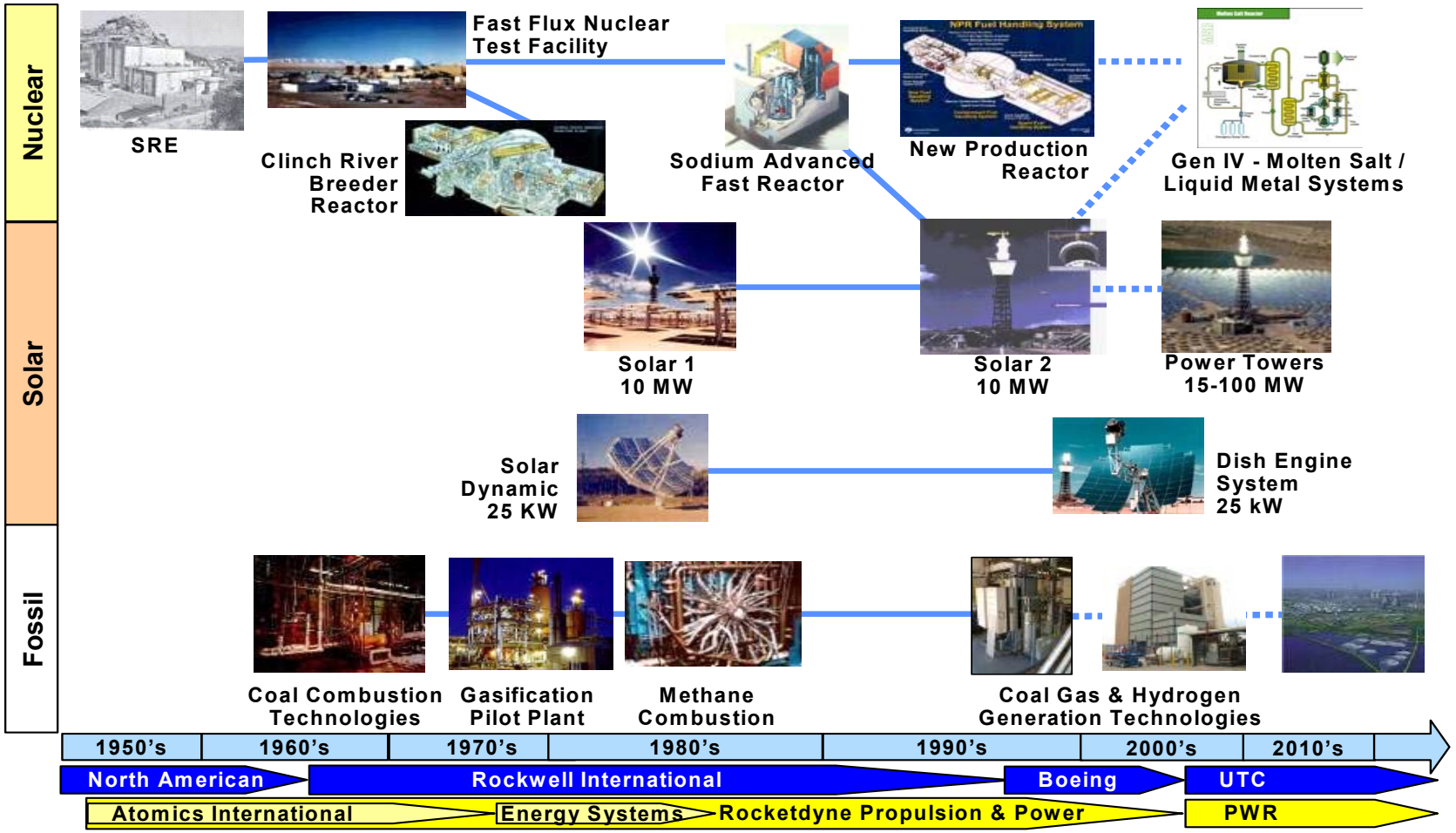
Rocketdyne Liquid Metal and Molten Salt Component Development and Test History

Mike McDowell
Program Manager
Solar & Liquid Metal Systems

Rocketdyne Energy Heritage

Pratt & Whitney
A United Technologies Company



50+ Years of Nuclear, Liquid Metal & Molten Salt Heritage

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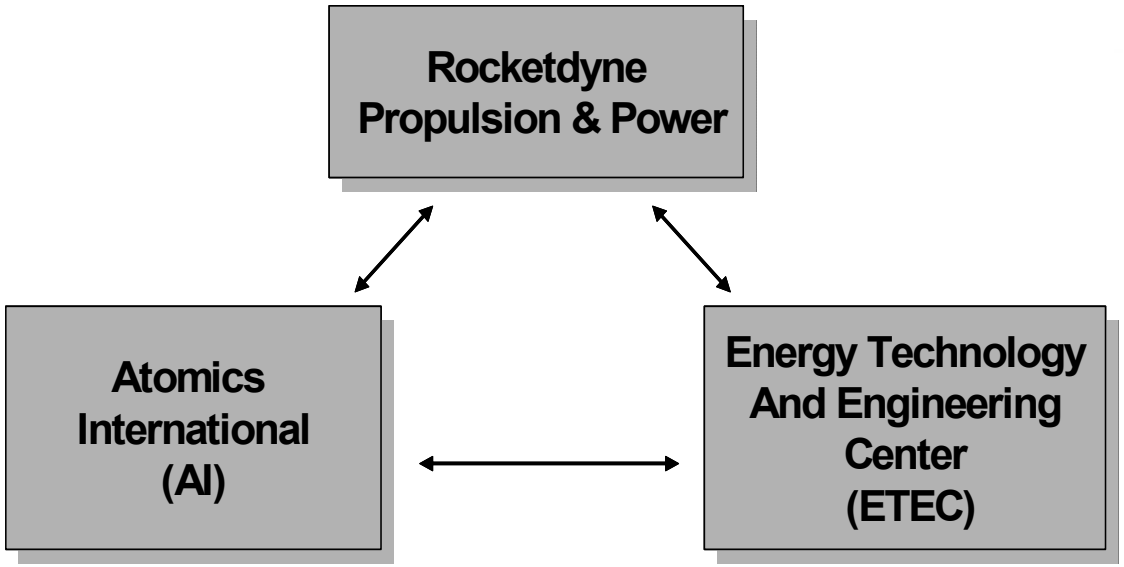

- Design
  - Reactor systems
  - Components
- Component fabrication
- Materials development
- Liquid metal technology
- Safety/reliability analyses
- Licensing

- Testing
  - Large components
  - Materials
- Liquid metal technology
- Operations

Wrote the "Liquid Metals Handbook" The authoritative source of liquid metal technology

Heritage in LMRs

Atomics International (Rocketdyne) Participation in LMR Programs

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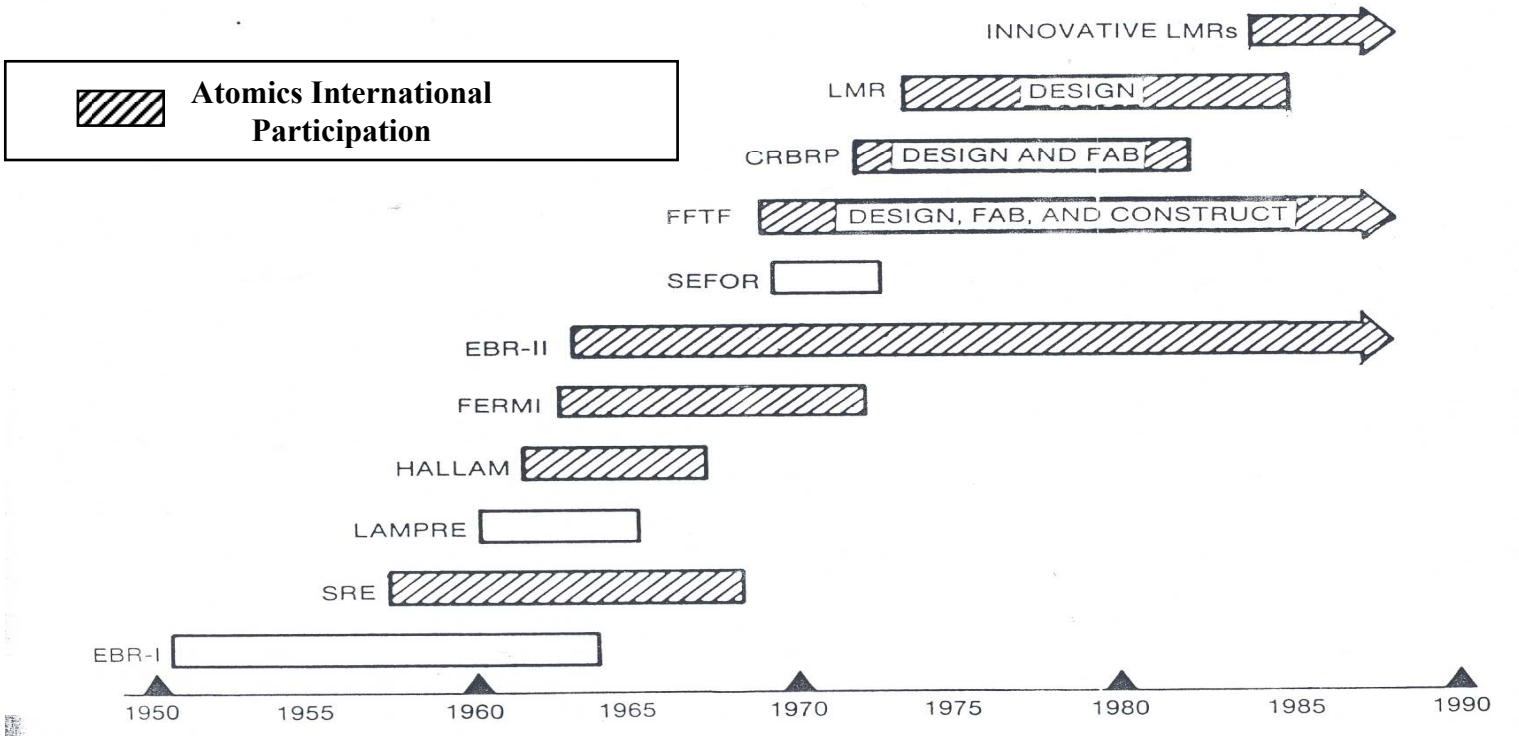
The History of U.S. Liquid Metal Reactor LMR Programs



Rocketdyne is the prime industry force in LMR technology

Heritage in LMRs
Sodium Reactor Experiment (SRE) 1957

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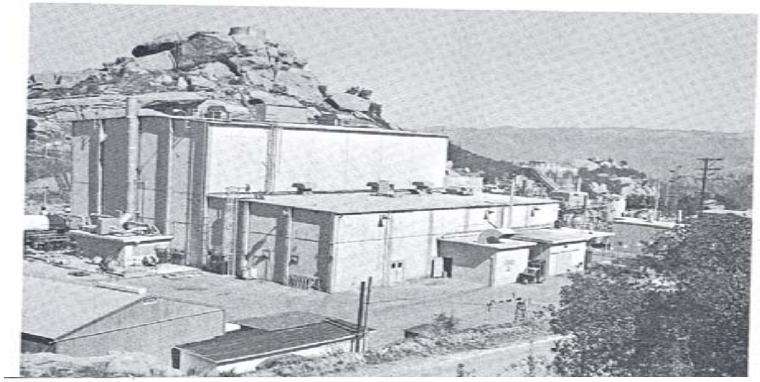
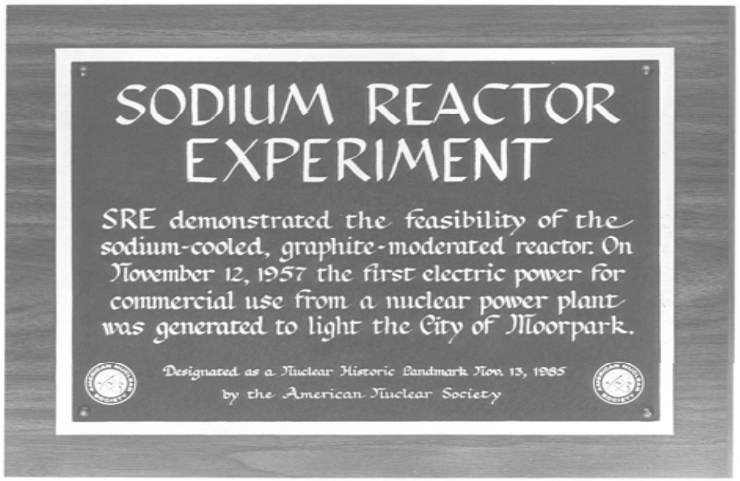
- Reactor designer: Atomics International
- First reactor in the world providing power to commercial grid-Moorpark (Nov. 1957, Santa Susana, Ca)
- Power: 20 MWth / 6 MWe
- Outlet temperature: 789 K
- Fuel: Unalloyed uranium metal fuel thermally bonded by NaK to 304 SS tubes
- Coolant: Sodium (Na)
- Moderator: Graphite
- Control rods: Boron-nickel
- Purpose:
  - Prototypic of power reactors
  - Reactor safety
  - Statistically significant data collection for study of fuel irradiation
  - Determine static and kinetic neutron behavior
  - Development and testing of sodium system components
  - Demonstration of maintenance and operability





Atomics International designed and built the first reactor that provided commercial power to a grid

Heritage in LMRs

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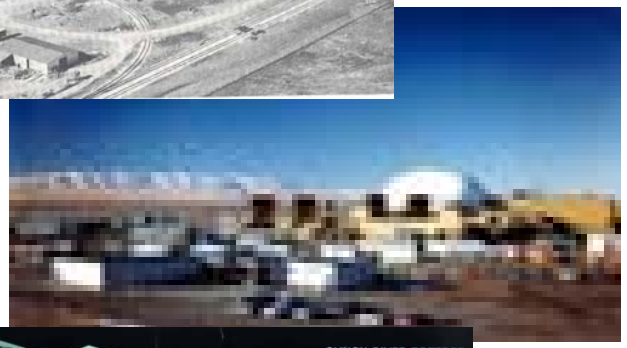
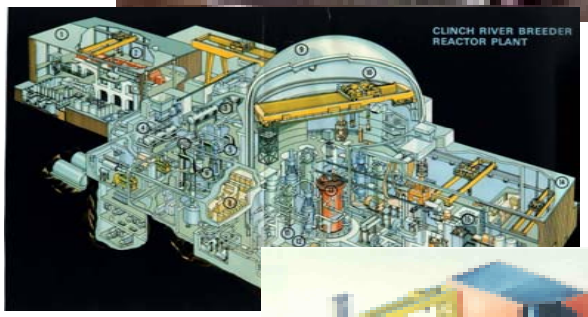
- **Hallam Power Plant (1962)**
  - Critical with sodium, August 25, 1962, Hallam Nebraska
  - Power: 241 MWt / 82 MWe
  - An improved version of the SRE
  - Role: Reactor designer

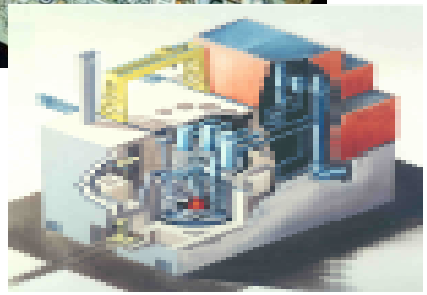
- **Fast Flux Test Facility (FFTF) 1970s-1980s**
  - 400 MWt technology test bed, Richland Washington
  - Role: Fuel handling systems
    EM pump
    Decay heat removal



- **Clinch River Breeder Reactor (CRBR) 1972-1982**
  - 1st commercial LMR, 375 MWe, Not completed, Tennessee
  - Role: Steam generator
    Emergency cooling system
    Purification & inert gas systems



- **Sodium Advanced Fast Reactor (SAFR) 1984-1988**
  - 350 MWe plant designed for inherent safety & low cost
  - Role: Prime contractor
    NRC one step license applicant



Heritage in LMRs

Santa Susana Field Lab Liquid Metal/Nuclear Achievements

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- **1954** – Initial Planning For AEC Liquid Metal Test Center
- **1956** – Nuclear Experimental Reactor (L-82)
- **1957** – Sodium Reactor Experiment (SRE) Goes Critical
- **1958** – Sodium Graphite Reactor Goes Critical; Organic Moderated Reactor Goes Critical; Radioactive Material Handling Facility Opens
- **1959** – Hot Lab Opens

- **1960s-1970s** – Fast Flux Test Facility (FFTF) Liquid Metal Component Tests
- **1970s-1980s** – Clinch River Breeder Reactor (CRBRP) Liquid Metal Component Tests
- **1980s-2000** – Japanese Liquid Metal Fast Breeder Reactor (LMFBR) Component Tests
- **1980s-Present** – Decommissioning and Cleanup

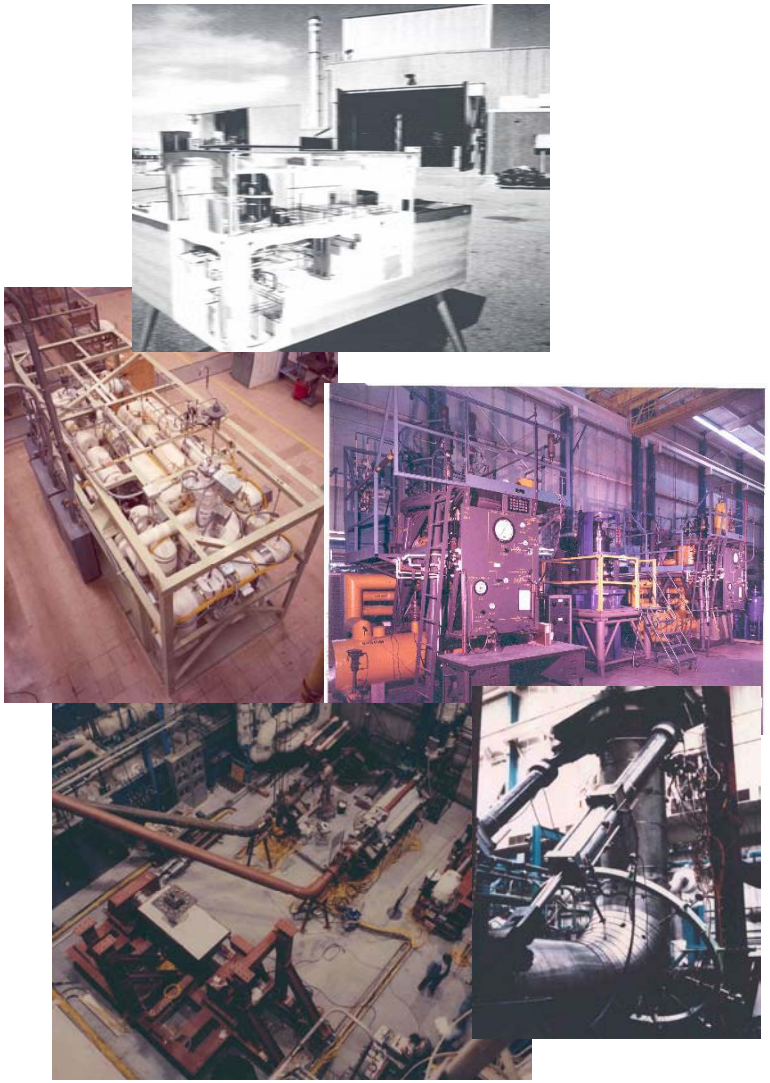
Liquid metal reactors were developed rapidly at SSFL

ETEC
History of testing

- Energy Technology Engineering Center (formerly Liquid Metals Engineering Center)
  - Operated by Rocketdyne for DOE
  - Dedicated to non-nuclear component testing
    - Steam generators
    - Pumps (Mechanical & EM)
    - Valves
    - Instrumentation
    - Operating procedures
  - Built & operated many Na & Li facilities
    - Up to 950K & 500M^3/min.
    - Over 500,000 hours of operation

ETEC Test Facilities

- Sodium-water reaction tests, due to hypothetical steam generator tube ruptures
  - Large Leak Test Rig (LLTR)
  - Test to: 900 deg F, 3.5K psig, 800 gallon capacity
- Small special purpose systems
  - Liquid Metal Development Laboratories (LMDL-1,-2)
  - Used for bellows, friction and wear of materials, electric trace heater life, instrumentation, natural circulation
- Gas blow down & seismic test facility
  - Thermal Transient Test Facility (TTF)
  - Material & structural testing: creep ratcheting, thermal/mechanical life cycles, thermal transients, seismic events
  - Gas testing applicable to GCR also

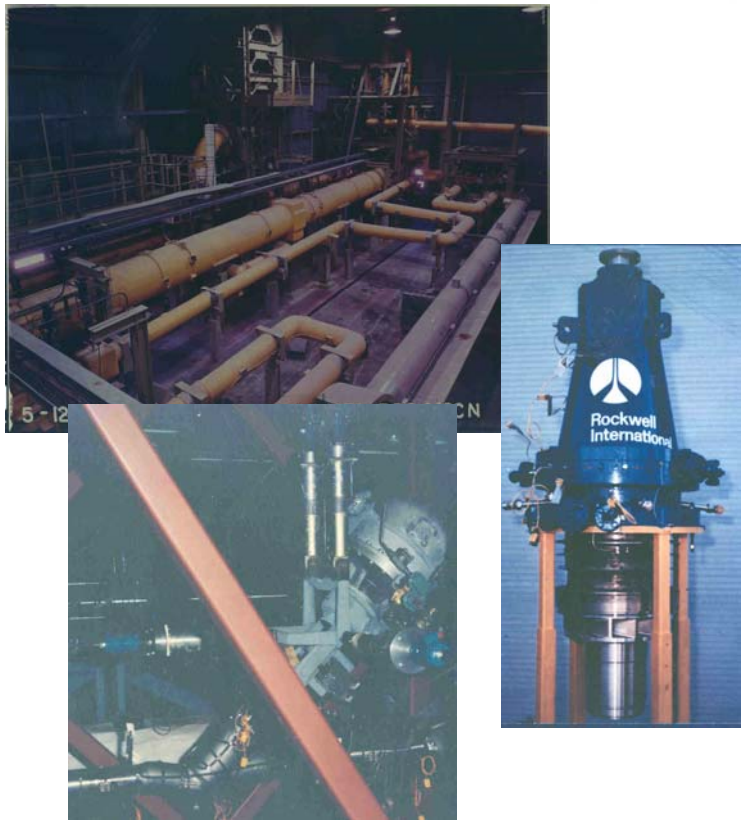


ETEC Test Facilities

- Largest facility in the world for testing SG (70 MWt)
  - Steam Generator test Facility (SGTF)
  - Complete Cogeneration Power Plant: 27 MWe
  - 3 SG test stands
  - Testing to: 3 million lb/hr, 3,000 psig feed water, 950F
- Largest sodium pump facility in the world
  - Sodium Pump Test Facility (SPTF)
  - Up to 36 in diam. Piping
  - Testing to: 100K gpm, 1100F, 250 psig, thermal transients
  - Completed last facility modifications in 2000
  - Large electromagnetic pump tested in 2001

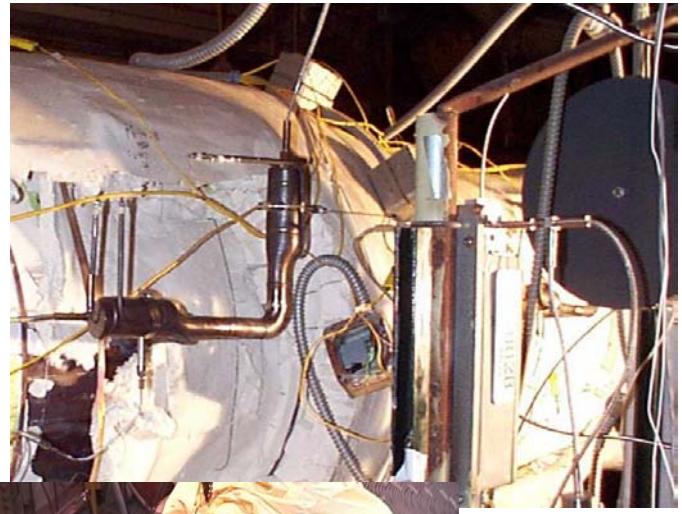
ETEC Test Facilities

- **Small Components Test Loop (SCTL)**
  - **Testing sodium components (instrumentation, pumps, valves, cold traps, piping and vessels)**
  - **Testing to: 3,500 gpm, 1200 deg F, 325 psig, thermal transients**



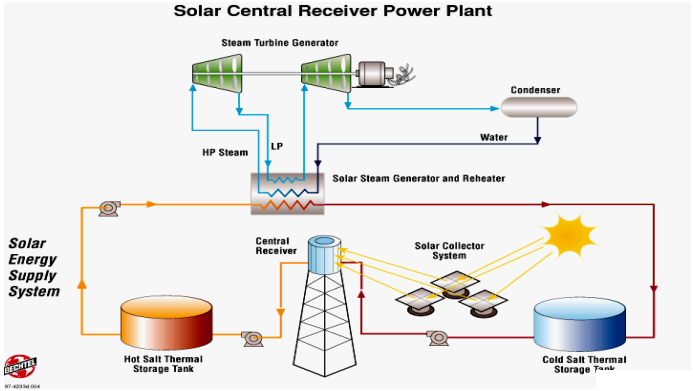
Unique Instrumentation Specification & Development Was Performed

- Unique instrumentation
  - High temperature environment
  - Unique LM electromagnetic properties
- Pressure transducers with NaK capillary standoff
- Flowmeters (Electromagnetic of several types & venturi)
- Level sensors
- Proximity sensors (mechanical device diagnostics)
- Impurity monitors



Solar Power Towers

Ready for Commercial Market Entry, Rocketdyne has the key technology



Solar 2 Demo Plant
(1994-1999)

- **10 MWe**
- **42 MWt**
- **3 hours storage**

- **Molten salt technology successfully demonstrated in Solar 2**
- **Key attributes …**
  - **High temperature …. high solar-to-electricity efficiency**
  - **Thermal storage …. dispatchable power with up to 24 hr/day capability**
  - **Flexibility in plant size & configuration …. tailor to market conditions & customer needs**
- **Rocketdyne technology**
  - **Only fabricator of high temperature receiver**

Molten Salt Experience

- Molten salts
  - Nitrate salts for heat transfer applications
  - Carbonate salts for oxidation and reduction reactions
  - Sulphate salt reduction for carbonate recycle
  - Chloride salts for pyrochemical partitioning
- Molten Salt Inter-Action in Coal Processing
  - Evaluated processes of carbon oxidation in molten salt
- Designed a molten salt melt station for Consolidated Edison Co.
- Molten Salt Oxidation Systems: Design, Build and Test
  - Tech support and leadership on bench and pilot scale
  - Used for destruction of propellants and other energetic wastes
- Molten Salt Materials Development
  - Evaluate and develop new materials for use in molten salt systems
- Molten Salt Test Facility (MSTF)
  - Commercial scale & permitted for testing components & processes
- Molten salt solar receiver, piping & storage tanks

Testing must successfully meet the challenges of liquid metal & molten salt operations

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Challenges	Solutions
High temperatures	Safe operating procedures High quality construction
High melting points	Electrical system preheat Fill & melt-out procedures
Materials compatibility	Material testing Material selection Purification
Pyrophoric behavior (flammability in air)	Operator safety training Engineered safety features

Current Liquid Metal Capabilities

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- Engineering capabilities
  - Over 50 engineers & techs with molten salt/liquid metal experience
    - Approximately 30+ personnel worked on Solar Two
    - Hundreds of engineering personnel with directly applicable expertise in thermal/fluids, materials, mechanical design, electronics, stress, civil, etc
  - System design and construction
    - Familiarity with different fluids (Na, Li, NaK, K, Hg)
    - High quality design and construction focused on safety
  - Pump design
  - Trace heat system design
  - Instrumentation specification and development
  - Materials specification
- Operations & testing
    - Recent large scale experience
    - Purification
    - Liquid metal & molten salt safety
    - Liquid metal & molten salt system transfer and fill

Policies, procedures and people to handle applicable liquid metals

Back up

Component Design and Testing

- Salt, steam and sodium solar receivers (1)(3)
- Large commercial size liquid metal pumps (2)(3)
- Molten salt and liquid metal tanks and vessels (2)(3)
- Electrical heat trace and insulation systems (2)(3)
- Large commercial size liquid metal steam generators(2)(3)
- Liquid to liquid and liquid to air heat exchangers (2)(3)
- Salt and liquid metal instrumentation (2)
- Salt and liquid metal piping systems (2)(3)
- Liquid metal cold traps and freeze seals (2)(3)
- (1) Designed at Rocketdyne and tested elsewhere
- (2) Designed and tested at Rocketdyne
- (3) Fabricated by Rocketdyne

Technical Capabilities Required for Test Facility Design

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- High temperature thermal fluid analysis
- High heat flux component mechanical design
- High temperature stress analysis
- Materials engineering
- Molten salt & liquid metal science and chemical engineering
- Instrumentation and control
- High temperature piping design and analysis
- Electrical heat trace and insulation design
- Valve engineering

ETEC Test Facilities

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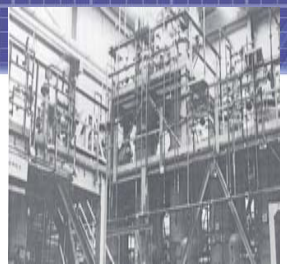
Small Components Test Loop (SCTL)

- I&C
- Pumps
- Valves
- Cold traps
- Others.

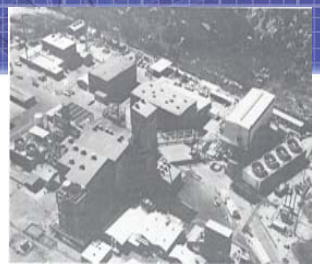
Large Leak Test Rig (LLTR)

- Study Na/H2O energetic reactions



Liquid Metal Development Labs (LMDL)

- Bellows
- Friction/wear
- Trace heater
- I&C

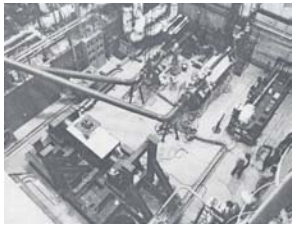


Sodium Component Test Installation (SCTI)

- Largest liquid metal steam generator facility in the world-70 MWt

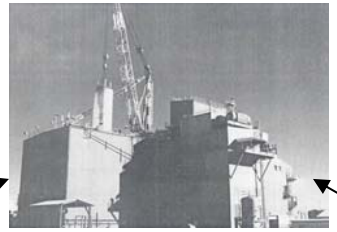
Vibration Facility

- Components
- Structure
- 40g acceleration
- 100 ton max



Thermal Transient Test Facility (TTF)

- Material testing
- Creep ratcheting
- Thermal/mech life
- Thermal striping

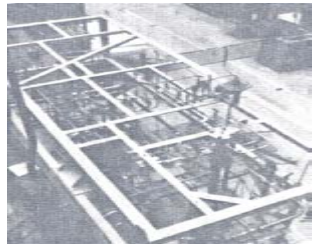


Component Handling and Cleaning Facility (CHCF)

- Sodium removal from large components
- Alcohol and steam processes

Sodium Pump Test Facility (SPTF)

- Largest Na pump facility in world
- 36 in. diam pipe
- 100,000 gpm
- 1100 deg F
- 250 psig



Bimetallic Lithium Pumped Loop (BLiP)

- Corrosion of metals in Li within a bimetallic loop
- Purification techniques

Radioactive Material Disposal Facility (RMDF)

- Radioactive waste
- Mixed waste treatment

Interactions of Hydrogen and Materials

Types of Hydrogen Embrittlements

Hydrogen Environment

Lower notch strength
Lower ductility
Surface cracking
Lower K_I Threshold
Faster crack growth
- Most alloys except a few (Cu, Al, Au, ..)

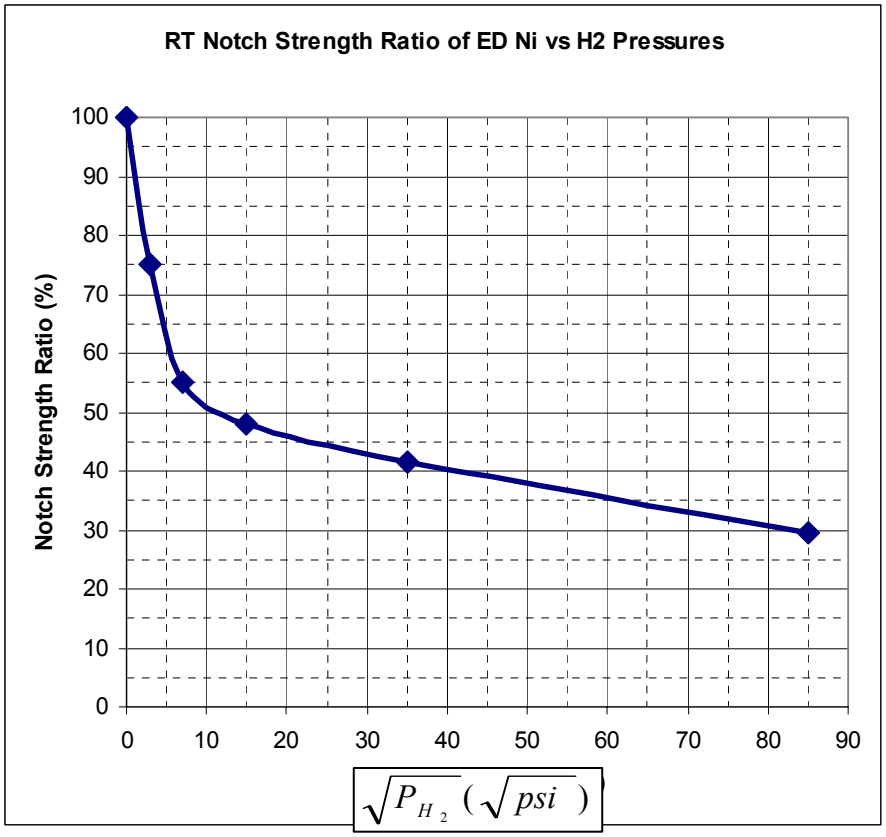
Hydrogen Absorption

Interstitial hydrogen embrittlement
- Steels
- Nickel

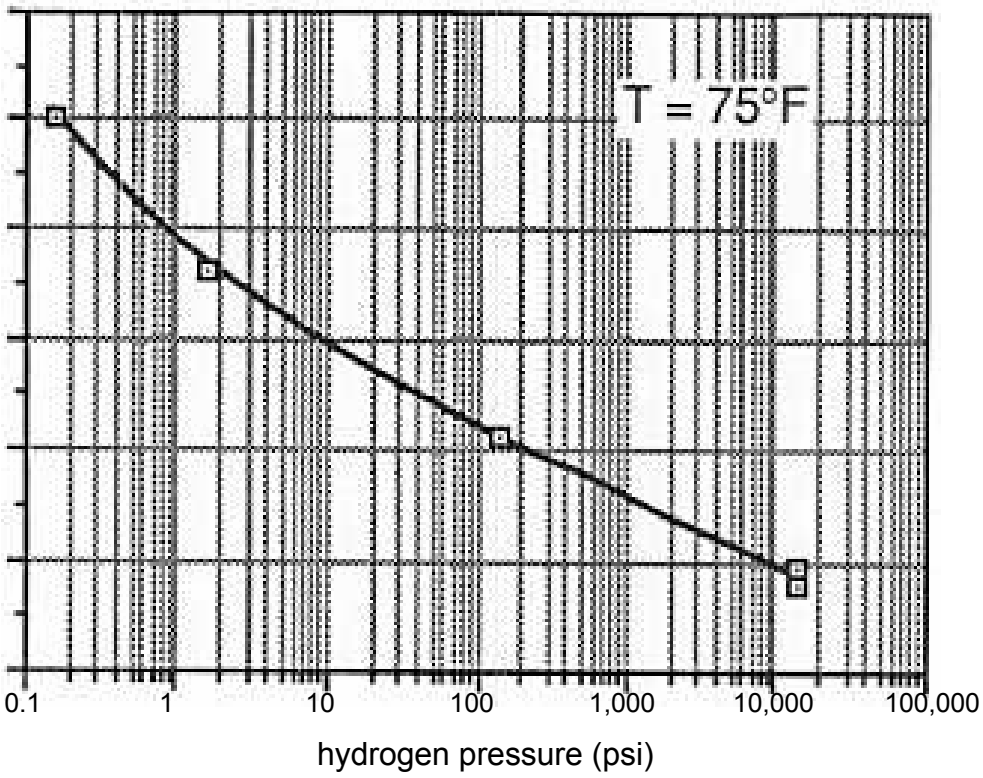
Hydrogen reaction embrittlement
- C in steels → CH4
- O in Cu → H2O

Hydride embrittlement
- Ti, Zr, Nb, Ta

Notch Strength Degraded by Presence of Hydrogen



Subcritical Crack Growth Threshold (Normalized) for Ti-6-4 as a Function of Hydrogen Pressure



For over 45 Years, Rocketdyne's Understanding of Hydrogen Effects on Materials Has been the Key to Space Efforts

1956-1960s	Nuclear rocket – MK9 turbopump
1960-1970	H_2-fueled J-2 engine carried astronauts to the moon
1961-1973	NASA-funded technology contracts in hydrogen effects
1964-1965	Aerojet and NASA H_2 tank failures focus attention on hydrogen embrittlement
1965-1970	H_2 turbopump testing
1969-20??	Reusable Space Shuttle Main Engine design, test, analysis, flight support
1989-20??	Higher temperature, longer life systems

Unprecedented Capability and Experience in Testing Materials under Hydrogen Environments

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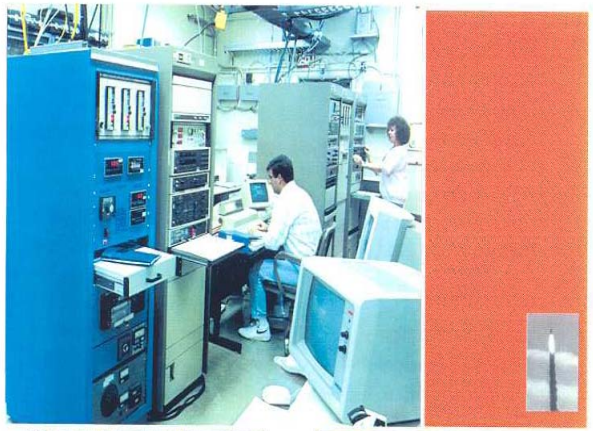
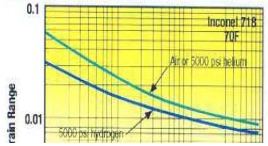
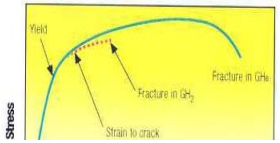
Rocketdyne's experience in understanding hydrogen effects is unequalled

Hydrogen envinronment embrittlement characteristics:

- Lower ductility
- Lower notch strength
- Surface cracking
- Crack propagation at low stress
- Higher crack growth rate
- Shortened fatigue life







Environmental Effects Laboratory High-Pressure Hydrogen Test Capabilities

Facility hydrogen system

- Purification system
- Pressurization system (30,000 psi)
- Purity monitoring
- Trace impurity test capability

Mechanical testing

- Tensile
- Creep
- High-cycle fatigue
- Low-cycle fatigue
- Fracture mechanics
  Elevated temperature
- Cryogenic temperature

Component Test

- NASP heat exchanger
- NASP sliding seals
- SSME bellows
- SSME drain line flow