Affordable Development and Qualification Strategy for Nuclear Thermal Propulsion

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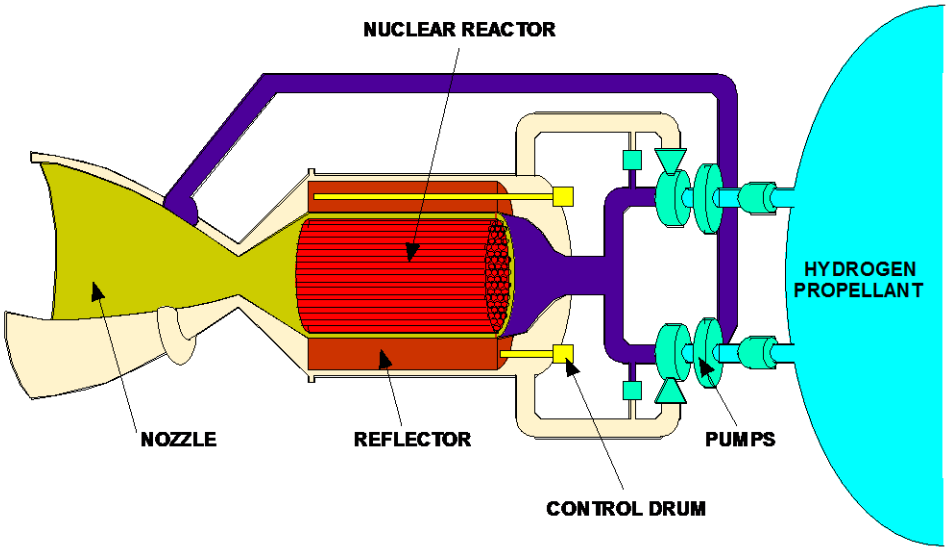
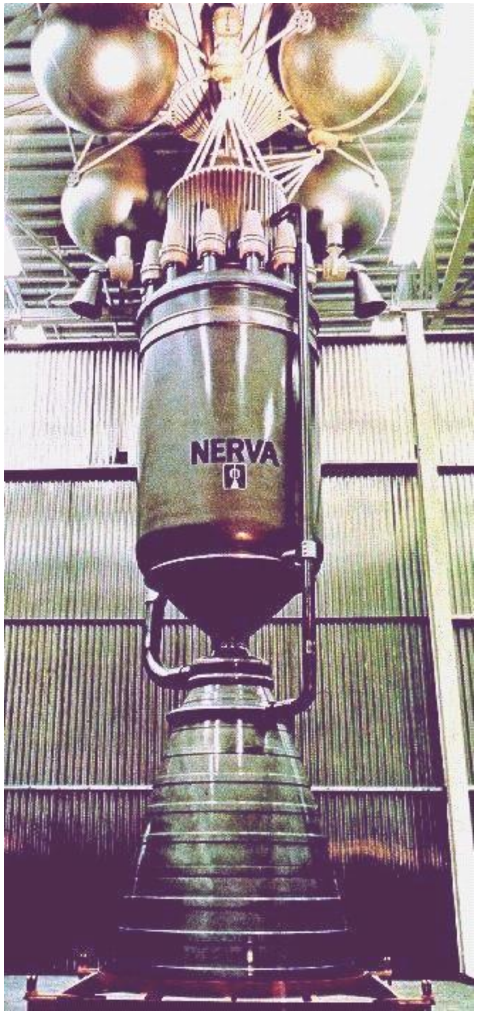
Agenda

- How does NTP work
- Lessons learned from past programs
- Development needs
- Programmatic considerations
- Fuels development
- Ground testing
- Other development needed
- Possible prototype flight test
- Logic flow for cost and schedule
- Summary

How does Nuclear Thermal Propulsion (NTP) Work?



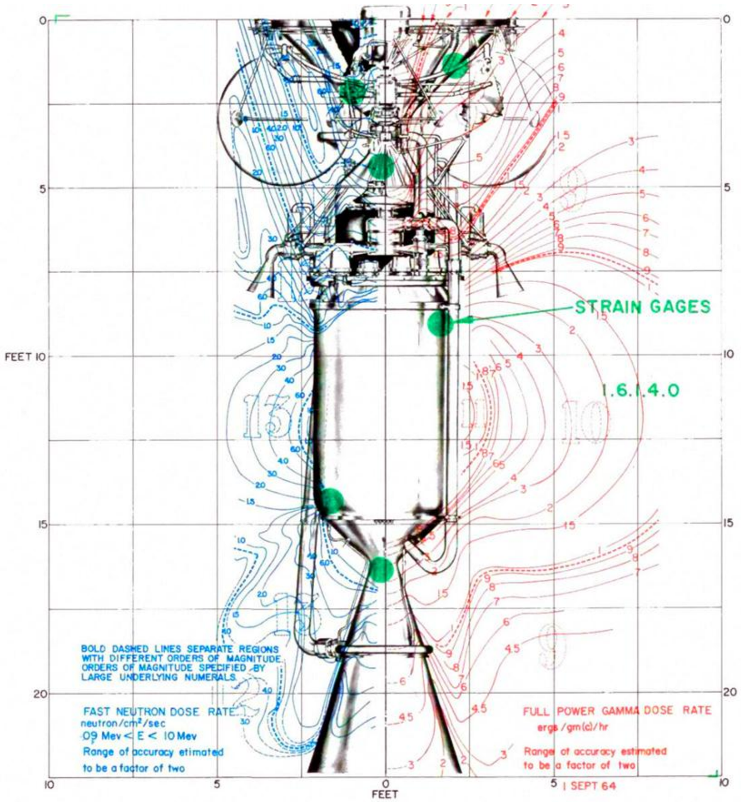
Major Parts of a Nuclear Thermal Rocket



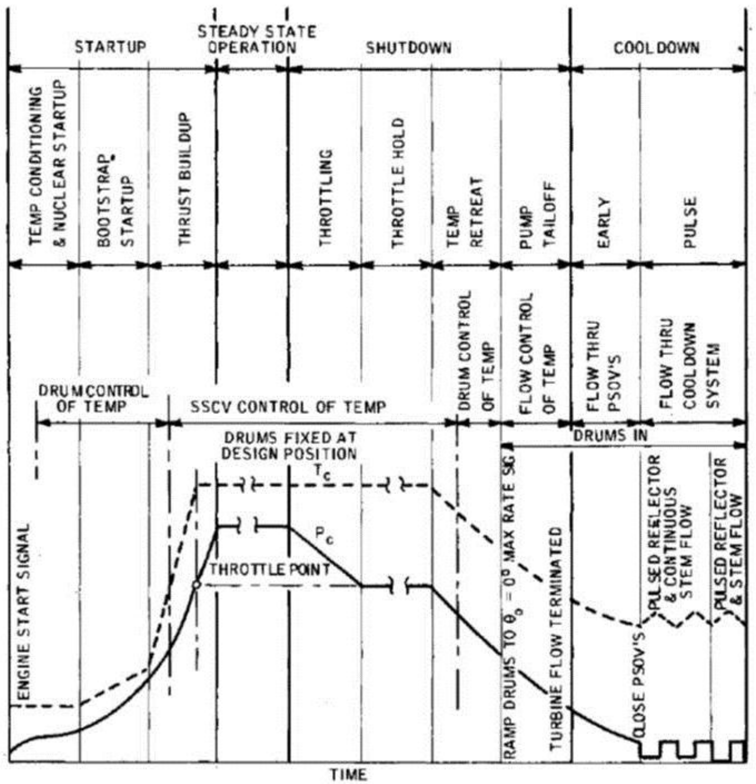
NERVA Nuclear Thermal Rocket Prototype

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor
- Specific Impulse directly related to exhaust temperature
- NTP Specific Impulse (~900 seconds) doubles over chemical rockets (~450second) due to lower molecular weight of propellant

How does NTP Work?



Predicted Radiation Profile for NTP



NERVA Engine Operational Phases

<u>Major differences between NTP and Chemical Propulsion:</u>

- NTP reactor exposes the engine components and surroundings with a radiation environment (gamma rays and neutrons), which drops with time after shutdown
- Long start-up (minutes) and extremely long shutdown (tens of hours for cooldown)

Lessons Learned from Past Programs

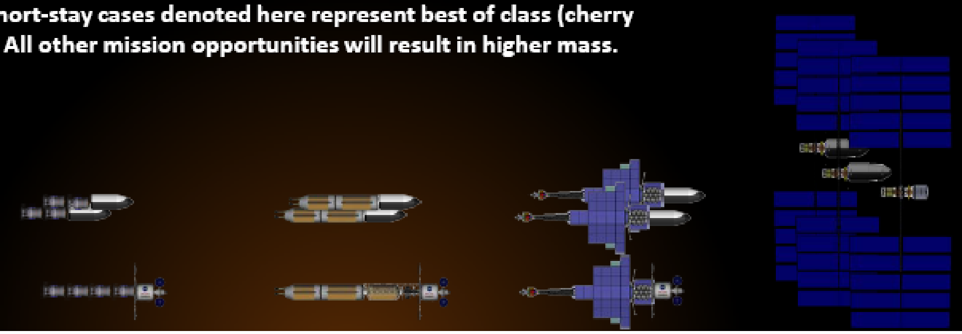
1. Technical feasibility of NTP established with Rover/NERVA program (1955-1973), Space Nuclear Thermal Propulsion (1987-1993), Cermet program (1960's to early 70's), and Russian (former USSR) fuel development program.
2. Several classes of fuels had the potential to meet the demanding requirements (e.g., carbon based and Cermet).
3. Heat transfer from fuel to propellant critical to maximize performance. Various fuel geometries investigated in the past (e.g., hexagonal cross section with multiple through holes, particle bed, twisted ribbon).
4. Current engine design requirements within limits of past programs.
5. Rates of fuel erosion acceptable in the past, but not acceptable today.
6. Other non-nuclear engine components (e.g., turbopumps, valves, etc.) have been qualified for chemical engines. Influences from radiation exposure is small and generally understood from past NTP tests.
7. Many mission analysis studies have been done in the past to determine how best to utilize NTP.
8. Past NTP programs terminated before flight test due to lack of mission.
9. Numerous program starts and stops wastes effort and causes work to be redone by new teams.
10. Recent lessons learned from the J-2X program (human rated in-space chemical engine)

Cost

CAUTION "Easy" short-stay cases denoted here represent best of class (cherry picked). All other mission opportunities will result in higher mass.

Cargo Missions

Crew Mission



	Chemical Propulsion		Nuclear Thermal		Nuclear Electric		Solar	
Parameter	"Stressing" [1] Long-Stay	"Easy" Short-Stay	"Stressing" [1] Long-Stay	"Easy" Short-Stay	"Stressing" [1] Long-Stay	"Easy" Short-Stay	"Stressing" [1] Long-Stay	"Easy" Short-Stay
Total Mass (mt)	~1,250	~1,460	~890	~860+	~770	~960	~780	X
# SLS Launches	~12	~13+	~9	~9+	~7	~9+	~7	X
SLS delivery to LEO (mt)	105 & 130	105 & 130	105	105	105 & 130	105 & 130	105 & 130**	X
SLS Shroud Dia./Barrel	10 / 22	10 / 22	10 / 25	10 / 29	10 / 25	10 / 25	10 / 15	X
Launch Spacing (days)*	50-120	10-110+	70-150	70-150	90-200	70-150	90-200	X

"Hard" Long Stay - Represents most stressing conjunction class (2037 long-stay) mission. Typical mission values will be less for other opportunities.
"Easy" Short-Stay - Represents the easiest opposition class (2033 short-say) mission. Values for other opportunities will vary greatly and will be much more stressing.
* Launch spacing lower/upper values represent spacing required for crew missions every opportunity (26 months) & every-other opportunity (52 months) respectively + 6 mo schedule margin.
**Depending upon SLS performance 1-2 ATV launches using a Ariane 5 class vehicle are required to provide consumables

Drake, B. G., "Human Mars Mission Definition: Requirements & Issues," presentation, Human 2 Mars Summit, May 2013

- **Latest Mars mission analysis shows fewer SLS launches for NTP vs chemical**
- **Cost saving from a single mission covers most of NTP development costs**

Engine	Thrust (lbs)	Period	Development Cost FY12
F-1	1500K	'59-'66	~$3.0B
SSME	470K	'72-'81	~$4.1B
J-2	200K	'60-'66	~$2.6B
RL10A-3	15K	'58-'63	~$0.9B

- **$7.6B FY13 invested in Rover/NERVA, but the investment covered a large variety of engine designs and test facilities. Current approach is focused on one small engine design and utilize a few existing facilities**
- **Developing chemical engines is also not cheap**

Development Needs

- Concept of Operations (Con-Ops) determines the overall functional activities which need to take place to design, develop, test, and fly a nuclear rocket. Identifying low TRL long lead components is critical.

- Engine requirements from mission analysis and NASA standards including human rating. JANNAF guidelines recommend 6 engines be developed for chemical engines, with 2 for flight certification.

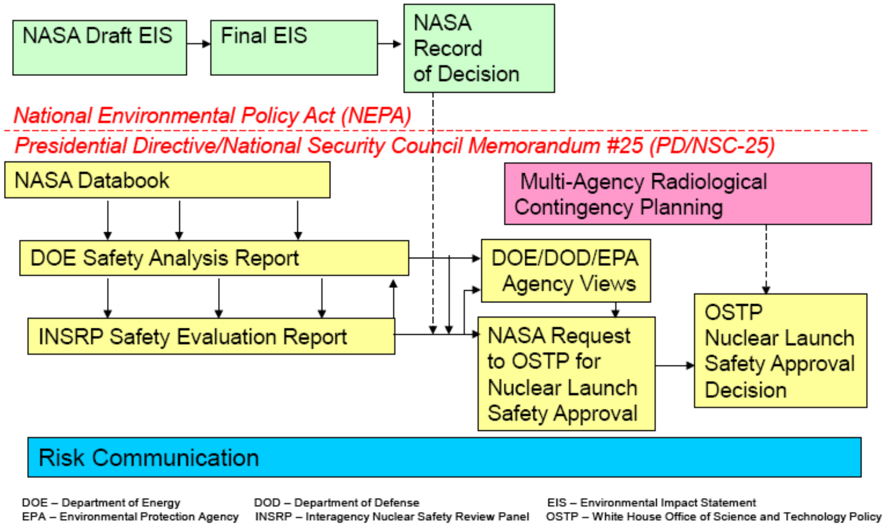
<u>Current NTP baseline design requirements:</u>

- Thrust ~ 25k-35k lbf
- Isp ~ 900 seconds with hydrogen
- Longest single burn ~ 45 minutes
- # Start-ups ~ 4
- Cumulative run time ~100 minutes

Development Needs (Cont'd)

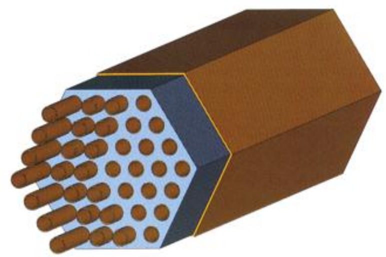
- Status of database from past work
  - Rover/NERVA Program: 20 reactors built and tested. 44 MWt to 4100 MWt. Operation from a few seconds to a few hours (cumulative). Peak temperature attained was 2750K in composite fuel. One unresolved issue was the leakage of fission products from the coated fuel.
  - Cermet Program: UO_2 particles embedded in tungsten matrix. Fuel tested very well in non-nuclear and nuclear environments. Never made a reactor test before cancelled. Added safety advantage with inherent sub-criticality under water.
  - SNTP Program: modified TRISO particle with UC_2 kernel and various coatings. Several non-nuclear and irradiation tests performed. Early tests showed flow instabilities needing more work.
  - Russian (former USSR) Program: extensive nuclear and non-nuclear tests on a variety of fuels. Reported 3100K achieved. Difficult to verify results.
- Key development items needing long lead development effort
  - Start with two candidate fuels (composite and cermet) before down select.
  - Full-scale NTP ground test facility with fission product containment.

Programmatic Considerations

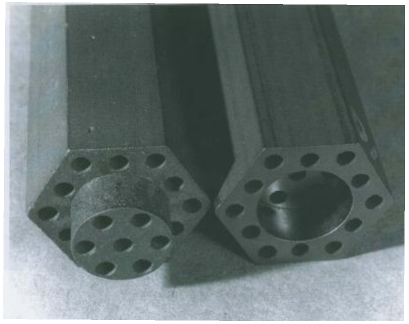


- National Space Policy regarding space nuclear power requires a nuclear safety launch approval process with approval by the president or his designee
  - Requires Nuclear Environmental Policy Act (NEPA), Presidential Directive/National Security Council Memorandum #25(PD/NSC-25), radiological contingency planning, and risk communication.
  - Processes have been previously used for radioisotope thermoelectric generators (RTG's).
  - Similar process will be used for NTP.
  - Cost and schedule understood.
- Safeguards and Security
  - Previous NTP programs used highly enriched uranium with U235 quantities identified as category 1 and requires top national security.
  - Current strategy investigating engine designs with lower U235 quantities having lower strategic significance to reduce the security cost and complexity.

Fuels Development

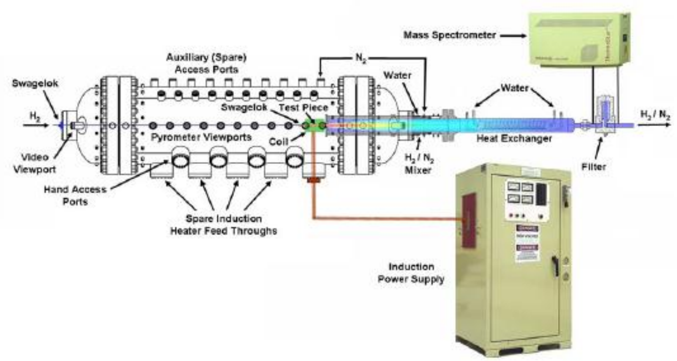


UO$_2$/W Cermet Fuel



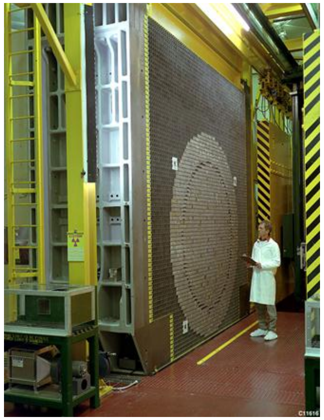
NERVA Composite Fuel

- The performance criteria that will be imposed on the fuels are listed below.
  a) Fabrications with acceptable quality assurance and control
  b) Temperature stability (>2700K for 1000+ s)
  c) Mechanical/Structural strength
  d) Chemical compatibility with hot hydrogen
  e) Transient performance (multiple restarts)
  f) Comfortable margins to failure
  g) Fission product retention under operating conditions
  h) Easily adaptable to bimodal applications in the future
  i) Robustness for use in wider applications (e.g. high power steady state or nuclear electric propulsion systems)
- Candidate fuels will be examined under non-nuclear tests, irradiation tests, and zero power tests.



Non-nuclear Fuel Tests

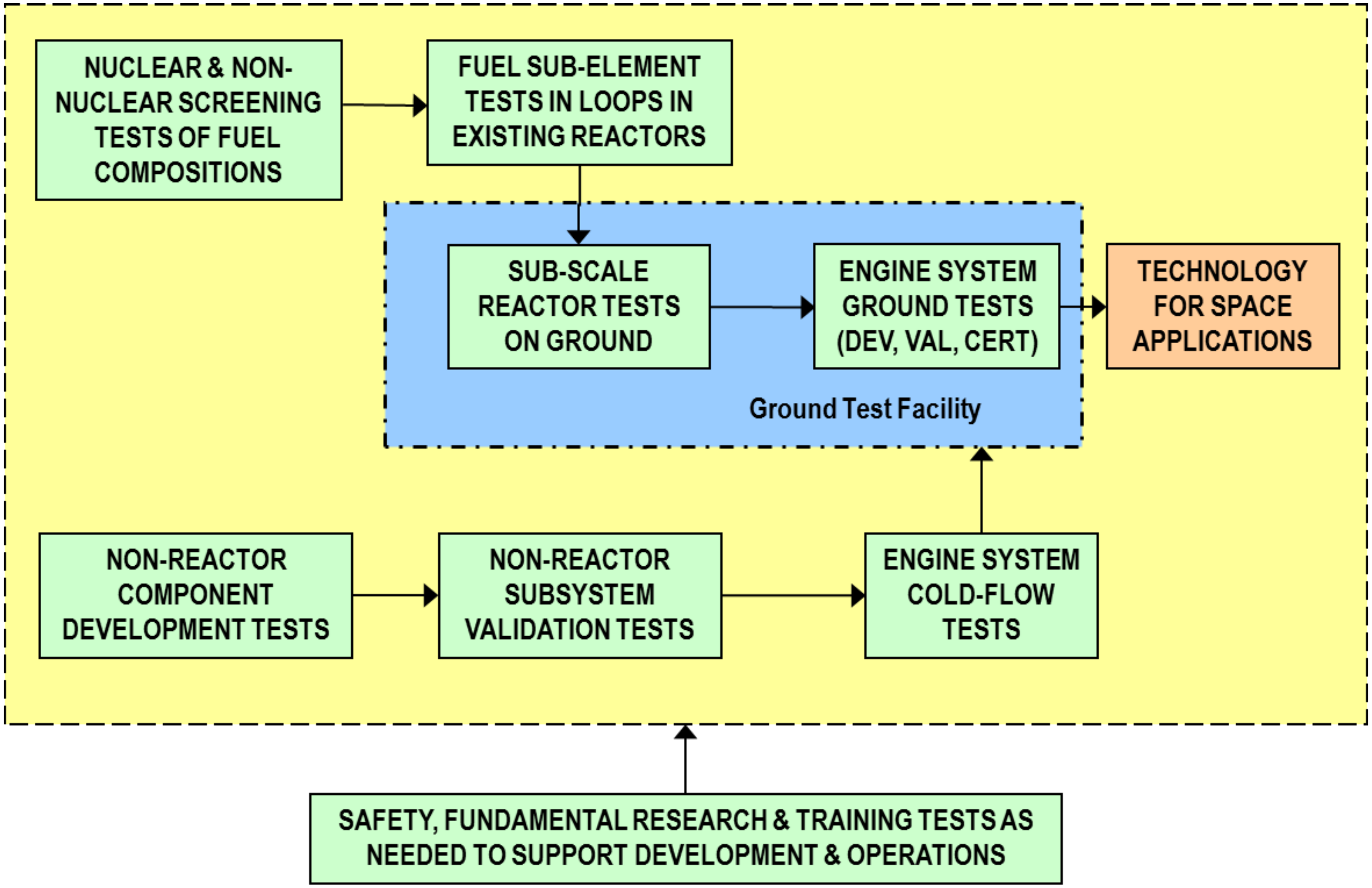
Irradiation Tests



Zero Power Physics Reactor

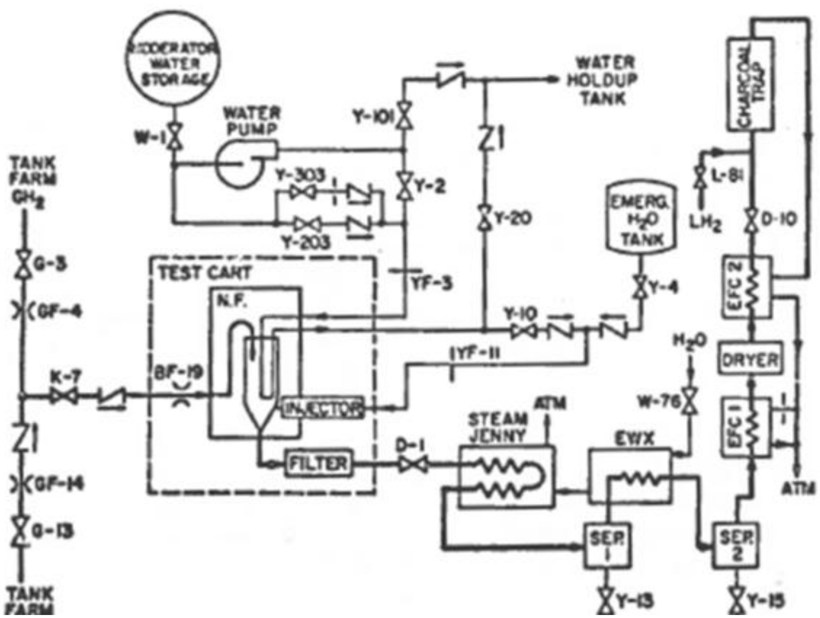
Ground Testing

NTP Test Topology

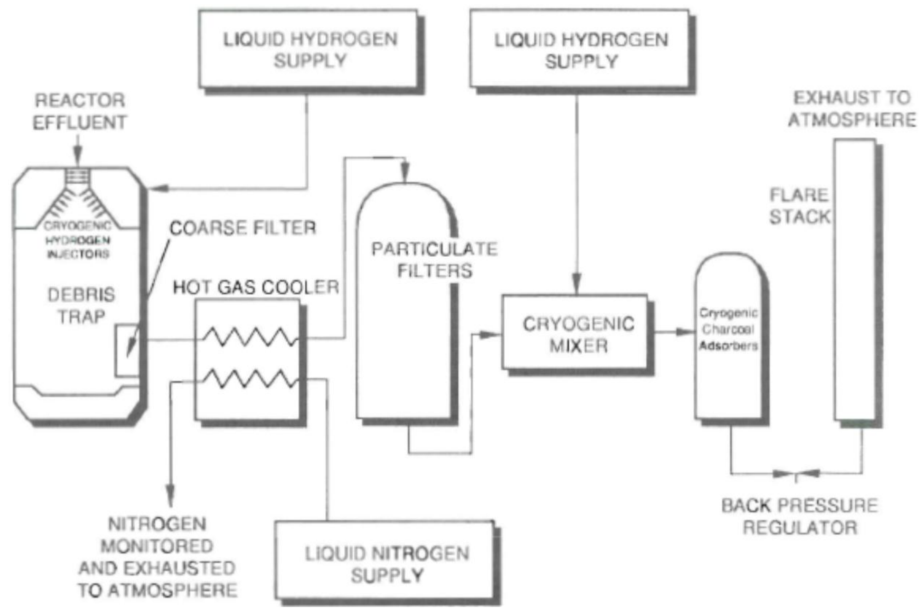


Ground Testing

The National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90), which states "Emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 10 mrem/yr".



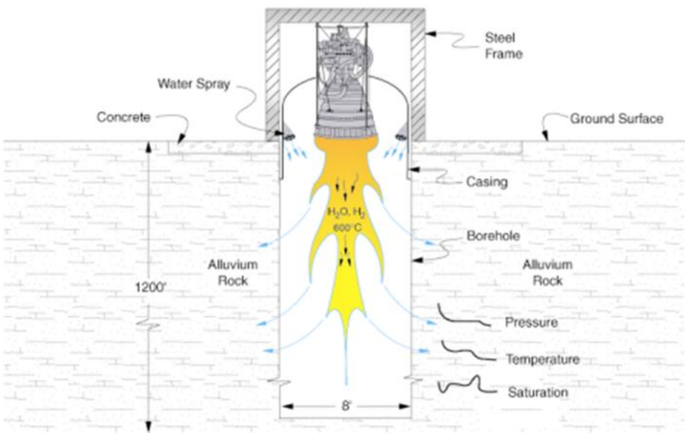
Nuclear Furnace successfully demonstrated exhaust filtering in 1972

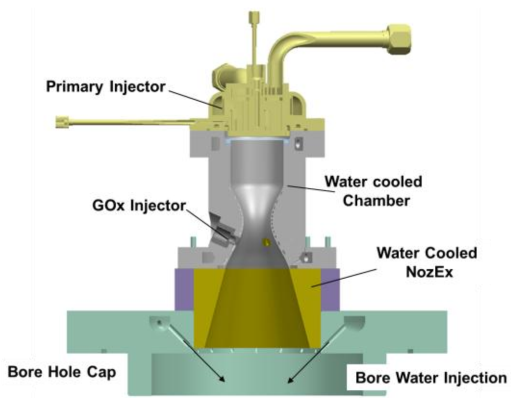


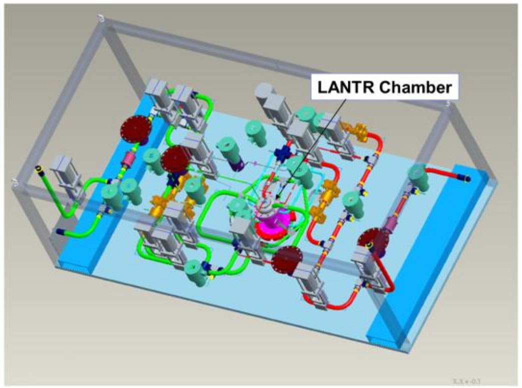
SNTP exhaust filtering concept

Ground Testing

Other fission product filtering concepts being investigated







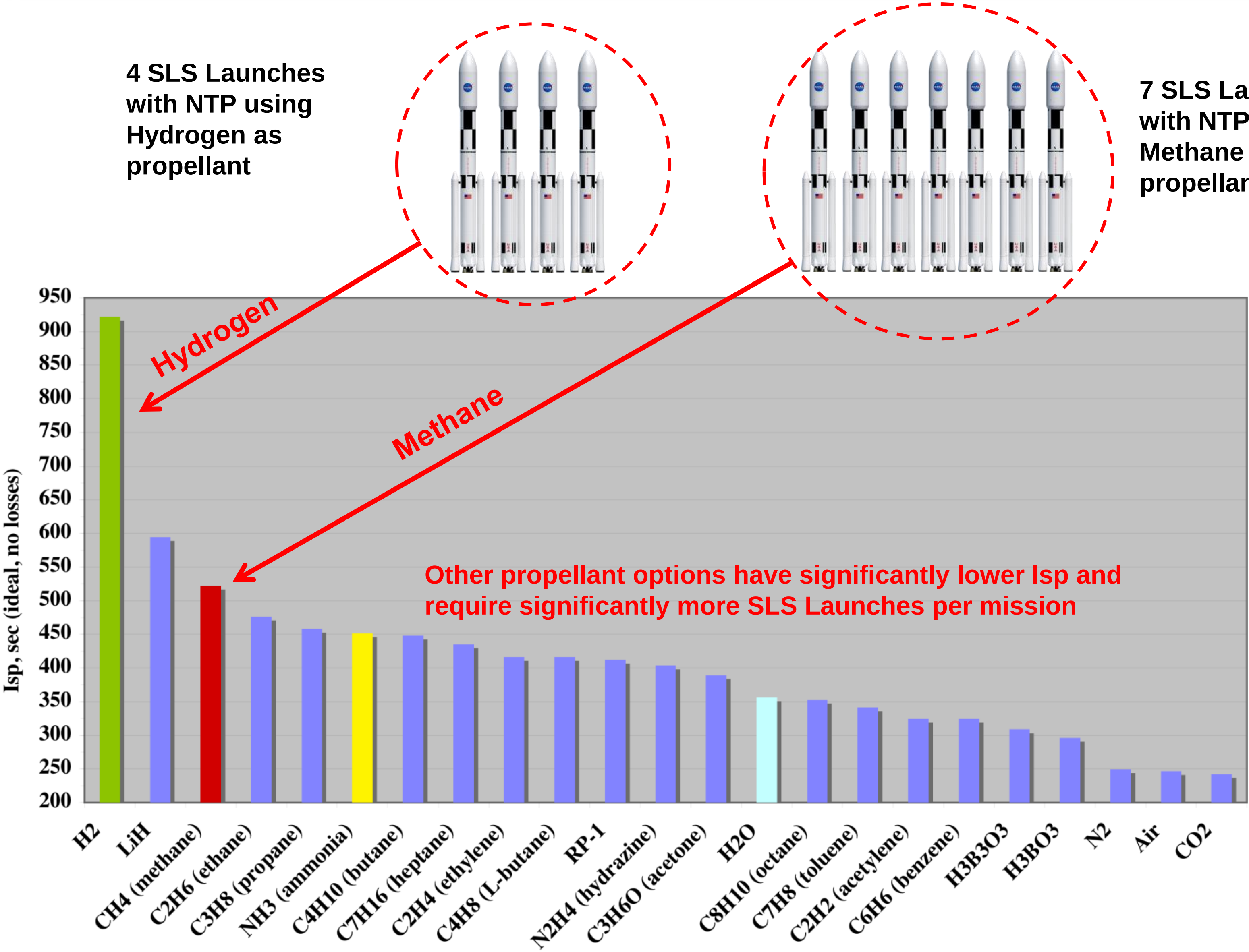
Sub-surface active filtering of exhaust (SAFE) concept

Hot hydrogen injection chamber built by Areojet Corporation and used by NASA for Lox augmented NTR testing. Possible Test rig for SAFE subscale testing using hot gas chamber22

Other Development Needed

- Turbomachinery-bearing selection, possibilities of saturated hydrogen, throtteability, and radiation exposure
- Valves-acceptable leakage, radiation exposure, and future manufacturers
- Nozzle Extensions-investigate use of chemical nozzles by similarity, nozzle cooling for an engine cluster
- Avionics, Actuators, and Power Generation-radiation exposure
- Analysis Tools-integrated reactor and rocket engine modeling
- Cryogenic Fluid Management-minimize hydrogen boil-off, coupling of stage lines, thermal management, and zero-g liquid acquisition

Other NTP Propellant Options



Note: Results based on
- 1000 psia chamber pressure
- 4850 R chamber temperature
- 150 area ratio nozzle

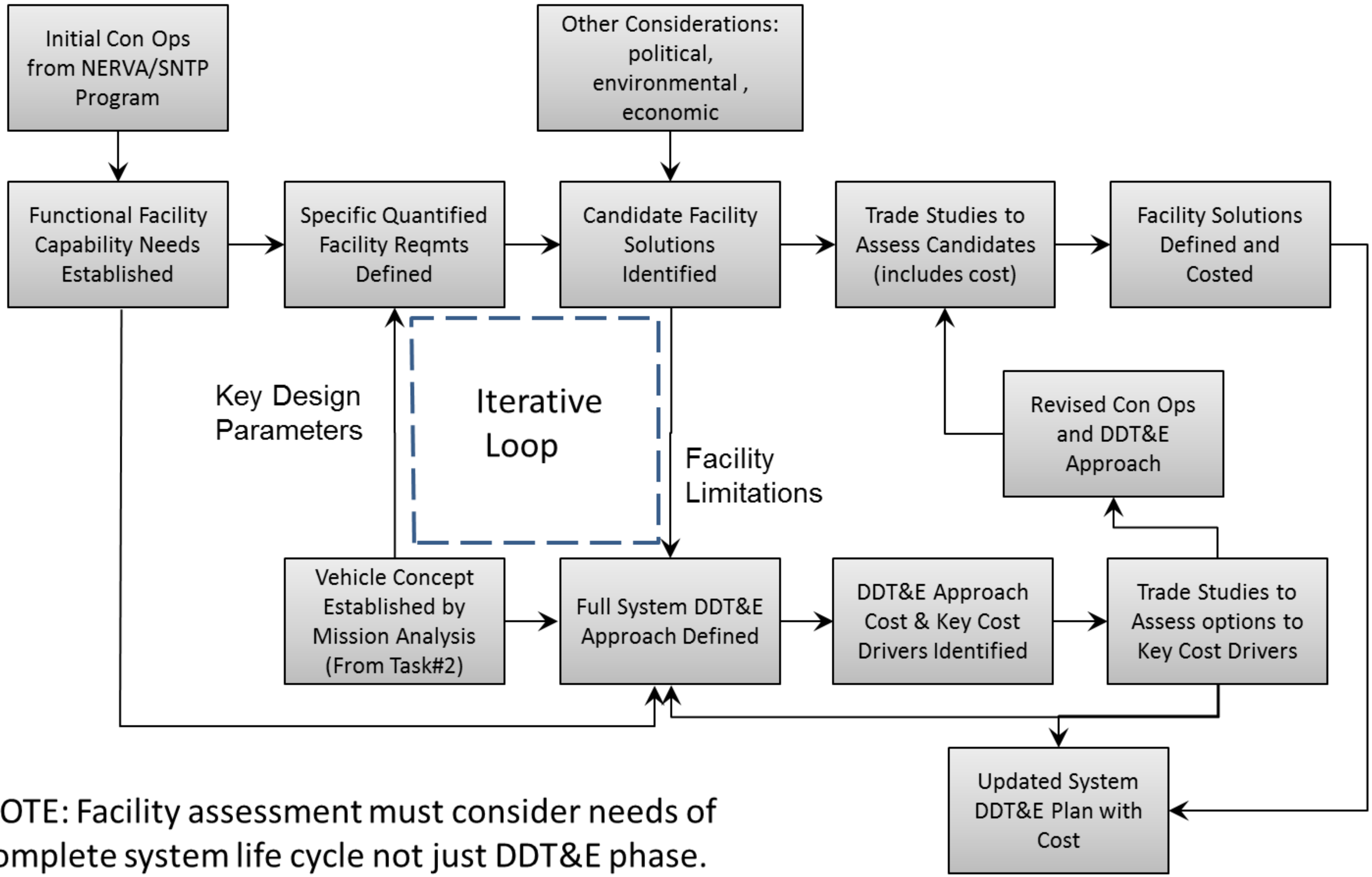
Possible Prototype Flight Test

Prototype flight test demonstrates the following:

- Full nozzle expansion,
- Radiate heat to space,
- Perform thrust vector control with engine operating,
- Validate reactor operation without effects from facility surroundings
- Monitor radiation effects on stage
- Exposure to space environment effects
- Engine inspection with space telerobotics

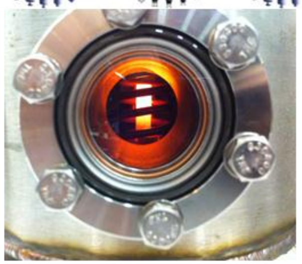
Also, Lessons Learned from ARES 1-X

Logic Flow for Cost and Schedule

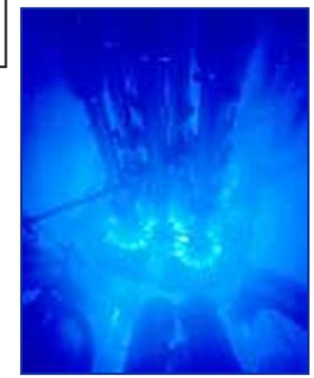


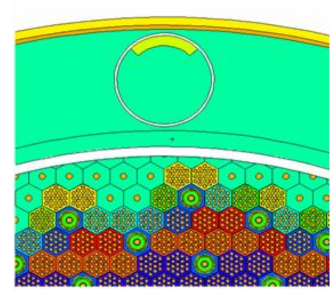
NOTE: Facility assessment must consider needs of complete system life cycle not just DDT&E phase.

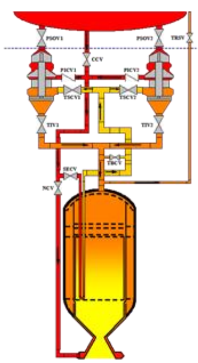
Summary



- Subsequent Missions with Upgrades
- Instrumented Prototype Flight Test
- Minimum Scaleable Ground Test
- Focused Nuclear Testing
- Maximize Non-nuclear Testing
- Robust Flexible Reactor Design
- Use of SOA Design Methods
- Develop Test Matrix
- Benign System Requirements
- Modest Initial Mission Requirements
- Utilize Large Existing Database







Accounting for all the factors which influence the development plan and quantify the factors based on experience, analysis, analogies or similarities, will build greater justification with less uncertainty to have an authority to proceed with NTP development