AN ACTIVE BROAD AREA COOLING MODEL OF A CRYOGENIC PROPELLANT TANK WITH A SINGLE STAGE REVERSE TURBO-BRAYTON CYCLE CRYOCOOLER

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ABSTRACT

As focus shifts towards long-duration space exploration missions, an increased interest in active thermal control of cryogenic propellants to achieve zero boil-off of cryogens has emerged. An active thermal control concept of considerable merit is the integration of a broad area cooling system for a cryogenic propellant tank with a combined cryocooler and circulator system that can be used to reduce or even eliminate liquid cryogen boil-off. One prospective cryocooler and circulator combination is the reverse turbo-Brayton cycle cryocooler. This system is unique in that it has the ability to both cool and circulate the coolant gas efficiently in the same loop as the broad area cooling lines, allowing for a single cooling gas loop, with the primary heat rejection occurring by way of a radiator and/or aftercooler. Currently few modeling tools exist that can size and characterize an integrated reverse turbo-Brayton cycle cryocooler in combination with a broad area cooling design. This paper addresses efforts to create such a tool to assist in gaining a broader understanding of these systems, and investigate their performance in potential space missions. The model uses conventional engineering and thermodynamic relationships to predict the preliminary design parameters, including input power requirements, pressure drops, flow rate, cycle performance, cooling lift, broad area cooler line sizing, and component operating temperatures and pressures given the cooling load operating temperature, heat rejection temperature, compressor inlet pressure, compressor rotational speed, and cryogenic tank geometry. In addition, the model allows for the preliminary design analysis of the broad area cooling tubing, to determine the effect of tube sizing on the reverse turbo-Brayton cycle system performance. At the time this paper was written, the model was verified to match existing theoretical documentation within a reasonable margin. While further experimental data is needed for full validation, this tool has already made significant steps towards giving a clearer understanding of the performance of a reverse turbo-Brayton cycle cryocooler integrated with broad area cooling technology for zero boil-off active thermal control.

INTRODUCTION

The cryogenic storage of liquid rocket engine propellants for long-duration space exploration missions requires a focused effort towards eliminating the external heat inputs that contribute to the evaporation of the propellant, commonly referred to as *boil-off*. This cryogenic boil-off increases the vapor volume, also known as the ullage, within a cryogenic tank, while decreasing the volume of the liquid, thus reducing the amount of usable propellant while raising the internal pressure. Once tank pressure rises above the allowable limits, the tank contents must be vented to reduce the ullage mass and return the tank contents to an acceptable pressure. This vent case causes some loss of the propellant, which must be compensated for by carrying additional propellant on board, which in turn increases the mass requirements for a mission.

Long-duration space exploration missions have much greater mass requirements when compared to short-term missions, in part due to the larger propellant volumes that are necessary to sustain them. In order to reduce the total propellant storage mass, active cooling systems in combination with passive thermal control techniques such as multi-layer insulation (MLI) can be used to achieve reduced boil-off (RBO), and zero boil-off (ZBO) of a cryogenic propellant. Both lead to an improvement in cryogenic storage efficiency, which has recently been established as the leading source of mass savings for future NASA long-duration missions[1]. This can be seen in Figure 1, where reduced boil-off is shown to have the highest potential of any category when considering the potential sources of mass reduction for a theoretical mission to Mars.

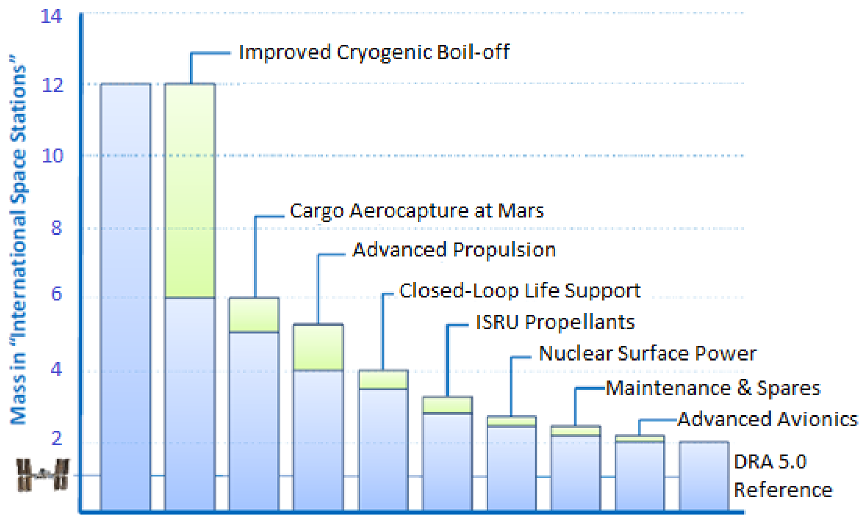

Figure 1. The major contributors to possible mass savings for a theoretical human exploration mission to Mars[1]. Reduced boil-off technologies are shown to be the largest source of potential mass reduction.

Active Cooling Systems for Zero Boil-Off Applications

During the course of a mission, heat enters the walls of a cryogenic tank and transfers into the propellant, causing undesired boil-off of the liquid. However, if this heat can be intercepted before it enters the tank wall, the propellant can be maintained at a low enough temperature to prevent boil-off from occurring, thus achieving ZBO. One method of heat interception is the use of passive thermal controls, which involve the use of static systems such as MLI and other insulation materials. An effective passive system can then be augmented with an active cooling system in order to eliminate the amount of heat entering the tank completely.

One method of achieving active thermal control of a propellant tank is the use of a broad area cooling (BAC) shield. A BAC shield is typically a shroud that either lies within the tank's MLI layers or is integrated directly onto the tank wall, and consists of multiple lines of tubing that are distributed over the surface. A working fluid, or refrigerant, is then flowed through the tubes, ideally absorbing all of the heat that would otherwise enter the propellant. Finally, a cryogenic cooler, or cryocooler, that is located somewhere within the working fluid circulation loop but outside of the BAC tubing rejects the absorbed heat to an external heat sink. An example of an active cooling system using BAC technology is shown in Figure 2. Here, a circulator moves the helium working fluid through the system, and a cryocooler rejects the added heat.

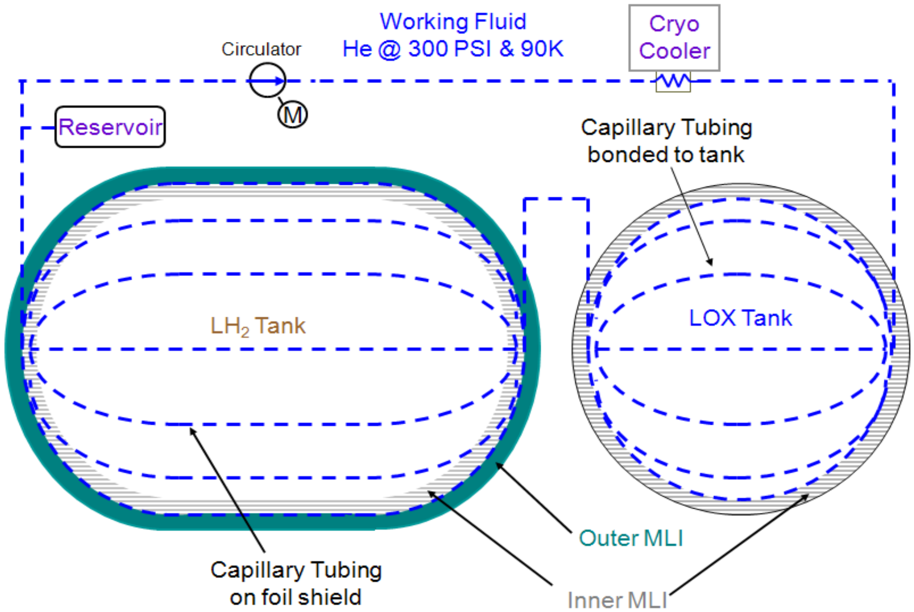

Figure 2. A broad area cooling system installed for a liquid hydrogen and liquid oxygen tank in parallel to one another. The BAC system on the LOX tank consists of tubes directly bonded to the tank wall, while the LH2 tank has tubes bonded to a metal shroud nestled within the MLI layers.

Active Cooling with Reverse Turbo-Brayton Cycle Cryocoolers

The majority of cryocoolers for current space applications involve the cooling of small electronics, such as infrared detectors. Because of the small heat removal requirements that are associated with these systems, the design of these cryocoolers is driven by high efficiency and low mass constraints. For the most part, these requirements can be met by Stirling cycle, pulse-tube, and Brayton cycle cryocoolers with a high degree of success. However, the higher heat removal requirements associated with active cooling systems for large propellant tanks adds a need to transport this increased heat across farther distances while maintaining minimal losses.

Turbo-Brayton cryocoolers produce a continuous cycle gas flow at a relatively high flow rate in comparison to other active cooling configurations, which allows for constant, high-capacity heat transfer from the cooling load to the heat rejection site. This site can be located remotely from the load, providing another degree of separation with which to minimize losses in the system as well as allowing more flexibility for effective integration into the spacecraft. Furthermore, the intrinsically high power density and proven durability of the turbomachinery used in this application make it a lightweight, high-capacity option for active thermal control[2].

The first turbo-Brayton cryocooler flight unit was NCS, a replacement cooling system for the Hubble Space Telescope's NICMOS instrument. NCS consisted of a 7W single-stage reverse turbo-Brayton cryocooler (SSRB) that supplied a working fluid at 70 K to cool the existing NICMOS circulation loop at an interface point. This system has shown excellent performance, and has been operating successfully without interruption since 2002[2]. This success with NCS, as well as other applications, has established the turbo-Brayton cryocooler as a flight-compatible system that can be applied in future space missions.

Modeling Objectives

With the increasing interest in reverse turbo-Brayton cryocoolers (RTBC) for ZBO cryogenic storage applications, the desire to quantitatively size and describe a characteristic system model has developed. However, few tools exist that can do so on a general scale, and none combine the RTBC technology with a broad area cooling design, particularly for flight-representative ZBO and RBO configurations. This has created the driving force behind the task described in this paper, which is to develop a high-level design tool that can be utilized to investigate the behavior of turbo-Brayton cryocoolers with broad area cooling for long-duration cryogenic storage.

In its current configuration, the tool is set up to quantify a single stage RTBC/BAC system, giving it the tentative name of Single-Stage Reverse Turbo-Brayton model with Broad Area Cooling (SStaRT_BAC). With this model, sizing of both the cryocooler and BAC tubing can be performed in unison, to achieve the most efficient configuration for effective active cooling performance.

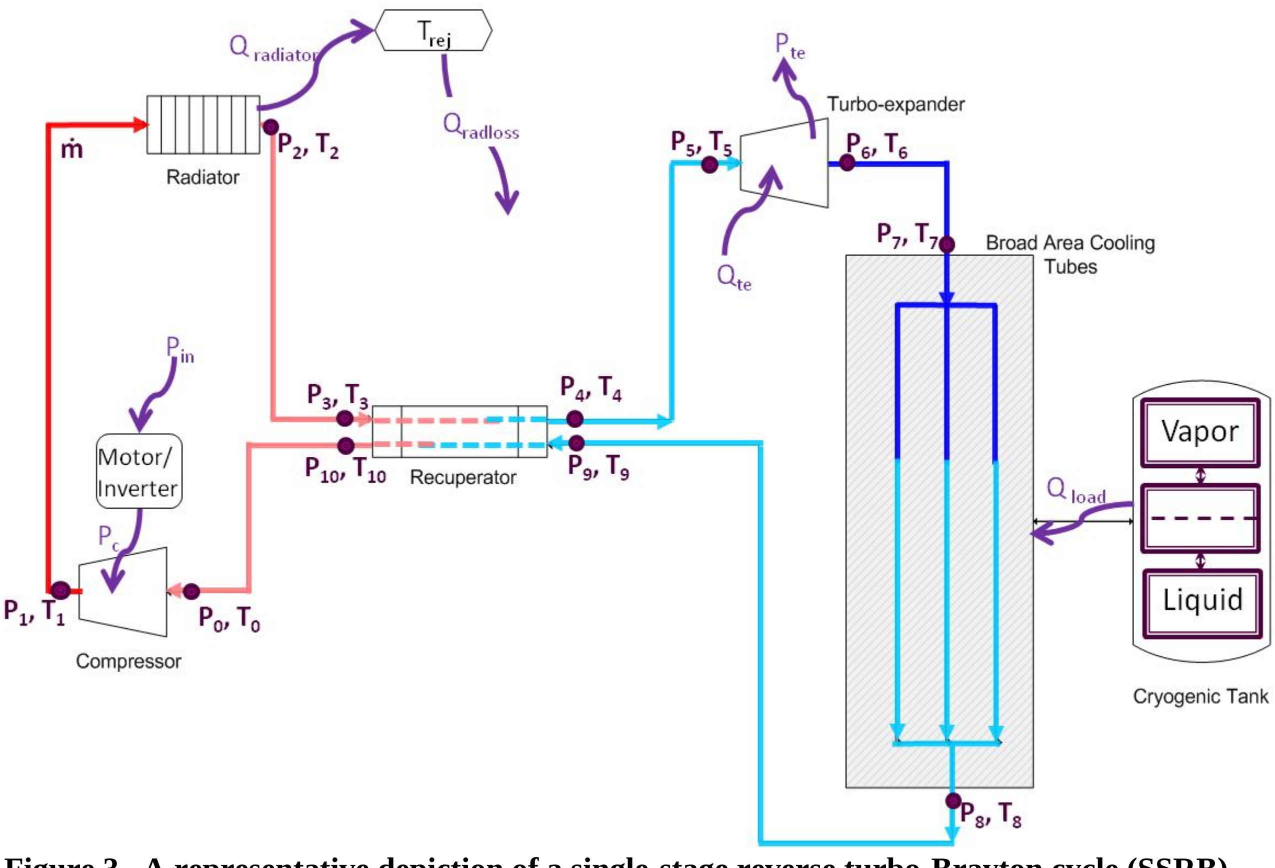

Figure 3. A representative depiction of a single-stage reverse turbo-Brayton cycle (SSRB) cryocooler system for the SStaRT_BAC tool. Highlighted points of operation are numbered in order, both beginning and terminating at the compressor inlet. The cycle gas temperatures are color-coded; red indicates the highest operation temperatures and pressures, and dark blue shows the lowest. Energy inputs and outputs are noted using the purple arrows, directed inwards or outwards, respectively.

REVERSE TURBO-BRAYTON CYCLE CRYOCOOLER TECHNOLOGY

In its simplest form, the Brayton cycle is the idealized thermodynamic cycle for a gas turbine engine[3]. When applied to refrigeration, the cycle acts as a heat pump where, in effect, heat is transferred from a low temperature source and rejected to a warmer temperature thermal sink. In this case, a compressor performs isenthalpic work to circulate the cycle gas by increasing its pressure. After exiting the compressor, heat is added to the gas while the pressure is held constant, thereby increasing its temperature and enthalpy. The gas then passes through a turbine, which cools it using isentropic expansion before it is allowed to move back to the compressor, during which time heat is further removed from the system isobarically[3]. A schematic of the SSRB system used for the current modeling task is depicted on the previous page in Figure 3, with important points in the system operation labeled numerically in increasing order, beginning at the compressor inlet. Figure 4 shows a sample temperature-entropy (T-S) diagram, with the numerical locations corresponding to those in Figure 3.

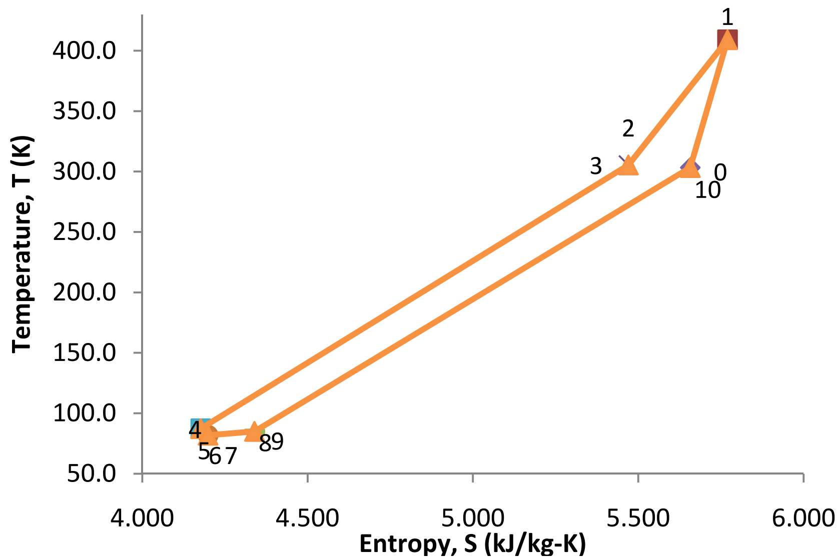

Figure 4. A temperature-entropy diagram of a representative SSRB model, as depicted in Figure 3.

For a turbo-Brayton cryocooler application, the Brayton refrigeration cycle uses a low-temperature working gas such as neon or helium that can be circulated to transport heat through the system. Circulation is provided by a centrifugal compressor, which is driven by a motor-inverter assembly[4]. This compressor adds a large amount of heat to the system, which is then removed by an aftercooler, such as a radiator. After leaving the radiator, the gas enters a recuperator, or counter-flow heat exchanger, where it transfers heat to the lower-temperature gas stream that is exiting the cooling load, further reducing its temperature[4].

Next, the coolant enters a turbo-expander, which provides additional cooling when the flowing gas drives a turbine, creating mechanical shaft work that can then be converted to electrical power and extracted at the warm end of the system using an alternator or similar device[4]. At this point, the gas is at its coldest temperature and lowest pressure before it enters the cooling load through the BAC loop, where it intercepts the heat entering the cryogenic tank. This heat is carried by the cycle gas into the aforementioned recuperator, where it picks up heat from the opposing gas stream in preparation for returning to the compressor to complete the cycle[4].

MODELING APPROACH

The modeling equations used in the representative cooling system previously depicted in Figure 3 are based on Francis Dolan's thermal model[5], initially crafted to support NCS. In it, component efficiencies are calculated outside of the modeling effort, and used as inputs in order to determine the performance parameters. Referring back to Figure 3, heat of compression is rejected by a radiator ($Q_{radiator}$), which takes the place of Dolan's aftercooler, as well as at the turbo-expander (P_{te}). In addition, power loss due to inefficiencies in the motor and inverter are assumed to be rejected completely from the system, reducing the input power (P_{in}) to equal the amount of energy used to increase the pressure of the cycle gas in the compressor (P_c). Further heat inputs to the system occur through radiation from the warm thermal environment into the tubing ($Q_{radloss}$), conductive heat transfer from the warm end of the turbine drive shaft to the cold cycle gas (Q_{te}), and the heat from the cooling load (Q_{load})[5].

In Dolan's model, the heat terms, performance parameters, temperatures, and pressures in the system are calculated using basic thermodynamic and turbomachinery equations. However, many of the lines in the system are simplified into one continuous system, which eliminates many from being included in the resulting pressure-temperature profile. Figure 5 shows the SSRB system in terms of the numerical notations used to describe the locations of reported fluid properties, such pressure and temperature, as well as to describe tubing segments. The modeling tool SStaRT_BAC determines the pressure drop through each tubing segment using the Fanning friction factor, rather than lumping the tubing into two segments, one for the low pressure gas and another for the high pressure gas. In addition, the updated model calculates fluid properties at each location, rather than assuming constant properties across the entire system.

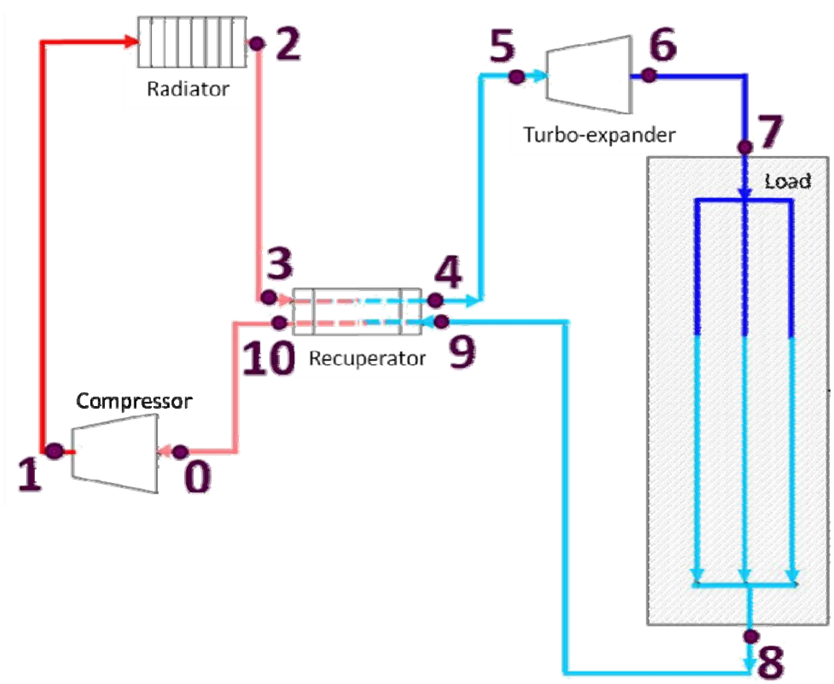

Figure 5. A simplified schematic of the SSRB system for the SStart_BAC tool, showing the notable locations for pressure and temperature locations as referred to in the model.

Comparison to Previous Modeling Efforts

Before integrating the broad area cooling system into the model, the system was compared to results published by Dolan[5] in order to verify its integrity in determining the cryocooler-side component performance. Table 1 shows the results of one such comparison, which confirmed a strong agreement between the previously published results and those from the updated model. A similar analysis was repeated three times, using a wide sampling of inputs in order to test the full range of the model. A high degree of consistency was displayed for each analysis, showing that the results fell within the expected range of 5% accuracy.

Table 1. Comparison of Reported Literature Results to Model Outputs without BAC

				Literature Data[5]	Excel Model Output	% Difference
Case Variables	Load Temperature	K	T_8	65	65	0.00%
	Rejection Temperature	K	T_{rej}	290	290	0.00%
	Mass Flow Rate	g/s	$\dot{m}_{gas}$	1.2	1.2	0.00%
	Inlet Pressure	atm	p_o	1.1	1.1	0.00%
	Compressor Rotational Speed	rev/s	N_c	8000	8000	0.00%
Calculations	Compressor Inlet Temperature	K	T_0	293.91	293.88	0.01%
	Compressor Tip Speed	m/s	u_c	383.02	383.02	0.00%
	Compressor Specific Work	J/kg	$\hat{W}_c$	124700	124701	0.00%
	Compressor Specific Speed	rad	$N_{s,c}$	0.27	0.27	0.00%
	Compressor Input (Shaft) Power	W	P_c	149.64	149.64	0.00%
	Compressor Exit Temperature	K	T_1	414.39	413.81	0.14%
	Compressor Pressure Ratio	----	PR_c	1.73	1.72	0.58%
	Compressor Exit Pressure	atm	p_1	1.91	1.89	1.05%
	Aftercooler/Radiator Exit Temperature	K	T_2	296.22	296.19	0.01%
	Recuperator High Press. Inlet Temp.	K	T_3	296.22	296.19	0.01%
	Recuperator Low Press. Inlet Temp.	K	T_9	65.23	65.22	0.02%
	Recuperator Low Press. Outlet Temp.	K	T_{10}	293.91	293.88	0.01%
	Recuperator High Press. Outlet Temp.	K	T_4	67.54	67.53	0.01%
	Turbine Inlet Pressure	atm	p_5	1.87	1.86	0.53%
	Turbine Outlet Pressure	atm	p_6	1.11	1.11	0.00%
	Turbine Pressure Ratio	----	PR_t	1.69	1.67	1.18%
	Turbine Conductive Heat Leak	W	Q_t	3.36	3.36	0.00%
	Turbine Inlet Temperature	K	T_5	70.24	70.23	0.01%
	Turbine Outlet Temperature	K	T_6	60.26	60.37	0.18%
	Turbine Overall Efficiency	----	η_{te}	0.57	0.57	0.00%
	Turbine Power to Alternator	W	P_{te}	12.39	12.30	0.73%
	Turbine Tip Speed	m/s	u_{te}	101.62	101.23	0.38%
	Turbine Rotational Speed	rev/s	N_{te}	10188	10149	0.38%
	Turbine Specific Speed	rad	$N_{s,te}$	0.82	0.82	0.00%
	Cold Load Inlet Temperature	K	T_8	60.72	60.59	0.21%
Summary	Cold Load Capacity	W	Q_{load}	5.32	5.50	3.38%
	Total Electrical Input Power	W	P_{in}	207.83	207.83	0.00%
	Power/Cooling Ratio	----	P_{in}/Q_{load}	39.1	37.8	3.32%
	Total Heat Rejection	W	Q_{out}	217.36	217.25	0.05%
	Relative Cycle Efficiency	%	η_{cycle}	8.85	9.16	3.50%

Incorporation of Broad Area Cooling System Model

The broad area cooling system modeling equations are directly based on those found in NASA GRC's Cryogenic Analysis Tool[6], and utilize the tank geometry, passive heat leak, and inlet pressure and temperature to determine the overall pressure drop, flow rate, and tube sizing information for the system. When integrating into the previously verified SSRB model, both codes had to be adapted in order to form a cohesive set of equations. In doing so, the passive heat leak is shifted to a user input for the model, while the mass flow rate an output determined by the broad area cooling equations. This causes improperly sized inputs to create a shift in the energy balance, so that an additional "thermal margin" must be included to account for the discrepancy between the cooling capacity available due to the inputs and the actual amount of heat being removed. This energy balance is shown in Equation 1.

$$P_c + Q_{radloss} + Q_{te} + Q_{load} + Q_{margin} = Q_{radiator} + P_{te} \qquad (1)$$

In a perfectly sized system, the thermal margin, Q_{margin}, is zero, as the SSRB system is removing the exact amount of heat entering the system. However, with the heat leak as an input, the system may appear to remove more or less heat than is required if the other inputs are not adjusted accordingly. To correct this error and determine the proper operating points for a given heat leak, other input parameters, particularly the compressor rotational speed, must be adjusted. A parametric study of various operating input conditions can be easily performed using the SStaRT_BAC tool in order to determine the optimal operating parameters for a specified cooling requirement. A large focus of these parametrics should be to find the compressor speed that will achieve the calculated flow rate.

Modeling Limitations and Scaling

The current version of SStaRT_BAC is currently formatted to model zero boil-off systems for a tube-on-tank configuration. Because the model is designed for a specific impeller diameter in both the compressor and the turbine of 0.60 in and 0.125 in, respectively, in order to match specific components that were used in Dolan's model, the cooling heat load is limited between 0 and 10 W[5]. In addition, the cooling load temperature is limited to a range between 55 and 90 K, and the heat rejection temperature is bounded from 260 to 325 K[5]. This is suitable for ground test configurations and LOX storage temperatures with relatively small tanks. However, for large-scale applications such as in-space depots, scaling must be taken into consideration in order to adapt the results for larger heat leaks.

In its simplest form, the Brayton cycle is the ideal thermodynamic cycle for a gas turbine engine, where the cycle efficiency increases with the pressure ratio[3]. This implies that increased scale also increases efficiency, so a larger cooling system will experience progressively improved performance. Zagarola and McCormick have documented an approach for modeling this relationship based on the assumption that the power of a turbomachine is proportional to the square of its characteristic length[4]. In order to investigate this further and expand SStaRT_BAC's capabilities, including the ability to support large-scale depots, future work will focus on incorporating these scaling relationships into the overall modeling approach.

PRELIMINARY RESULTS

SStaRT_BAC's Excel interface features a central page for user input and summarized results, a sample of which is provided below in Table 2. The inputs in the table are the results of a parametric analysis focused around a LOX ZBO application for a spherical aluminum propellant tank with a heat leak of 4 watts. For a heat rejection temperature of 300 K and a cooling load temperature of 85 K, the rotational speed of the compressor was varied until the thermal margin was zero. At this point, which corresponds to 7480 revolutions per second, it can be assumed that the system is properly sized for this application, and the displayed results accurately portray what would be occurring in a real operational system.

Table 2. Summary of Inputs for Preliminary Results from the SStaRT_BAC Model

Gas Properties (Assume Constant)				*Turbomachine Geometry*			
Circulation Gas	*(name)*	neon	----	**Impeller Outside Diameter**	$D_{c,o}$	1.524	*cm*
Cryoshroud/Enviornment Conditions				**Impeller Inside Diameter**	$D_{c,i}$	0.508	*cm*
Heat Rejection Temperature	T_{rej}	300	*K*	**Rotor Outside Diameter**	$D_{te,o}$	0.125	*in*
Cryogenic Tank Geometry				*Compressor Variables*			
Cooling Load Temperature	T_{load}	85	*K*	**Rotational Speed**	N_c	7480	*rev/s*
Constant Heat Leak (Load)	Q_{load}	4	*W*	**Inlet Pressure to Compressor**	p_o	1.1	*atm*
Tank Wall Material	*(name)*	aluminum	----	**Tangential Component of Gas Velocity at Impeller Discharge**	C_Θ/u_c	0.85	----
Wall Thickness	z_{wall}	0.037	in	*MLI Parameters*			
A:B ratio	a/b	1	----	**Number of MLI Layers on Tubes**	n_{MLI}	30	----
Tank Inside Diameter	$D_{tank,i}$	54.5	in	**MLI emissivity**	$\varepsilon_{s,MLI}$	0.05	----
Tank Inside Volume	$V_{tank,i}$	49	ft3	*Circulation System Tubing Parameters*			
BAC Tubing Outer Diameter	$D_{tubes,o}$	1/8	in	**Tubing Inside Diameter (ID)**	D_{tubes}	1	*in*

The total heat removed rejected to the radiator from a system operating at these conditions was determined to be approximately 180.1 W, and 6.77 W are removed in the turbo-expander when the shaft power generated by the cycle gas expansion is recovered using an alternator at the warm end. The total input power for the cryocooler is 182.9 W, and the cycle efficiency was 5.5%, with a circulation mass flow rate of 1.21 g/s. Figure 6 shows the temperatures at each major location of interest in the system, and Figure 7 shows the corresponding pressures. From these figures, the temperature and pressure distributions across the system are clearly visible.

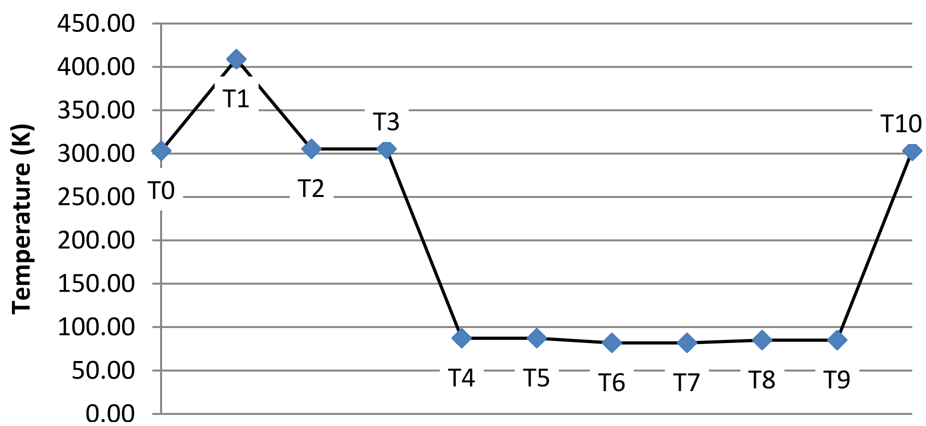

Figure 6. Temperature results obtained using the SStaRT_BAC tool with the inputs listed in Table 2. The numbered locations refer to the locations described in Figure 3.

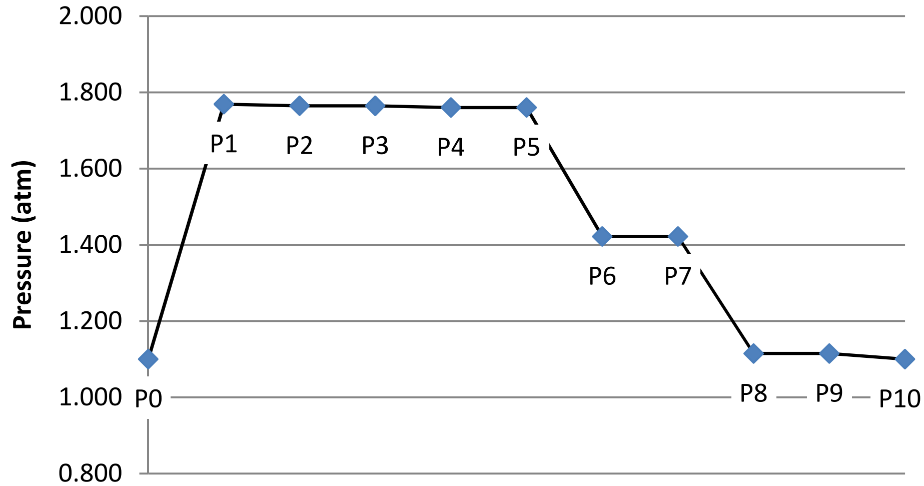

Figure 7. Pressure results obtained using the SStaRT_BAC tool with the inputs listed in Table 2. The numbered locations refer to the locations described in Figure 3.

CONCLUSIONS

The SStaRT_BAC modeling tool is constantly evolving, and as it increases in sophistication, a clear need for experimental data to provide a source for validation efforts has emerged. However, its accuracy in relation to previously published results has served to establish a high degree of confidence in the current model, which can be used to gain an understanding of the operational relationships between various components of an SSRB cryocooler when combined with BAC technology. This knowledge can then be utilized in order to size and develop a preliminary SSRB system design for zero boil-off cryogenic storage. The primary components of the SSRB are the turbomachines for compression and expansion, the recuperative heat exchanger for internal pre-cooling, the heat rejection system, and the load to be cooled via a BAC, as well as the power electronics. Turbo-Brayton cryocoolers are characterized by their low resonant vibration, flexible integration with spacecraft systems, ability to cool remote and distributed loads, their high technology readiness level (TRL) and its scalability to accommodate higher capacity lifts. Due to the excellent performance of turbo-Brayton cryocoolers for large-scale applications such as those anticipated for future long-duration missions, it is anticipated that this modeling effort will evolve into a key tool to support NASA's future endeavors.

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NOMENCLATURE

<u>Symbols</u>

ε	emissivity
η	efficiency
C_θ/u_c	tangential component of gas velocity at impeller discharge
D	diameter
m	mass (kg)
$\dot{m}$	mass flow rate
N	rotational speed
n	number of layers of MLI
P	power
p	pressure
PR	pressure ratio
Q	heat rate
T	temperature
u	tip speed (velocity)
W	work
V	volume
z	thickness

Subscripts

c	compressor
load	cooling load (broad area cooling system/cryogenic tank)
i	inner
o	outer
radloss	radiation losses through tubing
rej	heat rejection point
s	specific
tank	tank
te	turbo-expander
tubes	broad area cooling tubes or circulation tubes
wall	tank wall

ACRONYMS/ABBREVIATIONS

BAC	Broad Area Cooling
CAT	Cryogenic Analysis Tool
GRC	Glenn Research Center
GUI	Graphical User Interface
LOX	Liquid Oxygen
LH2	Liquid Hydrogen
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NCSA	NICMOS Cooling System
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIST	National Institute of Standards and Technology
RBO	Reduced Boil-Off
Refprop	Reference Fluid Thermodynamic and Transport Properties Database
RTBC	Reverse Turbo-Brayton Cycle/Cryocooler
SStaRT_BAC	Single-Stage Reverse Turbo-Brayton model with Broad Area Cooling
SSRB	Single-Stage Reverse turbo-Brayton cycle
TFAWS	Thermal and Fluids Analysis Workshop
TPSX	Thermal Protection Systems Expert (material properties database)
VBA	Visual Basic for Applications
ZBO	Zero Boil-Off

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