Space Nuclear Thermal Propulsion (SNTP)

Lessons Learned

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Thank You

Many thanks to Roger Lenard who was the Program Manager for SNTP and Timberwind

Without Roger's Leadership, this Program would have never happened

I am presenting a snapshot of work of over 400 people

All the credit for the accomplishments goes to them

What SNTP was about

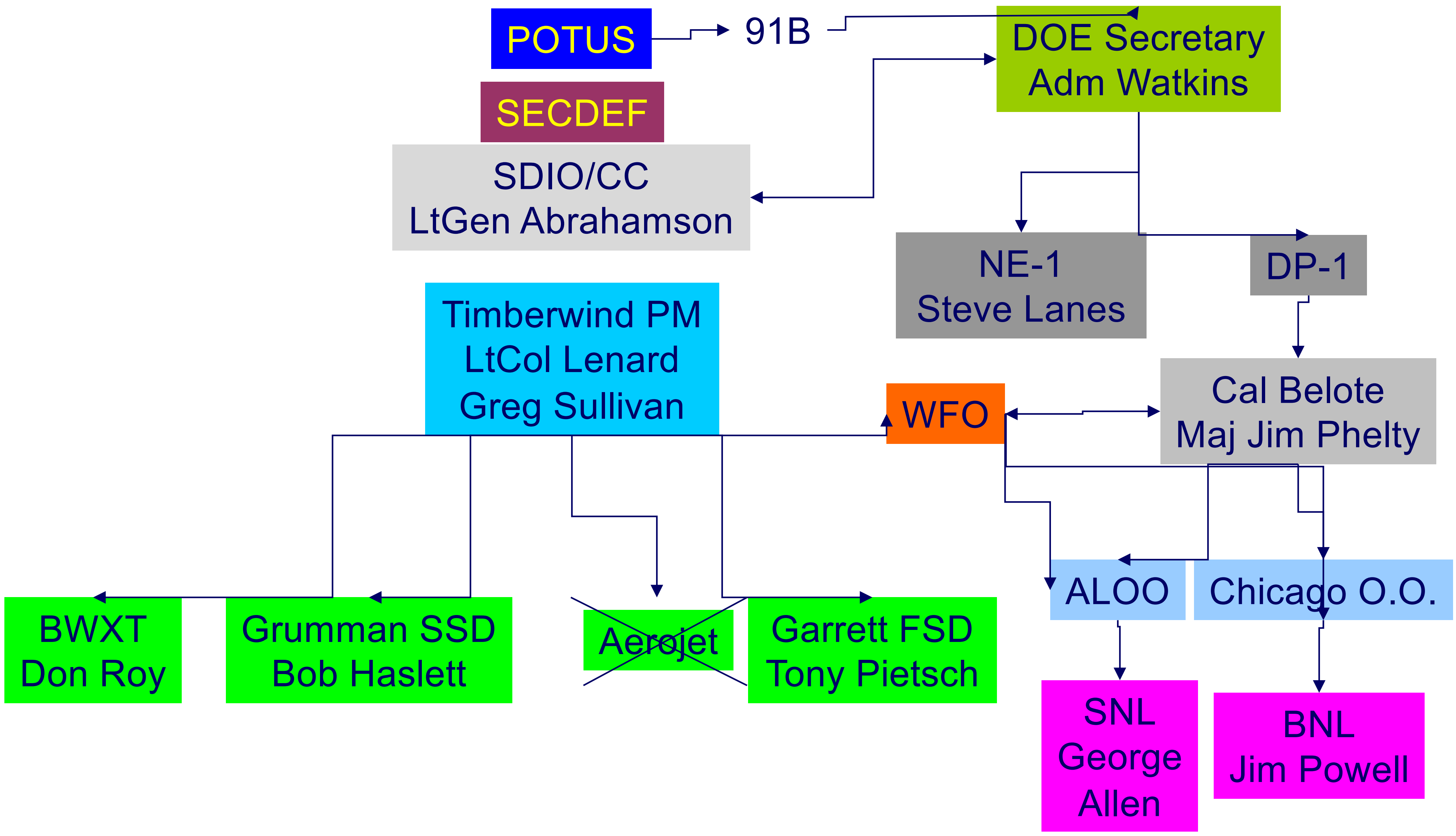
- Develop and test a high thrust-to-weight nuclear thermal rocket engine
- Integrate with a launch vehicle
- Validate feasibility of performing ground-based boost-phase intercepts of long-burn Soviet ICBMs in boost and post-boost phases
- Required
  - High thrust-to-weight ratios: >20 to 1
  - Rapid startup: < 10 seconds to full power
  - ~120 seconds operation
  - High I_{sp}: ~1000 seconds
  - 75,000 lbs Thrust
- Started: October 1987, Terminated 1992
- 2 National Labs, 4 Aerospace Contractors
- Approximately $400 M spent*

The Beginning

- July 1987: Team of Sandia, Brookhaven National Laboratories, XERAD, Grumman Space Systems, Allied Signal, Babcock & Wilcox, and Aerojet meet with LtGen Abrahamson
- Propose a high T/W* ground-based system to perform boost-phase intercepts
- Requires extremely high ΔVs and high accelerations
- Key technology: Particle-bed Reactor

* In generic terms, the goal was to put the power of the Hoover Dam (2 GW) in the volume 2/3 the size of a 55 gallon drum

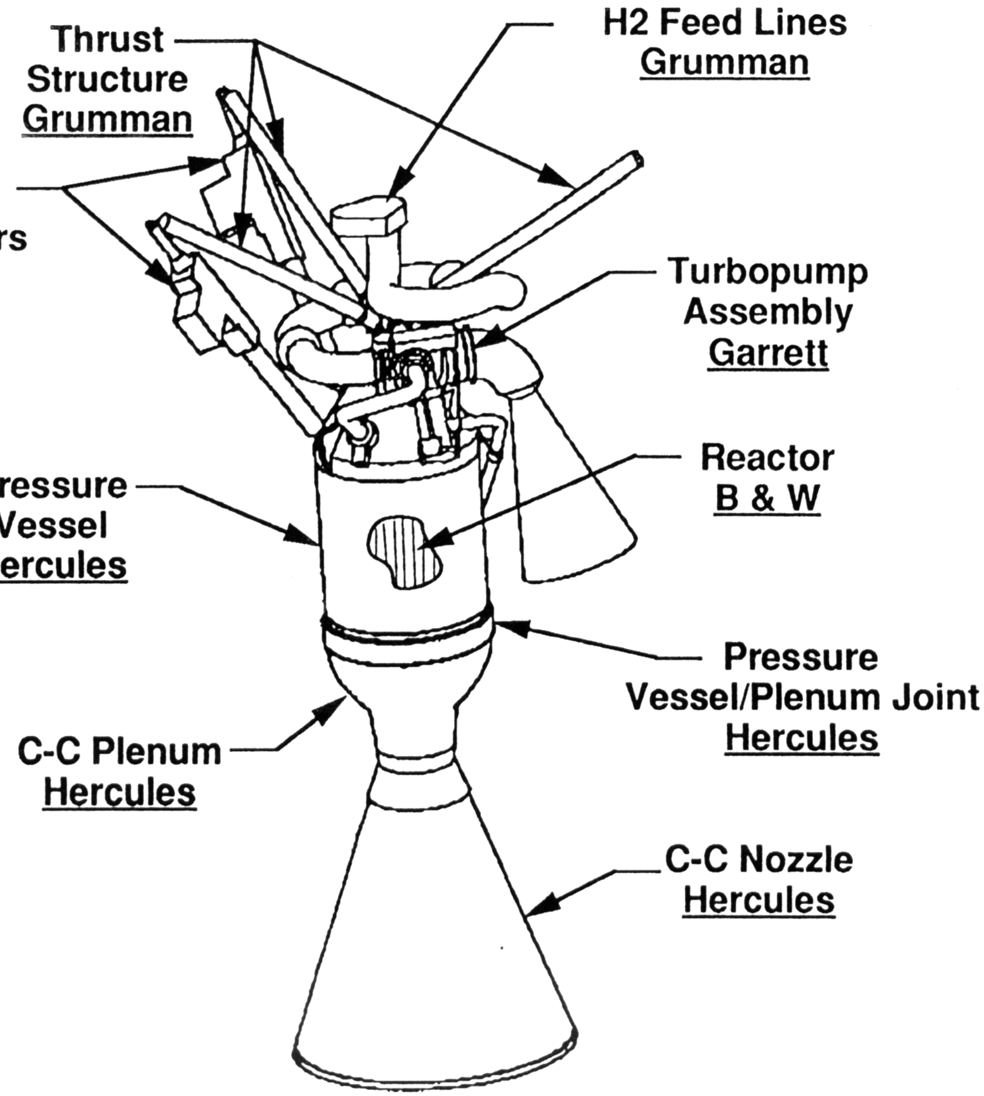
Timberwind Organizational Structure



Program Philosophy

- Select the technology: Particle Bed Reactor
- Ascertain deficiencies: In the PBR case, almost everything, but greatest discrepancy was lack of proven NTP fuel
- Keep the team small and focused at all times
- Design rapid, hard-hitting tests to determine shortfalls and success/failure routes
- Use the safety/EIS process to guide project direction
  - Define objectives clearly
  - Don't change direction
  - Follow the process
- Make that decision: When you have 450 people charging the case, you don't want them marching in place
- Don't belabor successes – concentrate on problems that the technical team cannot solve

SNTP PBR Engine Description



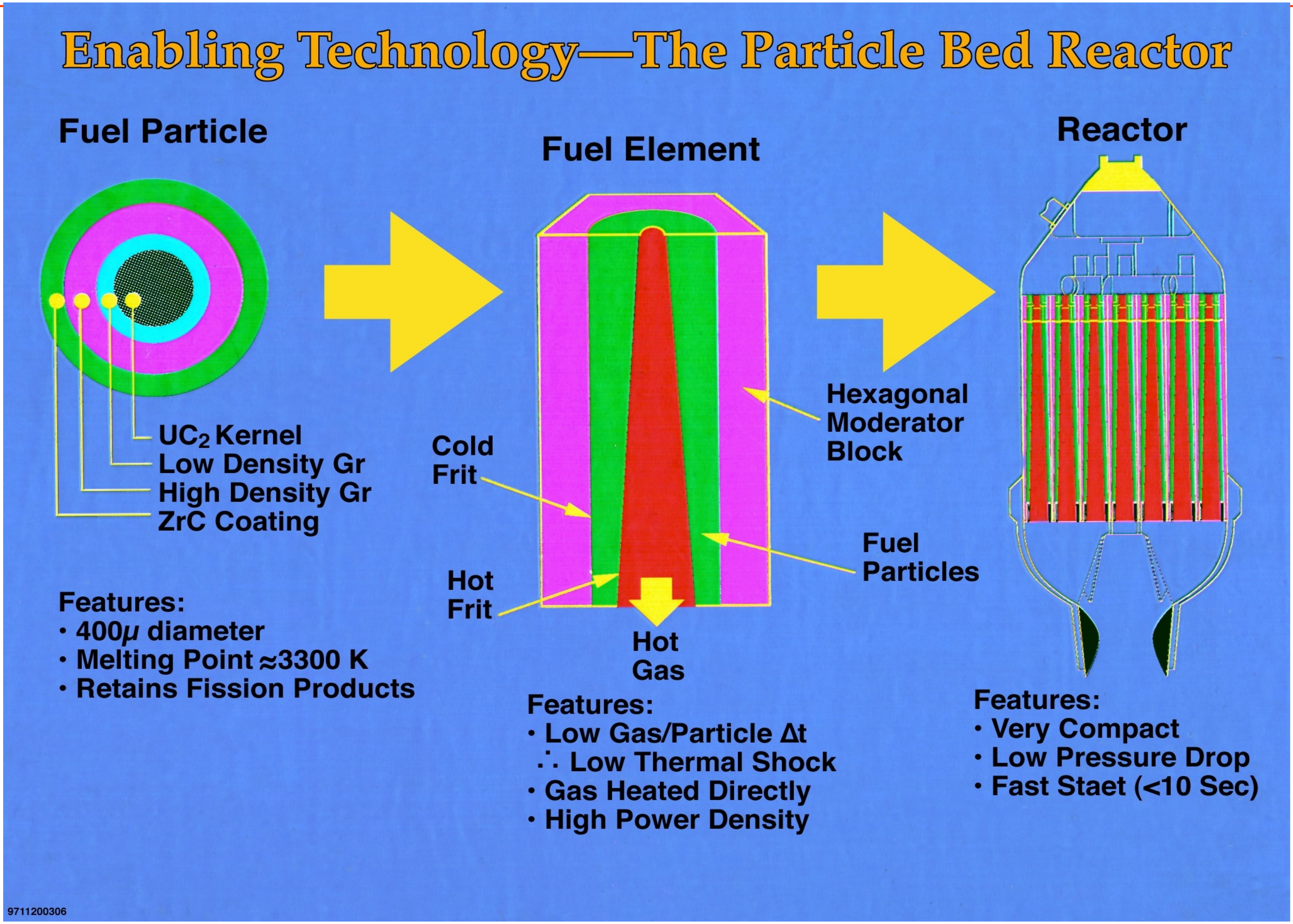
- **Design Goals:**
  - 20 - 80 klbf Thrust
  - 900 - 1000 Sec Isp
  - 25 - 35:1 Thrust-to-Weight

SPACE NUCLEAR THERMAL PROPULSION

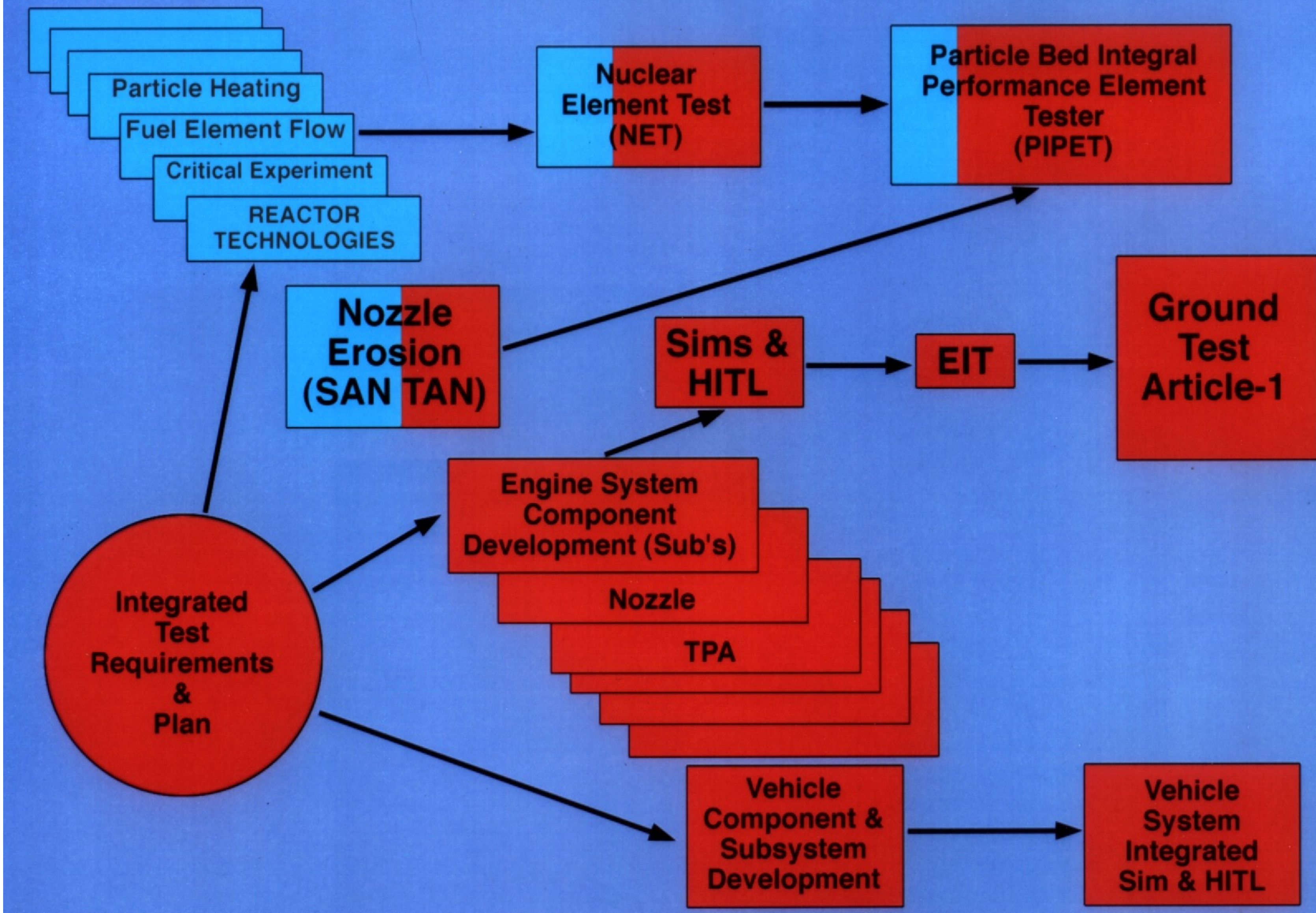
SNTP

Typical Engine Height ≈ 10 Ft (40 klbf Class)

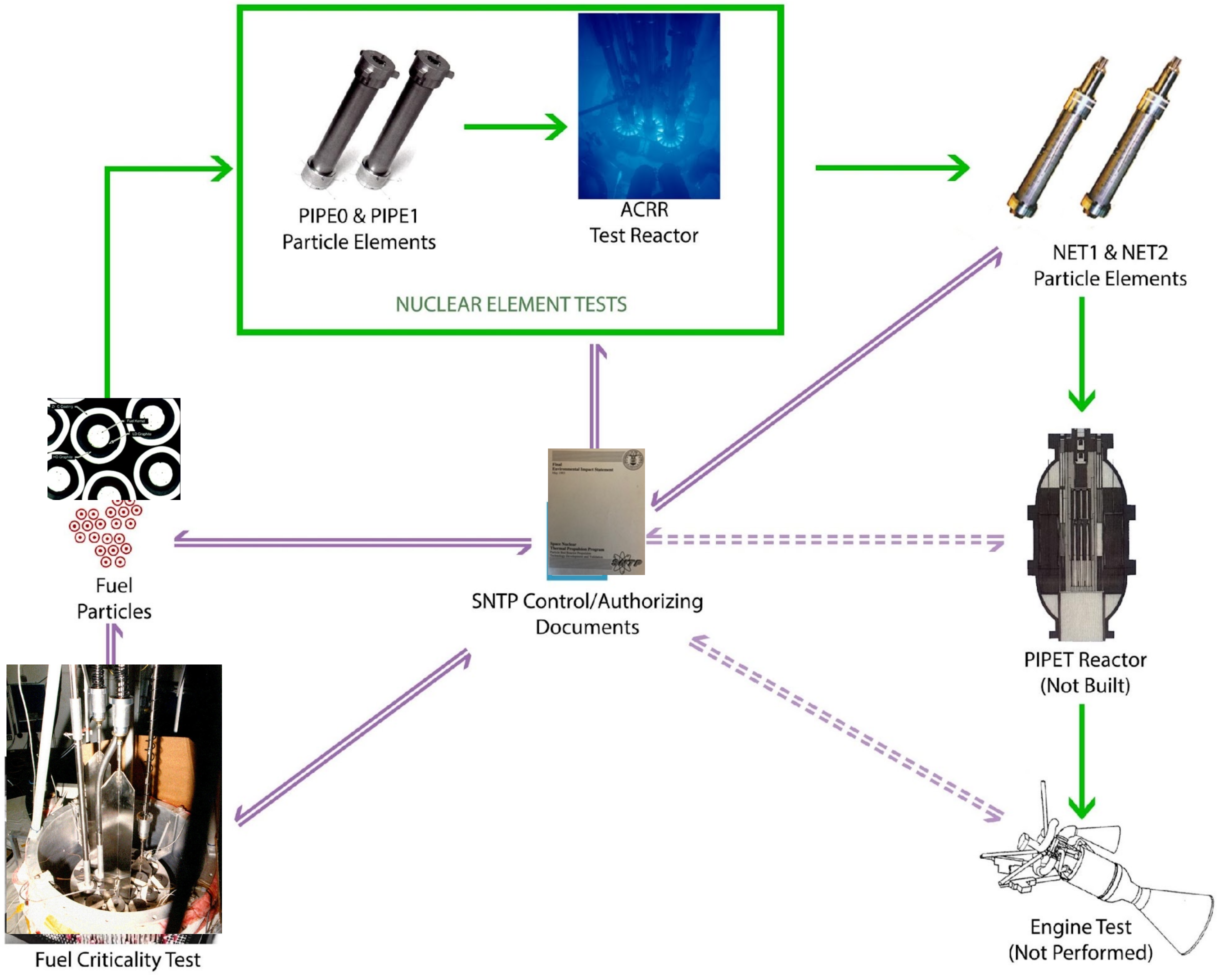
Particle Bed Reactor



Integrated Test Plan



Hardware Development Focused Around EIS and SARs



Prepared by A. X. Lenard

Some Observations

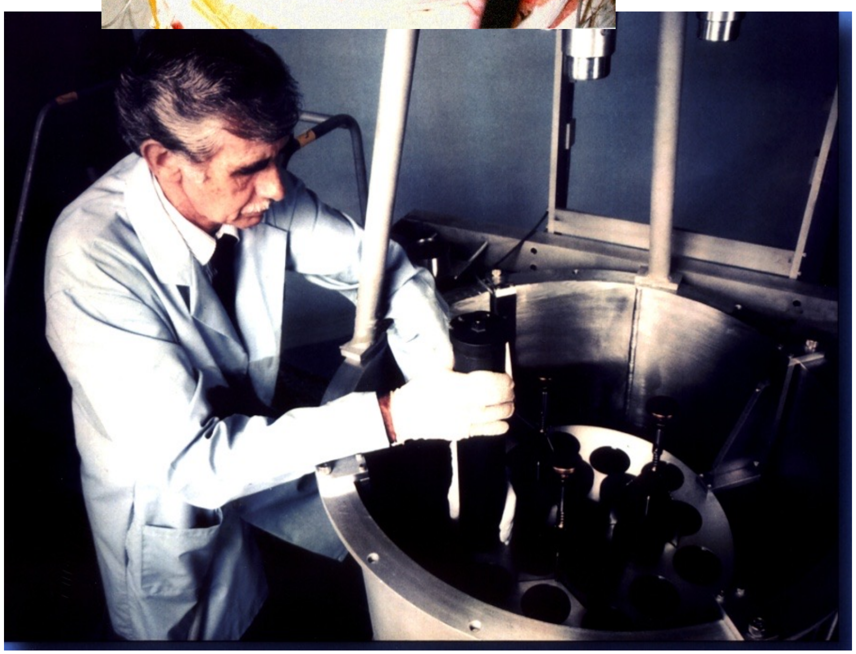
- The SNTP program had many firsts, developed substantial new hardware – focused on testing
- The critical experiment was of major importance both perceptually and in the determination of core performance
- CTE mismatches become extremely important when you have high temperature gradients – these are unavoidable with higher power densities
- New fuels can achieve NTP temperature requirements
  - UN appears to be a good selection for several reasons-works with LEU
  - Reticulated foams offer high power densities and an immobile geometry (no bed settling/reconfiguration during start stop cycles)
  - UNbZrC fuel (FSU development) is good fuel, but only with HEU
- New MCNP and hydrocodes will assist greatly in flattening power profiles

Other Programmatic Accomplishments

- Program was reviewed by a DOD, SNTP specific, Defense Science Board (DSB), and briefed two other DSB's
- Program received a written commendation from the DSB for progress made for funds expended
- *Designed, licensed and began testing a new reactor (critical reactor) in less than 18 months*. First new reactor licensed in over 10 years
- Developed first ever EIS for conducting ground tests of nuclear thermal rocket (scrubbed exhaust)
- Performed complete process-Preliminary Draft EIS, Draft EIS, and Final EIS – Public Hearings
- Performed task for 1/35th the projected cost and 28% of the forecasted time

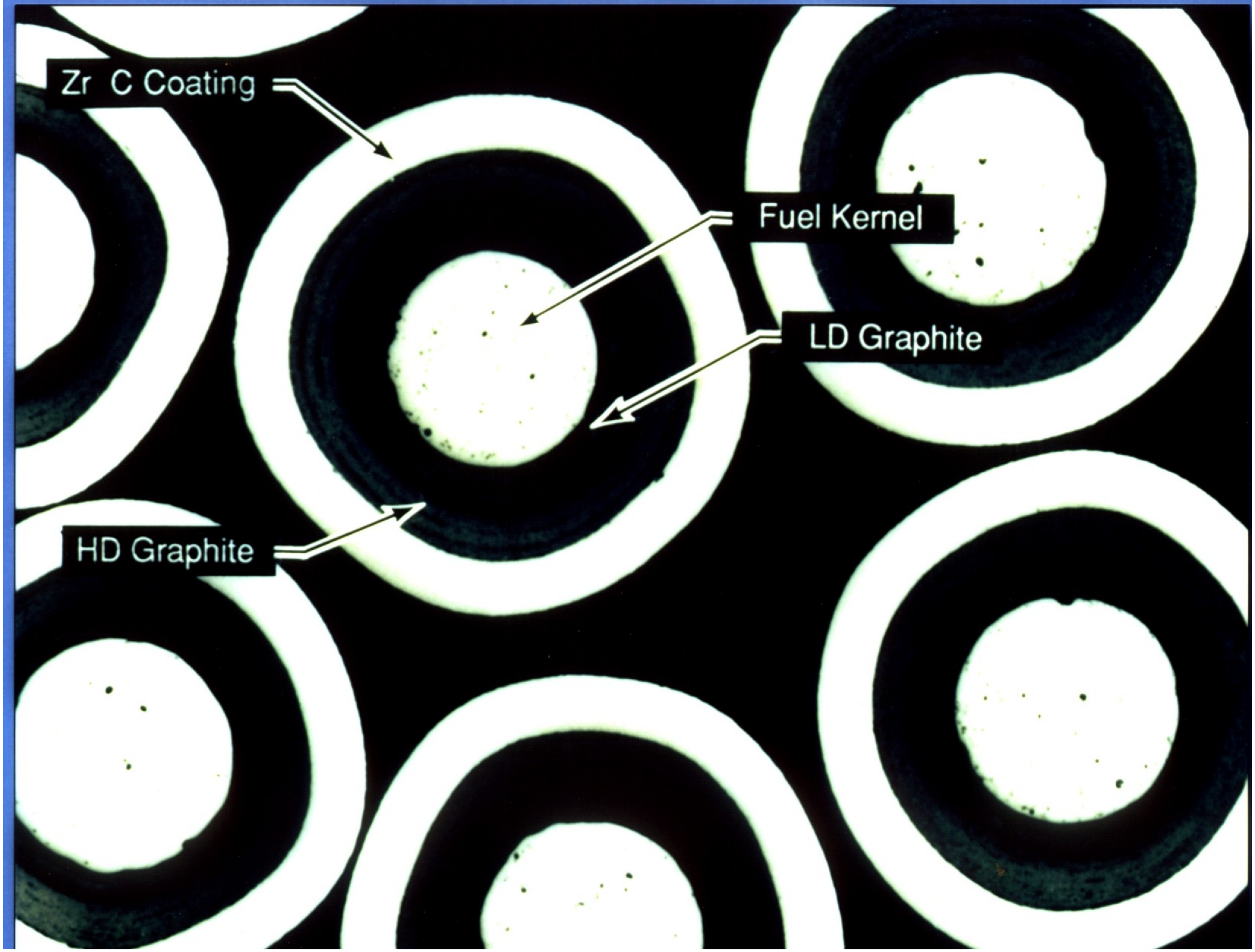
Supporting Slides

SNTP PBR Critical Assembly

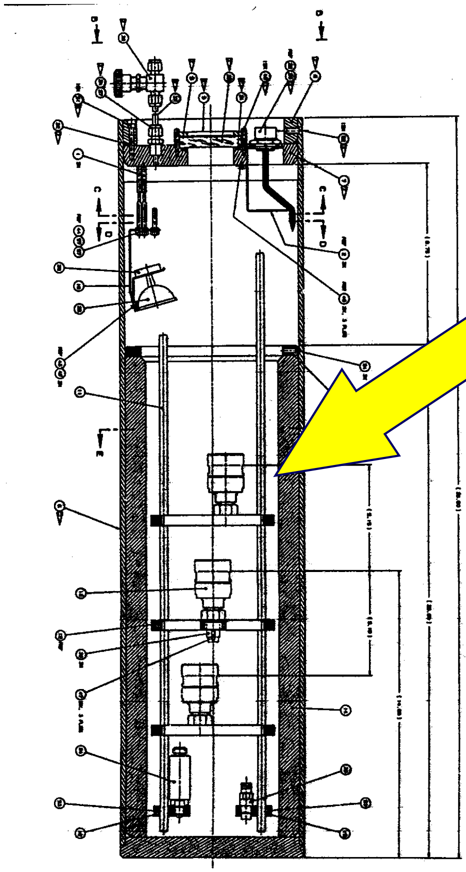


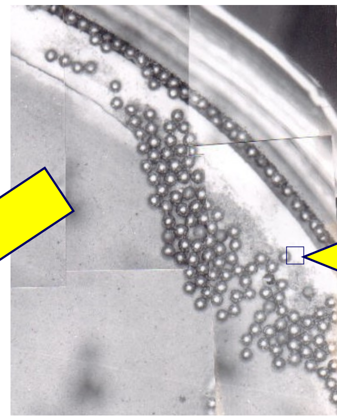
- Prototypic PBR assembly with fuel stalks
- Blended fuel to simulate ZrC coated TRISO
- Full test site SAR and independent review
- 18 months from start to first test
- $19M for assembly, fuel and safety reviews
- $6-7M for subsequent tests
- Tested at Sandia in SPR facility
- Test tank used for several other critical Assemblies – in use now

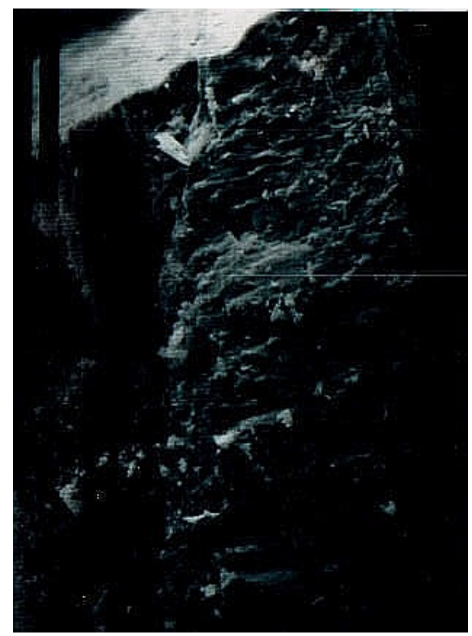
Prototypic Fuel Particles

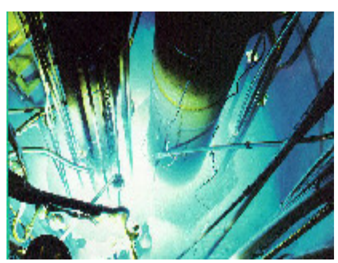


In-Core Particle Testing









PNT Accomplishments and Results

Accomplishments

- 4 Capsule Tests
- 12 Fuel Holders
- 200,000 Fuel Particle
- 1800 - 3100K
- 150 - 600 Seconds
- 1 - 4 Cycles
- Fission Product Release Measure

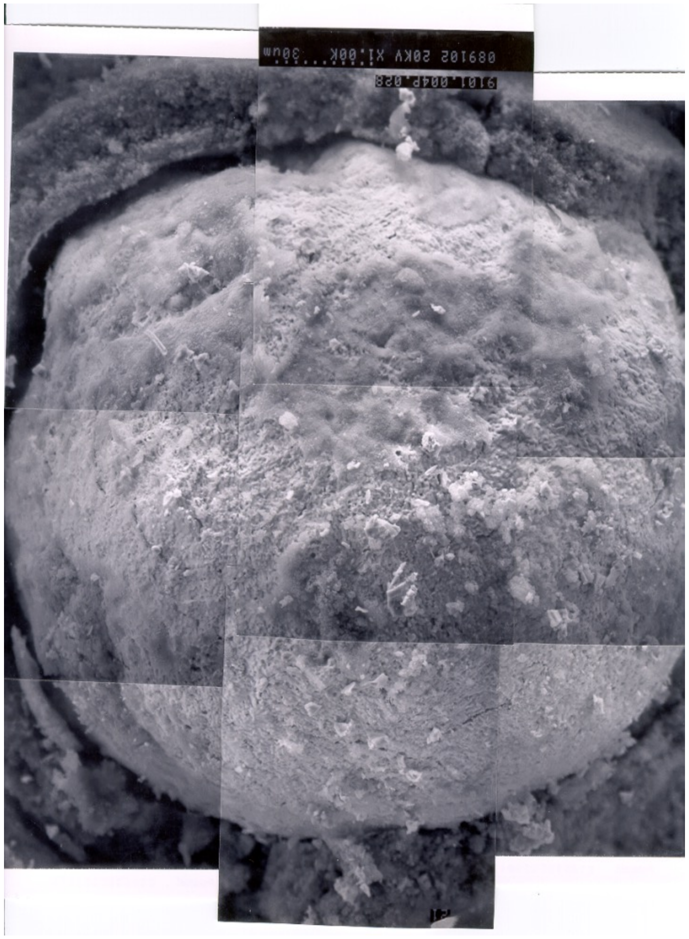
Results:

Performance Limits Determined For Baseline Fuel

Integrated Fission Product Release Model Operational

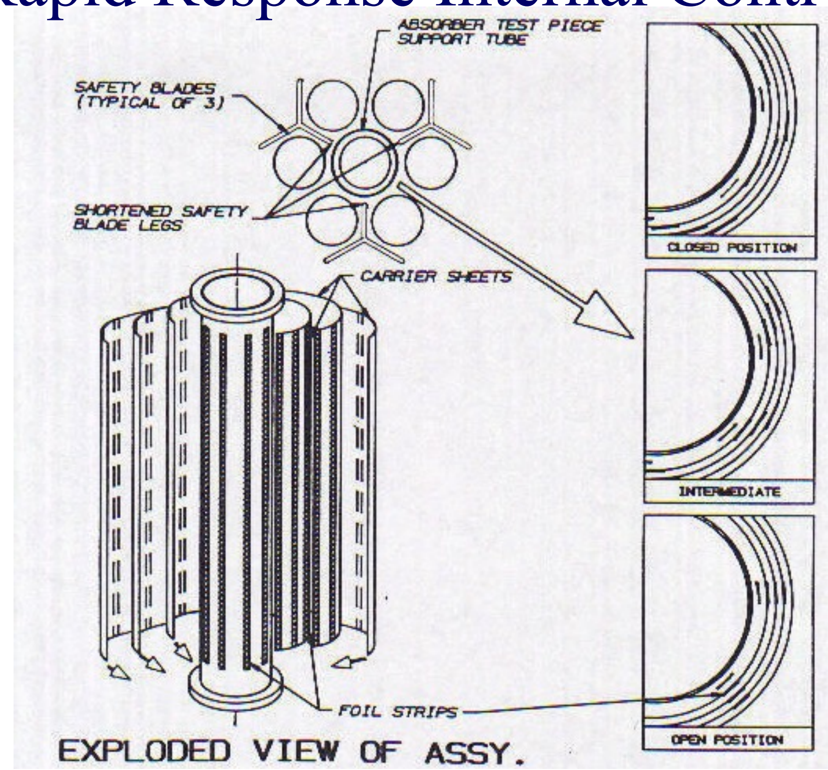
Lessons Learned

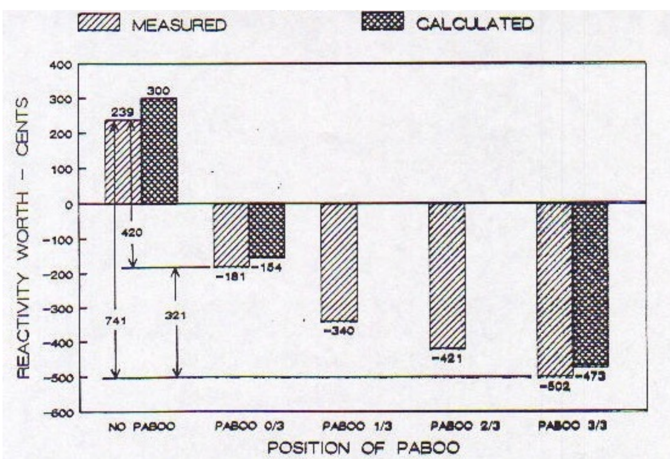
- If you don’t have the fuel ready-you don’t have bupkis
- Fission product retention will be exceptionally difficult in any material at 3000K, a reasoned discussion needs to occur to ascertain the virtues and liabilities of it as a requirement
- There are significant differences between in-core and ex-core testing; internal versus external heating
- Process knowledge and control is exceptionally important, you need to know what you did wrong as well as right
- *Toward the end of the program, we had a fuel particle that would operate satisfactorily for the original mission duration*



Some Significant Results

A Rapid Response Internal Controller

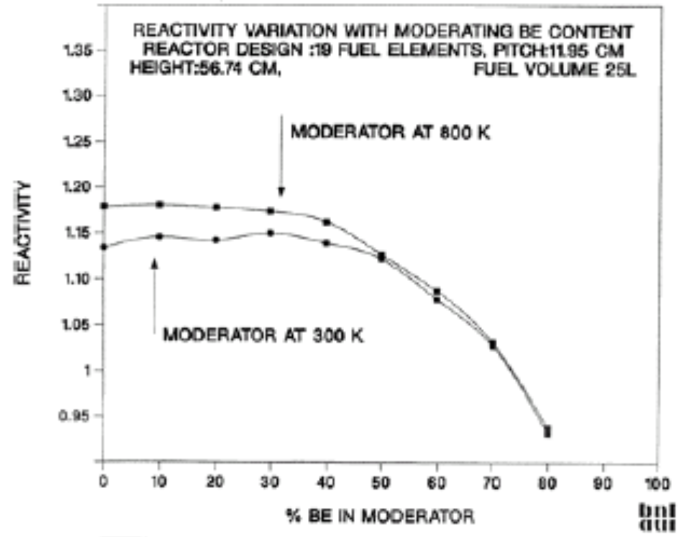




- Series 1: 10/23/89-10/27/89
  - 1st critical, safety and control
  - Reactivity worth; boron worth
- Series 2: 12/11/89-12/15/89
  - Pulse neutron reactivity
  - Moderator temperature coefficient 10-20C
  - Flux monitor tests
- Series 3: 1/15/90-1/19/90
  - Peek-a-Boo Experiment
  - Poly-filled void reactivity worth
- Series 4: 10/4/90-10/12/90
  - Fission density/power calibration
- Series 5: 10/29/90-11/2/90
  - Stalk swap
  - Moderator temperature coefficient 20-80C
- Series 6: 3/91
  - Warm rho
- Series 7: 4/91
  - Hot rho

Lessons Learned

- Rapid prototyping is extremely important – we got a new reactor running
- Exceptional team-building experiment
- Tremendous external appeal, particularly to review and safety boards
- It doesn't't need to take a long time
- It doesn't't need to cost a lot
- You'd be surprised at the new things you learn by doing real hardware

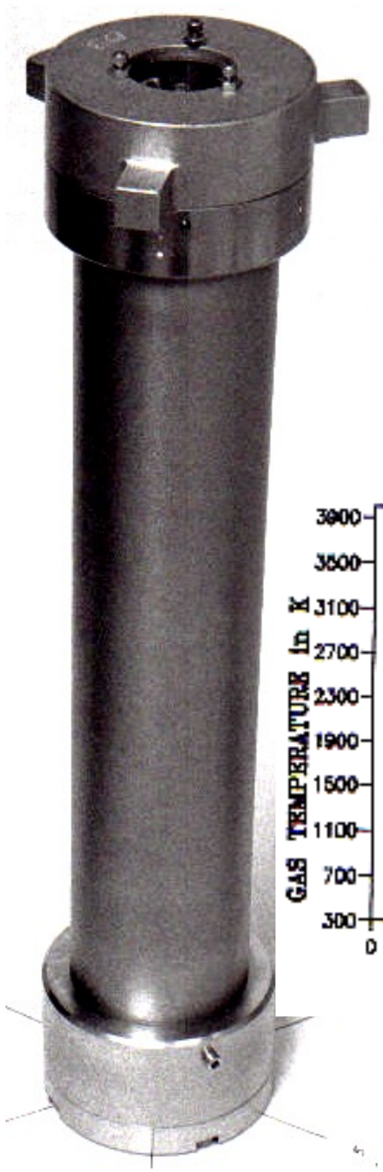


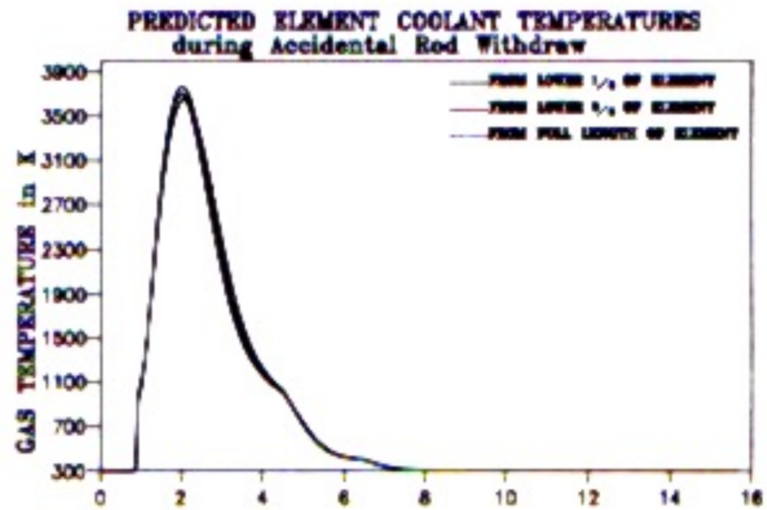
SNTP CX

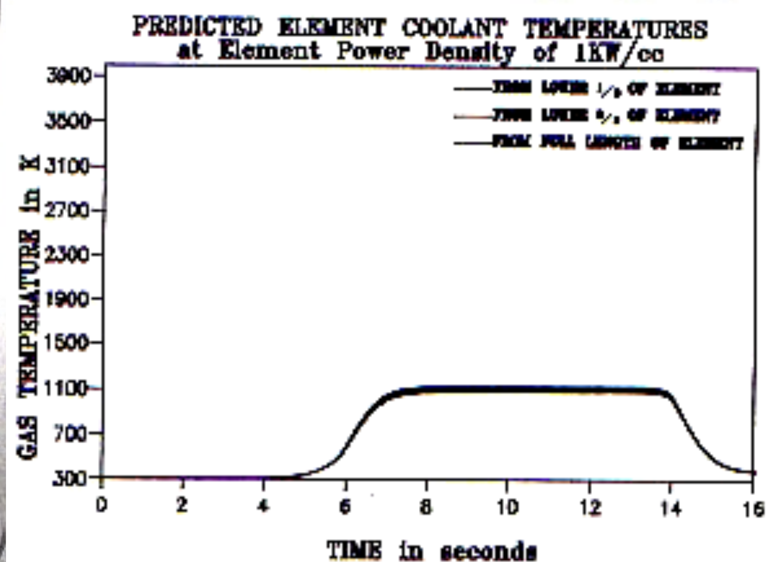
What do you mean it
Has a positive temperature
Coefficient ##$%^&**()!!!

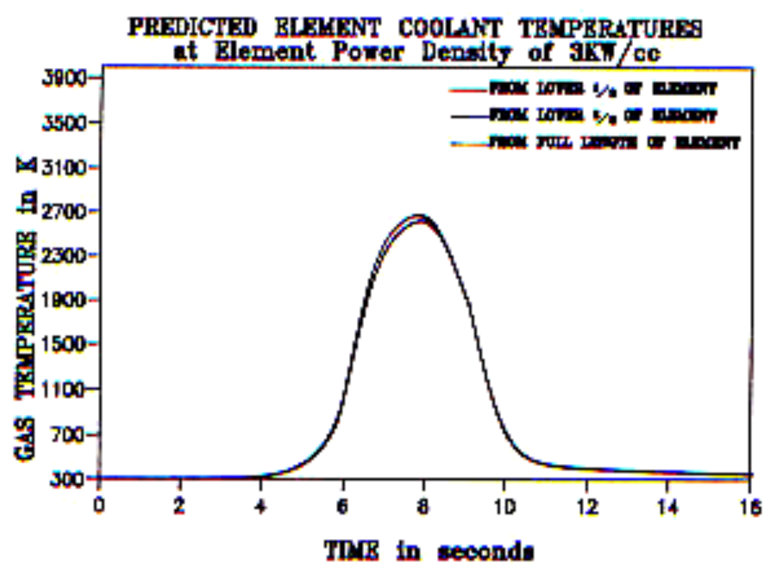
But it's only over
a narrow range

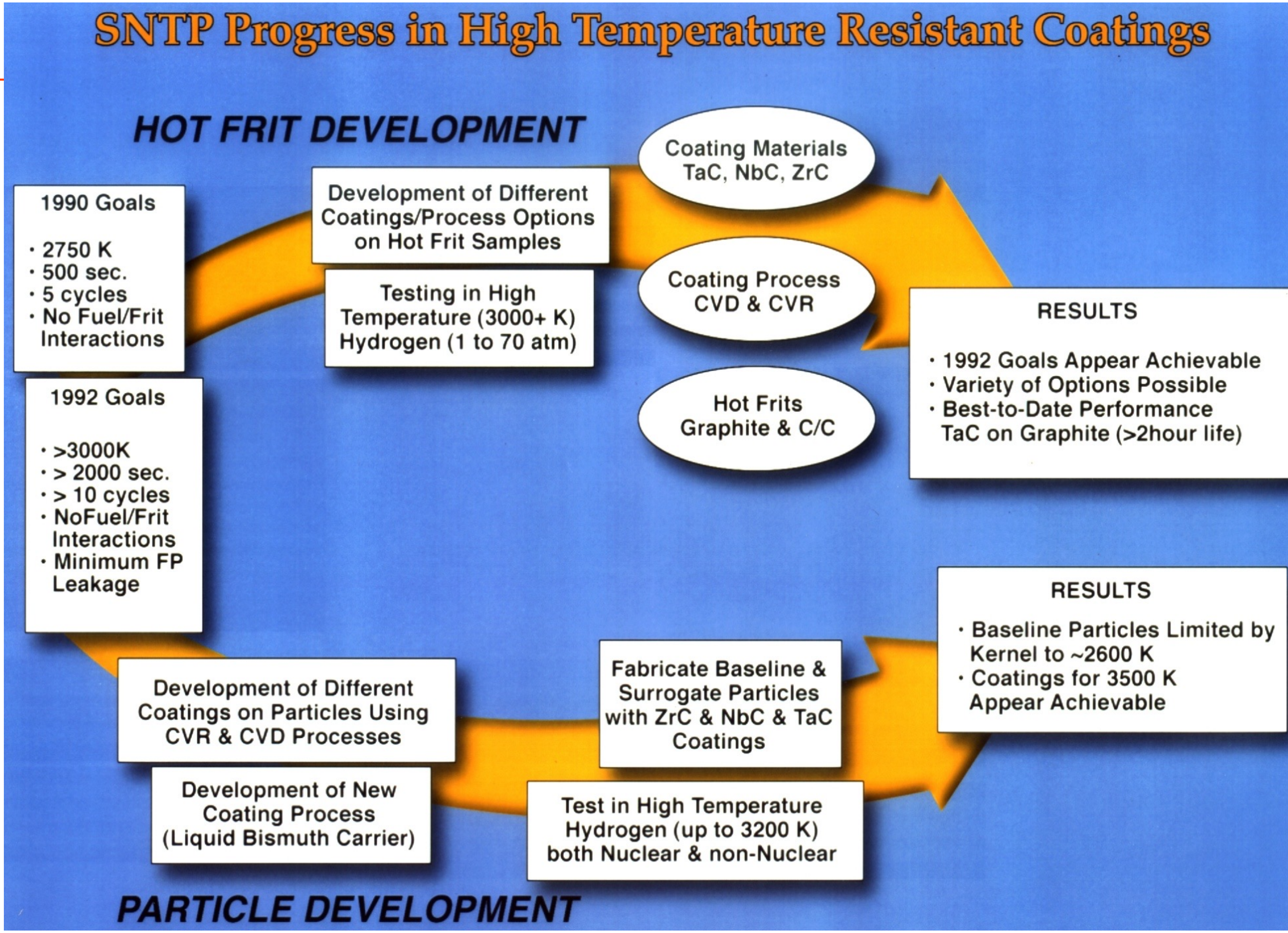
In-Core Element Testing







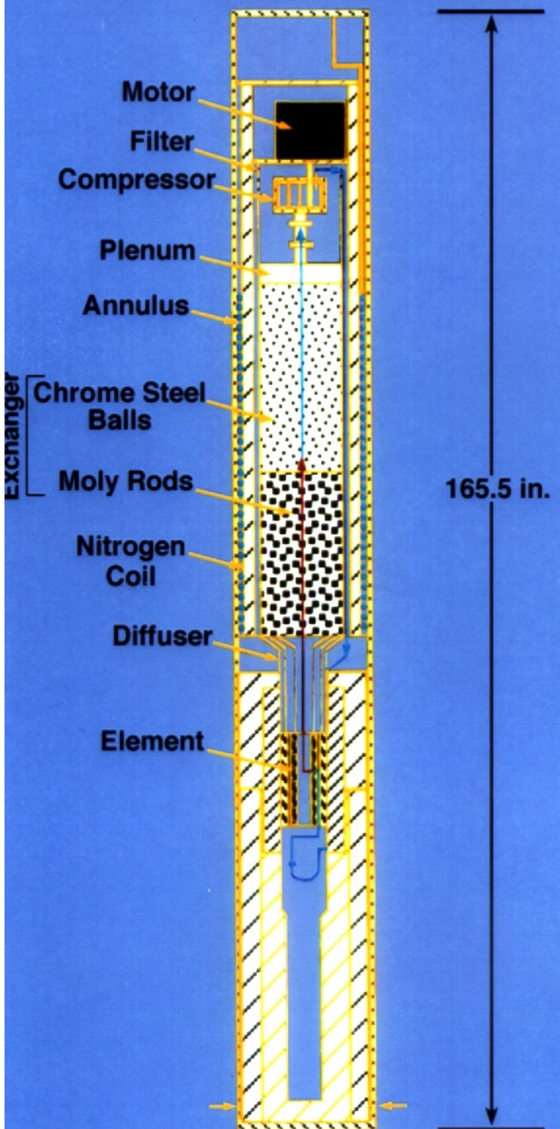



SNTP Progress in High Temperature Resistant Coatings
HOT FRIT DEVELOPMENT
1990 Goals
• 2750 K
• 500 sec.
• 5 cycles
• No Fuel/Frit Interactions
Development of Different Coatings/Process Options on Hot Frit Samples
Testing in High Temperature (3000+ K) Hydrogen (1 to 70 atm)
Coating Materials TaC, NbC, ZrC
Coating Process CVD & CVR
Hot Frits Graphite & C/C
RESULTS
• 1992 Goals Appear Achievable
• Variety of Options Possible
• Best-to-Date Performance TaC on Graphite (>2hour life)
1992 Goals
• >3000K
• > 2000 sec.
• > 10 cycles
• NoFuel/Frit Interactions
• Minimum FP Leakage
Development of Different Coatings on Particles Using CVR & CVD Processes
Development of New Coating Process (Liquid Bismuth Carrier)
Fabricate Baseline & Surrogate Particles with ZrC & NbC & TaC Coatings
Test in High Temperature Hydrogen (up to 3200 K) both Nuclear & non-Nuclear
RESULTS
• Baseline Particles Limited by Kernel to ~2600 K
• Coatings for 3500 K Appear Achievable
PARTICLE DEVELOPMENT

Nuclear Element Test (NET)

Closed loop, in reactor test of a complete fuel element in cryogenic hydrogen

NET Test Module Schematic



GOALS:

- Demonstrate integration of fuel element technologies
- Test to full temperature capability
- Validate fuel ele,emt designs
- Support
  - PIPET/GTA development
  - Fuel development
  - Model verification
  - Safety analysis

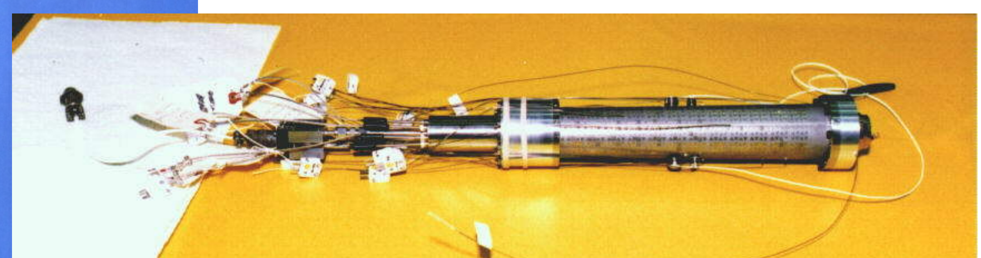
ACCOMPLISHMENTS:

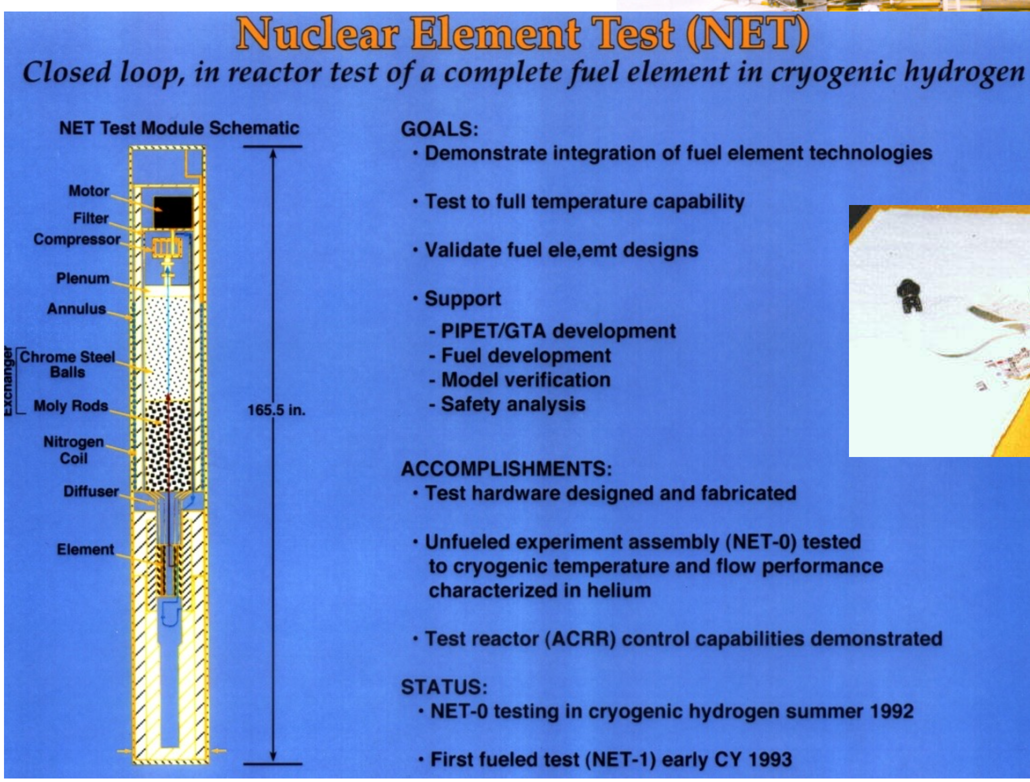
- Test hardware designed and fabricated
- Unfueled experiment assembly (NET-0) tested to cryogenic temperature and flow performance characterized in helium
- Test reactor (ACRR) control capabilities demonstrated

STATUS:

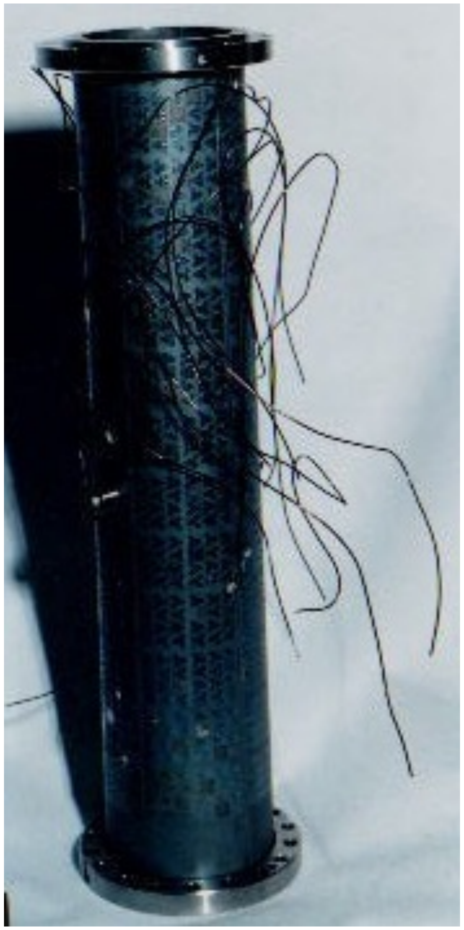
- NET-0 testing in cryogenic hydrogen summer 1992
- First fueled test (NET-1) early CY 1993

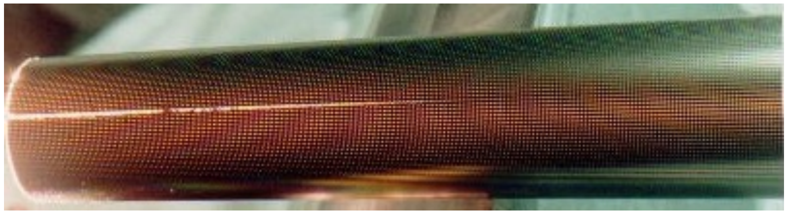
In-core Fuel Element Testing





Post-test Hardware

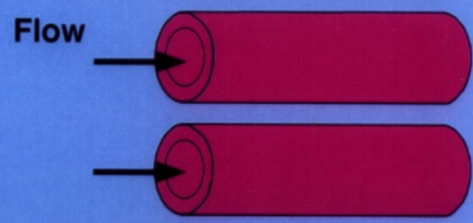
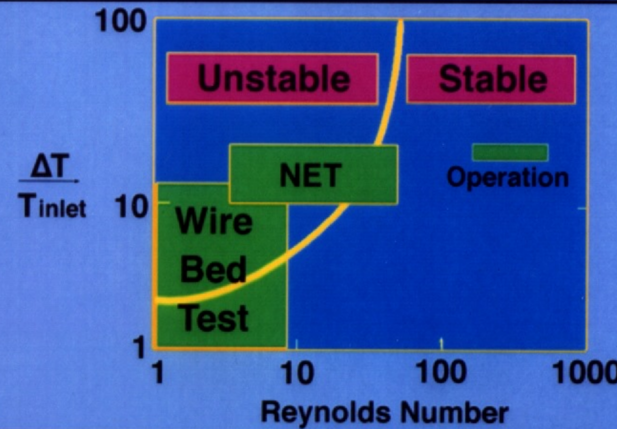




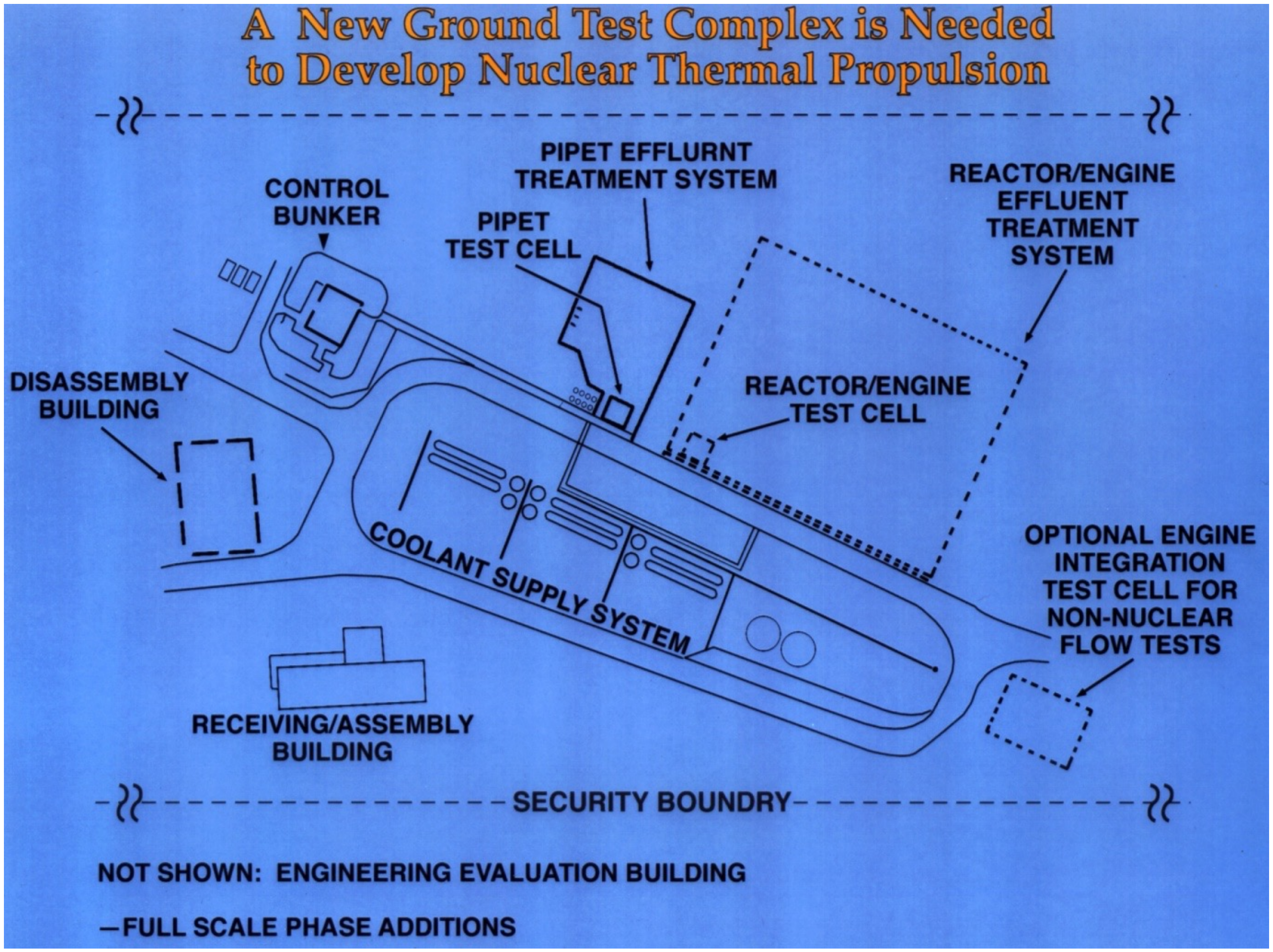
Post-Irradiation Evaluation

- The hot frit stress fractured
  - Un relieved CTE mismatch
  - Error in engineering design
- Design fixes were identified
  - -Termination of many (Clinton) SDI space programs prevented furthe hardware development
  - Nuclear portions of program were decommissioned

Thermal Hydraulic Design Validation Process

Task	Approach	Results
• Scoping Analysis (Conservative 1-D)	• Model Flow through parallel heated tubes 	
• 2D & 3D Analysis	• SIMBED code (Bnl) • TEMPEST code 9PNL/B&W) • FLOW 2D code (SNL) • PBRFLOW code (Grumman)	• Flow through bed is stable • Must prevent back conduction to cold frit
• Modify Cold Frit Design	• Insulate platelet frit from particle bed	
• Benchmark Codes	• Electrically Heated Wire Bed Test • NET series • PNT-3 series • Special Effects Tests	• To be in June, 1992 • NET start at end of 1992 • Ongoing • Ongoing
• Code Validation	• NET - Low Flow • PIPET - All prototypical conditions	• NET - End of 1992 • PIPET - Approx. 1995

Completed Title-I Design EIS PBR Test Facility



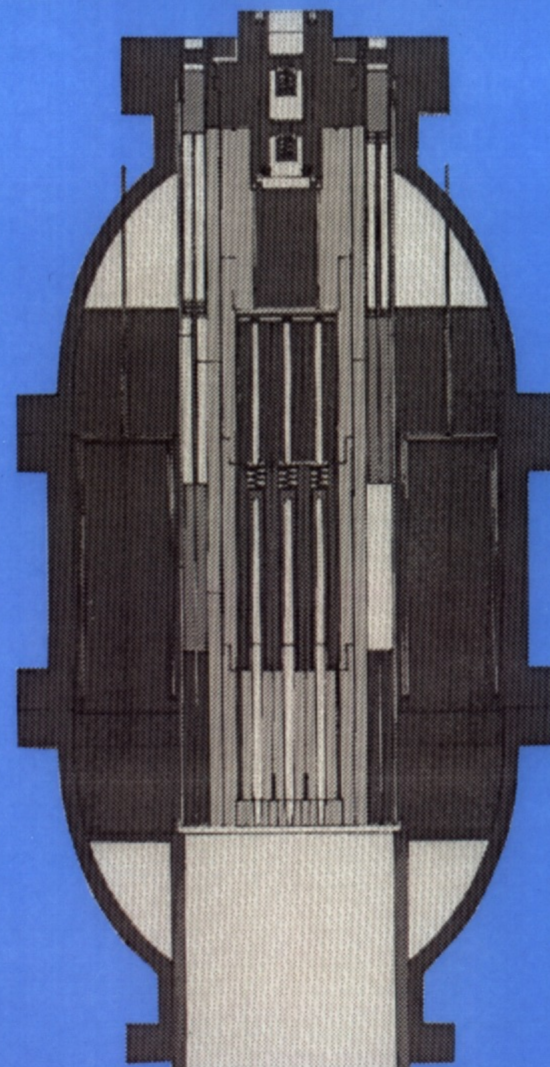
Saddle Mountain Test Station

- Phase I 550 MW_{th} PIPET
  - 2000-3000 s run times
  - ~ 50 MW/l power density
  - Confined test; numerous filters and scrubbers modest release fractions
- Phase II 2 GW_{th} Engines
  - 1000 s run times
  - 2-week intervals
  - 75,000 lb_f thrust
  - Confined test
- Completed Ground Test EIS and all supporting Documents
- Completed all public hearings
- Safety Analysis Reports
- $200M Phase I Test
- Phase II Facility Cost: TBD

PIPET

Fuel Element and Test Reactor Objectives

- Demonstrate Fuel Element Performance and Operability Under Prototypical Conditions.
- May be Used as a Test Bed to Help Resolve Other SNTP Program Technology Issues
- Support for Testing of Alternative Fuel Concepts



Summary

- Design – build – test: The only method to have a good final concept
- A tested fuel form is the foundation of an NTR – without it you have no program
- SNTP accomplished multiple hardware tests that provided clarity to many unknowns
- A ground-test EIS completed - major programmatic milestone
- May have available facility to test nuclear rocket engine

POST SNTP Advances

- Since SNTP, there have been some technical advances that NTR development easier
- But, the physics for a NTR have not changed
- Operational multi-use NTR does not require the very high power densities of the Timberwind concept-reduced risk
- Lessons-learned fostered some changes
  – High Assay Low Enriched Uranium (HALEU)
- Building an NTR is easier than before