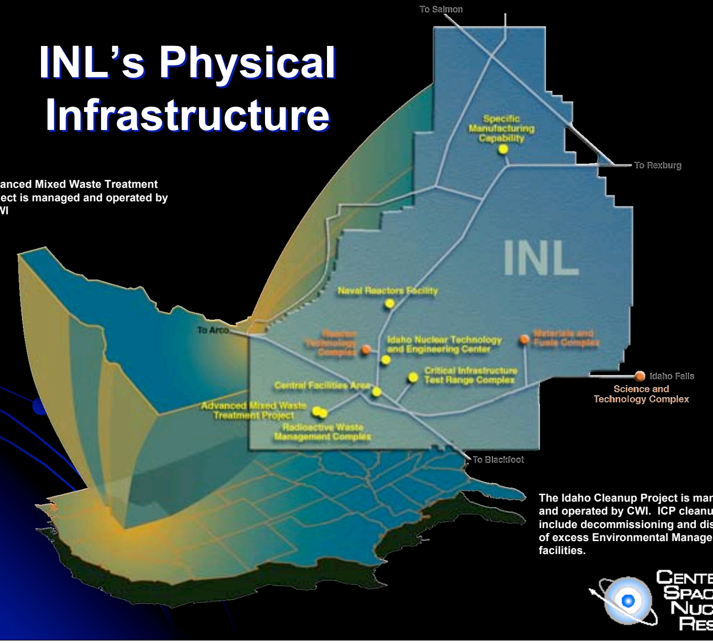
New Technologies for Space Exploration: Results of Investigations at the Center for Space Nuclear Research (CSNR)

Steven D. Howe, Ph.D.
Director
CSNR

Presented to the OPAG
November 9, 2007

INL's Physical Infrastructure

Advanced Mixed Waste Treatment Project is managed and operated by BBWI



The Idaho Cleanup Project is managed and operated by CWI. ICP cleanup efforts include decommissioning and dismantling of excess Environmental Management facilities.

Center for Space Nuclear Research

INL's Unique Facilities


Advanced Test Reactor


Hot Fuels Examination Facility


Space and Security Power Systems Facility


Transient Reactor Test Facility

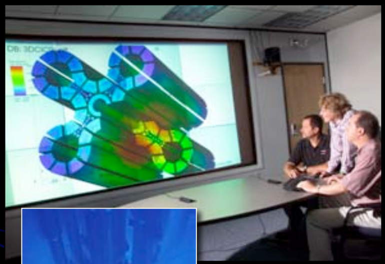

Fuel Cycle Facility


Zero Power Physics Reactor


Fuel and Storage Facility

Center for Space Nuclear Research

INL's Capabilities – Nuclear Energy




- Research and Technology Development for GEN IV Reactor
- Fuels and Materials Development and Testing
- Separations and Actinide Sciences
- Modeling and Simulation
- I&C and Intelligent Systems
- RTG assembly and testing
- Fusion safety
- Future System analysis

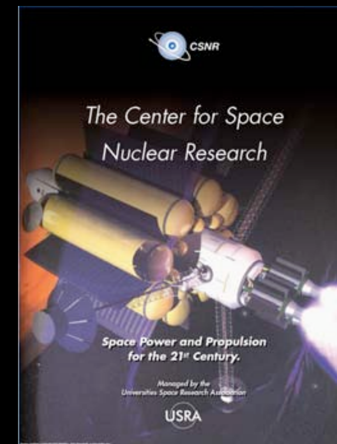
Center for Space Nuclear Research

Idaho currently plays a key late-stage role in RPS for space missions

- INL is responsible for final assembly and testing of Radioisotopic Thermoelectric Generators (RTGs)
- The New Horizons mission to Pluto – the highest-priority exploration mission of the decade – depended on INL fabrication

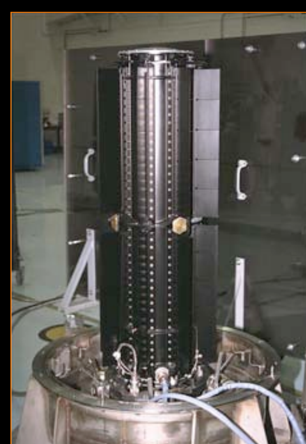
Role of CSNR

- Support the space nuclear research and educational mission needs of the INL
- Reinvigorate research and education in space nuclear engineering within U.S. universities.
- Be a focus for engaging university scientists in research and development of advanced space nuclear systems, including space power and propulsion systems, and advanced radioisotope power systems at the INL.
- Summer Fellowship Program.



Radioisotope Power Systems (RPS)

- Current RTGs are simple, robust, and proven technology
- Pu-238 running out – 24 kgs left
- CSNR is currently examining possible alternative isotopes and new materials to ensure immobilization in accident scenarios
- INL has facilities to fabricate new RPS systems
- Current design study: Using RPS sources for space power and for long duration (>2yr) Remotely Piloted Vehicles for planetary observation



Radioisotope Powered Flight

- Offers potential for months or years of continuous aircraft operation
- Utilization of radioisotope decay heat instead of combustion allows operation in oxygen-free environment
- Attractive for unmanned aircraft exploration missions in Martian atmosphere

Operation Basics

- Replace combustion chamber in jet engines with a radioisotope driven heat exchanger
- Operates for months to years based on isotope selection
- Somewhat throttled
- Utilizes ~95% of heat generated
- Stable, robust, long-lived

CSNR Sumer Fellows Study

- Mars airplane designed in the 2007 CSNR Summer Fellows program under Jon Webb's guidance
- Webb completing MS at ISU doing Titan airplane thesis
- Fellows examined
  - Isotope options
  - Engine type
  - Cooling options and heat transfer
  - Shielding estimates
  - Launch issues
  - availability

Mission Requirements

- Minimum flight time of 7-12 months
- Isotope shall provide 20-40 kWt
- Realistic isotope extraction/production costs
- Heat source assembly must survive re-entry and impact
- Minimal dose to workers during fabrication
- Total mass (including shielding) reasonable for our flight unit and for launch into space

- **Isotope Properties Considered:**
  - Half Life
  - Power Density (including compound form and isotopic concentration)
  - Dose rate / Shielding requirement
  - Production / Availability / Cost

Radioisotope Thermoelectric Generator (RTG) have been used since the Apollo days

- **Pu-238**
  - **Non-weaponizable**
  - **87.7 year half-life**
  - **Alpha decay plus gamma rays**
- **Heavily encapsulated**
- **Qualified against accident scenarios- fire, impact, explosion**
- **6-8% conversion efficiency**
- **No moving parts**
- **Around 200 kg/kWe**
- **Continuous power**

Suitable Isotopes Based on Power Density:

Isotope:	100% Isotope Power Density: (W/g)	Compound Form:	Melting Point: (ºC)	Compound Power Density: (W/g)	Mass Compound for 20 kW_t: (kg)
Sr-90	0.90	SrO	2530	0.44	45.46
Ru-106	9.91	Metal	2334	0.69	28.99
Ce-144	21.07	CeO_2	2400	0.65	30.77
Po-210	9.13	PoO_2	500	7.55	2.65
Pu-238	0.55	PuO_2	2400	0.39	51.29
Cm-242	12.3	Cm_2O_3	2265	10.05	1.99
Cm-244	2.63	Cm_2O_3	2265	2.15	9.31

Center for Space Nuclear Research

Engines Considered

- Turboprop
  - Used in low power, low speed Earth aircraft
  - Most (~90%) of thrust from propeller
  - Propeller efficiency decreases at high flight velocities
- Turbojet
  - Used in high speed Earth aircraft
  - Thrust generated from expansion of high pressure, high temperature exhaust gases in nozzle
- Ramjet
  - Used in supersonic Earth aircraft, missiles
  - No moving parts
  - Thrust generated from expansion of high pressure, high temperature exhaust gases in nozzle

Center for Space Nuclear Research

Materials Issues

- Confine isotopes
  - Resist high temperature migration
  - Launch abort reentry
- Good thermal conductivity
- High Z for self shielding
- Non-reactive with many fluids
- One candidate is a tungsten-rhenium cermet
- Utilize particles of isotope distributed in W-Re matrix
- INL LDRD INL, BSU, ISU and UI collaboration awarded grant - $250K/yr for 3 yrs
  - Acquired SPS furnace- delivered
  - Basis for joint NSF/EPSRC proposal with SRC in UK
  - Examine microstructure, gas and liquid diffusion, up to 70/30 vol fraction, Re fraction
- Potential for electrically heated turbojet using W-Re heat exchanger in FY2008 using INL funds

Center for Space Nuclear Research

INL

Conclusion

- Radio-isotope heated engines seem to be viable for long duration flight in non oxygenated atmospheres
- Relatively easy construction
- Allows for detailed mapping and scientific exploration of an entire planet within a few years time frame
- Capable of loitering over specified targets
- Capable of being re-tasked to new targets that are not in the viewing angle of current trajectory with no propellant consumption

Center for Space Nuclear Research

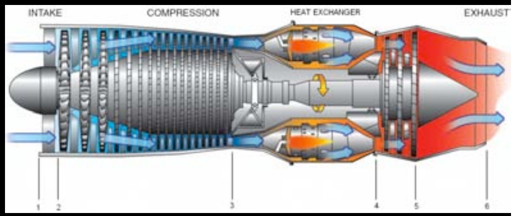
backup

Titan Flight Conditions

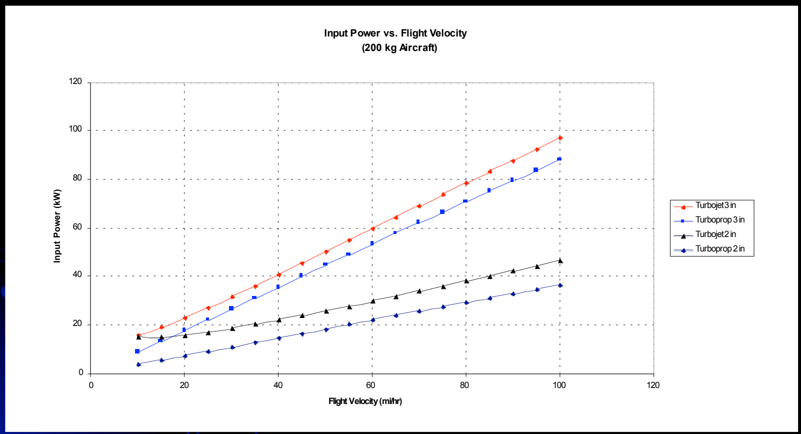
- 200 kg craft
- Flight Velocity of 10 to 50 mph
- Lift to drag ratio of 12
- C_L of 0.63
- Required thrust of 8 lb_f
- Wing planform area of ~10 ft^2

RP Jet (How it Works)

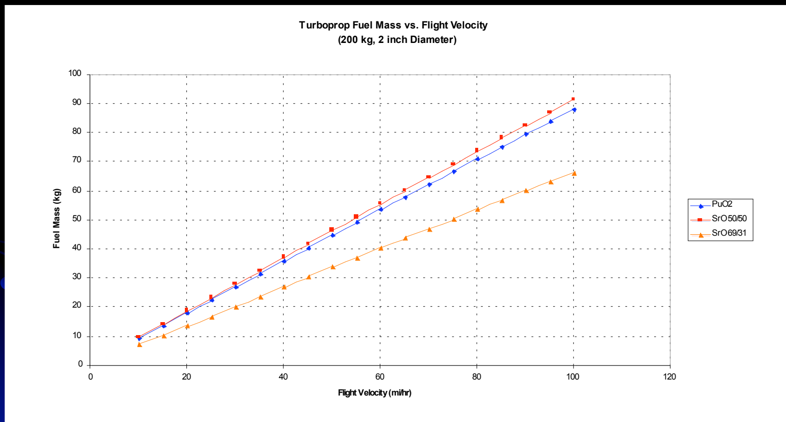
- Ram atmosphere flows into inlet / diffuser ($\eta_d \sim 0.95$)
- Power / Enthalpy is added in the heat exchanger ($\eta_{he} \sim 0.9$)
- Flow is expanded to ambient pressure in the nozzle ($\eta_n = 0.90$)
- $\eta_{total} = 72.675$ %



Required Input Power



Required Isotope Mass vs. Flight Speed



Center for Space Nuclear Research