A Comparison of Coolant Options for Brayton Power Conversion Heat Rejection Systems

John Siamidis [1] and Lee S. Mason [2]

[1] Thermal Energy Conversion Branch, Analex Corporation, 21000 Brookpark Rd., Cleveland, OH, 44135
[2] Thermal Energy Conversion Branch, NASA Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH, 44135
[1] (216) 433-3151, john.siamidis@grc.nasa.gov

Abstract. This paper describes potential heat rejection design concepts for Brayton power conversion systems. Brayton conversion systems are currently under study by NASA for Nuclear Electric Propulsion (NEP) and surface power applications. The Brayton Heat Rejection Subsystem (HRS) must dissipate waste heat generated by the power conversion system due to inefficiencies in the thermal-to-electric conversion process. Sodium potassium (NaK) and H_2O are two coolant working fluids that have been investigated in the design of a pumped loop and heat pipe space HRS. In general NaK systems are high temperature (300 to 1000 K) low pressure systems, and H_2O systems are low temperature (300 to 600 K) high pressure systems. NaK is an alkali metal with health and safety hazards that require special handling procedures. On the other hand, H_2O is a common fluid, with no health hazards and no special handling procedures. This paper compares NaK and H_20 for the HRS pumped loop coolant working fluid. A detailed Microsoft Excel (Microsoft Corporation, Redmond, WA) analytical model, HRS_Opt, was developed to evaluate the various HRS design parameters. It is capable of analyzing NaK or H_2O coolant, parallel or series flow configurations, and numerous combinations of other key parameters (heat pipe spacing, diameter and radial flux, radiator facesheet thickness, fluid duct system pressure drop, system rejected power, etc.) of the HRS. This paper compares NaK against water for the HRS coolant working fluid with respect to the relative mass, performance, design and implementation issues between the two fluids.

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John Siamidis
Analex Corporation - NASA GRC

Lee Mason
NASA GRC

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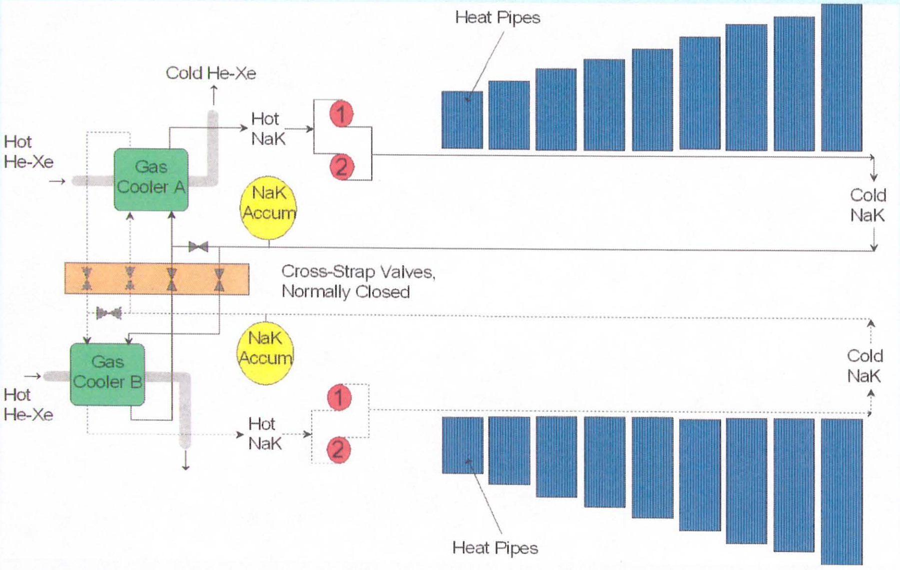
Introduction

- Nuclear Electric Propulsion (NEP) is a technology of interest because it has the potential to provide many benefits for deep space science missions.
- Surface reactors may be used for the moon or Mars to power human outposts.
- In both applications, the reactor power system (reactor, power conversion, and heat rejection), is a critical element.
- Closed Brayton Cycle (CBC) converters are one of several promising options for power conversion within a reactor system.
- The Heat Rejection Subsystem (HRS) must dissipate waste heat generated by the Power Conversion Subsystem (PCS) due to inefficiencies in the thermal-to-electric conversion process of the Brayton converters.

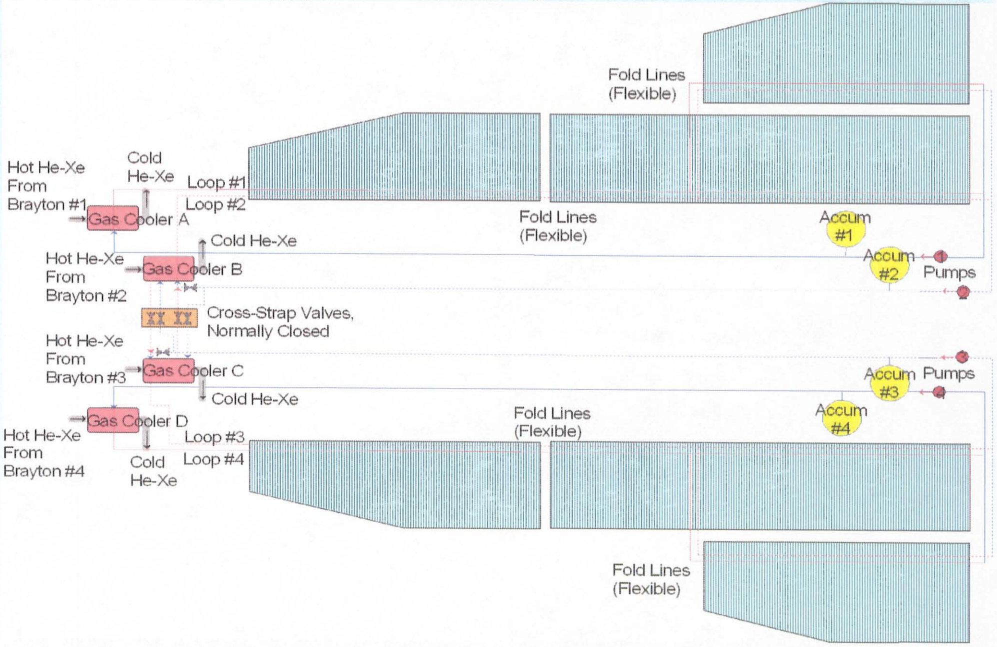
Introduction (Cont'd)

- Two previous design studies examined a possible heat rejection concept for a 100 kWe Brayton PCS for the proposed Jupiter Icy Moons Orbiter (JIMO) mission.

Two (2) 100 kWe Brayton Converters



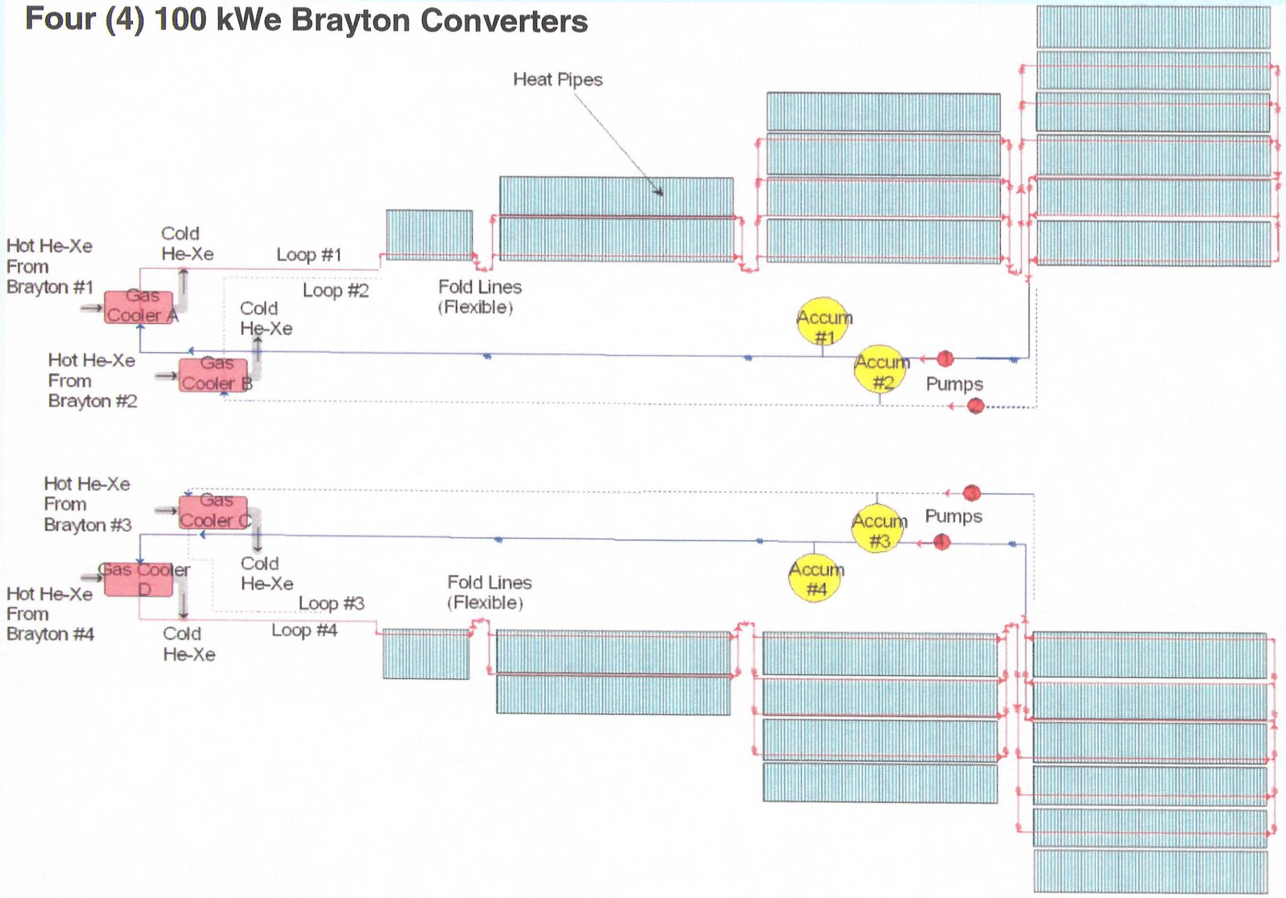
Four (4) 50 kWe Brayton Converters



- **The HRS consisted of a pumped sodium-potassium (NaK) heat transport loop coupled to a water heat pipe radiator.**
- **The studies discussed the interplay between heat pipe spacing and heat pipe diameter and their effect on heat pipe maximum power and maximum heat flux, system pressure drop and pump power for a fixed geometry radiator.**

HRS Design Concept - Overall

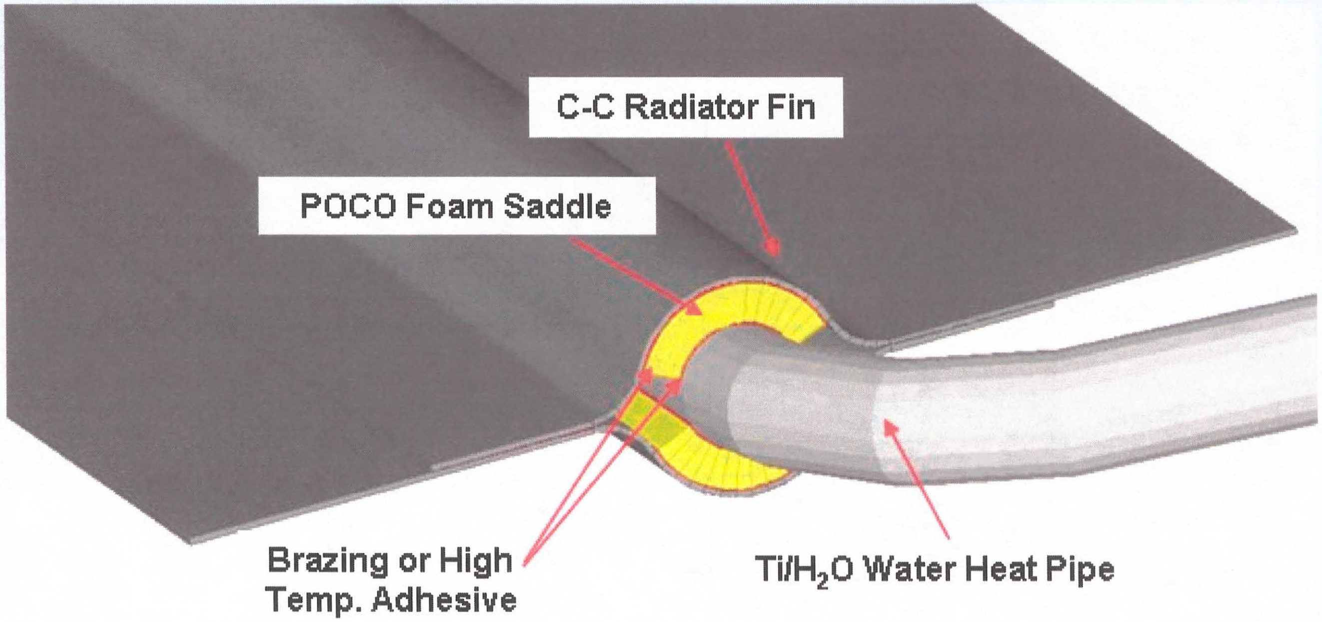
- This paper uses the previous design concepts as a starting point for more detailed definition of the Brayton HRS. Specifically, the paper evaluates two heat transport working fluids (NaK-55 and H_2O) for several system pressure drops and for several radiator inlet outlet temperatures.


Four (4) 100 kWe Brayton Converters

- Pumped NaK or H_2O coupled to a water heat pipe radiator.
- Two-sided heat rejection.
- Two loops share the same radiator area (single-fault tolerance).

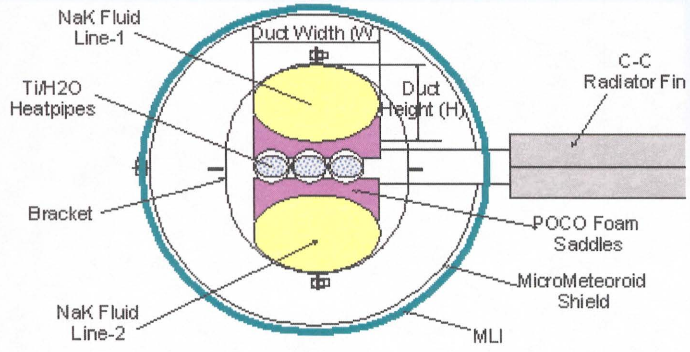
HRS Design Concept - Radiator

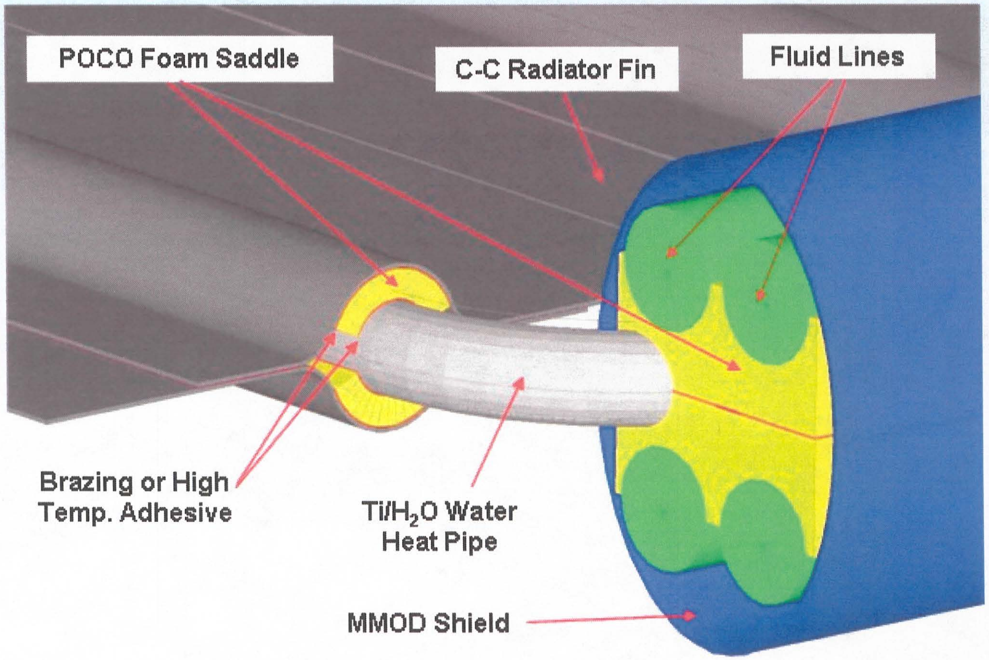
- The radiator panels use a construction consisting of regularly-spaced circular heat pipes contained within two composite facesheets.
- The heat pipes are thermally connected to the facesheets through a POCO™ foam saddle.
- The saddle provides compliance to address fin-heat pipe thermal expansion and a degree of micrometeoroid shielding.
- The heat pipe-to-saddle and saddle-to-facesheet bond is accomplished through brazing or high temperature thermal adhesive.



HRS Design Concept – Cooling Loops

- Pumped liquid H_2O or NaK-55 Heat Transport.
- The water heat pipes interface to the coolant through curved sections that are "sandwiched" between two cooling loops. One loop is active and the second is the backup.
- A POCO™ foam saddle is introduced between the heat pipe evaporators and the cooling loop ducts to improve heat transfer.
- The ducting is made of titanium. The duct cross-section is oval for NaK-55 and split circular for H_2O.

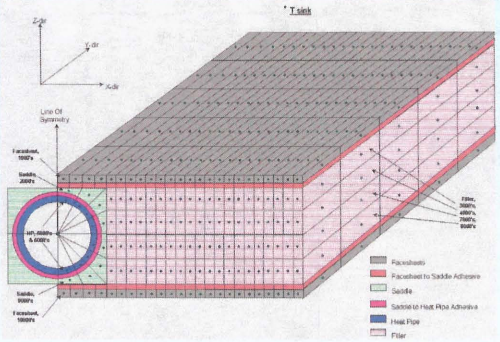


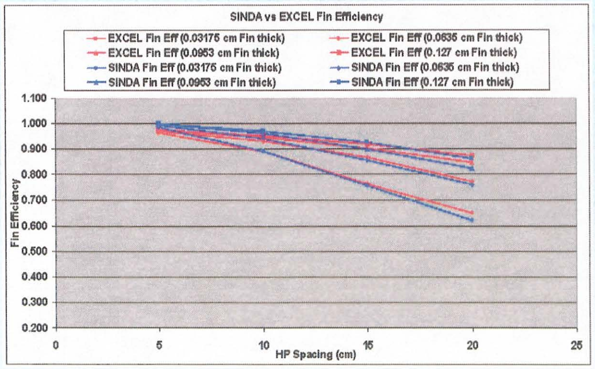


Analytical Model

- An Excel spreadsheet model, called HRS-Opt, was developed in the previous design studies. The model was modified to accommodate the updated HRS design, including NaK-55 and H_2O coolant properties.
- The fin efficiency is a critical part of this analysis since it varies widely with heat pipe spacing and facesheet thickness.

Detailed SINDA model

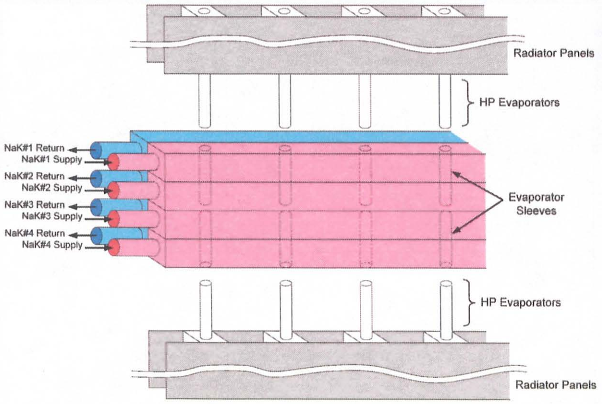


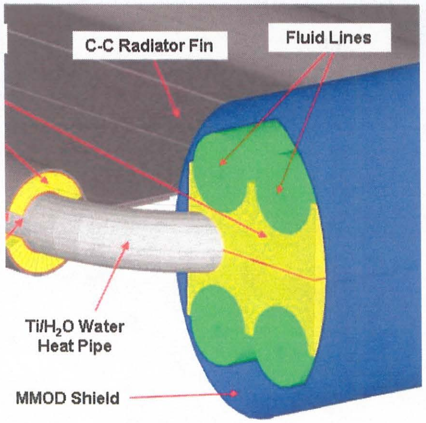


SINDA model and Closed-form equation results comparison

- The calculation of fluid loop system pressure drop was simplified from that required in the previous design study.

CFD Ace™, code generated pressure drops





Closed-form equation

$\Delta P = f *(L/d) * r * (u^2/2)$

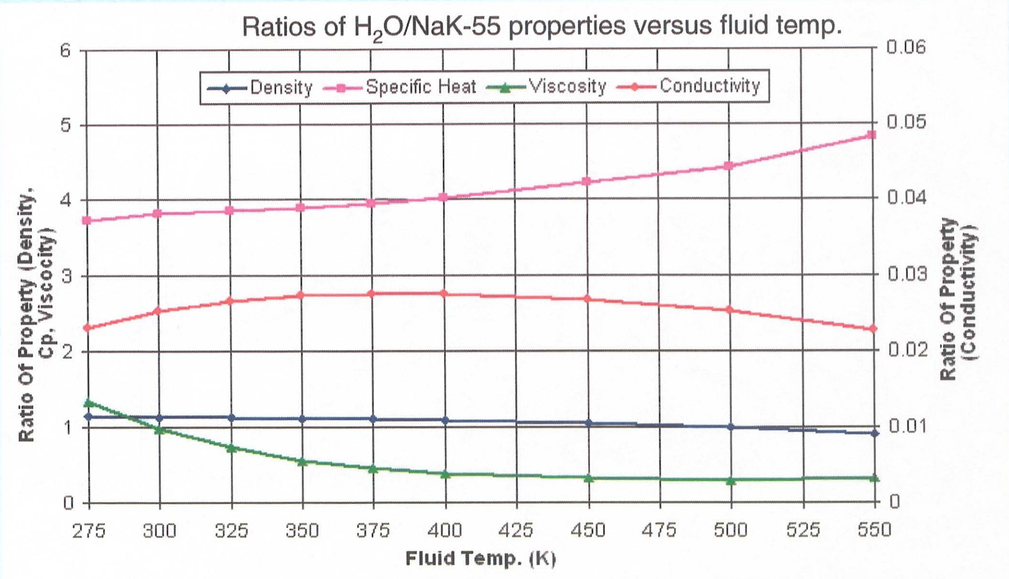
HRS Notional Design Parameters

- The Brayton HRS described in the previous design studies specified the primary thermal design requirements and configuration. These parameters were updated according to the latest HRS design.

Parameter	Previous design study	Updated HRS
Radiator heat load (kWt)	364	590 + 5% margin
Radiator inlet temperature (K)	556	507
Radiator exit temperature (K)	399	387
Radiator area (m^2)	170 (Includes 10% margin)	422 (Includes 10% margin)
Duct wall-thickness (cm)	0.05 cm (NaK-55)	0.075 (NaK-55) & 0.15 (H_2O)
Duct Cross section (cm^2)	Square (NaK-55)	Oval (NaK-55) & Circular (H_2O)
Duct Supply & Return Length (m)	~ 50	~ 200 (NaK-55) & ~ 365 (H_2O)
HP Tube wall thickness (cm)	0.05	0.07
Carbon-Carbon Facesheet In-plane Thermal Conductivity (W/m-K)	600	Function of Temperature
Heat Pipe Saddle Min. Thickness (cm)	0.10	0.375
Pump efficiency	15% (NaK-55)	20% (NaK-55) & 30% (H_2O)

HRS Design Variables

- The primary emphasis of this study is coolant fluid selection (NaK-55 or H_2O) and its effect on overall HRS performance.



NaK-55	H_2O
Alkali metal, health and safety hazard • Requires non-standard handling procedures in crewed environments and careful cleaning procedures prior to assembly and test	Common material, no health hazards • No special handling procedures required
Moderate specific-heat • Efficient single-phase pumped fluid option	Extremely high specific-heat • Very efficient single-phase fluid option • Specific-heat approximately four (4) times that of NaK-55
High thermal conductivity • Very small (~1K) fluid to wall temperature difference	Low thermal conductivity • Small (~6K) fluid to wall temperature difference
Low vapor pressure • Allows thinner and lighter fluid loop components	High vapor pressure • Requires thicker and more robust fluid loop components

HRS Design Variables (Cont'd)

Design Variables Used in Study (Part I: 42 cases).

Parameter	Value	Basis
Coolant Fluid	**Nak-55, H_2O**	Input
Heat pipe spacing (cm)	**7, 8, 9, 10, 11, 12, 13**	Input
Heat pipe inner diameter (cm)	1.25	Input
Fluid duct system pressure drop (kPa)	**100, 200, 300**	Input
Pump Efficiency (%)	20% NaK, 30% H_2O	Input
Radiator Area (m^2)	422 (Includes 10% margin)	Input
Facesheet thickness (mm)	Varied	Input
Duct size (NaK: W x H, H_2O: Dia) (cm x cm, cm)	Varied	Input
HRS mass (kg)		Calculated
Total pump power (watts)		Calculated

Additional Design Variables Used in Study (Part II: 3 cases, using minimum mass design point from Part I).

Parameter	Design Point	Design Point - 25K	Design Point +25K
HRS Coolant Inlet Temp. (K)	507	482	532
HRS Coolant Outlet Temp. (K)	387	362	412
HRS Coolant DT (K)	120	120	120

Sample Analysis

- A heat pipe spacing and heat pipe inner diameter was first selected. An iterative process of varying three parameters then followed.
- The fin facesheet thickness was adjusted until both the radiator coolant exit temperature and the radiator heat load reached their required values.
- At the same time, the duct size and heat pipe evaporator length were varied to achieve the assigned system pressure drop and evaporator radial flux limit.

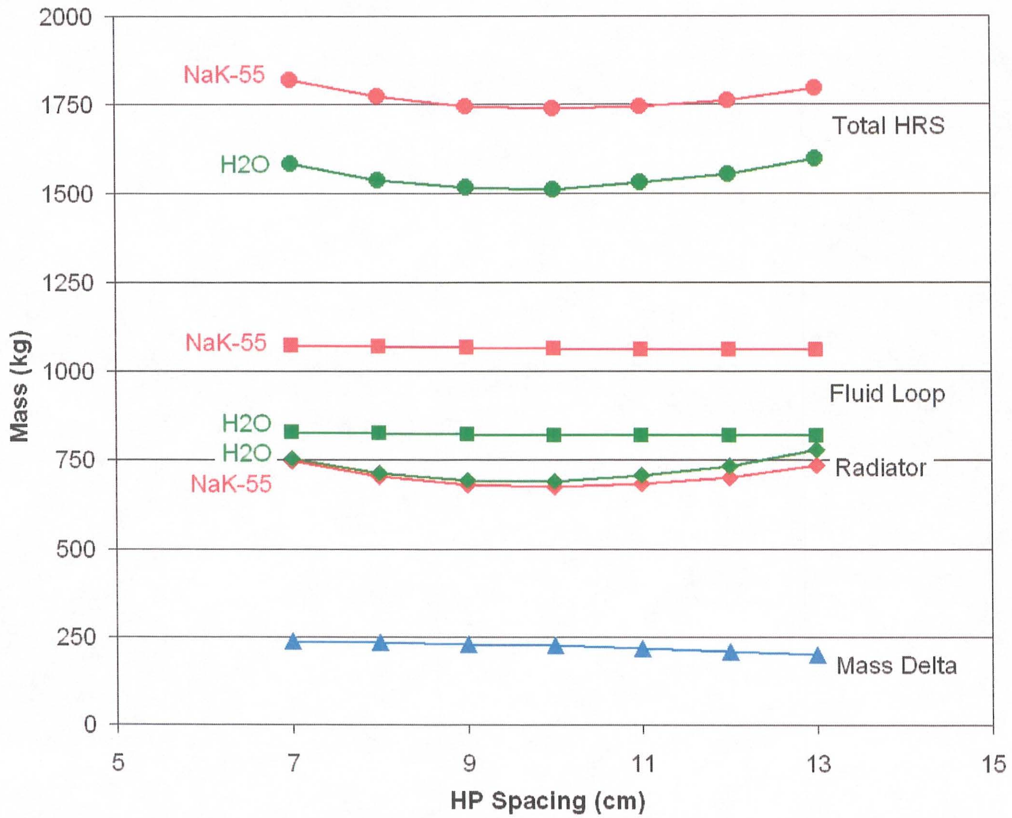
Parameter	Value	Basis
Coolant Fluid	H_2O	Input
Coolant Inlet Temp. (K)	507	Input
Coolant Outlet Temp. (K)	387	Input
Heat pipe spacing (cm)	10	Input
Heat pipe inner diameter (cm)	1.25	Input
Facesheet thickness (mm)	0.25	Input
Pump system pressure drop (kPa)	200	Input
Total pump power (watts)	478	Calculated
MAX heat pipe power (watts)	456	Calculated
Total radiator panel mass (kg)	689.7	Calculated
Total heat transport mass (with pumps and accumulators) (kg)	821.3	Calculated
Total HRS mass (kg)	1511.00	Calculated

RESULTS

Results

Variance of the HRS mass as a function of heat pipe spacing.

- The minimum mass HRS occurs at a heat pipe spacing of about 10cm for both coolants.



Pump system pressure drop = 200 kPa, heat pipe ID = 1.25 cm .

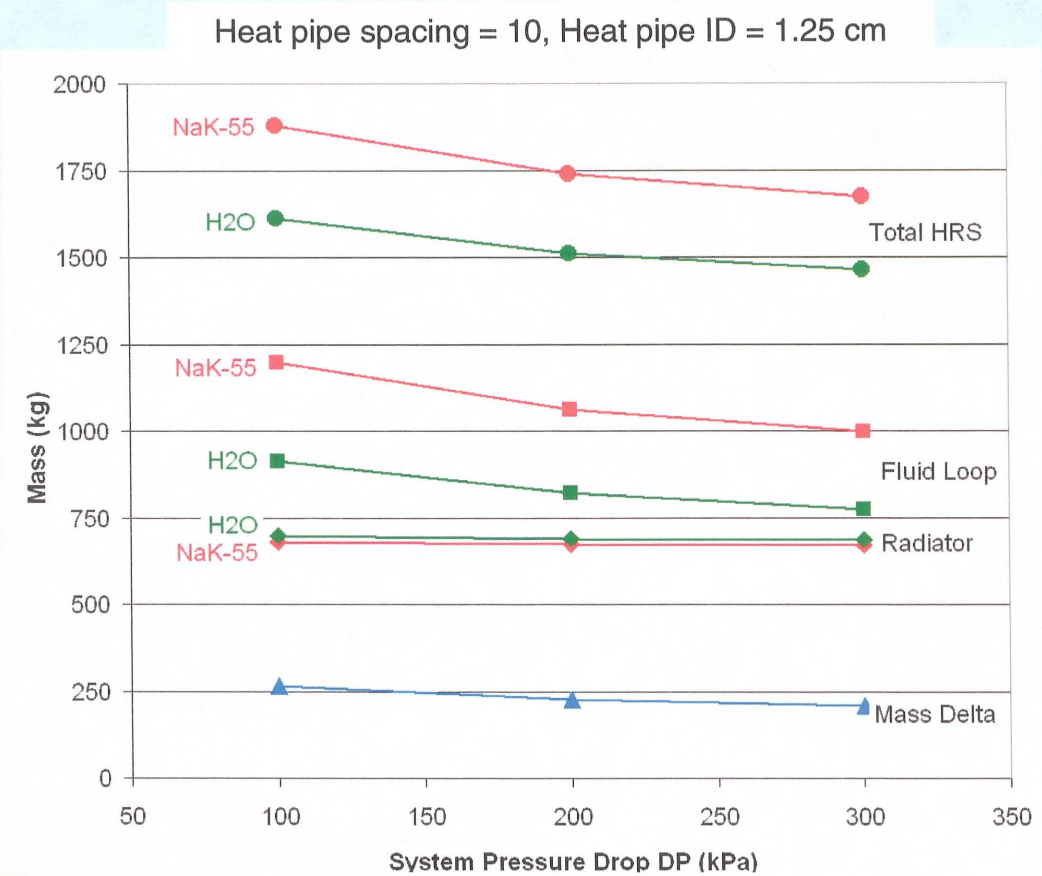
The HRS with H2O weights about 230 kg less than the HRS with NaK-55 at the minimum mass design point for the given parameters.

Similar trends were predicted for pump system pressure drops of 100 and 300 kPa.

Results

Variance of the HRS mass as a function of pump system pressure drop.

- Pressure drop was varied by changing the duct cross-section.
- A H_2O system requires heavier ducts to withstand the higher pressures as compared to NaK-55, but an overall weight saving is seen due to the smaller duct size and lower fluid inventory (fixed pressure drop).

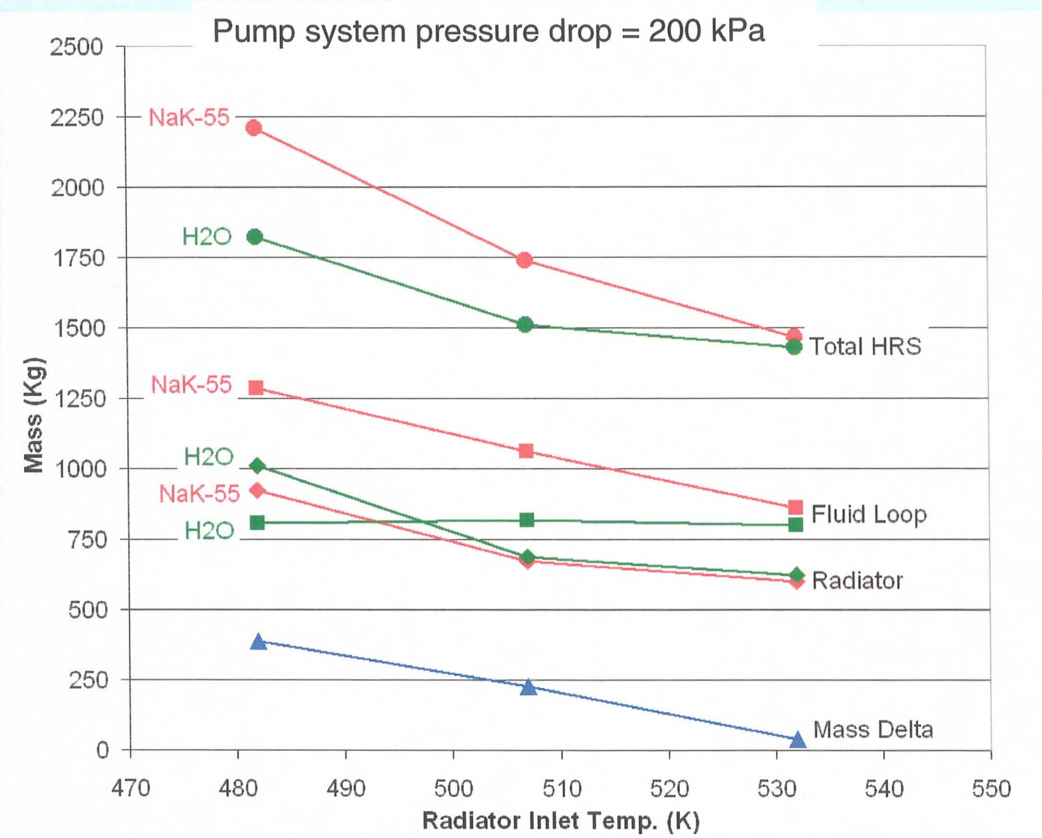


- The weight benefit realized through the H_2O HRS is due primarily to differences within the fluid loops.
- The weight benefit of an H_2O-based HRS is reduced somewhat as the pump system pressure drop increases.

Results

Variance of the HRS mass as a function of radiator inlet temperature.

- For each case, the heat pipe spacing and the heat pipe inner diameter were given fixed values. Then, the facesheet thickness was varied until both the radiator coolant exit temperature and the radiator heat load reached their required values.



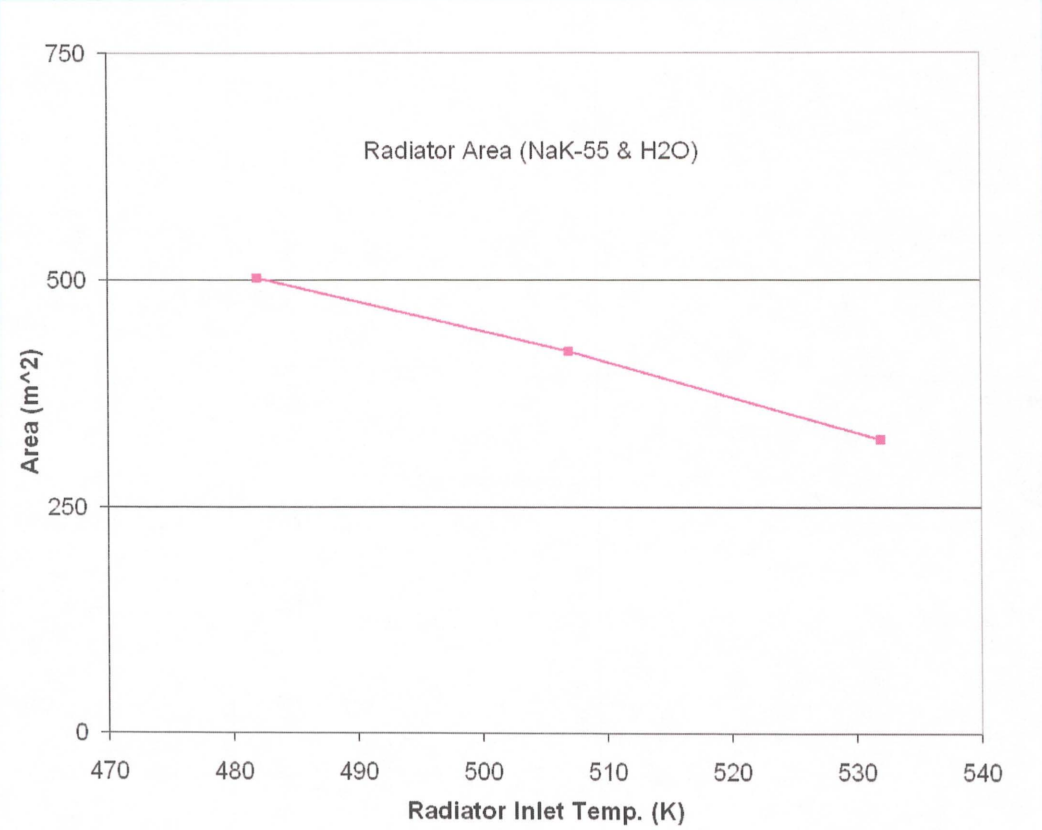
There is a significant mass decrease with increasing temperature due to the reduction in radiator area which permitted decreases in the duct supply and return lengths, allowing the duct cross-section to be reduced (fixed pressure drop).

The mass advantage for H2O is less pronounced at higher temperatures since duct wall increases are required due to the higher operating pressures.

Results

Variance of the HRS radiator area as a function of radiator inlet temperature.

- HRS area (same for both NaK-55 and H_2O coolants) decreases as the radiator inlet temperature increases. An HRS with a radiator inlet temperature of 532 K has 35% less area than an HRS with a radiator inlet temperature of 482 K.



Conclusions

- Earlier HRS design trades were conducted addressing heat transport approaches, material and fluid options.
- This paper discussed the interplay between radiator coolants (NaK-55 and H_2O) for various heat pipe spacings and pump system pressure drops for a fixed geometry radiator.
- It also discussed the interplay between radiator coolants (NaK-55 and H_2O) for various radiator coolant inlet temperatures for a fixed heat pipe spacing and fixed pump pressure drop system.
- Based on the results of this paper, there is substantial mass savings for a H_2O system over a NaK-55 system for the given radiator inlet outlet temperatures.
- This mass savings is a function of the system pressure drop and the radiator inlet temperature.
- The mass savings for the H_2O system decreases as the system pump pressure drop increases and as the radiator inlet temperature increases.

Conclusions (Cont'd)

- Additional trade studies are needed to further refine the HRS design and make the choice between NaK-55 and H_2O final. Other considerations must be taken into account in addition to the mass savings. These should include, but not be limited to:
  - Health and safety issues (toxic NaK vs. for non-toxic / non-hazardous water).
  - Technology development (NaK fluid loop requires extensive technology development).
  - Compatibility issues (NaK may have long-term compatibility issues) with fluid loop materials.
  - System Packaging (NaK fluid loop requires larger fluid and flex-hose diameters, complicates mechanical packaging, water fluid loop requires smaller fluid and flex-hose diameters, simplifies mechanical packaging).
  - Structural design and Integrity (Low pressure NaK fluid vs. high pressure H_2O system).