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

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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_2O 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.

Introduction

Nuclear Electric Propulsion (NEP) is a technology of current interest because it has the potential to provide many benefits for deep space science missions including maneuverability to multiple mission targets, extended duration science, increased instrument power, and high data rate communications. Surface reactors may be used for the moon or Mars to power human outposts enabling extended stays, in-situ resource utilization, and closed loop life support. In either case, 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. Brayton systems tend to optimize at efficiencies of about 20 to 25 percent with radiator temperatures in the 400 to 600 K range.

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 (Mason, 2003; Siamidis, 2005).

In the first design study (Mason, 2003) the PCS included two 100 kWe Brayton converters for a 100 kWe net output power. The HRS consisted of a pumped sodium-potassium (NaK) heat transport loop coupled to a water heat pipe radiator as shown in figure 1. The total radiator area was 170 m^2 configured in two separate wings that extended radially from a central truss structure. The radiator panels provided

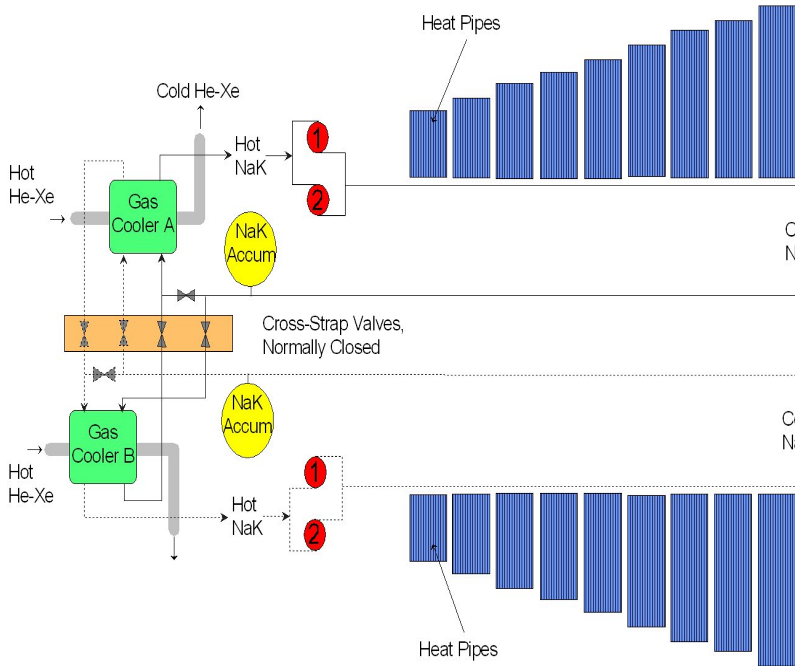


Figure 1.—Two Brayton heat rejection subsystem schematic.

two-sided heat rejection and were arranged in a “stair-case” configuration contained within a 10° half-angle as dictated by the conical reactor shield. Each radiator wing was dedicated to a single Brayton converter operating at 50 percent of rated power. Cross-strap NaK piping and a dual passage waste heat exchanger, allowed the full radiator (both wings) to serve a single Brayton converter operating at 100 percent power should a failure occur. The total mass of the HRS including radiator panels, pumps, plumbing, and deployment structure was reported as 854 kg, or 5 kg/m^2 (based on total surface area).

In the second design study (Siamidis, 2005) the PCS included four 50 kWe Brayton converters for a 100 kWe system. The HRS consisted of a pumped NaK heat transport loop coupled to a water heat pipe radiator as shown in figure 2. The radiator area was configured in two separate wings that extended radially from a central truss structure. The radiator panels provided two-sided heat rejection and were arranged in a “two-fold” configuration contained within a 10° half-angle as dictated by the conical reactor shield. Each radiator wing was dedicated to a single Brayton converter operating at 100 percent of rated power with the capability to service either or two Brayton units associated with that wing. The paper discussed the interplay between heat pipe spacing and heat pipe diameter and their effect on heat pipe maximum heat flux, maximum heat pipe power, heat pipe area exposed to micrometeoroid and orbital debris (MMOD), system pressure drop and pump power for a fixed geometry radiator.

This paper uses the previous design concept (Siamidis, 2005) as a starting point for more rigorous 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.

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. Historically the design of pumped loop and heat pipe space HRS used NaK-78 as the coolant fluid. For the present JIMO application NaK-55 was chosen over NaK-78 for its lower freeze-temperature (280 K) and higher specific heat.

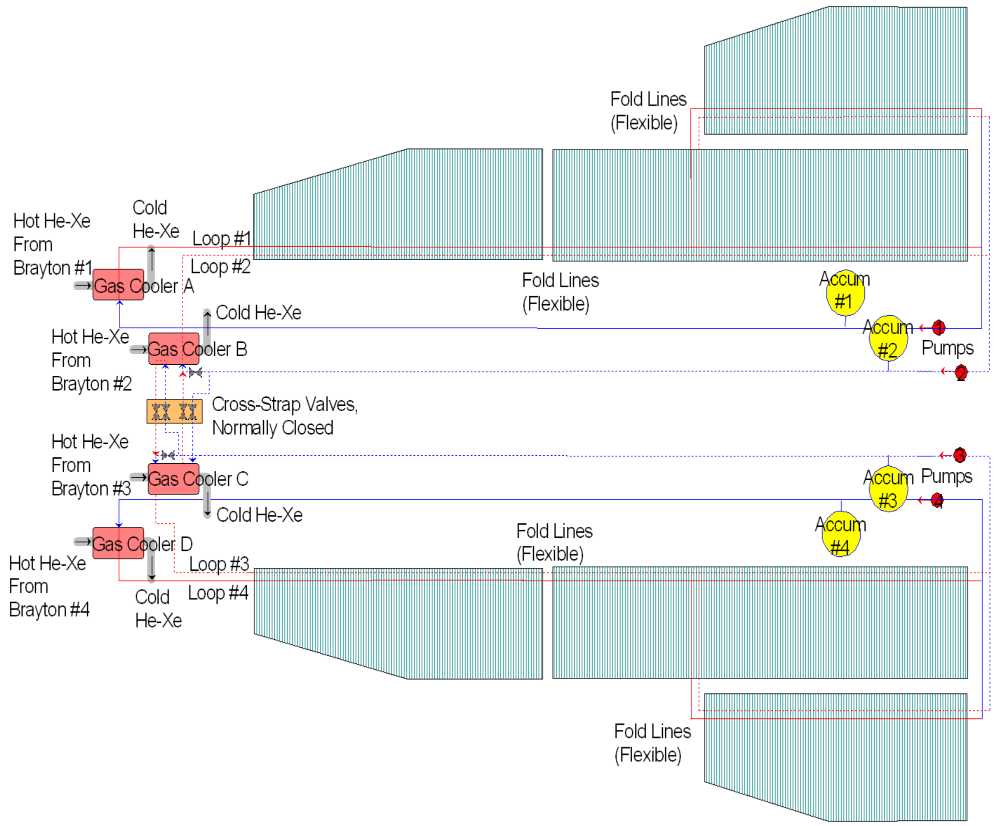


Figure 2.—Four Brayton heat rejection subsystem schematic.

The previous design concept (Siamidis, 2005) for JIMO has been updated. The PCS includes four 100 kWe Brayton converters to produce 200 kWe net output. The HRS consists of a pumped NaK or H_2O heat transport loop coupled to a water heat pipe radiator as shown in figure 3. The radiator area is configured in two separate wings that extend radially from a central truss structure. The radiator panels provide two-sided heat rejection and are arranged in a four boom/segment configuration contained within a 12° half-angle as dictated by the conical reactor shield. Under nominal operations one pumped-fluid loop is used to transport the waste heat from the gas-cooler of each of the two operating PCS units to a series of radiator panels containing water heat pipes and white-painted carbon-carbon (C-C) radiator fins. A separate, isolated pumped-fluid loop is provided for each of the two non-operating PCS units should a PCS-string switchover become necessary through a failure or anomaly condition. The HRS fluid loops of one operating and one non-operating PCS unit share the same radiator area for single-fault tolerance against failure of either the PCS unit or HRS fluid loop without loss of power generating capabilities.

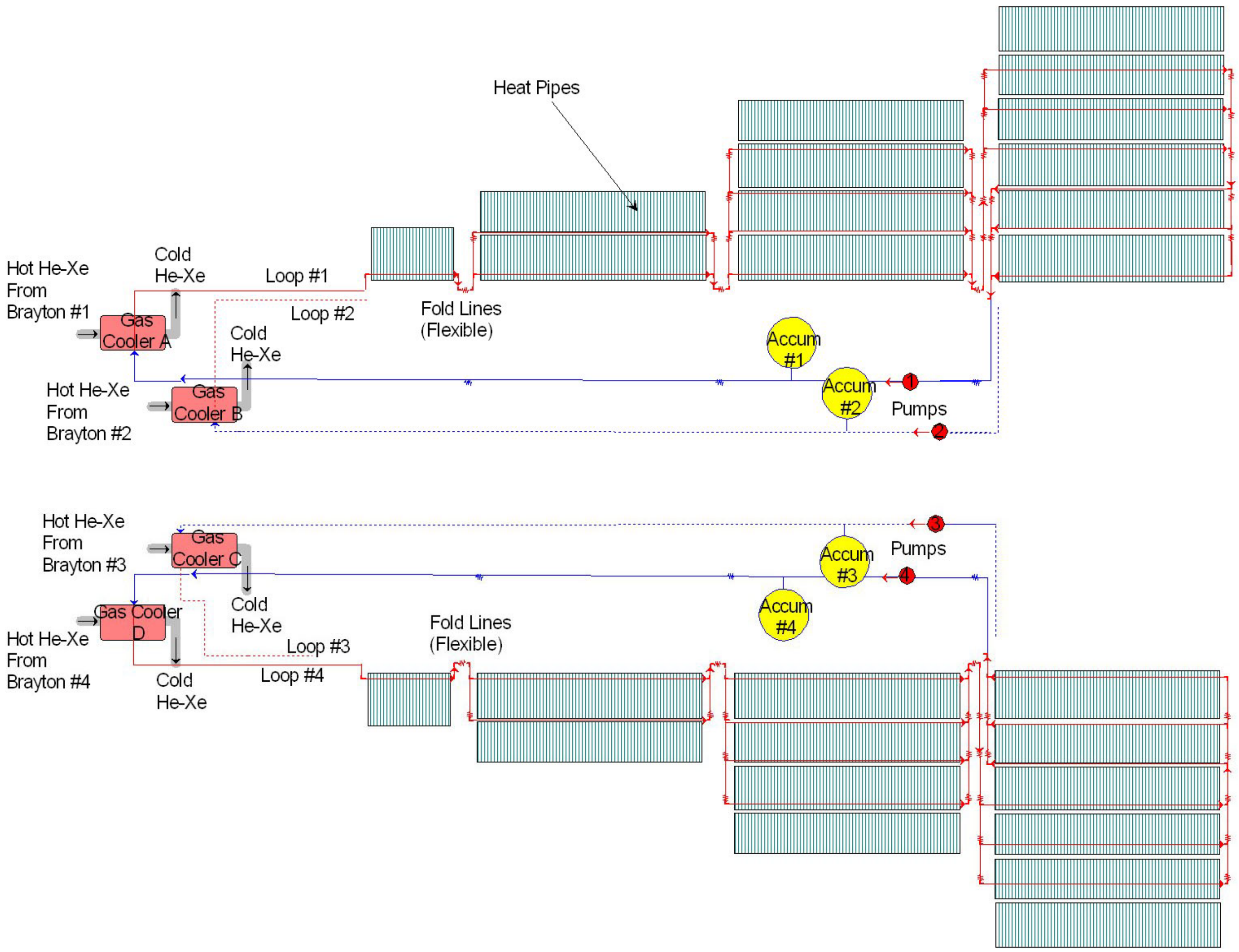
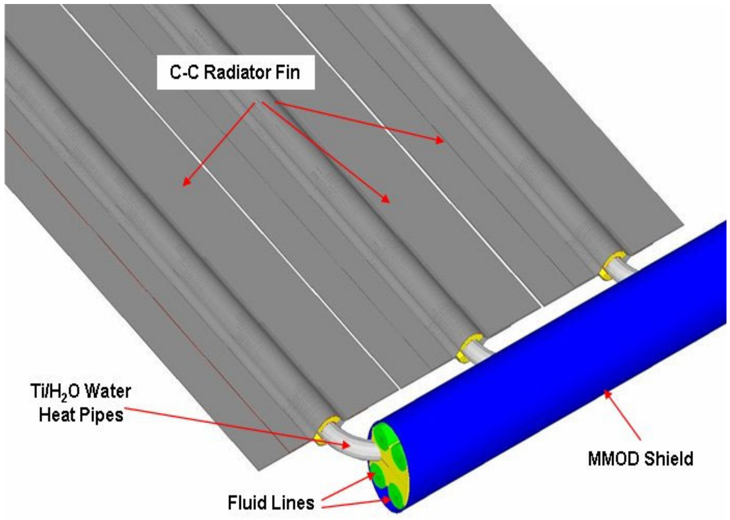


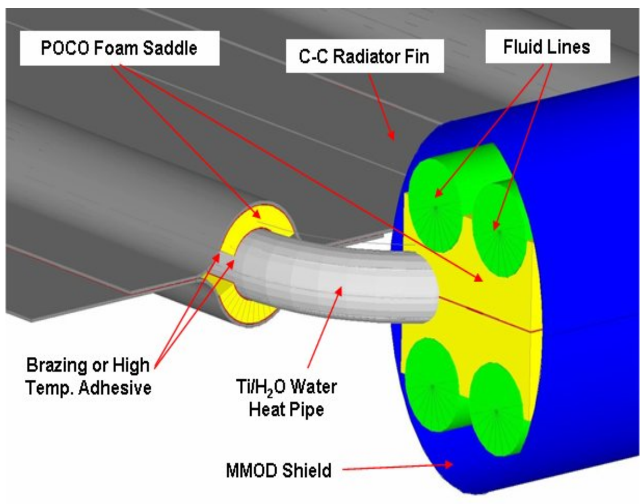
Figure 3.—Updated Brayton heat rejection subsystem schematic.

HRS Design Basis

The HRS accepts heat from the Brayton power converters and rejects it into space through the radiator panels. A NaK-55 or H_2O cooling loop connects the Brayton converters to the radiator panels. The Brayton gas coolers serve as the thermal interface to the coolant loops. The design was modified from four 50 kWe Brayton converters to four 100 kWe Brayton converters, each having its own dedicated cooling loop. During nominal operation, only two of the four converters are used to produce the required 200 kWe. The radiator panels use a construction consisting of regularly-spaced circular heat pipes contained within two composite facesheets as shown in figure 4.



(a) Radiator details



(b) Radiator/cooling loop details

Figure 4.—Radiator detail and heat pipe integration with cooling loop.

The heat pipes use water as the working fluid and titanium containment. Heat pipes provide an efficient means of spreading the heat across the radiator surface with minimal temperature drop. The high conductivity composite facesheets serve as the radiator fin. The heat pipes are thermally connected to the facesheets through a Poco™ (Poco Graphite, Inc., Decatur, TX) foam saddle extending along the entire axial length of the heat pipe. 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. One of the key advantages to this type of radiator is its ability to withstand damage from micrometeoroid and orbital debris (MMOD). A fatal MMOD impact to a single heat pipe, even though it will result in the failure of that heat pipe, would have minimal system performance impact.

The water heat pipes interface to the coolant through curved sections partially contained within the cooling loop as shown in figure 5. The heat pipe evaporators are "sandwiched" between two cooling loops. One loop is active and the second is the backup. A Poco foam saddle is introduced between the

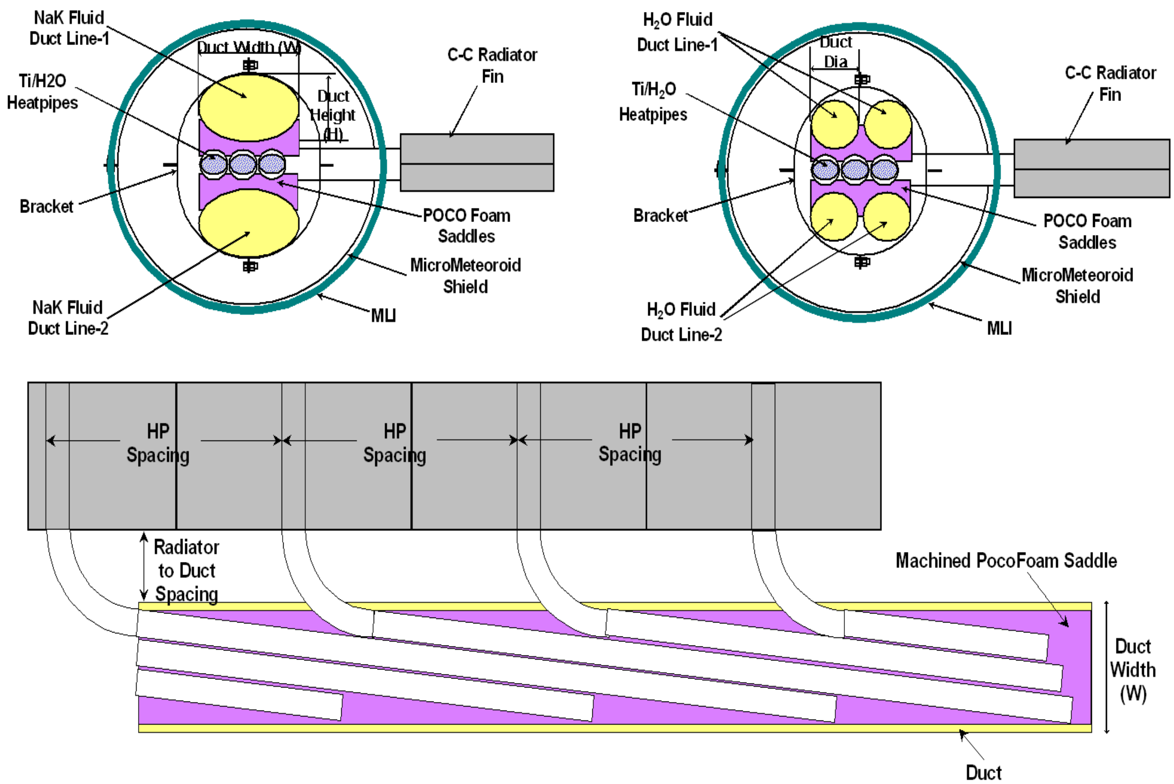


Figure 5.—Heat pipe integration with cooling loop.

heat pipe evaporators and the cooling loop ducts to improve heat transfer. The two HRS fluid loops provide fault tolerance against loss of either a PCS unit or HRS fluid loop without affecting power generating capabilities. The fluid ducting is made of titanium. The duct cross-section is oval for NaK-55 and split circular for H_2O. Each cooling loop includes a pump and a bellows accumulator.

Analytical Model

The design of the Brayton HRS depends on many parameters. An Excel spreadsheet model, called HRS-Opt, was developed to evaluate the design trade space described in the previous design study (Siamidis, 2005). Parameters were varied to compare the design options on the basis of pump system pressure drop and required pump power, heat pipe unit power and radial flux, radiator panel areal mass, and overall HRS mass. For the analysis presented in this paper, the HRS-Opt spreadsheet model was modified to accommodate the updated HRS design. Additional capabilities, including NaK-55 and H_2O coolant properties, were also added.

The fin efficiency is a critical part of this analysis since it varies widely with heat pipe spacing and facesheet thickness. A closed-form equation for fin efficiency (Gilmore, 1994) was adopted in HRS-Opt, as discussed in the previous design study (Siamidis, 2005).

The calculation of fluid loop system pressure drop was simplified from that required in the previous design (Siamidis, 2005). The previous design used heat pipe evaporators immersed within the fluid loop, oriented normal to the fluid flow. A computational fluid dynamics code (CFD Ace™, CFD Research Corporation, Huntsville, AL) was necessary to generate pressure drop parameters for use in HRS-Opt. The updated concept removes the heat pipes from the flow path, simplifying the flow geometry. Thus, a closed form fluid loop pressure drop calculation is possible. A simple equation, $[\Delta P = f * (L/d) * \mathbf{r} * (u^2/2)]$, (Holman, 1981) was used to calculate the system pressure drop in the coolant duct.

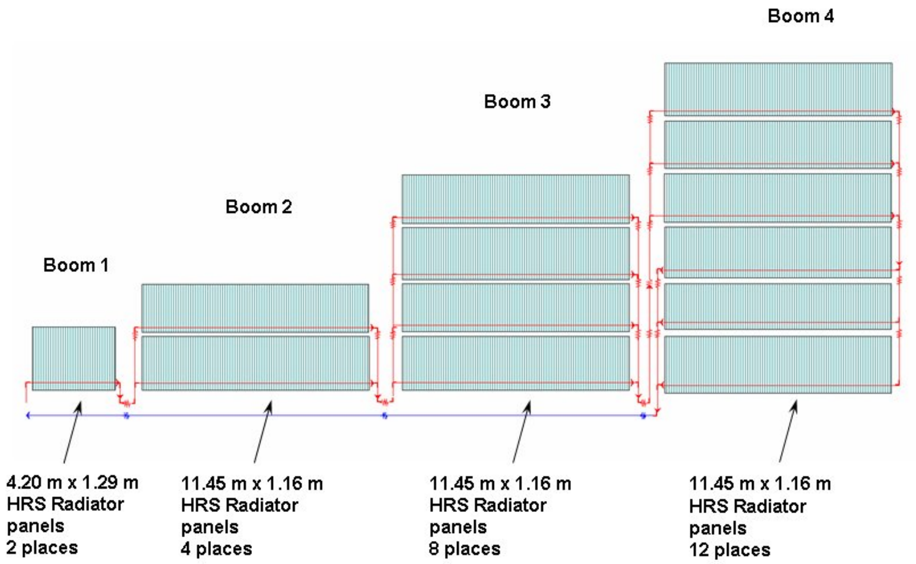


Figure 6.—Updated HRS radiator geometry.

HRS Design Parameters

The Brayton HRS described in the previous design study (Siamidis, 2005) specified the primary thermal design requirements and configuration. These parameters were updated according to the latest HRS design. Table 1 includes the major parameter changes from the previous design study to the updated HRS design, one-half of which is shown in figure 6.

Additional design details were needed before a substantive evaluation of the HRS trade space could be performed. This included a preliminary definition of construction materials and some of the dimensional parameters. For this study, these parameters were held constant, although the model allows them to be varied. The heat pipes were assumed to use water with a 10 percent liquid fill fraction. The assumed heat pipe containment was titanium (4.5 g/cm^3). The thermal saddles were assumed to be made of 0.54 g/cm^3 Poco graphite. The facesheets were carbon-carbon with a density of 1.92 g/cm^3 and thermal conductivity (normal to the direction of the heat pipes) varying as a function of temperature. The coolant duct was titanium with wall-thickness and cross-section given in table 1. The duct supply and return length for the H_2O (~ 365 m) is greater than that of NaK (~ 200 m) due to its split design as seen in figure 5.

TABLE 1.—DESIGN PARAMETER CHANGES

Parameter	Previous design study (Siamidis, 2005) HRS	Updated HRS
Radiator heat load (kWt)	364	590 + 5 percent 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) and 0.15 (H_2O)
Duct cross section (cm^2)	Square (NaK-55)	Oval (NaK-55) and Circular (H_2O)
Duct supply and return length (m)	~50	~200 (NaK-55) and ~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) and 30% (H_2O)

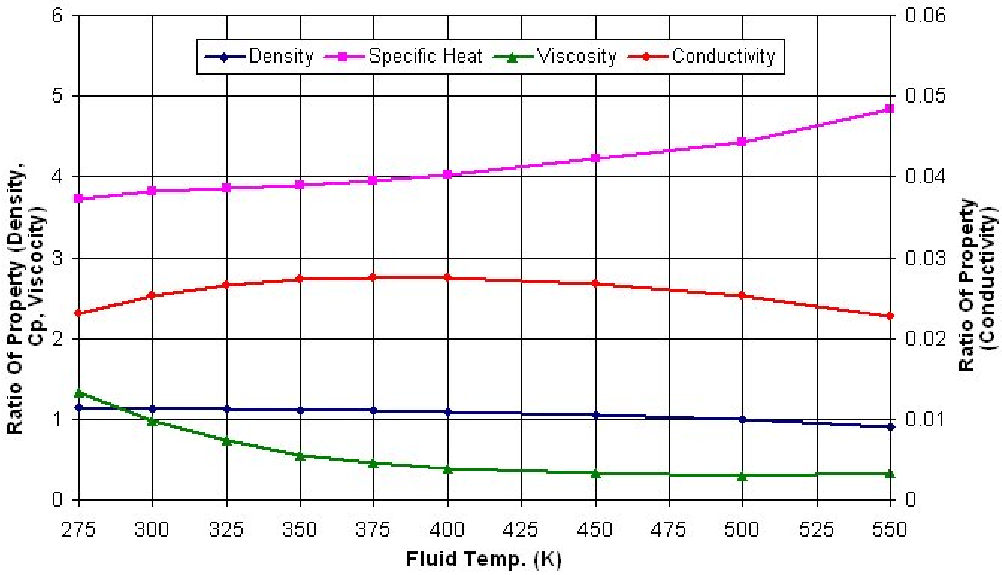


Figure 7.—NaK-55 and H_2O fluid property ratios for H_2O/NaK-55.

The primary emphasis of this study is coolant fluid selection and its effect on overall HRS performance. The coolant used in the previous design study analysis was NaK-78. This analysis compares NaK-55 with H_2O. NaK-55 was chosen over NaK-78 for its lower freeze-temperature (280 K) and higher specific heat. Higher specific heat reduces fluid mass flow rate and higher liquid density reduces fluid volumetric flow-rate, which in turn reduce fluid loop mass and pumping power. A comparison of the thermal properties of NaK-55 and H_2O are shown in figure 7 where the ratios of H_2O/NaK-55 properties are plotted versus fluid temperature. Other factors to consider in evaluating the two fluids are listed in table 2.

TABLE 2.—NaK-55 AND H_2O DIFFERENCES

NaK-55	**H_2O**
Alkali metal, health and safety hazard	Common material, no health hazards
• Requires non-standard handling procedures in crewed environments	• No special handling procedures required
• Requires careful cleaning procedures prior to assembly and test	
Moderate specific-heat	Extremely high specific-heat
• Efficient single-phase pumped fluid option	• Very efficient single-phase fluid option
	• Specific-heat approximately four (4) times that of NaK-55
High thermal conductivity	Low thermal conductivity
• Very small (~1K) fluid to wall temperature difference	• Small (~6K) fluid to wall temperature difference
Low vapor pressure	High vapor pressure
• Allows thinner and lighter fluid loop components	• Requires thicker and more robust fluid loop components
High electrical conductivity	Low electrical conductivity
• Eddy current losses reduce mechanical pump efficiency to ~20% net	• Highly efficient (>30%) mechanical-pumps
• Well suited for Electromagnetic Magnetic (EM) pumping options, pumping efficiency typically <15% net	• Electromagnetic Magnetic (EM) pumping not an option

Other design variables considered in this study were heat pipe spacing and system pressure drop. The range of parameters considered is provided in table 3. Given the seven different spacing options and three system pressure drops for each fluid, a total of forty-two individual design cases were examined. The primary output parameter of interest was the total HRS mass. The total HRS mass includes the radiator panel mass, and the fluid loop mass with ducts, pumps, accumulators, and other miscellaneous components such as flexible fluid joints.

TABLE 3.—DESIGN VARIABLES USED IN STUDY

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 (W)		Calculated

Once the forty-two individual design cases were analyzed, the minimum mass design point was used to further investigate the effect of different radiator inlet and outlet temperatures on the HRS mass for a fixed system pressure drop of 200 kPa. Table 4 provides the additional cases analyzed.

TABLE 4.—ADDITIONAL DESIGN VARIABLES USED IN STUDY

Parameter	Design Point	Design Point –25 K	Design Point +25 K
HRS coolant inlet temperature (K)	507	482	532
HRS coolant outlet temperature (K)	387	362	412
HRS coolant DT (K)	120	120	120

Analytical Results

The process used to analyze each configuration was as follows. A heat pipe spacing and heat pipe inner diameter was selected. An iterative process of varying three parameters then followed. The facesheet thickness was adjusted until the radiator coolant exit temperature reached the required value of 387 K and the radiator heat load matched the required value of 590 kWt. At the same time, the duct size and heat pipe evaporator length were varied to achieve the assigned system pressure drop (100, 200, and 300 kPa) and the 10 W/cm^2 evaporator radial flux limit respectively.

A sample case is reported in table 5 for 10 cm heat pipe spacing and a 1.25 cm heat pipe inner diameter. The resulting facesheet thickness required to achieve the 387 K radiator exit temperature was 0.25 mm. The heat pipe geometry and facesheet thickness resulted in a fin efficiency of 79 percent. The required pump system pressure drop was set at 200 kPa which resulted in a pump power of 478 W for each pump. The maximum heat pipe power and radial flux was 456 W and 10 W/cm^2, respectively. The total HRS mass was 1511 kg or 7.16 kg/m^2 (based on total surface area), and the radiator panel areal mass was 3.27 kg/m^2 (based on total surface area).

TABLE 5.—SAMPLE RESULTS CASE

Parameter	Value	Basis
Coolant fluid	H_2O	Input
Coolant inlet temperature (K)	507	Input
Coolant outlet temperature (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
Fin efficiency (%)	79%	Calculated
Total pump power (W)	478	Calculated
MAX heat pipe power (W)	456	Calculated
MAX heat pipe radial flux (W/cm^2)	10.0	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
Radiator panel areal mass—single sided (kg/m^2)	3.27	Calculated
Total HRS areal mass—single sided (kg/m^2)	7.16	Calculated

Based on the results of this paper, there is substantial mass savings for a H_2O system versus a NaK-55 system for the given radiator temperatures. The mass savings is a function of several parameters including the system pressure drop and the radiator inlet temperature. The mass savings lessens with increases in system pressure drop or radiator inlet temperature.

Figure 8 shows the variance of the HRS radiator, fluid loop and total mass as a function of heat pipe spacing for a heat pipe inner diameter of 1.25 cm and pump system pressure drop of 200 kPa for both NaK-55 and H_2O coolants. Results show that the minimum mass HRS occurs at a heat pipe spacing of about 10 cm for both coolants. Results also show that an HRS with H_2O weights about 230 kg less than an 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.

Figure 9 shows the variation of the total HRS mass, fluid loop mass, and radiator mass as a function of pump system pressure drop for a heat pipe spacing of 10 cm and heat pipe inner diameter of 1.25 cm. Pressure drop was varied by changing the duct cross-section. Overall duct length and mass flow rate were held constant. A smaller duct size increases the pressure drop, but reduces the duct mass, fluid inventory and fluid mass. Increasing the system pressure drop from 100 to 300 kPa, results in a weight saving of approximately 200 kg for the NaK-55 system and 150 kg for the H_2O system.

A HRS with a H_2O fluid loop weighs less than its NaK-55 counterpart, and this weight saving benefit is slightly affected by pump system pressure drop. The weight benefit realized through H_2O is due primarily to differences within the fluid loops and only marginally affected by differences in the radiator itself. While a H_2O system requires heavier ducts to withstand the higher pressures as compared to NaK-55, an overall weight saving is seen due to the smaller duct size and lower fluid inventory. The weight benefit of an H_2O-based HRS is reduced somewhat as the pump system pressure drop increases. As the system pressure drop increases from 100 to 200 to 300 kPa, the mass savings of the H_2O system decreases from 265 to 227 to 210 kg, respectively.

The second part of the analysis evaluated performance sensitivities with variable inlet and exit temperatures. For each case, the heat pipe spacing and the heat pipe inner diameter were given fixed values. Then, the facesheet thickness was varied until the radiator coolant exit temperature reached the desired value and the radiator heat load matched the design value of 590 kWt.

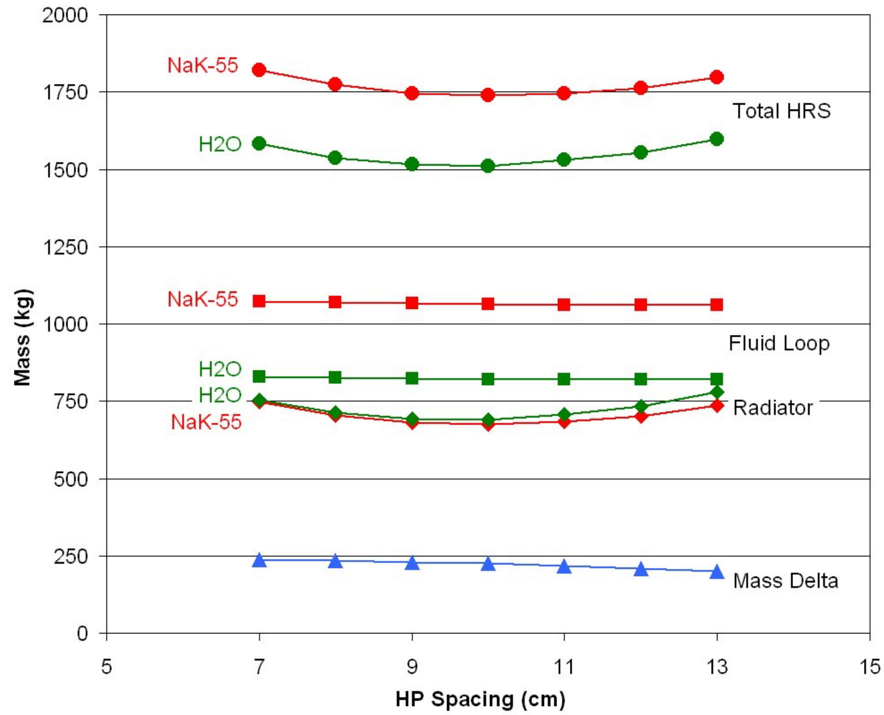


Figure 8.—HRS mass versus heat pipe spacing—200 kPa.

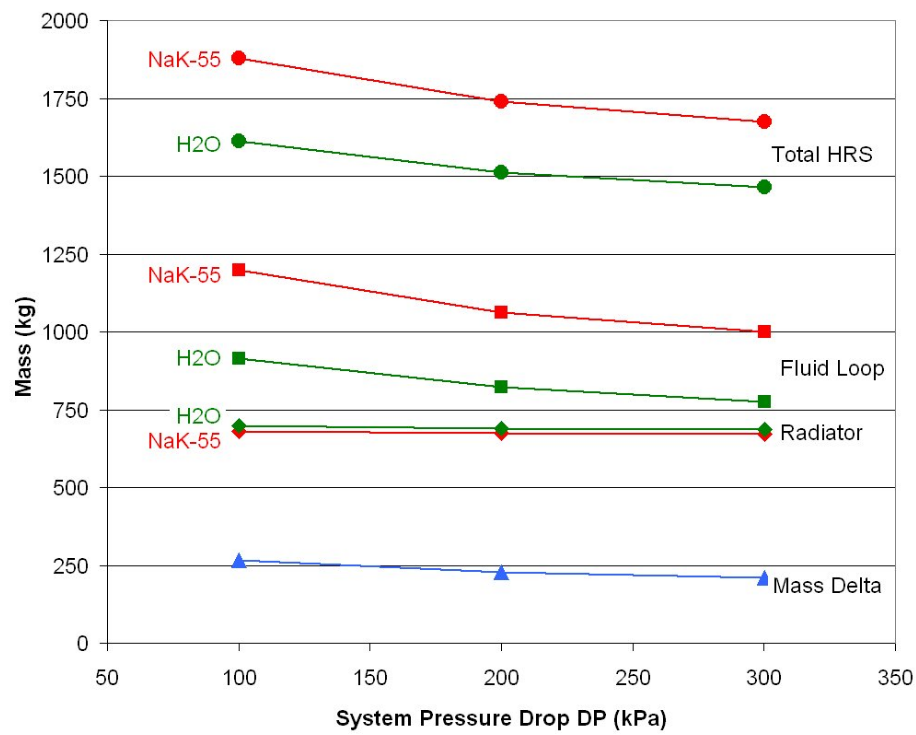


Figure 9.—HRS mass versus system pressure drop.

Figure 10 shows the variation of the HRS radiator, fluid loop, and total mass as a function of radiator inlet temperature for a heat pipe spacing of 10 cm, heat pipe inner diameter of 1.25 cm, and system pressure drop of 200 kPa with both NaK-55 and H_2O coolants. There is a significant mass decrease with increasing temperature due to the reduction in radiator surface area. The reduced area permitted decreases in the duct supply and return lengths, allowing the duct cross-section to be reduced commensurately given the assumption of fixed pressure drop. The higher temperatures did cause an increase in duct wall thickness as required for the elevated operating pressures. As the radiator inlet temperature increases from 482 to 507 to 532 K, the mass savings of the H_2O system decreases from 388 to 227 to 38 kg, respectively. The mass advantage for water is less pronounced at higher temperature since the duct wall increases are exacerbated by the much higher operating pressures.

Figure 11 shows the variance of the HRS radiator area as a function of radiator inlet temperature for a heat pipe spacing of 10 cm, heat pipe inner diameter of 1.25 cm and pump system pressure drop of 200 kPa for both NaK-55 and H_2O coolants. Results show that the 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 530 K has 35 percent less area than an HRS with a radiator inlet temperature of 480 K.

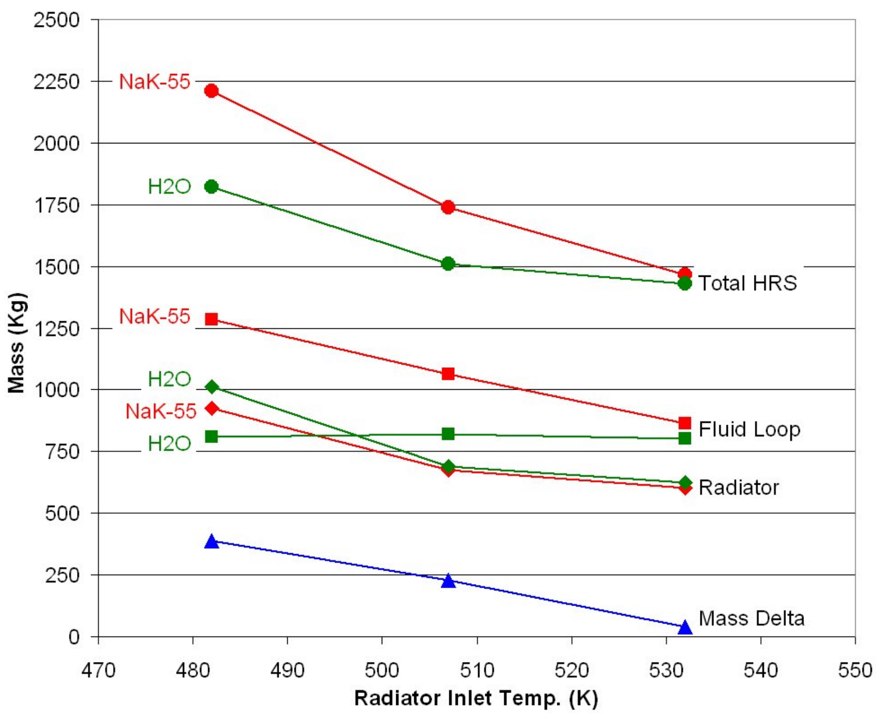


Figure 10.—HRS mass versus radiator inlet temperature.

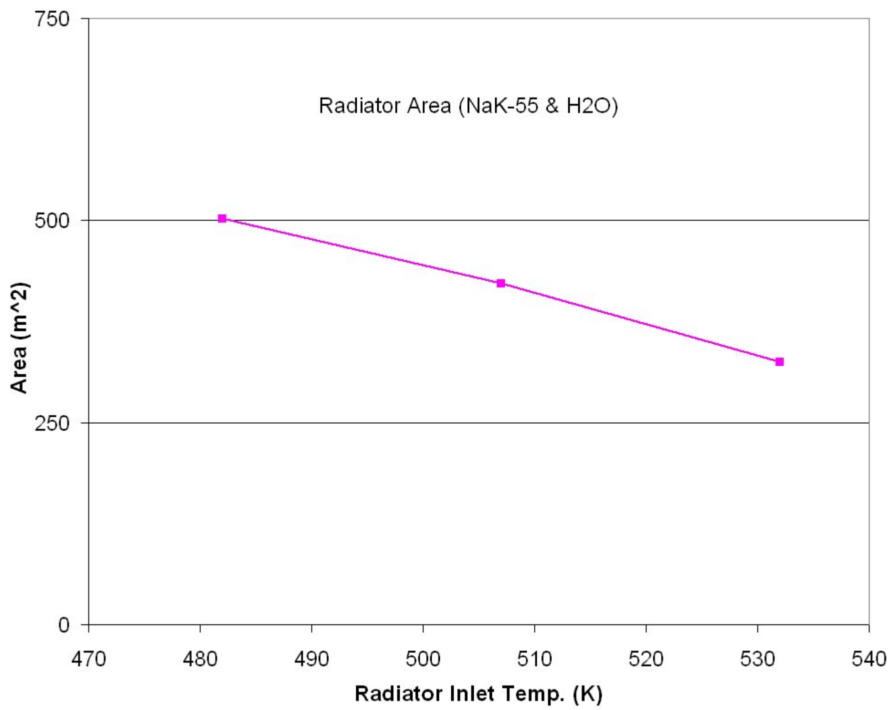


Figure 11.—HRS area versus radiator inlet temperature.

Conclusions and Recommendations

Earlier HRS design trades were conducted addressing heat transport approaches, material and fluid options, and deployed radiator geometries. This paper discusses 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 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.

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).

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Appendix—Nomenclature

T	Temperature (K)
ΔP	Pressure drop (kPa)
f	Friction factor
L	Length (m)
d	Diameter (m)
r	Liquid density (kg/m^3)
u	Velocity (m/s)

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13. ABSTRACT ***(Maximum 200 words)***

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.

14. SUBJECT TERMS

Brayton power conversion system; Brayton heat rejection system; Heat pipe radiator

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