Design of Accumulators and Liquid/Gas Charging of Single Phase Mechanically Pumped Fluid Loop Heat Rejection Systems

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For single phase mechanically pumped fluid loops used for thermal control of spacecraft, a gas charged accumulator is typically used to modulate pressures within the loop. This is needed to accommodate changes in the working fluid volume due to changes in the operating temperatures as the spacecraft encounters varying thermal environments during its mission. Overall, the three key requirements on the accumulator to maintain an appropriate pressure range throughout the mission are: accommodation of the volume change of the fluid due to temperature changes, avoidance of pump cavitation and prevention of boiling in the liquid. The sizing and design of such an accumulator requires very careful and accurate accounting of temperature distribution within each element of the working fluid for the entire range of conditions expected, accurate knowledge of volume of each fluid element, assessment of corresponding pressures needed to avoid boiling in the liquid, as well as the pressures needed to avoid cavitation in the pump. The appropriate liquid and accumulator strokes required to accommodate the liquid volume change, as well as the appropriate gas volumes, require proper sizing to ensure that the correct pressure range is maintained during the mission. Additionally, a very careful assessment of the process for charging both the gas side and the liquid side of the accumulator is required to properly position the bellows and pressurize the system to a level commensurate with requirements. To achieve the accurate sizing of the accumulator and the charging of the system, sophisticated EXCEL based spreadsheets were developed to rapidly come up with an accumulator design and the corresponding charging parameters. These spreadsheets have proven to be computationally fast and accurate tools for this purpose. This paper will describe the entire process of designing and charging the system, using a case study of the Mars Science Laboratory (MSL) fluid loops, which is en route to Mars for an August 2012 landing.

Nomenclature

AFT	=	*Allowable Flight Temperature*
BOL	=	*Beginning of Life*
CFC-11	=	*Trichloromonofluoromethane (Refrigerant 11)*
CIPA	=	*Cruise Integrated Pump Assembly*
CHRS	=	*Cruise Heat Rejection System*
GSE	=	*Ground Support Equipment*
HRS	=	*Heat Rejection System*
JPL	=	*Jet Propulsion Laboratory*
MER	=	*Mars Exploration Rover*
MMRTG	=	*Multi Mission Radioisotope Thermoelectric Generator*
MPF	=	*Mars Pathfinder*
MPFL	=	*Mechanically Pumped Fluid Loop*
MSL	=	*Mars Science Laboratory*

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MSLFT = *MSL Focused Technology Program*
NASA = *National Aeronautics and Space Administration*
NPSH = *Net Positive Suction Head*
PDT = *Pacific Design Technologies*
RAMP = *Rover Avionics Mounting Plate*
RIPA = *Rover Integrated Pump Assembly*
RHRS = *Rover Heat Rejection System*
WCC = *Worst Case Cold*
WCH = *Worst Case Hot*

I. Introduction

THE MSL mission, currently en route to Mars, follows the general design paradigm of the previous JPL rover missions to Mars (Mars Pathfinder, MPF[1,2,3,4,5] and Mars Exploration Rovers, MER[6,7]). The external configuration of the MSL spacecraft looks similar to that of MPF and MER. At 4.5 meters, the diameter of the MSL[8] spacecraft is almost twice that of the MPF and MER spacecraft (2.6 m). MSL features a rover enclosed in an aero-shell for protection during entry and descent onto the planet's surface. A Cruise Stage carries the lander and aero-shell enclosure from Earth to Mars and will separate from the Lander, just prior to Entry, Descent and Landing (EDL). Fig. 1 shows a rendering of the rover packed into the aero-shell enclosure with the Cruise Stage attached at the top. MSL is scheduled to land on Mars on Aug 5th, 2012.

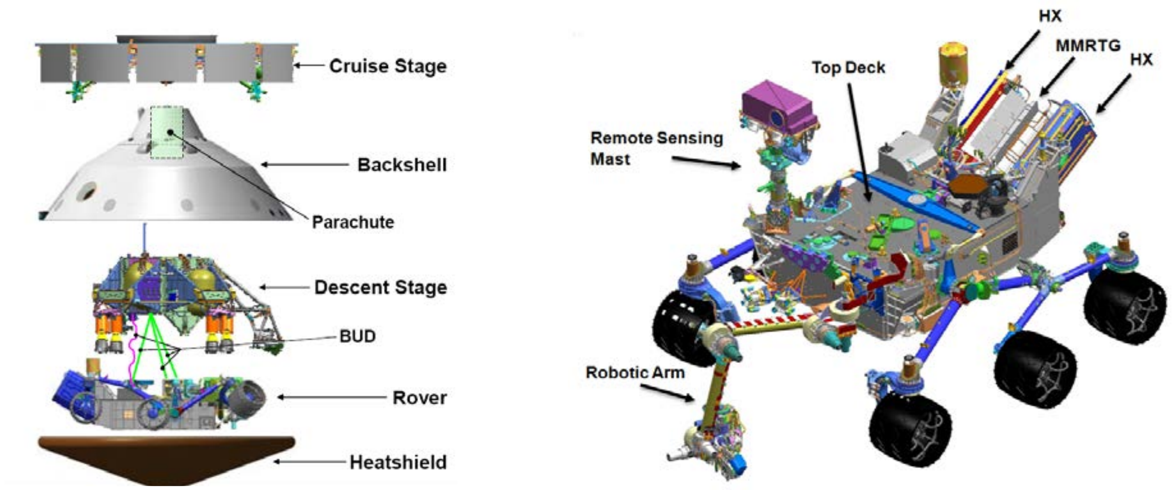

Figure 1. MSL Spacecraft and Deployed Rover.

The Multi Mission Radioisotope Thermoelectric Generator (MMRTG) is structurally attached to the rover and dissipates 2000 W of waste heat and weighs about 40 kg. The descent stage, containing the descent propulsion system and avionics, is adjacent to the stowed rover. The cruise stage contains the avionics, cruise propulsion system and the pumped loop radiators.

II. Overall MSL Thermal Architecture

The MSL spacecraft and the rover utilize mechanically pumped single phase fluid loop heat rejection systems (HRS) to create the backbone for thermal control of both systems: the Cruise Heat Rejection System (CHRS) and Rover Heat Rejection System (RHRS). Both fluid loops use Refrigerant-11 (CFC-11) as the working fluid. Figs. 2 and 3 show the overall thermal architecture.

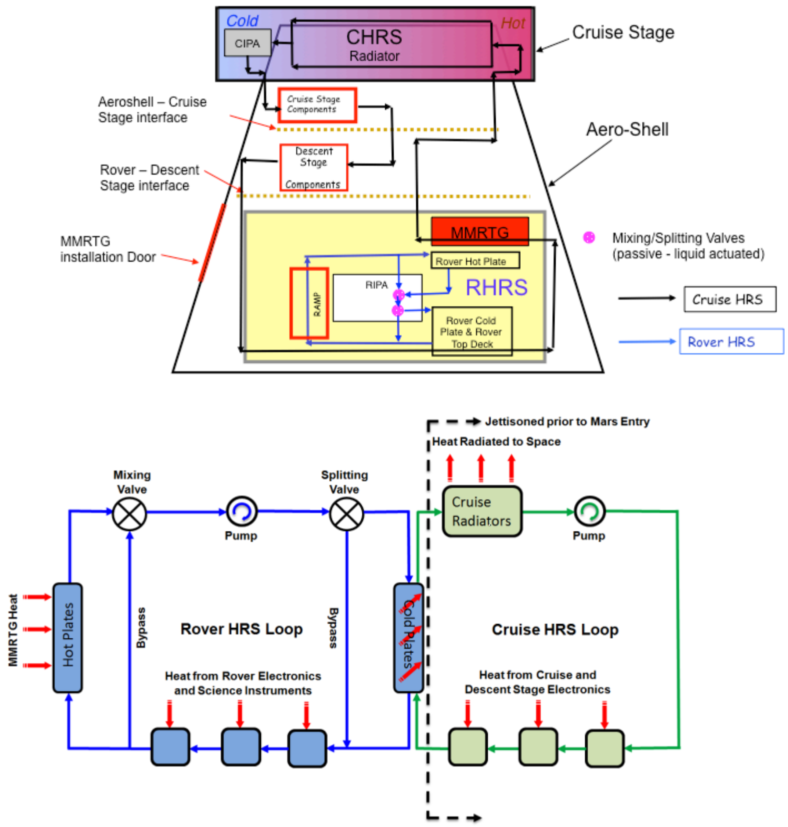

Figure 2. Schematics of Two HRS Fluid Loops.

The CHRS operates during the cruise portion of the MSL mission, from pre-launch to about an hour prior to the entry into the Mars environment. Its main function is to remove the waste heat from the MMRTG while maintaining its temperatures in a benign range (~100 to 180^{o}C). It also picks up dissipated heat from the equipment on the rover and on the Cruise/Descent Stages of the MSL spacecraft. Aluminum tubing is primarily employed in the loop, with a fraction being stainless steel.

Just prior to EDL, the working fluid in the CHRS loop is vented and the cruise stage containing the CHRS pumps is separated from the lander. Since EDL is short-lived (20 minutes) the thermal mass of the MMRTG prevents it from overheating, in spite of the lack of cooling of the MMRTG during this phase.

For the rover, the overall system approach is to utilize a single phase mechanically pumped fluid loop based HRS for the majority of the thermal control of the rover during Mars surface operations. The main impetus behind this is to utilize, as much as possible, the waste heat from the MMRTG to provide heat to the rover for cold conditions as well to use the RHRS to reject heat from the rover to external radiators during hot conditions.

The combination of the MMRTG waste heat and the fluid loop greatly simplifies the rover thermal design in terms of the level of thermal isolation required to maintain the rover and payload at allowable temperatures during cold conditions. It also greatly improves the robustness of the design, decouples the mechanical design and configuration from the thermal design and reduces the level of testing required. The references[8 to 12] provide a brief history of HRS loops, particularly from JPL's experience in using them for Mars missions.

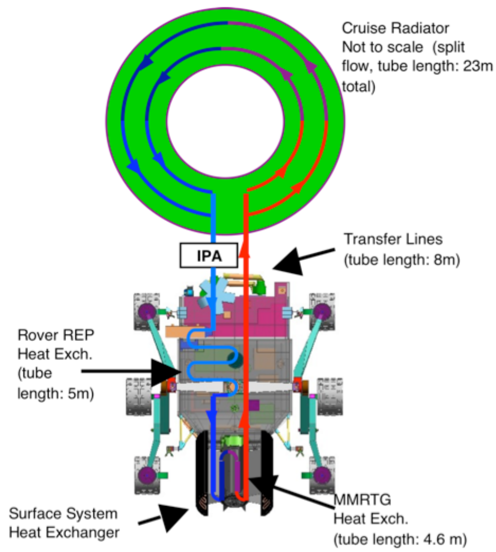

Figure 3. CHRS Fluid Loop Architecture.

Figure 4 has the schematic of the fluid loop of the RHRS. Both the Rover Integrated Pump Assembly (RIPA) as well as the Cruise Integrated Pump Assembly (CIPA) have two pumps each for the sake of redundancy. However, only one pump is powered at any time. There is also a metal bellows accumulator to accommodate volume changes due to temperature changes and small leaks in the system during the mission. A simplified schematic of the RIPA is shown within Fig. 4. Each of the two pumps has its own electronics to power it independently. The input power for RIPA (including the electronics) is 10 W. Each pump and thermal control valve subassembly has check valves upstream and downstream of them to ensure no recirculation flow occurs when one pump is idle and the other is running. The filters protect the pump bearings from particles in the flow stream. Each filter has a check valve in parallel to allow the flow to continue (although without providing protection for the pumps) in the event of a filter saturating or clogging. More detailed description of the two HRSs can be found in references 8-14.

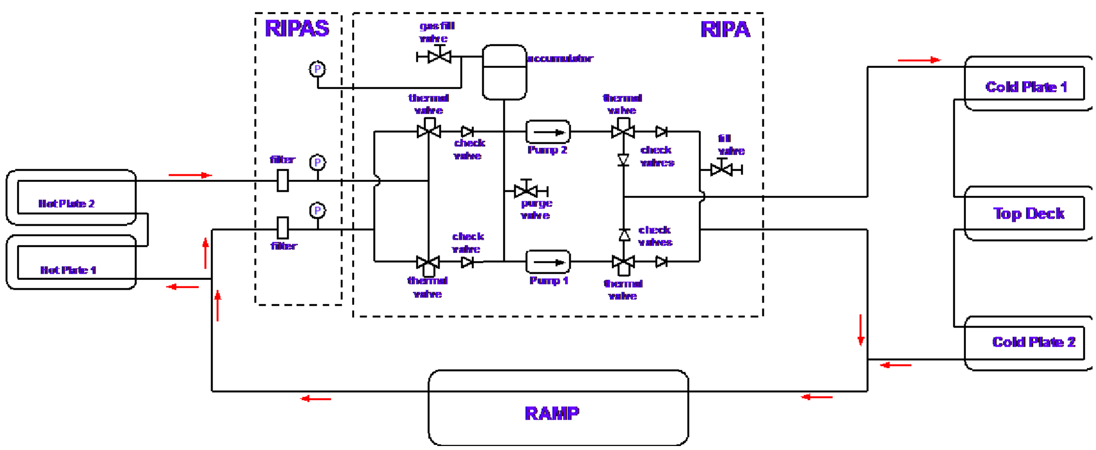

Figure 4. RHRS Schematic.

III. Volume Changes of Working Fluid During Mission

Since the temperature of the environment changes from launch through cruise (Earth to Mars) and on the surface of Mars (various seasons), as well as the changes in the operating conditions (power profiles), the working fluid (CFC-11) also changes continuously in temperature. The density of the fluid is a function of temperature, reducing in value with higher temperatures, and vice versa. These volume changes have to be accommodated during every phase of the mission. Since the volume of the HRS is fixed (rigid containment walls), the only way to accommodate these volume changes is to utilize an accumulator.

The temperature of the tubing and other components wetted by the working fluid vary from one location to the next, as well as over time. Since the total volume change of the fluid is a function of its bulk average temperature, as well as its total volume, an accurate estimate of the temperature of this fluid at every location is required as a function of time. Detailed thermal models of the entire spacecraft and rover were constructed to make these predictions during all phases of the mission. These models were already required to make sure all the components controlled thermally were in their allowable ranges. And the predictions from these same models also yielded the temperatures of the working fluid on the wetted surfaces. Fig. 5 shows a snapshot of the temperature predictions for the hottest and coldest extreme conditions experienced by the fluid in the CHRS.

Using the temperature distribution of the fluid in the HRS, a volumetrically weighted average temperature of the fluid in the entire system is computed. The density (or volume) of the CFC-11 changes by approximately 1.6% for a temperature change of 10^{o}C (the actual change is slightly non-linear with temperature, hence the actual density vs. temperature table is use to compute the accurate change in the density & volume).

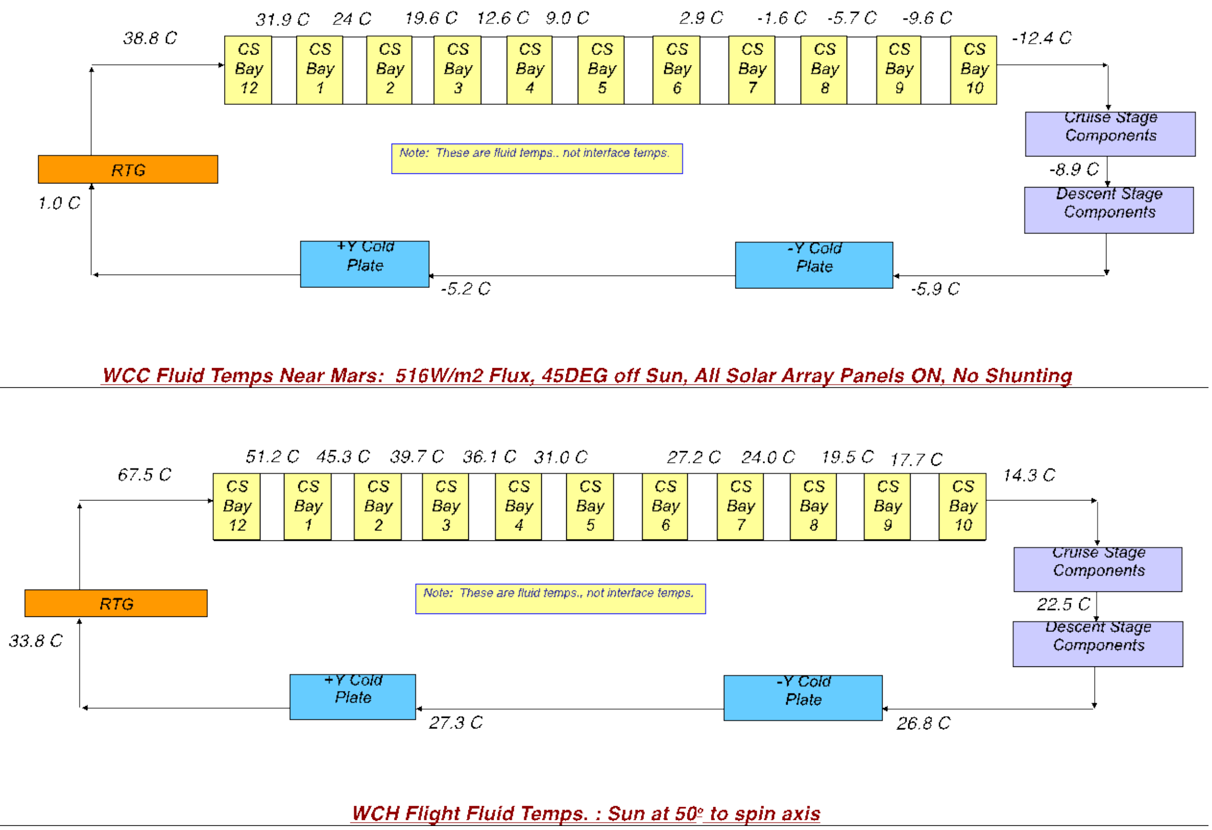

Figure 5. Temperature Distribution of the CFC-11 for the WCC & WCH Conditions for the CHRS

IV. Accumulator Design Description

The accumulator employed in MSL (Fig. 6) uses a bellows which expands and contracts (like a spring) in response to the volume changes. Within the accumulator subsystem there are two volumes: the liquid is inside the bellows whereas the gas (dry N_2) used to control the pressure of the fluid is outside of the bellows volume. The sum of the liquid and gas volumes is constant: as the liquid expands and contracts inside the bellows, it then correspondingly compresses or expands the gas outside of the bellows (within the housing). Hence an increase in the average fluid temperature leads to a decrease in the gas volume, which then leads to an increase in the gas/fluid operating pressure. Conversely, a reduction in the fluid temperature leads to a decrease in the operating pressure.

Since the liquid volume changes over the course of the mission due to the temperature change, the pressure also changes throughout the mission. Besides the accommodation of the liquid volume change via the available stroke of the bellows, one also needs to manage and control the pressure variation during the mission. Not only the maximum pressure at the warmest conditions needs to be below the maximum allowable pressure for the HRS, the pressure at every phase of the mission also needs to be above the value corresponding to two constraints: prevention of boiling of the liquid and cavitation in the pumps.

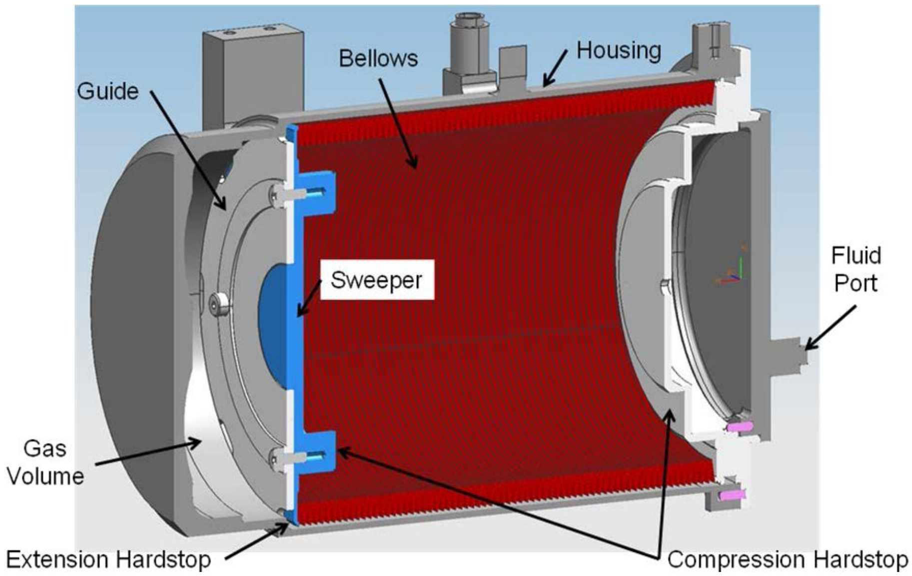

Figure 6. Accumulator Assembly Showing Bellows In Fully Extended Position (Maximum Fluid Volume, Maximum Pressure Of Gas)

V. Factors Affecting The Control of Operating Pressures During The Mission

The pressure at every location needs to be above the saturation vapor pressure corresponding to the local temperatures to prevent boiling. Since this is a single phase fluid system design, boiling of the liquid would create vapor which would be undesirable from the point of view of excessive pressure drops in the fluid flow and cavitation in the pumps. Additionally, the local liquid pressure within the pumps also needs to be higher than the saturation vapor pressure by the Net Positive Suction Head (NPSH) to prevent cavitation in the pumps. Cavitation in the pumps is undesirable from the point of view of creating the desired pressure head by the pumps, as well as damage to the pump impeller via pitting caused by cavitation.

The CFC-11 tables of saturation vapor pressure vs. operating temperature are used to arrive at the desired pressure within the system to prevent boiling throughout the HRS loop. The NPSH required was measured to be 0.2 MPa (30 psi) and it was then used to further constrain the pressure change during the mission to prevent cavitation.

VI. Key Design Features of the Accumulator Used For MSL

The key volumes (liquid/gas) and available stroke of the accumulator bellows for the CHRS are shown in Fig. 7. The total CHRS volume with bottomed out bellows was measured to be 6 liters and the bellows had an available stroke of just less than a liter which was in excess of that required for the volume change (0.4 liters) experienced by the liquid during the mission, thus providing ample margin against the belows either bottoming out or stretching beyond its structural limits.

Capability Type	Volume (liters)
Liquid Stroke Available	1
Min Gas Volume	0.4
Max Gas Volume	1.4

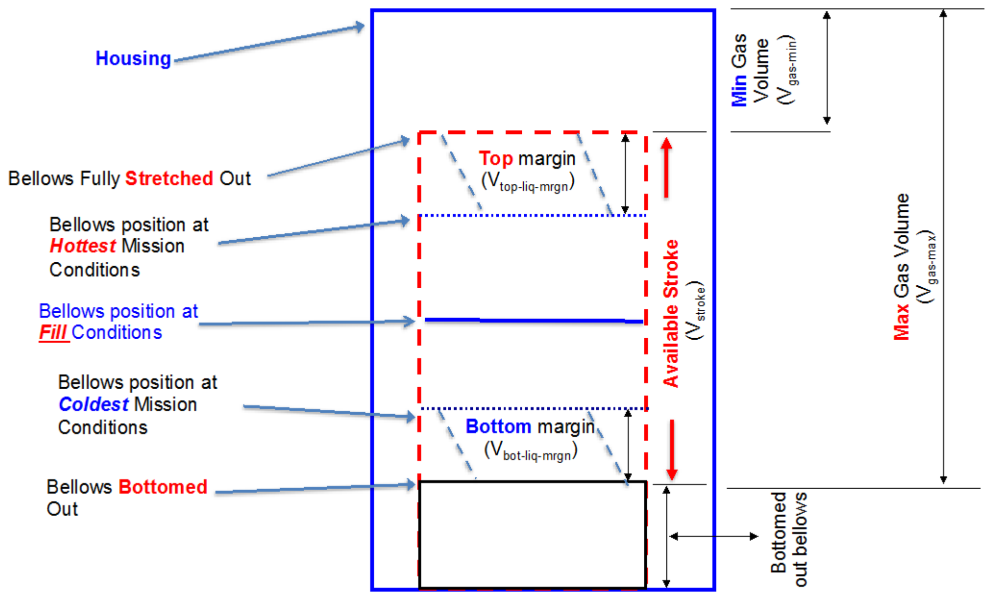

Figure 7. Accumulator Volumes

VII. Basic Process and Relationships For Designing The Accumulator

$$(PV)_g = (m_g/M)RT_g \quad (1)$$

$$dV_l/dT = (d\rho_l/dT)_T \quad (2)$$

Where, the following refer to the gas within the accumulator housing: P = Pressure, V_g = Gas volume, m_g = mass of gas, M = molecular weight of gas, T_g = temperature of gas. And the following refer to the liquid in the entire HRS: V_l = Volume of liquid, ρ_l = density of liquid, and the subscript T refers at a given liquid temperature.

Hence, the basic process of sizing the accumulator, assuming a fixed fluid mass for a closed system, consists of first determining the total volume of the liquid at the minimum and maximum temperatures that are experienced by the HRS during the mission. They use the temperature predictions shared earlier in this paper and the corresponding change in the density of CFC-11 (Eq. (1)). The change in the liquid volume then represents the minimum required volumetric stroke of the bellows.

Based on the kind of mechanical fittings used in the HRS, and the operating pressures and temperatures, a total liquid leak is computed for all these fittings during the mission duration. The liquid leak rate is computed by extrapolating the typical gaseous helium leak rates of these fittings to a corresponding liquid Freon-11 leak rate by using standard equations that use molecular weight and operating pressure ratios to make these estimates. Additionally, error bars for the measurement of the available stroke, volume calculations, and uncertainty in liquid fill parameters, etc. are added to the minimum required bellows stroke. Finally, some margins (30-60%) are added to this stroke to arrive at a design value of the bellows stroke to ensure against bottoming out or exceeding the maximum allowed stretch of the bellows, from the structural integrity point of view. The total margin is then broken into two individual margins on the bottoming and topping out of bellows to bias the margins against the corresponding temperature (and consequently the volume) margins required to avoid violating these two limits.

The next step is to size the gas volume in the accumulator, to maintain the pressure below the maximum expected operating pressure, MEOP (200 psia for MSL), while also ensuring that the pressure never falls below that required to prevent local boiling and pump cavitation.

For a fixed mass of gas in the gas side of the accumulator housing, using Eq. (1) for the minimum and maximum gas volumes, V_g, we get the following relationship:

$$P_{g\_cold} * V_{g\_cold} / T_{g\_cold} = P_{g\_hot} * V_{g\_hot} / T_{g\_hot} \quad (3)$$

Where subscripts hot and cold refer to the hottest and coldest conditions.

But since the sum of the liquid volume in the bellows and gas volume in the housing is constant, the volumetric stroke of the bellows (liquid expansion or contraction) must equal the corresponding gas contraction or expansion volumes. Hence if the maximum liquid stroke is $\Delta V_{bellows\_stroke}$, then this should also be the difference of the maximum and minimum gas volumes, as shown in Eq. (4).

$$\Delta V_{bellows\_stroke} = V_{l\_hot} - V_{l\_cold} = V_{g\_cold} - V_{g\_hot} \qquad (4)$$

Simultaneous solution of Eqs. (2), (3) and (4) yields the required gas volume in the coldest condition, V_{g_cold}, as shown in Eq. (5). Knowing the required gas volume in the coldest conditions, then yields the gas volume, V_{g_hot}, in the hottest conditions using Eq. (6), which is obtained by inserting Eq. (5) in Eq. (4). The total external volume of the accumulator housing is then the sum of the maximum volume of the gas (V_{g_cold}) and the minimum, fully contracted bellows volume (when the bellows is in the most contracted configuration, there is a finite, non-zero volume of the metallic convolutions of the bellows). Note that local predicted temperatures within the accumulator housing (not the liquid temperatures) are used to compute the pressure of the gas in the accumulator housing.

$$V_{g\_cold} = \Delta V_{bellows\_stroke} / \{1-(P_{g\_cold}/P_{g\_hot})*(T_{g\_hot}/T_{g\_cold})\} \qquad (5)$$

$$V_{g\_hot} = \Delta V_{bellows\_stroke} / \{1-(P_{g\_cold}/P_{g\_hot})*(T_{g\_hot}/T_{g\_cold})\} - \Delta V_{bellows\_stroke} \qquad (6)$$

The pressure values for the hottest and coldest conditions are obtained as follows. For the hottest conditions, the max allowed pressure (from the structural integrity capability of the accumulator) minus some margin is used as the value of P_{g_hot} (for MSL the MEOP is 200 psia and a 20-30 psia margin was employed yielding a value of 170 to 180 psia for P_{g_hot}). The value of P_{g_cold}, which then dictates the maximum gas volume, may require one or two iterations - it is initially assumed to be a value which is greater than that required for avoiding local boiling at any location in the loop and no cavitation at the pump, for the coldest HRS conditions. After that selection is made, calculations are performed to verify that the computed operating pressure in the intermediate mission conditions (between coldest and hottest) does not violate the boiling and cavitation requirements for those conditions. This then provides the minimum volume required for the accumulator. Additional tuning of the size can then be done to reduce the maximum expected operating pressure (hottest conditions) by using larger margin against the MEOP, or using a higher value of P_{g_cold} to provide additional margin against boiling and cavitation. This then becomes a part of the risk-resource trade at the system level.

VIII. Key Pressures, Volumes, Temperatures & Operating Conditions for MSL HRSs

Once the accumulator is sized (gas and liquid volumes, as well as bellows stroke), including all margins and error bars, for this given volume, the calculations are performed to predict the nominal pressures that would be expected during each of the following phases of the mission: starting from launch, all the way through cruise, landing and surface operations on Mars. Note that the CHRS is vented before landing to separate the cruise stage from the lander, so its function stops at Martian atmospheric entry. But the RHRS continues to function during Martian surface operations. This then finally verifies that pressures will always be within the required limits throughout the mission (the temperature profiles for the entire HRS for each phase of the mission is used to make these pressure predictions). Table 1 summarizes the expected pressures for the RHRS, along with other salient operating conditions. All these calculations are programmed in a detailed EXCEL spreadsheet for a very rapid turnaround design and analysis process.

Table 1. RHRS Operating Conditions During Surface Mission Phase

Total System Volume (bottomed out bellows)	Min Average Temp	Max Average Temp	Required Stoke	Stroke Margin	Min Gas Pressure @ Min Temp	Max Gas Pressure @ Max Temp	Gas loading pressure (bellows bottomed out)	Liquid loading pressure (bellows lifted)
(Liters)	(°C)	(°C)	(liters)	(%)	(psia)	(psia)	(psia)	(psia)
4	-50	50	0.7	30	60	180	60	110

IX. Filling The HRSs On The Ground Prior To Launch

Prior to thermal testing of the spacecraft and rover, as well as just before launch, the HRSs need to be filled with the working fluid (CFC-11) and the pressurant gas (dry N_2). The amount of liquid and gas has to be very carefully metered to ensure that the correct mass of these is filled to allow for the two systems to meet the key requirements of accommodation of the liquid volume changes as well as the maintenance of the correct pressure levels in the mission.

The position of the bellows during the post-fill operational condition extremes is already known using the accumulator sizing spreadsheet. Hence the mass of the liquid and the gas required within the HRSs and the bellows is known for these two extremes (it is the same mass for a closed system, but has different volumes due to the change in the HRS liquid density via its temperature change). So the mass of these two fluids (liquid and gas) is also the same at the time of filling the system. Hence the fundamental approach to arrive at the fill levels is to use the measured temperatures at the various locations in the HRSs at the time of filling the system (before test or before launch) to calculate the position of the bellows within the housing for those temperatures in the HRSs (for a fixed mass) at the time of filling.

The fill process is then to simply fill the liquid and gas to a level that would be experienced by the HRS if during the mission it were at the operating conditions during the fill. The accumulator design spreadsheet is modified to make the prediction of the volume of the liquid and gas at the temperatures experienced during fill. This then provides the position of the bellows under the fill conditions. There is no liquid volume gauge in the system, so the actual position of the bellows within the housing is measured by using the change in the pressure of the system as the liquid is being filled in the system (while it is compressing the gas in the accumulator) - using the ideal gas law and the volume information of the gas side of the housing. Variations of Eqs. (1) through (6) (ideal gas law and change in the CFC-11 liquid density as a function of temperature) provide the change in the volume of the bellows as a function of the corresponding change in the gas side pressure during the liquid fill.

The basic process of filling consists of the following steps:

1) Pressurization of the gas side of the accumulator to a low level and the pulling of a vacuum on the liquid side of the HRS. This bottoms out the bellows.
2) Increase of the pressure in the gas side to a level computed based on the temperature of the HRS at the time of filling. The gas side fill valve is then locked, and the gas fill is complete.
3) The liquid (CFC-11) is then filled on the liquid side until the bellows begins to lift off from its fully compressed state. The pressure on the gas side does not rise during the liquid fill until the bellows lifts off; hence this clearly marks the initial position of the bellows before the liquid is filled further.
4) Finally the liquid is further inserted until the pressure in the gas side reaches a predetermined level based on the temperatures of the system during the fill process. The liquid valve is then locked shut and the liquid fill is complete. At this juncture the entire fill process has been completed.

X. EXCEL Spreadsheet for Filling HRS with CFC-11

The pressure levels used (shown in table 1 above) for the gas and liquid fills (values in steps 2 and 4 above) are computed using a very sophisticated and detailed EXCEL spreadsheet constructed for the MSL mission. It has the following HRS parameters programmed in: all the relevant CFC-11 properties (density as a function of temperature), the capability of the accumulator (available bellows stroke & minimum/maximum gas volumes), the temperature profiles for each element of the HRS as a function of the mission phase (worst case cold and worst case hot conditions), the volume breakdown of each element of the HRS (radiator tubing, MMRTG tubing, heat exchangers, pump assemblies, accumulator bellows, Rover Avionics Mounting Plate (RAMP) and cold plates, connecting lines and miscellaneous fittings), plus margin and error calculations. The RAMP is used to mount the various electronics that are thermally controlled inside the rover chassis; the cold plates are next to the RTG and used as radiators of waste heat.

The only inputs required are the temperatures of each of the 9 elements of the HRSs at the time of filling (which is obtained by spacecraft or rover telemetry). Prompts for reasonable expected values of these temperatures are also provided to help ascertain that the inputs are checked for errors. Checks for boiling at every location (based on programmed in temperature profile expected in the mission) as well as cavitation in pumps are automatically performed. If any of these requirements are violated, the user is cautioned and guidance provided to change the load pressures to ensure that these will not be violated. Upon entering the temperatures during fill conditions, the spreadsheet instantaneously provides all the loading pressures during the gas and liquid fills. This spreadsheet was successfully employed during all load operations prior to testing as well as during pre-launch loads. A sample snapshot of the fill spreadsheet is shown in Table 2 with the spacecraft temperatures in the input domain, and the corresponding output of the fill pressures for the CHRS.

Table 2. Sample Snapshot of EXCEL Fill Worksheet for CHRS

	Value	Unit	Equation for Column F
THRM-2804 (THRM-T-RTG_1): data on BCB	*70*	°C	-
THRM-2813 (THRM-T-RTG_2): data on BCB	*70*	°C	-
THRM-2042 (THRM-T-CHRS-INLET-T): data on CPAM-A or THRM-2169 (THRM-T-CHRS-INLET-P): data on CPAM-B	*11*	°C	-
THRM-2041 (THRM-T-CHRS-OUTLET-T): data on CPAM-A or THRM-2170 (THRM-T-CHRS-OUTLET-P): data on CPAM-B	*11*	°C	-
THRM-2168 (THRM-T-CIPA_2): data on CPAM-B	*20*	°C	-
THRM-2028 (THRM-T-DSE-A-BASE) : data on CPAM-A	*25*	°C	-
THRM-2506 (THRM-T-HRSPL-AV-O): data on DPAM-B	*25*	°C	-
THRM-2815 (THRM-T-COLDPL-OUT): data on BCB	*20*	°C	-
THRM-2730 (THRM-T-CPPY-OUT): data on RPAM-B	*20*	°C	-
Final Liquid Fill Load Pressure *(fill with liquid until this pressure is achieved on flight gas pressure transducer)*	*127.7*	*psia*	$=(P_{max\ @\ max\ T + max\ stroke})*(V_{gas\ min + top\ liq\ margin})/(T_{CIPA-max}+273)*(T_{room}+273)/(V_{gas\ @\ Troom + bot\ liq\ margin})$
Initial Gas Load Pressure with bottomed out bellows *(fill with gas while bellows bottomed out to this pressure on flight gas pressure transducer)*	*86.5*	*psia*	$=(P_{liq\ chrg})*(V_{gas\ @\ Troom + bot\ liq\ margin})/(V_{gas\ max})$
CHRS Average Fluid Temperature during fill (calculated from inputs)	20.4	°C	*Volume weighted temperature average*
Final CHRS Pressure with Operational CIPA Pumps and CHRS Thermally Stable during Launch (WCH)	170		$=P_{sys\ max}-P_{mrgn\ against\ max\ allowable\ P}$

XI. Conclusions

This paper presented an overview of the design of the accumulators and the process of filling the HRSs with CFC-11 for the Mars Science Laboratory. The accumulators have performed successfully during launch and cruise operations (spacecraft is still in cruise, landing on Mars is scheduled for August 5). The pressures experienced by the two HRSs during launch and cruise operations have been close to these expected from the fill process and predicted by the fill spreadsheets. The successful employment of these accumulators, and the corresponding design and fill process used for MSL have paved the way for their use in future interplanetary missions in their current or extrapolated forms.

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