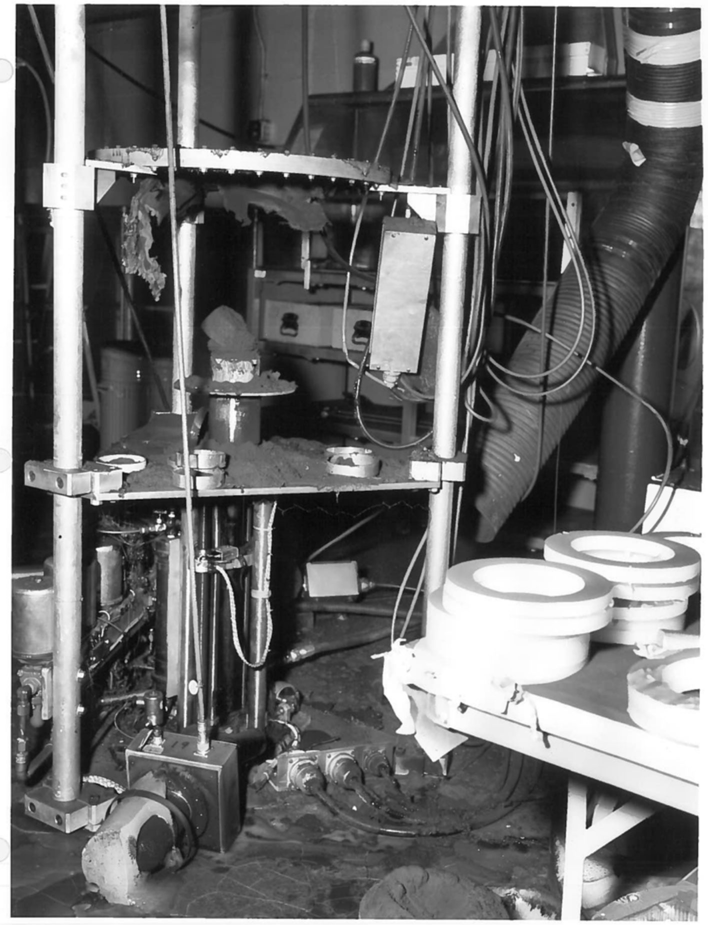
LLNL Criticality Accident, March 25, 1963

- Critical Experiment on the Nimbus Machine using 47 kg of HEU reflected by beryllium
- Upper assembly was concentric HEU rings surrounded by Be. Lower assembly was a solid HEU ram
- Stepwise insertion of HEU ram to different heights (set using a polyethylene safety ring), seven measurements made without incident
- Eighth insertion produced prompt criticality

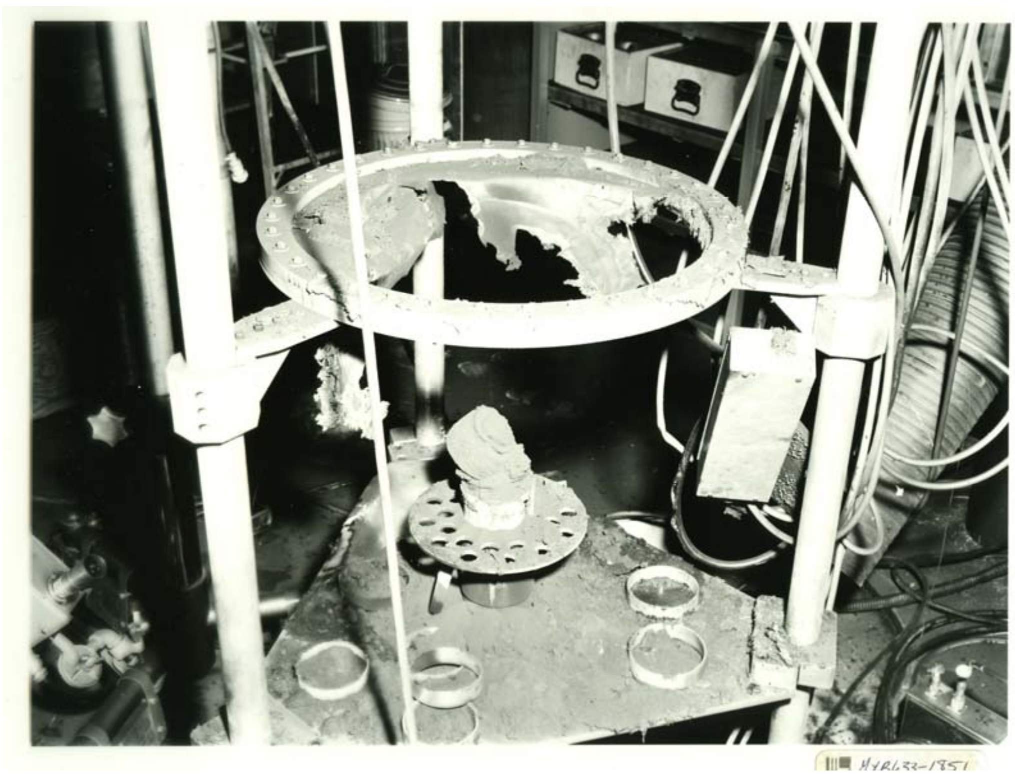


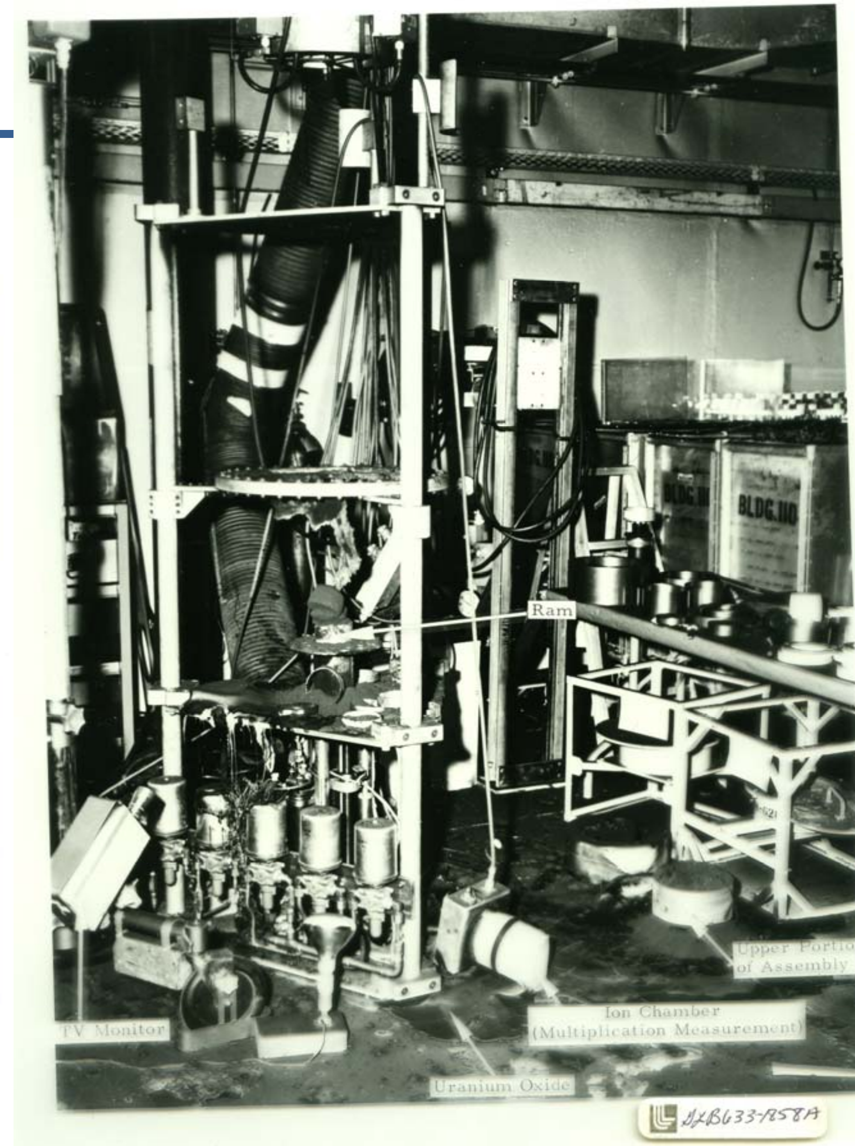
LLNL Criticality Accident, March 25, 1963

- A loud bang was heard in the control room
- Scram and criticality alarms actuated
- TV monitor in the shielded control room showed the assembly in flames
- 3.76×10^{17} fissions
- 15 kg uranium burned to oxide, 10 kg uranium melted onto the floor
- $100,000 damage to facility, but no personnel exposure

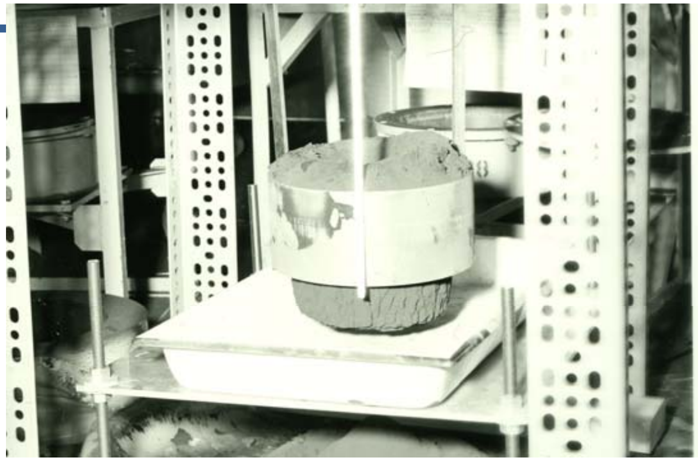


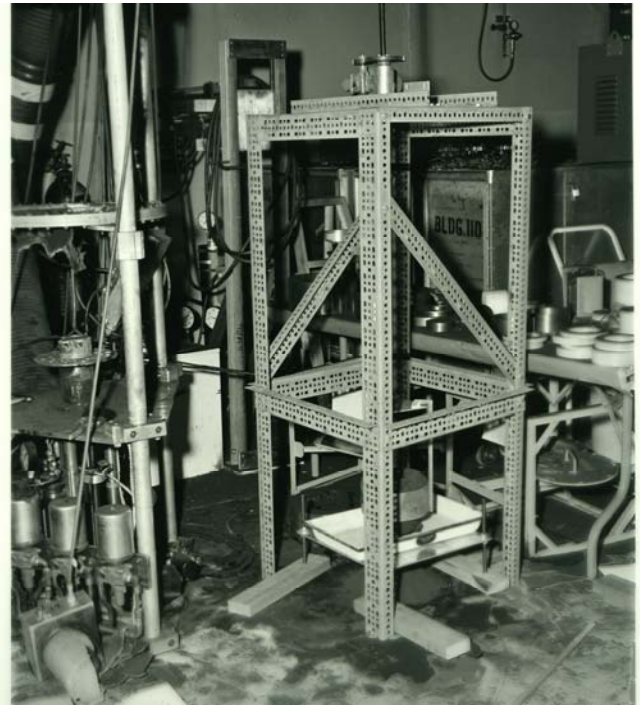
Accident Photos





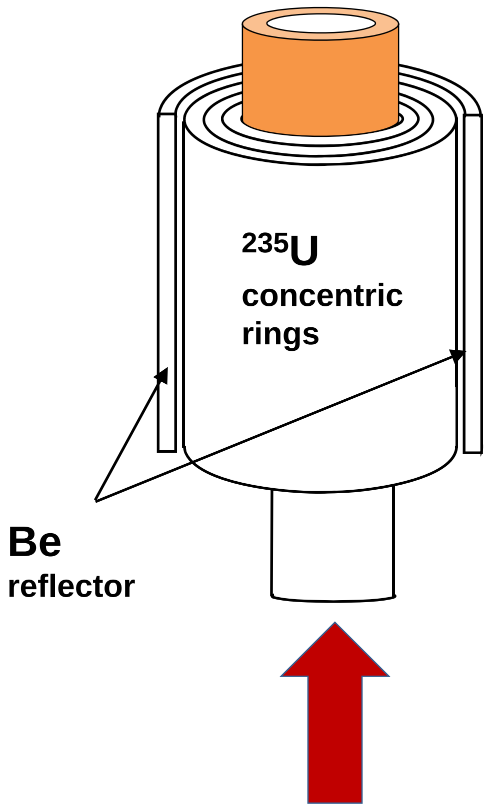
Top Assembly





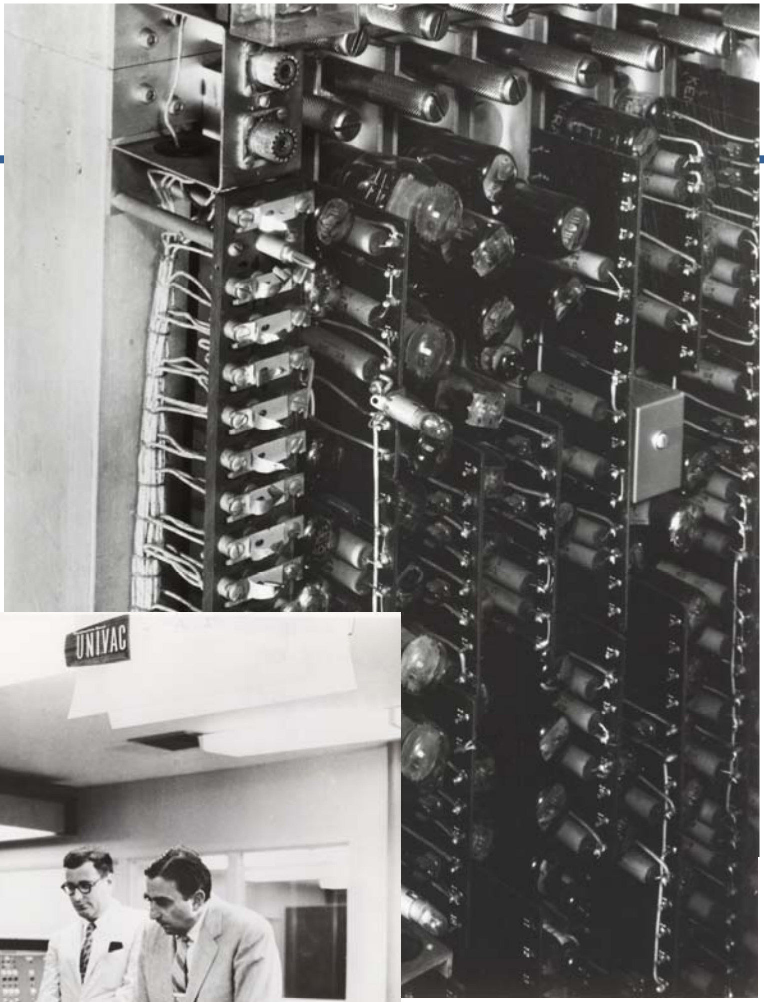
Reasons for the Accident

- Mechanical failure of the machine
- During first seven steps, ram was slightly off-center, pushing the inner-most uranium cylinder upward instead of sliding inside it
- On step eight, the inner cylinder seated, causing a huge spike in reactivity
- Cameras were positioned in such a way that the operators could not see the top of the assembly
- Program had been cancelled, operators were working at midnight to get additional data



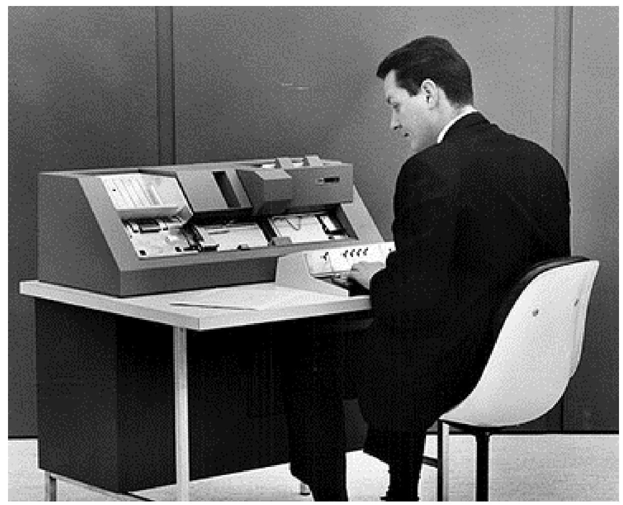
Calculations Through the Years

Univac 1- 1952



Some Tools We Used

Courtesy of James Toth



Entire Laboratory Sharing One Machine

- At first, programming was difficult using punched cards
- Robert Hughes was sent to IBM to help develop FORTRAN
  — Listed as a contributor in the original FORTRAN manual

LLNL's IBM 701, 1954, 12X Faster than Univac-1

Upgrading Engineering Education

The important process of upgrading the educational level of engineers at the Laboratory was driven primarily by Ed Hulse and Wally Decker.

In 1963, for most engineers the BS was the terminal degree. EE began a two-fold upgrade program. First, the existing staff was enrolled in refresher and (then) new technology courses. Second, an effort was made to hire engineers with advanced degrees, primarily Masters degrees, and to a more limited extent, PhDs. The number of PhD degrees in Engineering in 1963 was less than one percent of the total.

> ***"In 1963, for most engineers the BS was the terminal degree."***

This was a long-range effort that required changes at the university level to begin graduating more MS and PhD engineers. Some of

Diffusion Theory Calculations

SPADE

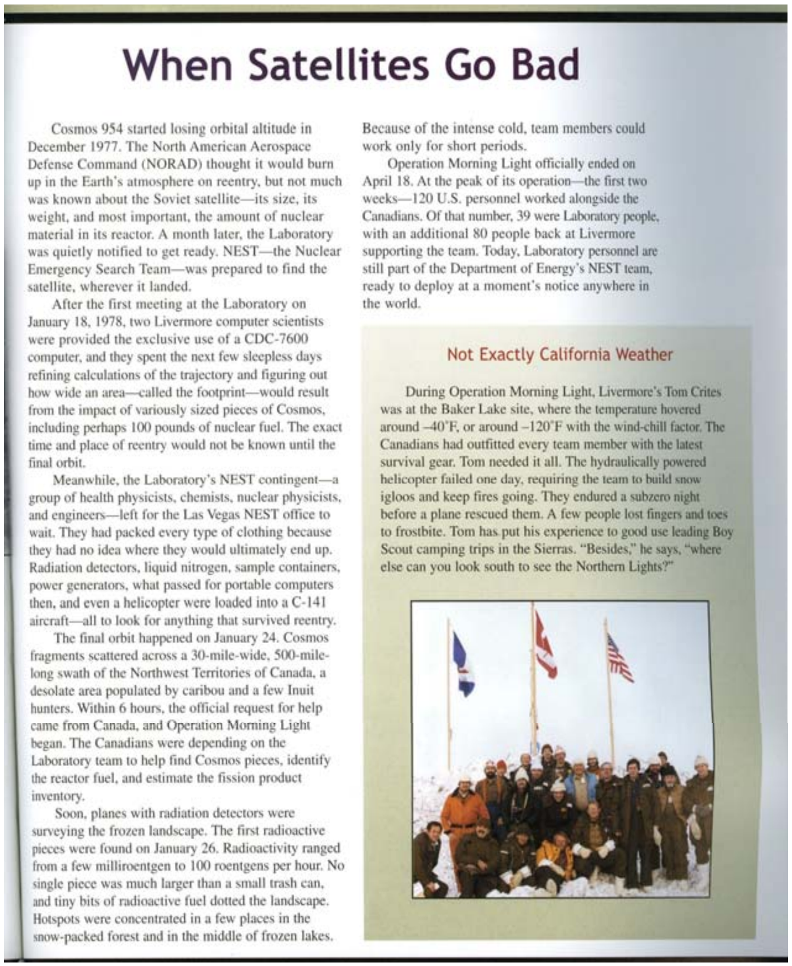
BeO/U^{235}	K_{eff}
124	1.002600
247	1.000246
493	1.005203
986	1.006617
1920	1.007013
3826	1.006610
7660	1.017758

SNOOPY

C/U^{235}	Height (in.)	α (sec^{-1})	k_{eff}
598	36.0	733	0.965926
	37.0	511	0.978538
	37.5	397	0.984555
	38.0	276	0.990409
	38.55[a]	150[a]	0.996645
1200	38.0	377	0.964162
	39.0	258	0.976690
	39.5	204	0.982683
	40.0	149	0.988502
	40.6[a]	70[a]	0.995266
2280	43.0	157	0.977543
	43.5	129	0.982671
	44.0	102	0.987661
	44.5	74.8	0.992519
	45.2[a]	38.0[a]	0.999104
9103	53.0	45.7	0.977730
	54.0	33.5	0.985504
	54.5	26.6	0.989267
	55.0	20.4	0.992951
	55.8[a]	9.5[a]	0.998686

[a] Values found by extrapolation to delayed critical.

Some Excitement



When Satellites Go Bad

Cosmos 954 started losing orbital altitude in December 1977. The North American Aerospace Defense Command (NORAD) thought it would burn up in the Earth's atmosphere on reentry, but not much was known about the Soviet satellite—its size, its weight, and most important, the amount of nuclear material in its reactor. A month later, the Laboratory was quietly notified to get ready. NEST—the Nuclear Emergency Search Team—was prepared to find the satellite, wherever it landed.

After the first meeting at the Laboratory on January 18, 1978, two Livermore computer scientists were provided the exclusive use of a CDC-7600 computer, and they spent the next few sleepless days refining calculations of the trajectory and figuring out how wide an area—called the footprint—would result from the impact of variously sized pieces of Cosmos, including perhaps 100 pounds of nuclear fuel. The exact time and place of reentry would not be known until the final orbit.

Meanwhile, the Laboratory's NEST contingent—a group of health physicists, chemists, nuclear physicists, and engineers—left for the Las Vegas NEST office to wait. They had packed every type of clothing because they had no idea where they would ultimately end up. Radiation detectors, liquid nitrogen, sample containers, power generators, what passed for portable computers then, and even a helicopter were loaded into a C-141 aircraft—all to look for anything that survived reentry.

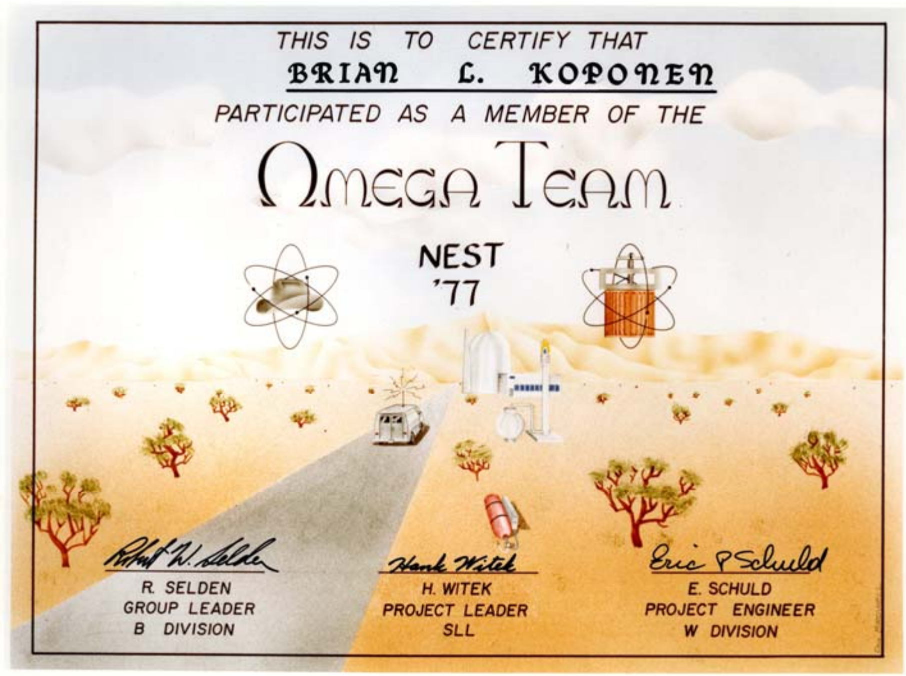
The final orbit happened on January 24. Cosmos fragments scattered across a 30-mile-wide, 500-mile-long swath of the Northwest Territories of Canada, a desolate area populated by caribou and a few Inuit hunters. Within 6 hours, the official request for help came from Canada, and Operation Morning Light began. The Canadians were depending on the Laboratory team to help find Cosmos pieces, identify the reactor fuel, and estimate the fission product inventory.

Soon, planes with radiation detectors were surveying the frozen landscape. The first radioactive pieces were found on January 26. Radioactivity ranged from a few milliroentgen to 100 roentgens per hour. No single piece was much larger than a small trash can, and tiny bits of radioactive fuel dotted the landscape. Hotspots were concentrated in a few places in the snow-packed forest and in the middle of frozen lakes. Because of the intense cold, team members could work only for short periods.

Operation Morning Light officially ended on April 18. At the peak of its operation—the first two weeks—120 U.S. personnel worked alongside the Canadians. Of that number, 39 were Laboratory people, with an additional 80 people back at Livermore supporting the team. Today, Laboratory personnel are still part of the Department of Energy's NEST team, ready to deploy at a moment's notice anywhere in the world.

Not Exactly California Weather

During Operation Morning Light, Livermore's Tom Crites was at the Baker Lake site, where the temperature hovered around –40°F, or around –120°F with the wind-chill factor. The Canadians had outfitted every team member with the latest survival gear. Tom needed it all. The hydraulically powered helicopter failed one day, requiring the team to build snow igloos and keep fires going. They endured a subzero night before a plane rescued them. A few people lost fingers and toes to frostbite. Tom has put his experience to good use leading Boy Scout camping trips in the Sierras. "Besides," he says, "where else can you look south to see the Northern Lights?"



The LLNL NCS Group Through the Years

Early History of Criticality Safety at LLNL

- Prehistory (Pre 1960)-
  - "Slim" Knezevich, Criticality Safety Committee, and L/N Divisions
    - One-man handbook criticality engineer
    - When Slim needed a new page in the handbook, he told CSC
    - CSC would convene, determine best way to address issue
      - Critical/Subcritical Experiment- N Division
      - Calculation- L Division
- 1960– LLNL Criticality Safety Office Established
  - Clint Kolar, Group Leader
- 1980's- LLNL Criticality and Safety Analysis Group
  - Chuck Barnett, Group Leader
  - Six Engineers

The Challenging Years for the LLNL NCS Group

- 1993- Voluntary Retirement Incentive for UC Employees
  - Entire Crit group retired or left
  - Crit group dissolved
    - Dave Heinrichs too young to retire, too stupid to leave
    - Rich Evarts was hired
    - Both were farmed out to multi-disciplinary safety teams

Audit and NCS-Related Shutdown at LLNL

- 1996- DOE Headquarters Audit Declares Criticality Program Failure (Adolf Garcia lead)
  - Federal expectation for NCS changed significantly in the early 1990's
  - LLNL had a largely expert-based NCS program before the retirements
  - B332 (Plutonium Facility) Shutdown for 18 months
  - Decision to reconstitute the group
    - LLNL Management determined 11 people required
  - Song Huang hired as group leader

The Rebuilding Years

- 1996-2006- Song Huang Formalized the Group
  - Instituted Quality Assurance Implementation Plan the formalized best business practices
  - Created the Standard Criticality Control Conditions (SCCCs) that standardized criticality limits and controls
  - Formal NCS evaluations documented for **all** fissile material operations
  - Formal audits using external SMEs
  - Documented quarterly walk-throughs and annual operations reviews
  - Dedicated computer resources with configuration control

Modern NCS Era at LLNL

- 2007-Present, Dave Heinrichs
  - 10 NCS Engineers
  - With new LLNS contract, we left ES&H and joined Nuclear Operations, becoming a division
  - Traditional NCS Work
    - Upgraded weapons criticality statements
    - Addressed huge NCS workload increase due to LLNL deinventory
    - Provided NCS Support for TA-18 move to Nevada
    - SARP Support
    - SQA Challenges

Branching Out Beyond NCS Field Support

- Less support needed after deinventory, providing time to pursue R&D
  - Critical Experiment Design
  - Multiphysics simulation
  - Code and methods development
  - Nuclear accident dosimetry
  - Operations