MODELING A TRANSIENT PRESSURIZATION WITH ACTIVE COOLING SIZING TOOL

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ABSTRACT

As interest in the area of in-space zero boil-off cryogenic propellant storage develops, the need to visualize and quantify cryogen behavior during ventless tank self-pressurization and subsequent cool-down with active thermal control has become apparent. During the course of a mission, such as the launch ascent phase, there are periods that power to the active cooling system will be unavailable. In addition, because it is not feasible to install vacuum jackets on large propellant tanks, as is typically done for in-space cryogenic applications for science payloads, instances like the launch ascent heating phase are important to study. Numerous efforts have been made to characterize cryogenic tank pressurization during ventless cryogen storage without active cooling, but few tools exist to model this behavior in a user-friendly environment for general use, and none exist that quantify the marginal active cooling system size needed for power down periods to manage tank pressure response once active cooling is resumed.

This paper describes the Transient pressurization with Active Cooling Tool (TACT), which is based on a ventless three-lump homogeneous thermodynamic self-pressurization model[1] coupled with an active cooling system estimator. TACT has been designed to estimate the pressurization of a heated but unvented cryogenic tank, assuming an unavailable power period followed by a given cryocooler heat removal rate. By receiving input data on the tank material and geometry, propellant initial conditions, and passive and transient heating rates, a pressurization and recovery profile can be found, which establishes the time needed to return to a designated pressure. This provides the ability to understand the effect that launch ascent and unpowered mission segments have on the size of an active cooling system. A sample of the trends found show that an active cooling system sized for twice the steady state heating rate would results in a reasonable time for tank pressure recovery with ZBO of a liquid oxygen propellant tank.

INTRODUCTION

The storage of cryogenic liquid rocket engine (LRE) propellants is a complex process, in part due to the extremely low temperatures required to maintain cryogens in the liquid phase. During storage, heat from the propellant tank's surroundings causes the temperature to increase, resulting in evaporation of the liquid cryogen to create a vapor layer, also known as the ullage. As the increased ullage mass causes the tank pressure to increase beyond the desired pressure for engine operation, or startbox pressure, the tank contents must be vented as boil-off to allow them to return to the startbox pressure before rocket firing. This boil-off requires additional propellant to be stored on board in order to compensate for its loss. This increased storage capacity requirement necessitates a larger tank that can accommodate the additional propellant, adding even more mass to the system. This increased mass is acceptable for short-duration missions, as penalties for the additional propellant mass are less than that of adding an active cooling system to the tank. However, this does not hold true for longer missions, where mass savings is a primary concern in considering mission costs. With this in mind, increasingly efficient methods of active cooling are being considered in order to reduce overall system mass for long-duration space exploration. One way to accomplish this is to minimize the cryogen boil-off with active cooling by maintaining the propellant temperature so that no liquid mass is lost through evaporation, effectively stabilizing the tank pressure and eliminating the need for a vent.

Increased cryogenic storage efficiency is achieved through a combination of both active and passive thermal control. Passive control involves the use of techniques such as thermal coatings and insulation, including Multi-Layer Insulation (MLI), to minimize the amount of heat leak that enters the tank. Active control, on the other hand, requires a cooling system that intercepts the heat entering the tank and transfers it elsewhere using a cryogenic cooler, commonly referred to as a *cryocooler*. By sizing passive thermal control for steady state heat loads in combination with an active cooling system sized to handle both passive and transient heating, zero boil-off (ZBO) can be achieved. NASA Glenn Research Center's Cryogenic Analysis Tool (CAT)[2] can be used to perform the sizing of both passive and active thermal control systems by determining the total system mass and power as a function of heat. This heat term corresponds to a cooling system lift that intercepts heat entering the cryogenic tank, preventing a rise in tank pressure.

In order to quantify the tank pressure rise that can contribute to a boil-off condition, numerous efforts have been made to characterize ventless cryogenic tank pressurization. These efforts have produced a wide variety of methods to approach the completion of an accurate tank pressurization model, ranging from those involving the basic lumped homogeneity assumption to the more detailed computational fluid dynamic models, which take into consideration tank temperature stratification and discrete fluid physics. However, the current models in existence do not have the capability to quantify the marginal active cooling system size needed to manage tank pressure response during transient heating. As such, the purpose of this effort is to adapt an existing pressurization model[1] to characterize the tank pressure response associated with a given active cooling system size. In particular, this model will address the tank pressure profile during the launch ascent phase of a mission, which imposes a high quantity of heat on relatively large cryogenic tanks that lack a vacuum jacket. The transient heat inputs from this phase will be quantified using a recently validated launch ascent heating model from Kennedy Space Center, known as the Launch Ascent Tool[3], while the subsequent passive heat leak is determined by an off-line analysis. The amount of time required for full tank depressurization that occurs with the aid of the active cooling system will be monitored in addition to the maximum tank pressure, with the cooling system lift being varied in a series of parametric runs. From these runs, an optimal lift value can be determined, and a cooling system size can be determined using CAT's mass and power correlations[2].

This paper documents the creation of a preliminary modeling design tool that is intended to provide an accessible, user-friendly interface for the study of an active cooling system's impact on tank pressure response during the application of a given heat load. This tool is named the Transient pressurization with Active Cooling Tool (TACT), due to the emphasis placed on modeling transient heating profiles. Using TACT, parametric analyses can be run in to establish the optimal active cooling system size for a variety of tanks, propellants, and external heat loads coupled with a transient heat schedule.

SELF-PRESSURIZATION MODELING APPROACH

Literature Review of Potential Methods

Numerous studies exist that analyze the autogenous pressurization of a propellant tank, providing a wide array of approaches for the generation of a theoretical model. This can cause choosing a modeling approach that applies to the needs of this particular effort to seem a rather daunting task. Fortunately, previous literature surveys, such as one documented by Barsi[1], make the task easier. From his comprehensive review, a number of modeling methods were considered for use in TACT. A few of the potential choices are summarized below.

Some of NASA's earliest work with quantifying cryogenic storage pressurization rates was accomplished through experiments performed aboard Aerobee sounding rockets in the 1960s, such as work performed by Knoll and others that involved the self-pressurization of a small spherical liquid hydrogen (LH2) dewar[4]. As found in similar studies performed by Nunamaker, *et al.* and Aydelott, the simple thermodynamic model predictions significantly underestimate the propellant self-pressurization rate[5,6]. Lacovic, *et al.* later reported the occurrence of significant thermal stratification in the ullage[7], which was further confirmed during ground testing performed by Beduz, *et al.*[8] and others. This phenomenon, which indicates uneven heating in the ullage, is not accounted for in the aforementioned models, and is a primary cause of the associated error.

During this time, Aydelott compared the homogeneous thermodynamic model from previous studies with a new surface evaporation model that assumes the sensible energy of the liquid goes entirely into the vaporization of the liquid to maintain saturated conditions in the ullage[9]. In contrast, the former approach consists of a simple energy balance applied to a homogeneous system in accordance with the First Law of Thermodynamics, where the liquid and vapor are both saturated and at the same temperatures[1]. As mentioned previously, the homogeneous model under-predicts the rate of the tank pressurization. In contrast, the surface evaporation model tends towards over-prediction, since it neglects to incorporate the sensible heat of the liquid into the overall energy balance.

To reduce the error margin produced by the aforementioned approaches, models were developed to couple energy transport with mass transport by dividing the tank system into liquid and vapor zones with constant temperatures across each zone. This allowed correlations to be applied to model the mass and energy transport between the zones. A two-zone model, with zones for both the liquid and the ullage, was developed by Reimer[10]. Estey, *et al.* then expanded this model to include a third zone that bounded the liquid-vapor interface[11]. This was followed by additional efforts that divided the tank into axial zones to describe the tank wall, liquid, ullage, and interface[12, 13, 14]. These multizonal models showed better agreement with experimental data, although some over-prediction can still be observed.

Recently, sophisticated computational models have come into focus, stemming from investigations into the causes of the thermal stratification that was observed in previous tests. Nikitin and Polezhaev investigated the buoyancy and Marangoni convection at various locations in the ullage by assuming each point had a static, spherical surface[15]. Cherkasov then expanded this assumption into a flat, shear-free surface[16]. In addition, Lin and Hasan studied buoyancy in the liquid region using numerical methods, attempting to quantify the temperature field using liquid subcooling equations[17]. Grayson *et al.* extended that analysis by including a gas phase, allowing a freely-evolving, adiabatic interface[18, 19].

Overall, these research efforts were limited in their ability to predict tank pressurization with a consistently sufficient degree of accuracy, and, in many cases, the source of variance from empirical data is either unexplained or misunderstood[1]. This is exacerbated by a lack of detailed experimental results, making the validation of future modeling attempts difficult. Despite this, these modeling approaches and many others not mentioned here can be used to give a firm understanding of cryogenic propellant behavior during ventless storage and provide a solid foundation on which to base future efforts.

Modeling Choice for Present Task

The intended purpose of the TACT modeling tool is to create a general pressurization design tool to assist in determining the initial sizing of active cooling systems in managing transient heating loads without the need to vent. As such, an approach is needed that is simple in application, but accurate enough to provide a reliable first-order estimate of the pressurization profile that would result from a minimized set of inputs. With this in mind, the most sophisticated models can be eliminated, as their increased accuracy does not outweigh the costs of their higher increased computational requirements. Ultimately, a well-documented, homogeneous thermodynamic model was chosen, as it would yield acceptable results while maintaining the necessarily low degree of complexity.

The homogeneous thermodynamic model provides an analytical prediction of the pressurization rate by applying an energy balance over a closed liquid and vapor system, where both the liquid and vapor phases are saturated and at equal temperatures. From this assumption, it follows that the energy of the liquid and vapor will change relative to each other, assuming that the increased heat transfer during boundary layer development is negligible. This assumption causes the liquid phase to become the largest contributor to the energy balance, resulting in an under-predicted pressurization profile[1].

After considering a variety of homogeneous pressurization modeling approaches, the Barsi thermodynamic model[1] was selected as the preferred method to be used for TACT. In it, Barsi describes a three-lump, homogenous thermodynamic model, with one lump set aside for the saturated incompressible liquid, another for the saturated vapor, and a third for tank wall, all at the same temperature. This approach's iterative nature and simple but effective calculation methods give it a strong advantage when being applied to a preliminary design modeling code, such as TACT. In addition, the heating term is isolated in such a way that it a simple matter to incorporate an active cooling term into the equation. This, coupled with its suitable accuracy, particularly in predicting the rate of pressurization, makes it the authors' choice for creating a general, first-order design tool for the purposes of this task.

Pressurization Results Comparisons with Existing Tools

In an effort to validate TACT's application of the Barsi homogeneous thermodynamic model, comparisons were made with results of previously validated modeling efforts involving both homogeneous thermodynamic and multizonal approaches. Both models were generated using results of an approach[20] developed and validated based on experiments performed at NASA's K-site cryogenic facility for LH2 tank self-pressurization[21,22]. The self-pressurization codes were initially run for a 4.955 m^3 ellipsoid aluminum LH2 tank with an initial pressure of 14.94 psia.

The profile was generated over 20 hours with no active cooling and a 30 W constant heating rate. All three models were compared against the experimental data at two initial liquid fill levels. As seen in Figure 1 and Figure 2, TACT's results after 20 hours agreed with results from the other similar models within 2%.

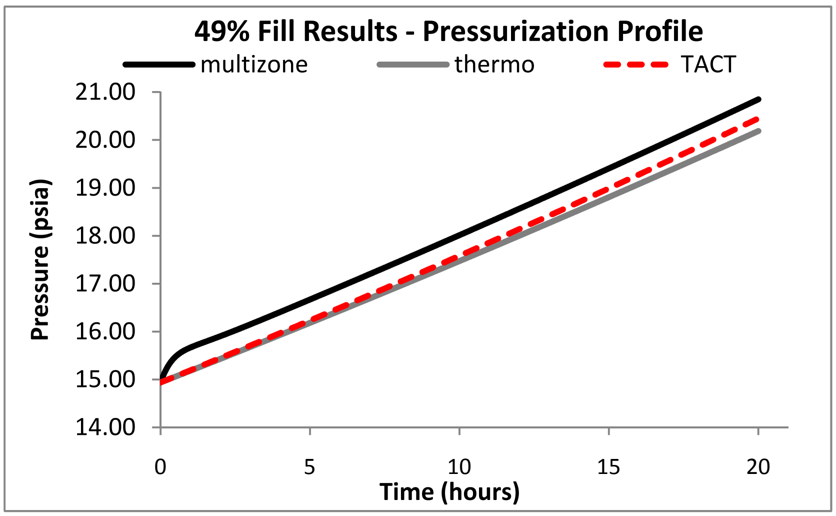

Figure 1. Comparative results from TACT and two similar modeling efforts[20] for an LH2 tank with a 49% liquid fill level. "Multizone" refers to a multizonal model, while "thermo" refers to a homogeneous thermodynamic approach.

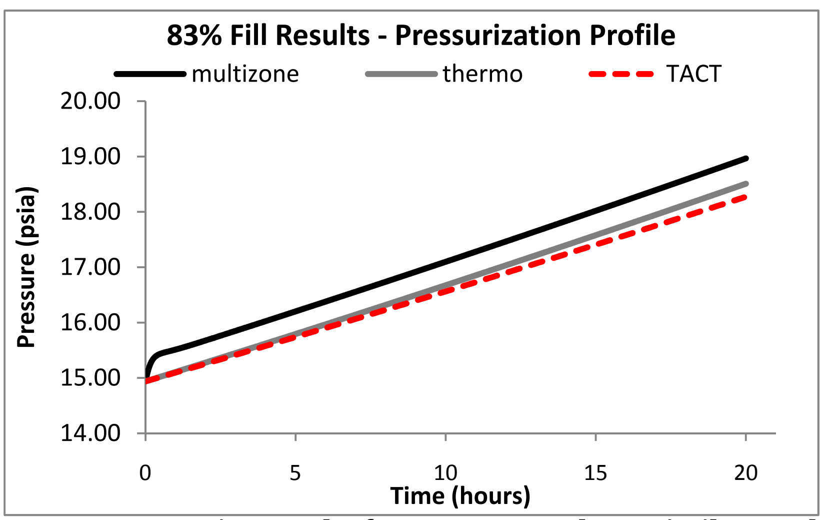

Figure 2. Comparative results from TACT and two similar modeling efforts[20] for an LH2 tank with an 83% liquid fill level.

After noticing the slight differences in the rates of pressurization among the three models, read by taking the slopes of the curves in Figures 1 and 2, the data from the two external models was extrapolated to 80 hours and compared to results from a TACT modeling run of equal length. For a liquid fill level of 83%, the results were found to be within 3% of the previous models, which is well within the acceptable limits for a preliminary design modeling approach. Figure 3 shows a plotted comparison of all three modeling results.

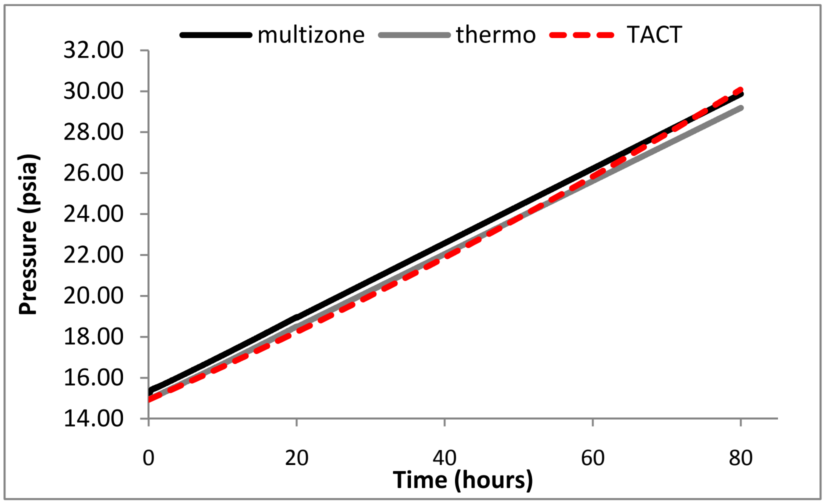

Figure 3. Comparative results from TACT and two similar modeling efforts[20] for an LH2 tank with an 83% liquid fill level after 80 hours.

ACTIVE COOLING SYSTEM DESIGN

As mentioned previously, the TACT modeling task has emerged from a need to investigate the effect of the heat removal capacity, or available cooling lift, of an active cooling system on tank pressurization. Specifically, the task's primary objective is to determine the amount of time needed for a cryocooler operating at a given lift to return a propellant tank to a desired startbox pressure after a transient heating profile. This particular goal was established due to the need for an active thermal control system to be sized to handle a transient heating case in a reasonable amount of time. Past experiments have shown that an active cooling system that is sized with only the passive heat leak in mind may take longer than expected to handle transient heating loads. One example of this is found in the NICMOS cooling system installed in the Hubble Space Telescope, which took over 90 days to overcome the static heat of the system despite being designed to do so in 40 days. Recent ground tests that have been performed to simulate active cooling performance with transient heating further support these results.

Despite the need for a low-mass sizing solution for active cooling systems to handle transient heating, an effective means to do so has yet to be established. Currently, cooling systems designed by the Air Force Research Laboratory have a thermal margin of three times the predicted passive heat leak[23], while Goddard Space Flight Center typically designs an active cooling system for double the predicted steady state passive heat leak[24]. In both cases, the cooling lift requirements are typically less than one watt, which is much lower than expected for this task. These applications also utilize a vacuum jacket around the cryogenic tanks. Though the design margin is designed to accommodate the transient heating as well as the unexpected parasitic heats, the presence of this vacuum jacket minimizes the launch ascent issue and transients in general, which will not be the case for larger propellant tanks. This transient heating case has a strongly negative impact on system operation, creating either an unnecessary increase in mass and cost or an impractically long time requirement for the tank to return to a designated final pressure, respectively. It then follows that cryogenic storage can be enhanced by finding the lowest mass solution to handle transient heating within a realistic amount of time.

TOOL DEVELOPMENT

Because this pressurization sizing tool will one day be integrated into the Cryogenic Analysis Tool (CAT) [2], TACT's format and inputs must be compatible with the CAT workspace. This requires an Excel-based approach to the modeling task and careful consideration as to which input parameters are essential to execution. Consequently, Excel's VBA Developer was chosen as the source code platform and a decision was made as to which parameters would be available as inputs by the user, and which could be calculated internally. Those chosen as user inputs are split into the general categories of fluid and tank parameters. The fluid parameters consist of the type of cryogen, the initial fill level as a percentage of total volume, the initial pressure, the final, or startbox, pressure, and the time at which the active cooling system will be turned on. The tank input parameters include the tank geometry, cryocooler lift, and the passive and transient heating rates. In order to accommodate a range of heat profiles, the code has been developed to accept either a profile generated from existing launch ascent heating data or data entered by the user. The launch ascent profile is hard-coded into TACT using KSC's Launch Ascent Tool[3]. The user is then given an option to use the enclosed data or a custom profile that can be entered manually with up to twenty time steps.

In addition to inputs, the output parameters that will provide a good basis of comparison for active cooling system performance must be specified. This includes a complete pressure profile for the mission segment, separated into two segments. The first is a self-pressurization profile, which displays the pressure curve as a function of time for the extent of the power down period, when the cooling system is not operational. The second is the profile that is generated from the time that the cooling system is turned on until a designated startbox pressure is reached. From the resulting data curves, the maximum pressure reached in the tank and the amount of time necessary for the active cooling system to return the tank to its startbox pressure are determined. During comparative analysis, the system producing the lowest maximum pressure and shortest amount of time needed to return to the startbox pressure has the most desirable performance.

In addition to cooling performance, the additional mass that accompanies a larger capacity cooling system must be taken into consideration. This mass is calculated using CAT[2], which has been incorporated into TACT with minimal modification. The cooling system masses derived from CAT can be used to perform parametric analyses in order to find the balance between optimal cooler performance and minimal cooling system mass. The results of the parametric runs can then be used to find a low mass solution for sizing an active cooling system that recovers the tank pressure in a reasonable time period according to the designated operating conditions.

Barsi Model Integration into Excel/VBA

After choosing a modeling approach and defining the requirements, the task turns to integrating both aspects into the Excel/VBA platform in an efficient and flexible manner. The saturation temperature derivative derived in Barsi's homogenous thermodynamic model[1] is adapted to TACT by subtracting the cooler lift from the heating rate, as seen in Equation 1. Using Equation 2, the saturation temperature can then be integrated using this derivative and used to find the updated saturation pressure. The process is iterated until the final conditions are reached.

$$\left|\frac{dT^{sat}}{dt}\right|_x = \frac{\dot{Q}_{load} - \dot{Q}_{cooler}}{m_w C_{w,x} + \rho_{v,x} V_{v,x} \left|\frac{dh_v}{dT^{sat}}\right|_x + \rho_{f,x} V_{f,x} \left|\frac{dh_f}{dT^{sat}}\right|_x + L_x \left|\frac{d\rho_v V_v}{dT^{sat}}\right|_x - V_t \left|\frac{dp}{dT^{sat}}\right|_x} \tag{1}$$

$$T_{x+1}^{sat} = T_x^{sat} + (\Delta t_x) \left|\frac{dT^{sat}}{dt}\right|_x \tag{2}$$

The temperature derivative varies at each time step as a function of the updated fluid properties and heat contribution, which requires the values to be updated at each data increment. The fluid properties, as well as some derivative terms, are calculated using NIST's Refprop VBA module, which was adapted for use with this specific tool.

The pressurization code is contained in a VBA module titled *RunMainSub*. This module contains four subprocedures: *RunMain*, *TotalTransient*, *SelfPressurization*, and *CoolerOn*. The model inputs are read into *RunMain*, where they are converted into the required units of measure and assigned to their respective variables to be passed among the subprocedures. In addition, the transient heat leak profile is read into two data arrays that are sized according to the specified profile type, with one holding the heat leak value, and the other holding the time at which the heat leak is recorded. The tank wall mass, internal volume, and tank wall heat capacity are then calculated using functions stored in the *TankParameterFunctions* module.

Next, *RunMain* calls the *TotalTransient* procedure, which clears the output area and defines the default time step. After an analysis was performed to determine the error tolerance that resulted from varying its value, the default time step was set to 300 seconds, which will yield consistent results among the majority of data runs. This value is used for all cases except the launch ascent heating profile, where the time step is assigned according to the existing data.

Once set-up is complete, the actual pressurization code is executed within the *SelfPressurization* and *CoolerOn* subprocedures. The former runs until the time to turn the cooling system on is reached, as specified by the input data, at which point the latter is called. *CoolerOn* is then executed until the designated startbox pressure is reached. However, if the cooler is on from the start of the run so that the "cooler on" time is zero, the *CoolerOn* subprocedure is called first, and *SelfPressurization* is never executed. Both codes contain nearly identical language with the exception of their end criteria.

The cooler heat leak term in Equation 1 is set to zero for the duration of the *SelfPressurization* subprocedure, and the load heat leak is equivalent to the heat leak from the transient profile until the profile has ended, where it defaults back to the passive heat leak value. When the *CoolerOn* subprocedure is called, the cooler heat leak term becomes equal to the cryocooler lift, which is held constant. Cooling is achieved when the cooler heat term exceeds the load heat term, making the derivative take a negative value and effectively decreasing the saturation temperature.

PARAMETRIC RESULTS

In conjunction with the TACT modeling objectives, a parametric study was performed to find the lowest mass solution within a reasonable amount of time for a fixed scenario. The modeling runs for the study were set to mimic the conditions of a theoretical liquid oxygen (LOX) ZBO example. The tank and fluid parameters were set at the same values for each run, and the cryocooler lift was varied between 6 and 15 W. The test conditions are summarized in Figure 4, which is representative of the input menu as viewed by the user within the TACT workspace.

Fluid Input Parameters:		
Fluid:	oxygen	
Fill level:	95	%
Initial Pressure:	15.0248	psia
Duration of "cooler off" period:	12	hr
Start Box Pressure (Final Pressure):	15	psia
Tank Input Parameters:		
Tank Wall Material:	aluminum	
Wall Thickness:	0.037	in
A:B ratio:	1	-----
Tank Inside Diameter:	54.5	ft^3
Tank Inner Volume:	49	m3
Layers Of MLI:	**40**	-----
Weight Factor (baffles, supports, etc.)	0.3	-----
Transient Heat leak (click to enter values):	Heat Leak	W
Passive Heat Leak (constant):	4	W
Cryocooler Lift:	**10**	**W**

Figure 4. Summary of inputs as they appear in the TACT workspace, with the values used for the parametric data runs reported in this section.

During the launch ascent heating profile, cooling occurs as the cryocooler lift begins to exceed the heat input, decreasing the temperature at a rate that is dependent upon the amount of heat being removed. When the heat term is negative, the temperature derivative becomes negative, as shown in Equation 1. This causes the temperature to decrease, effectively reducing the pressure in the tank. Therefore, cooling does not occur until the heat leak term is less than zero, when the cooling lift exceeds the heat input into the tank. Figure 5 demonstrates a portion of the resulting heating curves for three different cryocooler lifts during launch ascent transient heating, which ends at 120 hours. After this point, the heat profile enters a constant passive heat leak of 4 W.

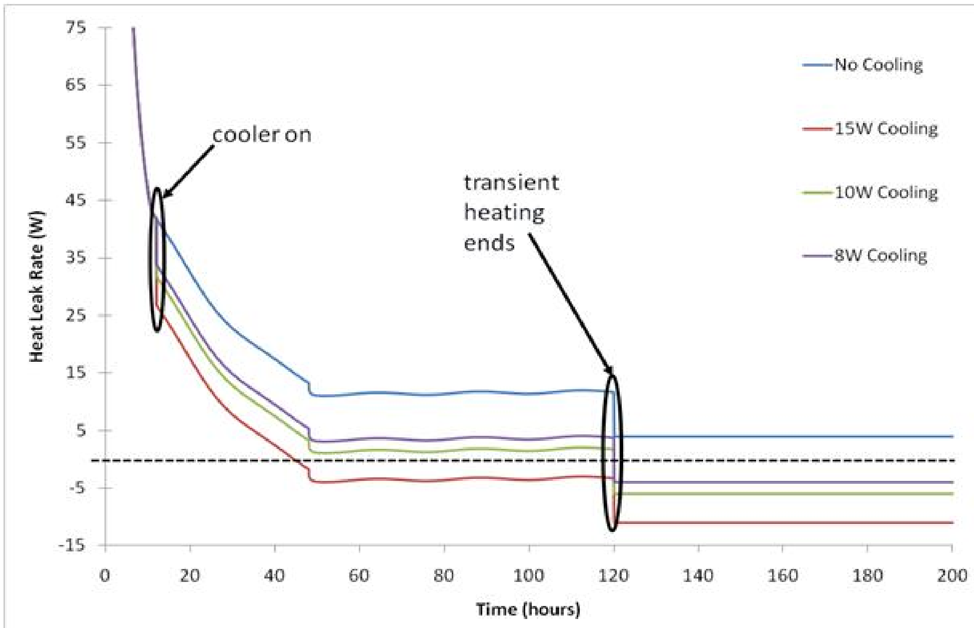

Figure 5. A portion of the transient launch ascent heating profile, adjusted for the application of various cooling system lift capacities. After 120 hours steady state occurs and the imposed heating rate from the model is changed to the inputted steady state heat. In this case, this is a step decrease in the tank heating rate.

As the plot in Figure 5 demonstrates, the cooler lift does not exceed the heat leak until after passive heating begins for both the 10 W and 8 W cooling curves. Indeed, this will be true for all heat leaks less than the launch ascent steady state heating value of 11 W. Therefore, the maximum pressure at these lower lift values will occur at some point near the transient heating end time, while higher lift values will result in a maximum pressure occurring much earlier in the profile. The ventless pressurization profiles in Figure 6 clearly illustrate this effect.

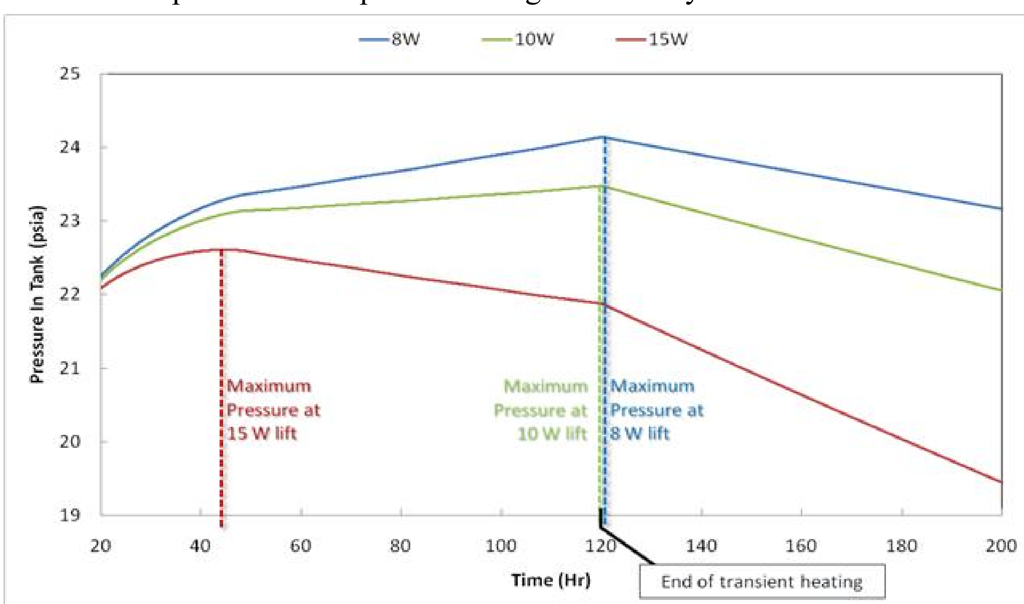

Figure 6. An excerpt of the ventless pressurization profiles at various cryocooler lifts. Lower capacity lifts have a maximum pressure occurring around the transient heating end time, when the cooling lift abruptly exceeds the heat input.

After each run, the amount of time required for the system to return to the startbox pressure and the maximum pressure reached in the tank are recorded from a profile such as those shown in on the previous page in Figure 6. The cooling system mass is then retrieved from the embedded CAT worksheet, along with the tank wall and MLI masses. By varying the cryocooler lift, a the results of each run can be combined to investigate the active cooling system sizing relationships, as shown in Figure 7, where the cryocooler lift is plotted as a function of the resulting time to completion. As expected, the amount of time required to allow the tank to return to the startbox pressure increases as the cooling system capacity decreases.

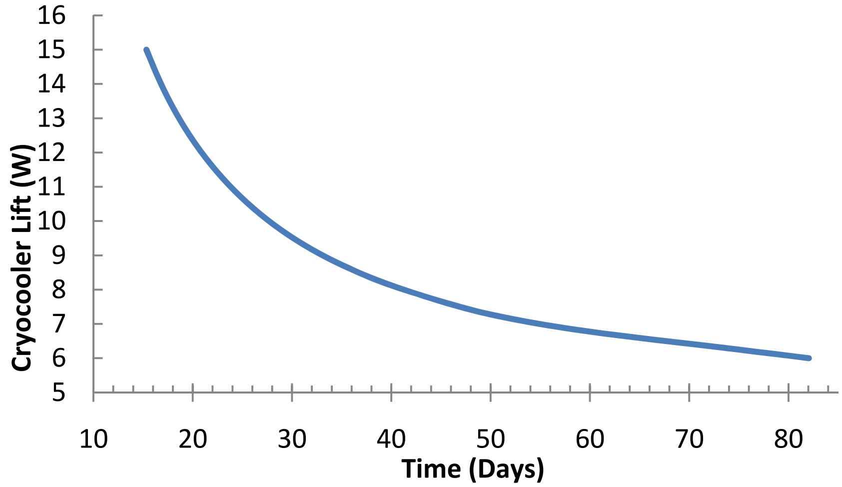

Figure 7. A parametric study demonstrating the effects of cryocooler lift on the time required to return to startbox pressure.

The lift is also plotted as a function of the maximum pressure reached in the tank, as seen in Figure 8, confirming the projected trend of an increase in maximum pressure as cryocooler lift decreases. As with the curve in Figure 7, this trend results from the increased heat input into the tank that accompanies a lower cryocooler lift. This heat speeds up the rate of temperature rise inside the tank, which raises the pressure along with it. Of particular interest in Figure 8 is the sudden shift in slope that can be observed between 12 W and 11 W. This change is caused by the heating profile's sudden change in value that occurs when the launch ascent phase ends, as discussed earlier in Figures 5 and 6.

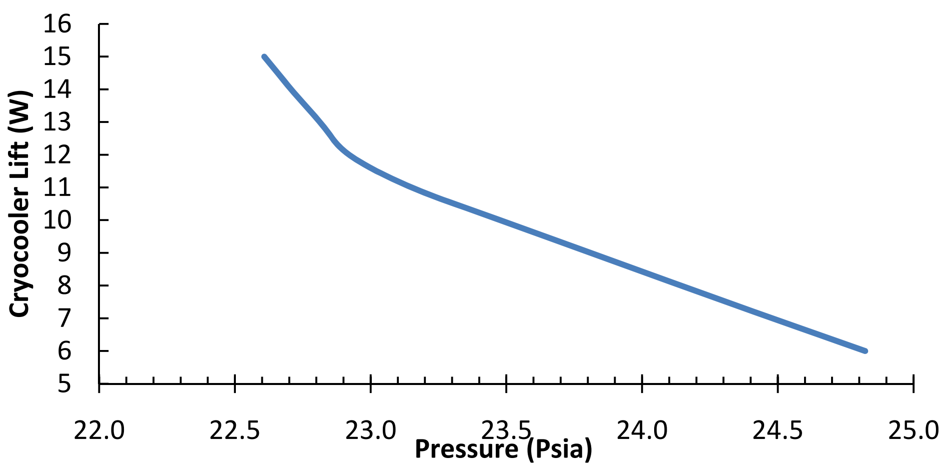

Figure 8. A plot showing the effect of cryocooler lift on the maximum pressure reached inside the tank.

To determine a low mass solution for sizing a cooling system to handle the transient heating case, the total system mass is plotted as a function of the total time to completion, as shown in Figure 9. As anticipated, the curve is very similar to the earlier graph in Figure 5, since the only portion of mass in the system that experiences a change in quantity at each cryocooler lift is the cooling system mass. Since the total system mass increases proportionally to the lift, a point is reached at which the benefits of a higher cryocooler lift, such as decreased maximum pressures and shorter depressurization times, are outweighed by the mass increase that accompanies it.

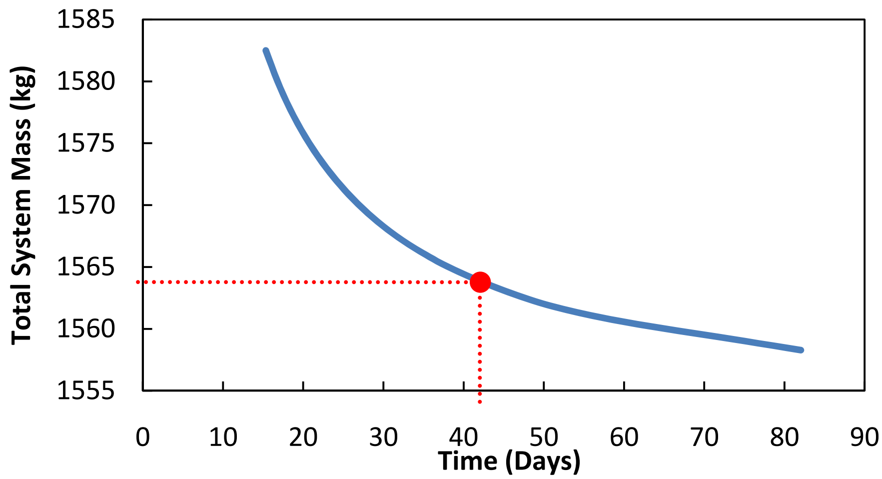

Figure 9. The total system mass, including that of the tank wall, propellant, and cooling system, as a function of the total time to completion. The selected operating point occurs at the lowest, left-most point on the curve, as shown in red.

As shown above, a low mass solution that provides a reasonable time to return to startbox pressure of about 42 days occurs when the total system mass is approximately 1,564 kg. This time value can be used to find the corresponding cooling system mass associated with this time using Figure 10, where the black lift lines indicate the cryocooler lift that corresponds to the cooling system mass. The current analysis shows the desired cooling system lift is roughly 8 W, with a cooling system mass of around 33.5 kg. Since the passive heat leak in this case is 4 W, it can be stated that, for this specific application, a design margin of twice the cooling load is acceptable for handling the transient heating loads within 42 days for this application.

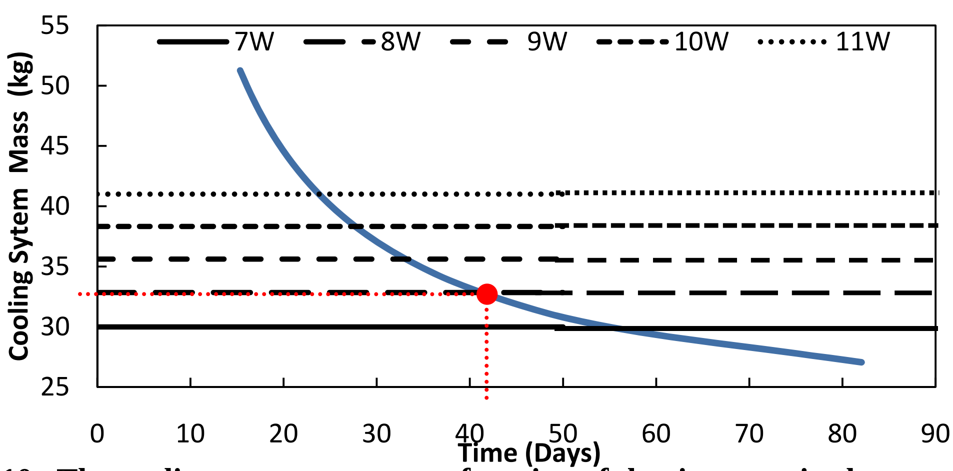

Figure 10. The cooling system mass as a function of the time required to return to startbox pressure is shown in blue, while the cryocooler lift that corresponds to its associated mass is indicated in black. The selected operating point is shown in red.

CONCLUSIONS

The TACT modeling tool is being developed as an effective tool to perform preliminary sizing of active cooling systems to manage tank pressure during a transient heat profile, such as that which is encountered during launch ascent. In its current state, parametric studies can be performed for a ventless pressurization scenario in order to determine the optimum cryocooler size that will minimize mission mass and time requirements for cryogen storage. A variety of transient heat profiles can be used, depending on input by the user.

Comparisons of ventless pressurization profiles with constant heating and no active cooling have been made between TACT's results and those from models at NASA that use a similar approach. The results of these comparisons show good agreement among the pressurization rates, although the magnitude of the final pressure is underestimated in comparison to multizonal modeling and experimental results, due to the nature of a three-lump homogeneous approach. This inherent under-prediction must be acknowledged when attempting to utilize the tool for high-level analytical performance estimations of the pressurization profile. However, for a low-level parametric sizing analysis, the consistent rate estimation is sufficient to produce reliable results for use in preliminary design.

Future efforts should include validation of the modeling results to actual test data, as well as incorporation into the Cryogenic Analysis Tool[2] in order to obtain an effective, comprehensive sizing tool for future cryogenic design tasks. In addition, current work is being done in comparing ventless pressurization to pressurization runs with an instantaneous vent set to occur at a designated point in time, in order to determine the mass loss and time savings associated with a vent scenario. Initial results have shown that, for a long-duration mission over 30 days, a ventless mission profile has by far the greatest mass savings. With this in mind, TACT has the opportunity to grow to become a powerful sizing tool in designing future missions requiring long term cryogen storage.

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NOMENCLATURE

Symbols

ρ	saturation density (kg/m^3)
C	constant volume heat capacity (J/kg-K)
fill%	Initial percentage of liquid volume in tank
fluidname	propellant fluid type
h	specific enthalpy (J/kg)
L	latent heat of evaporation (J/kg)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
p	propellant saturation pressure (MPa)
$\dot{Q}$	heat rate (W)
T^{sat}	propellant saturation temperature (K)
t	time (s)
tankmaterial	tank wall material type
V	volume (m^3)

Subscripts

0	value at initial time step
cooler	cooling system
f	liquid phase
final	value at final time step
load	energy (heat) into tank, including passive and transient heat leaks
t	tank, or total (not including wall)
v	vapor phase
w	tank wall
x	value at current time step

ACRONYMS/ABBREVIATIONS

CAT	Cryogenic Analysis Tool
GRC	Glenn Research Center
GUI	Graphical User Interface
LOX	Liquid Oxygen
LH2	Liquid Hydrogen
LRE	Liquid Rocket Engine
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIST	National Institute of Standards and Technology
Refprop	Reference Fluid Thermodynamic and Transport Properties Database
SMiRF	Small Multi-purpose Research Facility
TACT	Transient pressurization with Active Cooling Tool
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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