An Innovative Very Low Thermal Power Waste Heat Recovery System for Thermal Control of Deep Space Missions

- *A Thermal Flask in Space*

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Problem Statement

- **Typical deep space missions like Juno (to Jupiter at ~5 A.U.) and the currently envisioned Europa Clipper Mission (to Europa, a moon of Jupiter) would rely on solar photovoltaic power**
  - **Need extremely large & heavy solar arrays because solar intensity is so low at those locations**
- **Also would require as much as 200-300 W of electrical power for thermal control due to their size**
- **Hence any power that would be needed for thermal control is extremely limited**
- **This is prohibitively large and leads to needing very large and heavy solar arrays (on the order of ~20-30 m^2) *just for thermal reasons***
- **Hence there is a need to come up with a thermal architecture and design that would not need such prohibitively large thermal power levels**
- **Power needs for thermal control are related to keeping typical spacecraft components within their allowable temperature limits**
  - **Propulsion System: +15°C → +50°C; Electronics: -40°C → +50°C; Battery: -20°C → +30°C**

Typical Environments Encountered

- **Near Earth Cruise**
  - *Warm* (benign); 1 A.U.
- ***Possible* Venus Gravity Assist (e.g., Venus)**
  - *Very Hot* (Worst Case Hot) Case; ~0.7 A.U.
    - 2x Sun flux from Sun (Direct)
    - 1.5x Sun Flux from Venus (Albedo)
- **Cruise to Outer Planets**
  - ***Very Cold*** (Worst Case Cold) Case**;** as far as ~10 A.U.
    - 90-130 K sink temperature at outer planet

Description of Proposed Architecture

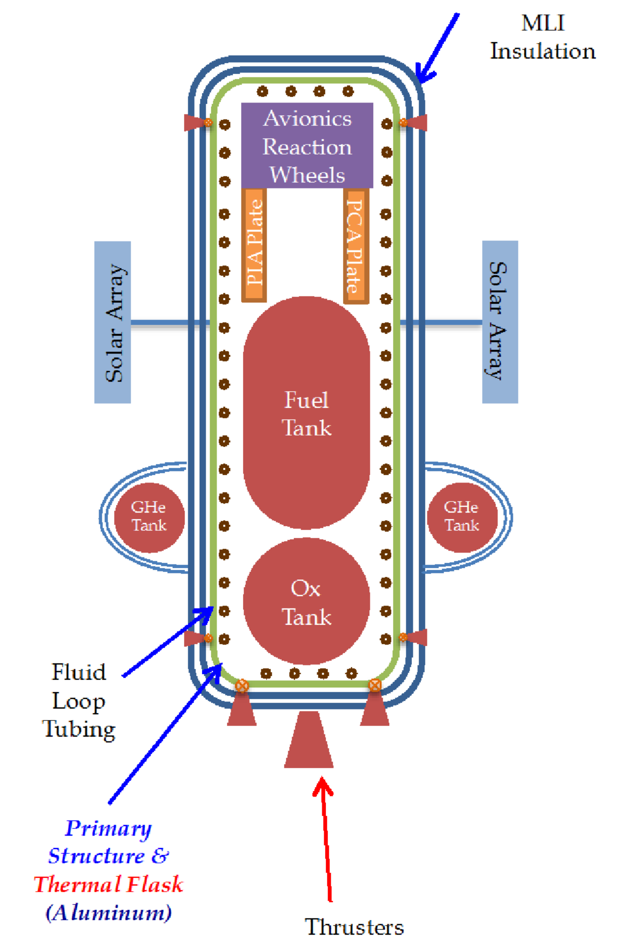


Figure 1. Schematic of Thermal Flask Architecture

- **Harvest waste heat from heat dissipating components**
  - Avionics, Instruments, Telecom, ACS, etc.
  - Dissipate ~200 W for reasonable spacecraft functionality
- **Waste heat comparable to that required for components that need survival heat**
  - Propulsion system, etc.
  - Need ~ 200 W for thermal control
- **Pick up waste heat by single phase fluid loop tubing & supply to components that need it via tubing attached to it**
  - Mechanical pump is prime mover of fluid
- **Hence create a _thermal flask_ that has fluid loop tubing attached to it**
  - All key s/c components reside in flask
  - Except for solar array, antennae, thrusters, instrument apertures, etc.
  - Entire flask is covered with MLI blankets

Description of Fluid Loop

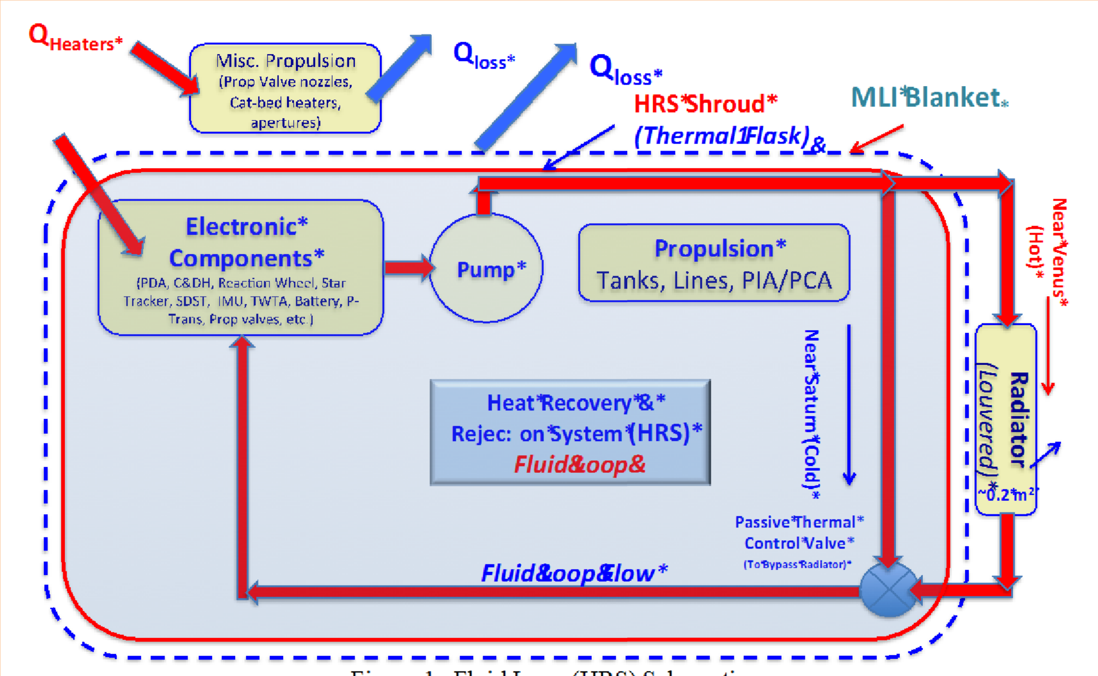


Figure 1. Fluid Loop (HRS) Schematic

- **Completely Autonomous Thermal Control**
  - Passive thermal valve automatically detects fluid temperature
    - Directs flow either to a radiator (hot conditions)
    - Or away from radiator (cold conditions)
    - Heritage from last 20 years of JPL deep space missions

Example Heat Balance

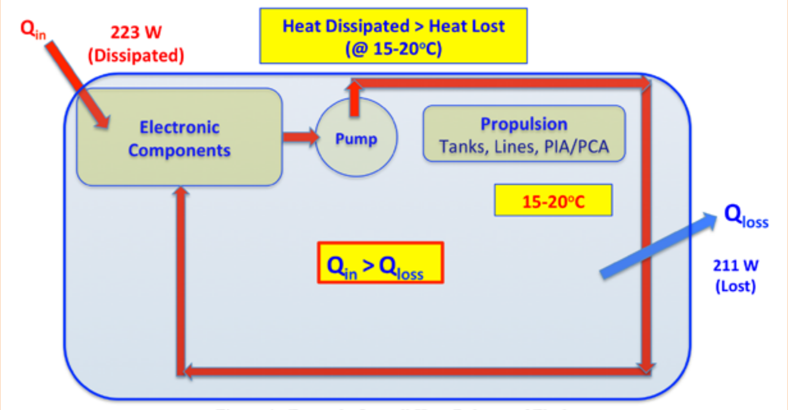


Figure 1. Example Overall Heat Balance of Flask

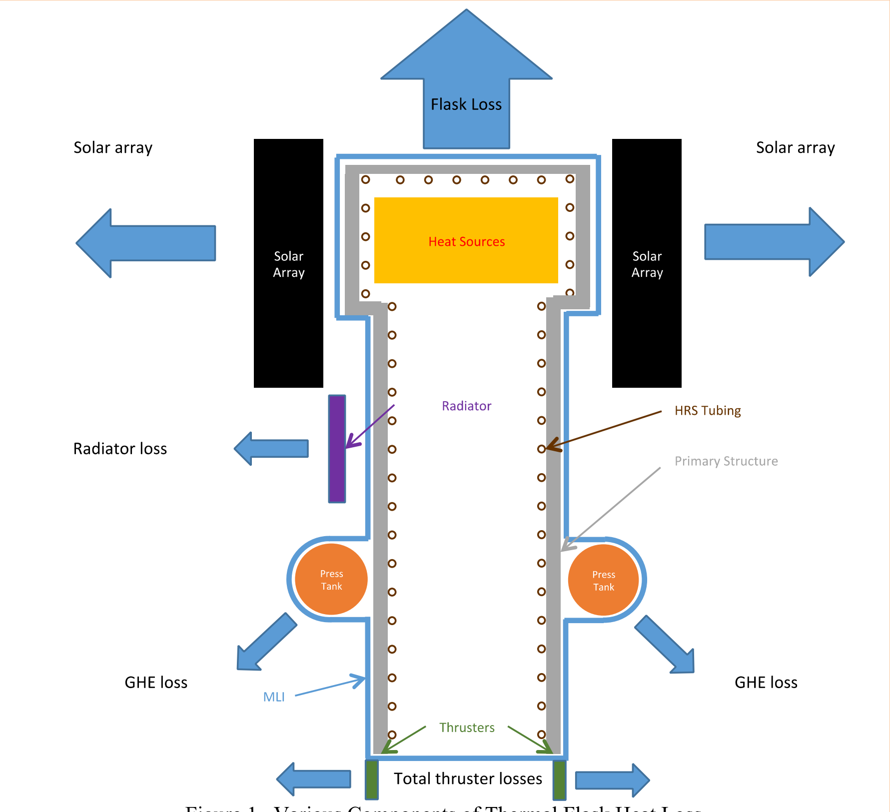
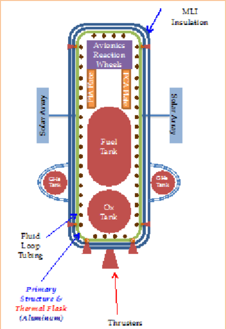


Figure 1. Various Components of Thermal Flask Heat Loss

- **Almost isotherm flask (due to fluid loop)**
- **Maintains flask's temperature around 15-20 C**
- **Minimal use of heater power to augment waste heat harvested**



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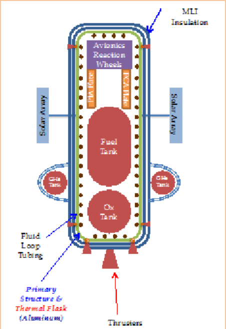
Novelty of Architecture

- ***This is a novel concept that could enable missions because it could almost eliminate the need for thermal control power for a large size spacecraft that is designed for deep space***
- **Without this concept, missions could potentially be prohibitively heavy & expensive to provide large amount of power for thermal control in extremely cold environments that such missions would encounter**
- **This concept is completely automatic**
  - Requiring no on-board or ground directed control of its function
- **It is also quite simple in its implementation because all the spacecraft components would be placed inside an aluminum shell with standard MLI insulation covering it**
  - ***Thermal Flask shell has dual function of s/c structure & thermal control***
- **This work is radically different from previous missions that utilized solar arrays for power where electrical heaters (~200 W) were utilized just to thermally control the spacecraft components**
- **Missions that had Multi-Mission Radioisotope Generator (MMRTG) nuclear power sources (e.g., Cassini) did not encounter this problem because of ample waste heat available from MMRTGs**
- **Solar missions do not have that luxury, hence the need to come up with novel schemes like the one proposed here to enable them**


Heritage & Technology Assumptions

- **The fluid loops utilized to make this architecture work have a long and extremely successful heritage from JPL's Mars missions**
  - Starting from Mars Pathfinder (MPF)
  - Followed by the two Mars Exploration Rovers (MERs, Opportunity and Spirit)
  - And the recent Mars Science Laboratory (MSL) Curiosity Rover mission
- **In particular, the Curiosity Rover utilized waste heat from the MMRTG to thermally control the rover on Mars**
- **HRS (fluid loop) technology is well established (TRL-9) for last ~20 years for application in extremely successful spaceflight projects**
- **Number of pumps inside an assembly can be further increased for long life missions to increase reliability**
  - MSL Cruise HRS pump assembly has 3 pumps, 2 redundant, only one on at any time
  - This would lead to an insignificant mass increase with no change in power
- **MLI blanket properties have been well characterized for several decades on several flight projects**
  - For large and small size blankets



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Other Options Investigated

- **Due to severe power constraints, only options that harvested waste heat from components to service other components (like propulsion) were considered:**
  - Options that relied on significant use of electrical heat were deemed unattractive
    - Due to reasons cited before
  - Fluid loop (HRS) based thermal bus was the most logical option for thermal control
    - For cold and hot conditions
  - Heat pipes or loop heat pipes were not deemed to be as attractive
    - From testing, integration, ATLO, and modularity reasons as well as a multi component serving autonomous thermal bus

- **Within the HRS approach, an earlier option considered was to employ local HRS plate clamshells to surround propulsion system to maintain their temperatures:**
  - Smaller surface area/mass of plates
  - Would need thermal isolation of these components from the cold structure
    - Which would be difficult to satisfy simultaneous thermal and structural needs
  - Heat losses via conduction & MLI around clamshells would be comparable to an all enclosing thermal flask

- **Thermal flask approach that encloses the entire spacecraft except solar arrays, Helium tanks, thrusters and some small components was found to be the most attractive**
  - Integrated structure and thermal flask system
    - ~3 mm or 1/8” thick aluminum shell with local stiffening features
    - Reasonable total mass
  - All components inside flask are thermally and mechanically coupled to integrated structure/flask
    - No need for thermal isolation based complexity

Rules of Thumb for Sizing & Performance

- **The heat loss from the flask should be proportional to the external surface area of the flask for a given controlled temperature as shown below:**

$$Q = \sigma \varepsilon A (T_{flask}^4 - T_{\sin k}^4)$$

- **The total heat loss would then be simply the harvested heat plus any heat dissipation in the locations where the heat is supplied**
  - **e.g. propulsion module**

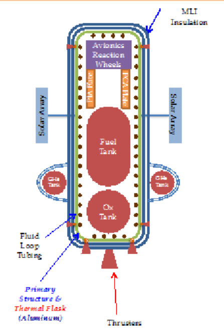
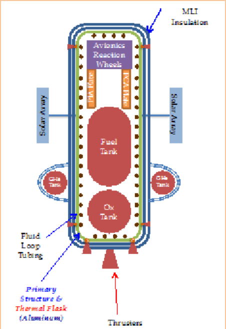


Figure 1. Schematic of Thermal Flask Architecture

Applicability & Limitations

- **Obviously this architecture is most well suited for missions that are very power-starved and which could encounter very cold environments**
  - Like the ones that go to outer planets
- **Key assumption is that significant amount of dissipation is present from which waste heat could be harvested**
- **This architecture relies on enclosing all (or most) thermally controlled components within the flask**
- **If the configurational constraints present a challenge to this assumption then a single flask concept may not work as well**
  - And it would have to be broken into mini-flask-regions
  - Which would make the configuration more complicated to implement
- **There will inevitably be some components that will have to protrude out of the flask**
  - e.g., solar array and supporting structure, thrusters, apertures of star scanner, sun sensor, instruments, radiators, etc.
- **There would be some thermal-mechanical design challenges to minimize these parasitics to minimize the waste heat recovery required to overcome all the heat losses**



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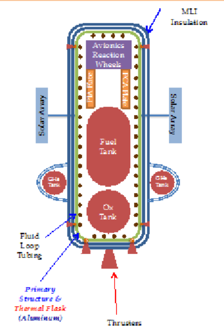
Possible Improvements

- **Reduction of MLI blanket emissivity would directly benefit the thermal design's efficiency**
  - Since the primary heat loss from the flask and correspondingly the required harvested heat is directly proportional to the MLI blanket effective emissivity
- **The large blanket surfaces that would cocoon the flask would be amenable to substantial improvements because the edge seam losses can be minimized**
  - The edge seam losses are the largest contributors of MLI emissivity increase due to local compaction of the blanket layers
- **Additionally, two mechanically separated blankets, which are not in contact with each other, could greatly reduce the heat loss**
- **Maximization of packing of components within the flask envelope would also minimize heat loss**
  - Because the external surface area of the flask is what determines the total loss
  - So anything that could fit inside would already have its heat loss accounted for by loss from flask external area
- **Minimizations of protrusions out of the flask would also be beneficial**
  - Since those external components would tend to run cold and would increase the parasitics losses from the controlled warm surfaces of the flask



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Conclusions

- **The thermal flask architecture presented in this paper describes an attractive, practical, simple and power efficient approach for the thermal design of future deep space solar power based missions**
  - **That are extremely power starved due to the very small solar flux available at large distances from the Sun**

- **It relies on harvesting waste heat from heat dissipating components via mechanically pumped fluid loop tubing**
  - **And then, via the same tubing, directing it to a “thermal flask” that contains all the essential thermally controlled spacecraft components within it**

- **The thermal flask serves as the spacecraft structure as well as a thermal cocoon to create a warm environment that the spacecraft components are slaved to**

- ***The simplicity, robustness and low thermal power needs of this approach, along with the ease in its implementation and testing makes it a very enabling architecture for future deep space missions***

Acknowledgements

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration