Nuclear Thermal Propulsion (NTP)
Engine Component Development

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“To extend and sustain human activities beyond LEO, rapid crew transit is required.”

- NASA STMD Technology Roadmap
Engine Development Realities

• ROVER/NERVA was NOT an engine by modern standards
  − Does not meet modern design and demonstration requirements
  − Non-“Flight like” operations and ambiguous parameters (e.g. valve timing, reactor and turbopump start-up transient, etc.)

• Millions of seconds of flight engine experience have been accumulated since ROVER/NERVA

• Mission architecture concepts are often overly optimistic
  − Design variables “firewalled” to optimal performance (e.g. 300:1 vs. 150:1 area ratio nozzles)

• Majority of benchmarked engine design codes that meet human rating requirements are not applicable for NTP
  − Codes are “cheated” to make work

• Fiscal constraints: NTP limited only where absolutely needed
  − Not required for robotic missions
  − National direction (e.g. human Mars mission): single or multi-mission
Honest Limitations Assessment

- Insanity: doing the same thing over and over and expecting different results. - Albert Einstein

- Policies are in place to eliminate HEU for non-defense purposes
  - Reduced Enrichment for Research and Test Reactors
  - Global Threat Reduction Initiative
  - HEU reactors have been and continue to be converted to LEU
  - Law makers stated that HEU reactor usage damages the nation’s position to urge other nations to not use HEU.

- HEU cost excessive
  - Shot-term HEU availability not a concern and has little impact on upfront cost
  - HEU substantially increases long term security, handling, facility and operating costs

- Low NTP duty cycle = low burn-up
  - Reusability not considered for first generation designs since fuel materials will undergo significant degradation

- LEU NOT practical unless an affordable process can be developed to reliably produce 95-98 wt% $^{184}$W.
Prioritized Engine Development Criteria

• Affordability
  − One engine concept to meet human Mars mission requirements
  − Maximize in-house development and leverage relevant industry capability
  − Minimize security and processing constraints: LEU

• Practical, Realistic, Robust, Conservative Design
  − Eliminate exotic concepts, materials or processes (except fuel)
  − Eliminate material with inherent susceptibility to failure in NTP environment
  − Utilize existing and projected (within 10 yrs) manufacturing capability
  − Off-the-shelf components where practical (will not drive engine design)

• Conform to established requirement standards
  − NASA human rating: impacts factors of safety and test demonstrations
  − NRC reactor control, safety, and operation criteria

• Performance
  − Differentiate between “must have” vs “nice to have”
  − Reliability primary driver
• Human mission requirements drive engine design
  - L. Kos studies baseline 3 engine cluster, total thrust 75-105 klbf

• Engine Thrust Class
  - NTP T/W not linear with engine size

• Total burn time
  - Lower with higher thrust engine
  - Major impact on engine duty cycle and engine reliability

• NTP engine cost **NOT** linear with thrust
  - Majority of cost is fuel development
  - Decreasing engine size for cost has negligible impact on total cost
  - Subscale flight demos will not be used to fulfill human rating and a second engine will have to be designed and drive up costs

<table>
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<th>Engine Thrust (klb)</th>
<th>Burns (no.)</th>
<th>Total Burn time 2033 (min)</th>
<th>Total Burn time 2033 (min)</th>
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Courtesy L. Koss
Expected Development Plan

**FUEL**
- DU manufacture, characterization, test (coupon & fuel element)
- DU property measurement
- LEU coupon manufacture
- LEU coupon irradiation
- LEU fuel element manufacture
- LEU fuel element irradiation

**ENGINE SYSTEM**
- Initial Power Balance
- Power balance using low-fidelity empirical data
- Power Balance using high-fidelity empirical data
- Full-scale non-nuclear cold flow system test

**REACTOR PHYSICS**
- Component, design, analysis, manufacture
- Low fidelity separate effects tests
- Component, design, analysis, manufacture
- High fidelity separate effects tests
- Component, design, analysis, manufacture
- High fidelity combined effects tests
- Initial Zero Power Critical
- Prototypic Geometry ZPC
- ZPC vs. Temperature

**TRL**
- 3
- 4
- 5
- 6

Full-scale nuclear engine test
Integrated NTP Development

- **Engine Systems**
  - Reactor Neutronic Analysis
  - Power Balance

- **Reactor**
  - Fuel
  - Tie-tubes
  - Reflector Rings & Control Drums
  - Injectifold
  - Bottom plate
  - Internal Shield

- **Thrust Chamber Assembly**
  - Pressure Vessel
  - Regen Nozzle & Nozzle Extension

- **Turbopump**

- **Propulsion Module**
  - Lines, Ducts, Valves
  - Thrust Vector Control
  - Controller
  - Distance truss

- **Neutronic Model**
- **Parametric Model**
- **Integrated Component Models**
- **155.7 kN (35 lb.) x 3**
Objectives FY15-17

- **Engine System: Power & Neutronic Balance**
  - Steady state
  - Start-up and shut-down transients
  - Reliability requirements

- **Components**
  - Design, analyze, build, and non-nuclear test functional prototypes
  - Injectifold, tie-tubes, reflectors/drums to TRL 5
  - Turbopump, shield, core bottom plate to TRL 3

- Empirically anchor component, fuel, power balance models to reduce uncertainty to address human rating

- Empirical cost and schedule estimates for fuel, component, engine, and processes
Component Example: Injectifold

- Design 7-fuel element subscale prototype
  - Utilize existing tools and identify limitations

- Manufacture
  - Stereolithography (plastic)
  - DLMS (stainless or aluminum)

- Dissimilar metal joining
  - Welding samples of Zircaloy-4 tubes
  - Brazing samples of Zircaloy-4 tubes

- Integration & Assembly
  - Weld/braze Zircaloy-4 tubes to injectifold

- Test
  - Cold flow
  - Hot fire (NTREES)

- Integrate data into NTP specific models
  - Empirically benchmarked
  - Iterative cycle restarts until adequate fidelity obtained
Conclusions

• NTP engine design highly dependent on mission.
• Unlikely that NTP will be developed for missions other than rapid human transit.
• Engine design and component development loosely linked to engine thrust class.
• The majority of the required tools exists to facilitate engine design but do not meet human rating standards
• NTP specific tools require development through both experimental and analytical methods.
Recommendations for Future Work

• Complete prototype component designs
  – Basic analysis
  – Materials selection
  – Manufacture trade space evaluated

• Manufacture Prototypes
  – Subscale to full scale

• Test Prototypes
  – Iterative prototypic operating environment
  – Characterize data for model implementation

• Develop preliminary models
  – Analytical with empirical benchmarking
  – Facilitate second iteration design evolution
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• The opinions expressed in this presentation are those of the author and do not necessary reflect the views of NASA or any NASA Project.