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Benefits of Modular Ball Valves in Thermal Control Systems

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Ball valves offer numerous benefits in thermal control system applications. Straightforward to design and consisting of few parts, ball valves can be more compact than other styles of valves, saving mass and volume. Reconfigurable for specific functions, a ball valve can provide proportional control and/or isolation. The valve seats allow robust sealing for internal leakage while maintaining a low actuation torque, allowing ball valves to be actuated in many ways, including the ability to turn by hand for manual override functionality without needing extra gearing or long lever arms. Ball valves also have a comparatively low-pressure loss, especially in the fully open position, which benefits the often-limited pressure loss budget of a spacecraft thermal control system. Ball valve components require less restrictive tolerances and are mostly axisymmetric making them readily manufacturable. Ball valves have proven quite durable, handling the loads during the launch and descent of spacecraft. The general methodology for designing ball valves is also consistent across a large range of sizes. In addition to all the performance benefits, the modularity of ball valves to perform different tasks can reduce nonrecurring engineering cost of a system. Due to this cost reduction and adequate performance characteristics, Sierra Space is developing a line of modular ball valves. These valves, evolving from previously qualified Sierra Space ball valves, can proportionally control, isolate, and divert flow. This paper will discuss the advantages of ball valves in spacecraft thermal control systems and detail the development of Sierra Space's line of modular ball valves.

Nomenclature

APRV	=	Ascent Pressure Relief Valve
CRES	=	corrosion resistant stainless steel
DTV	=	Debris Tolerant Valve
ECLSS	=	environmental and life support system
HAZ	=	heat affected zone
HFE	=	hydrofluoroether
ID	=	internal diameter
LIFE	=	Large Integrated Flexible Environment
NRE	=	nonrecurring engineering
PGW	=	propylene glycol water
PPRV	=	Positive Pressure Relief Valve
PTFE	=	polytetrafluoroethylene
sccs	=	standard cubic centimeters per second
TCS	=	thermal control system
TWPCV	=	Three-Way Proportional Coolant Valve
VIV	=	Vacuum Isolation Valve

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I. Introduction

THERMAL control systems (TCS) have the important task of collecting and rejecting heat waste in spacecraft. To transport the heat waste from the crew and hardware generating it to the rejection device, various flow control devices that direct flow are needed. This is often accomplished with valves of various styles. Though some of the styles may work in the same applications, they can have drastically different performance characteristics and have differing design and manufacturing concerns. Beyond splitting, bypassing, and isolating flow, TCS also requires proportional flow control to keep the loops at appropriate temperatures. Because TCS power, pressure, and mass budgets are often limited, it is imperative to balance all concerns when deciding on the valve style needed. In addition to performance concerns, cost must be accounted for to be competitive in the evolving commercial space market. A singular or modular valve design that works in different implementations can greatly reduce the nonrecurring engineering (NRE) cost of a system that has multiple valve applications. This paper will first discuss the general advantages of ball valves in thermal control systems as reasoning to why Sierra Space has chosen to develop a line of ball valves, and then detail the development of Sierra Space's new generation of ball valve.

II. Valve Types and Their Characteristics

There is nuance in deciding which of the many types of valves is best for a specific application. A few of the common valve types used for flow control are ball valves, butterfly valves, globe valves, gate valves, and solenoid valves, all of which use a ball or disk to press against a seat, which seals the various flow paths. A ball valve is a rotary valve that has a spherical ball to control flow. It does so by aligning the ports in the ball with the flow paths in the valve body. A butterfly valve is another type of rotary valve that uses a flat disk to control flow. The disk matches the internal diameter (ID) of the valve body so that when it is perpendicular to the flow path, it is fully sealed. See Figure 1 for examples of these rotary valves.

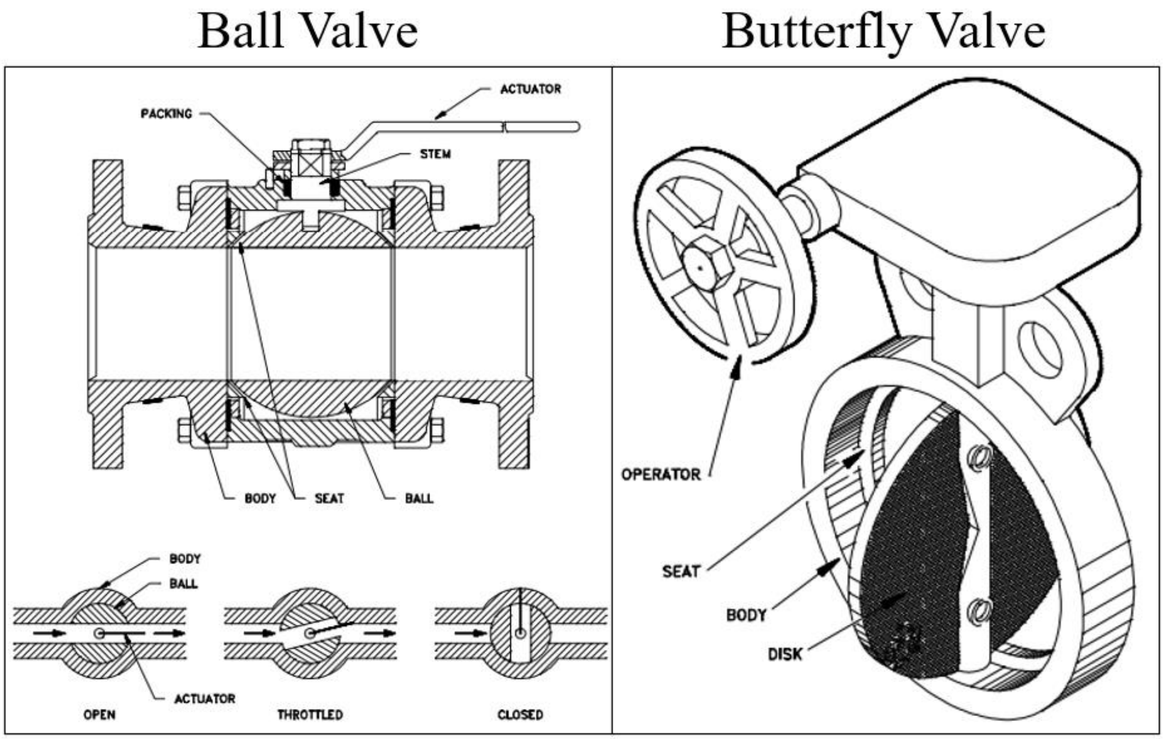

Figure 1. Rotary ball and butterfly valves[1].

A globe valve is a linearly actuated valve that uses a disk to plug and unplug the flow path. The linear action of the disk acts in the parallel direction of the flow. A gate valve is another linearly actuated valve that uses a disk to open and close the flow path. The linear action of the disk is in the perpendicular direction of the flow path. See Figure 2 for examples of these linear valves.

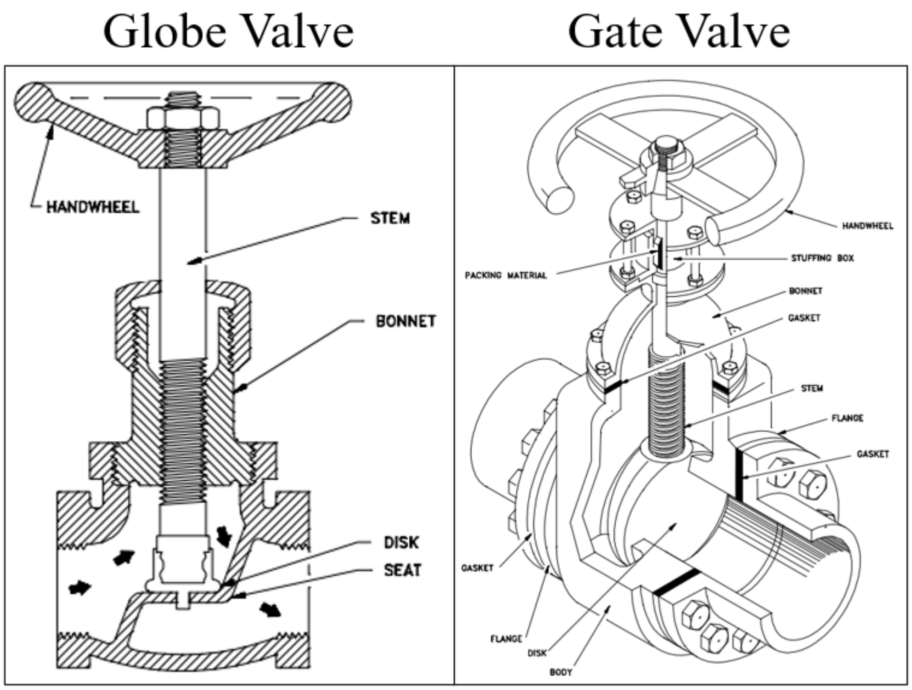

Figure 2. Linearly actuated globe and gate valve[1].

A solenoid valve is an electromechanically operated valve that mechanically acts like a globe valve but is actuated by a solenoid. Each of these valves have benefits and disadvantages.

A. Performance

In a thermal control system, pressure budgets are often strict, thus it is important to have low loss factors across a valve. In the fully open position of a ball valve, the port in the ball is the same as the ID of the inlet and outlet lines, thus it is only slightly restricting the flow for a low loss factor. Gate valves also do not produce a high pressure drop across the valve in the fully open position because the disk is completely removed from the flow path. Globe valves, however, produce a relatively large pressure drop because of the two (or more) right angle turns in the flow path, even when the disk is fully removed in the open position. Butterfly valves also produce a higher pressure drop because the disk is always present in the flow path.

There are many cases in a thermal control system that require the flow to be isolated/bypassed, e.g. part maintenance or replacement while still running other parts of the loop. Therefore, sealing must be stringent with low internal leakage values. Because the ball in a ball valve is nearly in constant contact with the seats, the seats are less prone to damage than the other valves. Consequently, there is less risk that they will degrade with time, so they can continue to provide low internal leakage throughout their life. Gate valves are prone to vibrating while opening since the disk is not fully supported in the partially open state, making them vulnerable to damage on the sealing surface of the disk which could lead to leakage[2]. Since the disk in a butterfly valve is constantly in the flow path, it is susceptible to damage or erosion to the sealing surface on the disk[2].

Thermal control systems also have proportional control application, e.g. temperature control valves. Temperature control valves regulate the temperature of the pumped fluid loops by managing the amount of flow going to the heat rejection device and the bypass leg. Gate valves rarely act as proportional control devices because they are prone to erosion in the partially open state, so they are typically implemented as on-off valves. Solenoid valves also do not have the ability to regulate flow because the solenoid actuator cannot put the valve in a partial flow state. Butterfly valves and globe valves, on the other hand, have configurations that are often used to throttle flow. A standard full port ball valve does not linearly control flow, however, minor tweaks to the port geometry allows for precise linear flow control.

The power budget in a thermal control system is frequently limited, therefore it is essential for a valve to have a low turning torque so the actuator does not have to draw significant power. Ball valves tend to have a lower actuation torque than globe and butterfly valves. Since the linear movement of the globe valve disk is in the axis of the flow through the orifice, it will require higher torque to actuate the valve against the flow direction. Similarly, butterfly valves may require larger torque to keep them in a partially open state since the flow is pushing against the disk. Not only is low torque good for the power budget, but it allows a human to actuate the valve without needing extra gearing or a large lever arm. Human spaceflight applications may require a manual actuation option, so removing the need for gears saves weight and space.

Though solenoid valves only require a pulse of power to actuate the valve, the actuation speed is rapid which can cause concern for water hammer to downstream components. The other valve types do not have that issue because they can be actuated slowly enough to not generate the effect. Rapid actuation is necessary in some applications, however, like an emergency shutoff or other short time to effect situations.

Another advantage of ball valves is that they can have more than two ports. Multiport valves can save significant weight and complexity in a system. Globe valves can have three ports and ball valves can have up to five ports. This allows for less tubing which makes routing and packaging of parts easier. Larger multiport valves can take the place of multiple two port valves which saves weight and contributes to fewer unique components for easier system implementation. Butterfly and gate valves are limited to two ports.

It is important that the mass of all components in an aerospace application is as small as possible to accommodate for the tight mass budget. Though butterfly valves have a smaller form factor, their mass savings comes at large line sizes. At the smaller line sizes, 0.5 inch (1.27 cm) to 1.25 inch (3.175 cm) tube outer diameters, often used in thermal control systems, they do not have significant mass savings. Besides butterfly and ball valves, globe valves are the only other valve that can throttle flow, and they tend to be heavier than the others at the same respective flow capacities. Both globe and gate valves have a larger form factor to accommodate for the linear rising of the stem as the valve opens and closes. A non-rising stem is possible for a linear valve but adds complexity to the parts and assembly of the valve.

B. Design

As mentioned in Section II.A, ball valves and globe valves are the only valve types discussed that can be designed with different numbers of ports. A two-port globe valve is a fundamentally different valve than a three-port globe valve. The valve body, sealing disks, seats, and assembly steps significantly change between the two. A two-port ball valve can easily be changed to a three- to five-port ball valve by only changing the ball and valve body. However, with each additional port, external leakage paths are added which require special attention to ensure leakage requirements are met. Section III provides an example of modifying a ball valve to have different number of ports.

Beyond changing the number of ports, ball valves are easily modular for different applications. By changing one part, the ball, the performance of the valve can be altered to be application dependent. For example, if a three-way valve implementation needs switching capabilities while limiting pressure drop, a ball with full ports can be used. If a separate three-way valve application requires proportional flow control, only the ball needs to change port profiles to achieve throttling capabilities.

Further, the design of a ball valve follows the same general recipe for a large range of line sizes (0.5 inch (1.27 cm) -5.0 inch (12.7 cm)). This allows for easy changes across multiple vehicles that use differently sized TCS tubes.

C. Manufacturing

Butterfly and ball valves consist of few unique parts. Most of the ball valve parts are axisymmetric, unlike globe valves, making them readily machinable. There are many ways to assemble ball valves, which further allows for modularity. Ball valves are also made up of robust components that are not easily damaged during assembly. Butterfly valves tend to be longer and skinnier than the cube-like ball valve parts. Because of this, the butterfly valve parts can be considered more delicate. Robust parts are important as they need to survive loads from launch and descent.

D. Verdict

Based on performance, design, and manufacturing characteristics, ball valves have the widest breadth of benefits that are important in typical TCS applications. Ball valves are effective at throttling flow, isolating flow, and have low turning torque. Though butterfly valves typically weigh less, ball valves have a lower pressure drop and can be multi-port.

Applications that ball valves are not well suited for include: required large line sizes where the mass savings (and consequently cost savings) from a butterfly valve is significant, having a design envelope that is long and skinny like a butterfly or linearly actuated valve rather than cube-like, and needing fast response time which a solenoid valve could do better. The advantages and disadvantages of each valve type are summarized in Table 1.

Table 1. Summary table of valve type advantages and disadvantages.

Type of Valve	Advantages	Disadvantage
Ball Valve	Low turning torque, low pressure drop, can throttle flow, can be multi-port	Heavier at large line sizes
Butterfly Valve	Light weight, small packaging volume, can throttle flow	Cannot be multi-port, prone to sealing surface wear over time
Globe Valve	Can throttle flow, can be multi-port	High pressure drop, high turning torque, heavy
Gate Valve	Low pressure drop	Cannot throttle flow, cannot be multi-port, prone sealing surface wear over time
Solenoid Valve	Quick response time	Water hammer concern, cannot throttle flow

Though they are not the best in every application, ball valves are easily modular to accomplish varying tasks to keeping NRE costs down. Knowing their weaknesses ahead of time allows for accommodation elsewhere. A system could be optimized for every valve application, but that could lead to excessive amounts of unique valves which would drive cost up. Rather, Sierra Space has chosen to develop a product line of ball valves for thermal control systems that aims to cover most standard TCS applications.

III. Sierra Space Ball Valve Development

NASA has published a report on the aerospace valve industrial vendor base that detailed common obstacles to on-time and high-quality delivery of aerospace valves[3]. Though a lot of the barriers were based on NASA acquisition processes, some design and manufacturing concerns were reported. One concern identified is that the job market for skilled and specialized technicians is highly competitive. When developing a new line of ball valve, it was important to maintain a low complexity design to mitigate this obstacle. This was done by requiring only basic methods for mechanical assembly, which does not use more than basic hand tools and common aerospace practices. Another reported hurdle is the strong emphasis on schedule that leads to cost, performance, and quality problems. A remedy to this was to design the valves such that they follow a similar formula across multiple sizes and applications, which cuts down on time spent on design and NRE. With lessened design time, more time can be spent assuring performance and quality are held to the highest standard. These concepts served as motivation for the updated ball valve development.

A new generation of ball valve, the Three-Way Proportional Coolant Valve (TWPCV) was developed pivoting off the valves originally designed for Sierra Space's Dream Chaser® spaceplane TCS (see Figure 3 for images of both). The TWPCV is in development for use in Sierra Space's LIFE® habitat (Large Integrated Flexible Environment) TCS. With lessons learned from the Dream Chaser development, the updated valves come in multiple sizes, have improved manufacturability, and better performance. LIFE has a larger TCS than

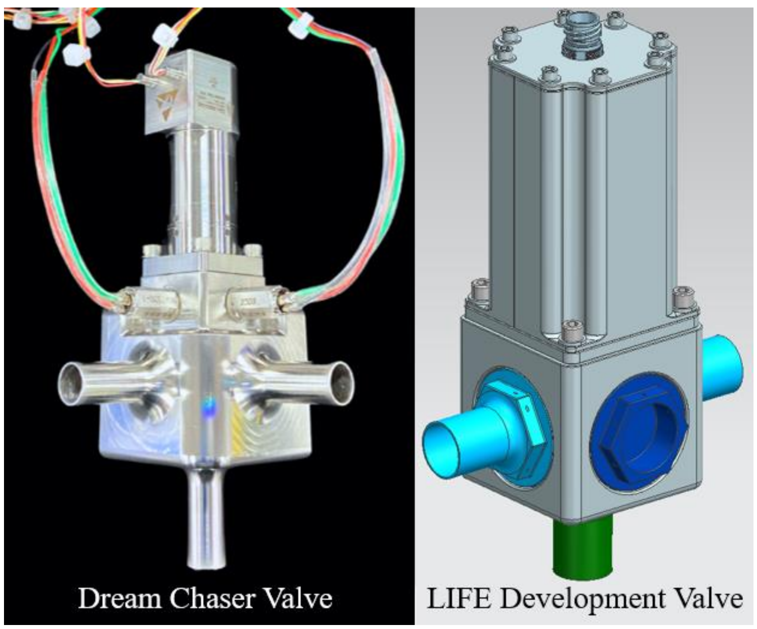

Figure 3. Images of the ball valve originally designed for Dream Chaser (left) and the Three-Way Proportional Coolant Valve (TWPCV) in development for LIFE (right). *The Dream Chaser valve is line size 0.5 inch (1.27cm) and the TWPCV line size is 1.0 inch (2.54 cm). The bottom port of both are inlets with two outlets on the sides.*

Dream Chaser with more components and differing applications. To have fewer unique parts, one valve must be multipurpose to accommodate for these different applications. Therefore, the TWPCV is used for proportional flow control, flow splitting, bypass, and isolation.

To efficiently control the temperature of the TCS loops, the percentage of flow being directed through each flow path should be linear with respect to the ball angle. The predecessor valve has a measured 33.3˚ to 39.4˚ valve control authority where the flow was varied (37% - 43.8% of the total 90˚ travel). Initial simulations for the updated TWPCV shows at least a 50˚ control authority (56% of the total 90˚ travel) where not only is the flow varied, it is highly linear, see Figure 4. This was achieved by moving the two outlet ports so that they are colinear rather than at a right angle. This allows for the ports to be larger and wider. The larger ports also contribute to a lower pressure drop across the valve. The valve is equipped with absolute position sensing which pairs well with the low slope of the linear flow curve for highly accurate flow control. Additionally, the port layout and size allow for reduced, but usable, capability in contingency cases where the flow needs to be directed between the baselined outlets rather than through the inlet. One such case is in a package with redundant valves as seen in Figure 5. Nominally, the primary valve varies the flow to the system outlets via varying the flow between its own Outlet One and Two since the backup valve is set to full flow to Outlet Two. In the worst stuck valve case, the primary valve is stuck with full flow directed to its Outlet Two. Here, the back-up valve can vary its position to determine how much flow goes to System Outlet One (up to 100% flow) or through the back-up valve's Outlet One and Outlet Two to get to the System Outlet Two (<100% flow depending on system).

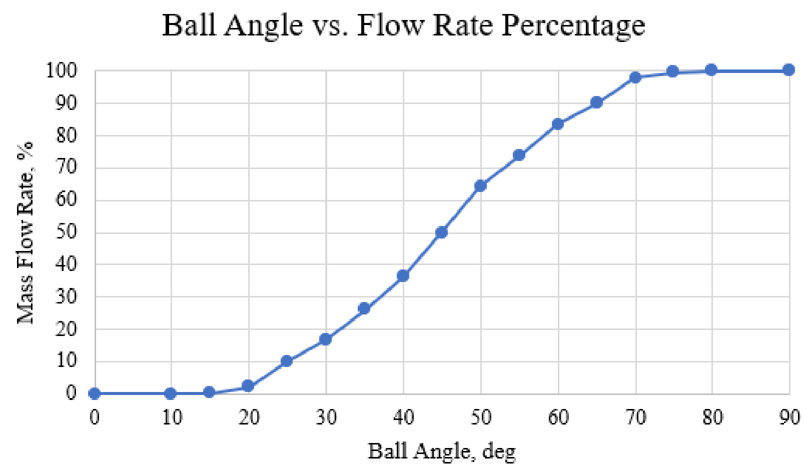

Figure 4. Three-Way Proportional Coolant Valve Ball Angle vs. Mass Flow Rate Percentage.

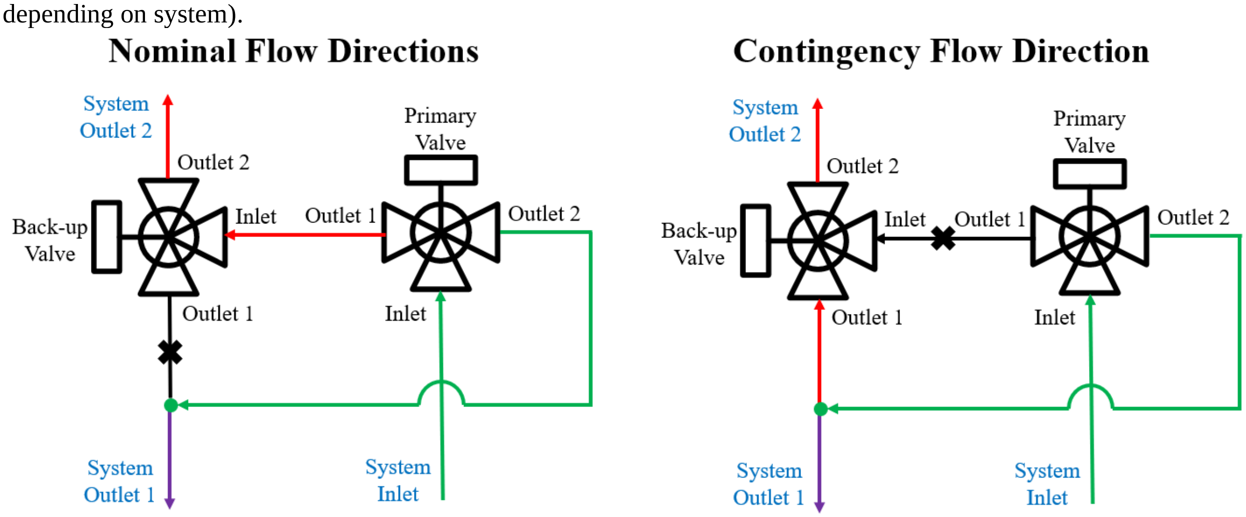

Figure 5. Redundant valve package in nominal and contingency state.

Beyond proportional control, the TWPCVs will be used to isolate and bypass parts of the loops. Effective isolation requires strict internal leakage rates. The seal geometry in all versions of the valves follows the same formula so internal leakage for the TWPCV is expected to stay consistent to its predecessor. Gaseous helium internal leakage rates on the magnitude of 1E-5 sccs are routinely measured during qualification testing for the control valves. With satisfactory internal leakage and a linear flow curve, the TWPCV can appropriately be used for flow splitting or switching as well.

The materials used in the valve are chosen to withstand launch and decent loads as well as to be compatible with the working fluid and other system components. The metallic parts include corrosion resistant stainless steel (CRES) and nickel superalloys. The seat material choice has evolved from standard PTFE (polytetrafluoroethylene), to modified/glass-filled PTFE, finally to a modified copolymer version of PTFE. This progression was due to shedding issues, material wear, and compression set. Elastomer o-ring seals are easily interchangeable to accommodate typical TCS working fluids like PGW (propylene glycol water), HFE (hydrofluoroether), and others.

Due to the seat and ball material choice (modified copolymer and 8 microinch surface finish (0.2 micrometer) CRES, respectively), actuation torque is kept low while still maintaining adequate sealing. The Dream Chaser ball valve routinely measured an actuation torque below 25 in-lb (2.8 Nm). This low torque permits the use of a direct manual actuation without needing gears. The manual actuation is accomplished via the removable actuator package. The fully integrated actuator package includes all the electronics (motor and gearhead, position sensing element, and control board)[4]. The actuator package does not interface with the flow path so it can be removed from the valve to expose the drive interface without disrupting the flow (see Figure 6). There, a hand tool can replace the actuator package for manual actuation. All current sizes of TWPCVs (0.5 inch (1.27 cm), 0.75 inch (1.905 cm), and 1.0 inch (2.54 cm) line size) are designed to use the same actuator package for commonality and to reduce the number of spares needed. Additionally, the integrated actuator enables streamlined packaging. The Dream Chaser valve control board was housed in a separate electrical box so harnesses from the motor and end of travel switches to the box were exposed and a baseplate was needed to keep all the components together. With the integrated actuator, the valve and all its electronics are connected and can be fastened into the next higher assembly level solely from the valve body.

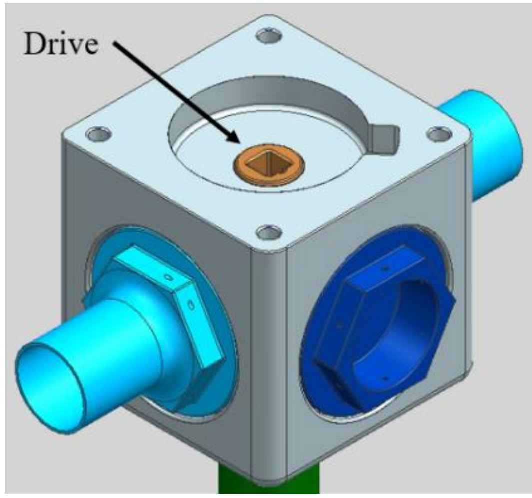

Figure 6. TWPCV with actuator package removed to expose the drive interface.

With the large quantity of valves expected for LIFE TCS, there is an emphasis to improve manufacturability from the original valve. The valve body machining time is expected to be greatly reduced by simplifying the body so that it does not include tube stubs. Figure 3 shows the tube stubs and valve body as one part on the Dream Chaser valve. It also shows the LIFE valve with the gray valve body and removable blue and green tubes stubs and tail pieces. By removing the tube stubs, the valve body is cubic so it can start from a smaller piece of raw material. Even though the tube stubs still must be manufactured as a separate part, they too have a final form factor not far from a piece of raw round stock. Though separating the tube stubs and valve body into different parts introduces new leak paths, there are dual seals on every external leak path to lower the chance of failure. The removal of tube stubs from the valve body also allows for a modular approach to tube stub locations. The five sides of the valve can all be either tube stubs or capped with a tail piece depending on how many and where the tub stubs need to be located, see Figure 7. The ball geometry may have to change based on valve function, however only one new part is created for an entire new valve application.

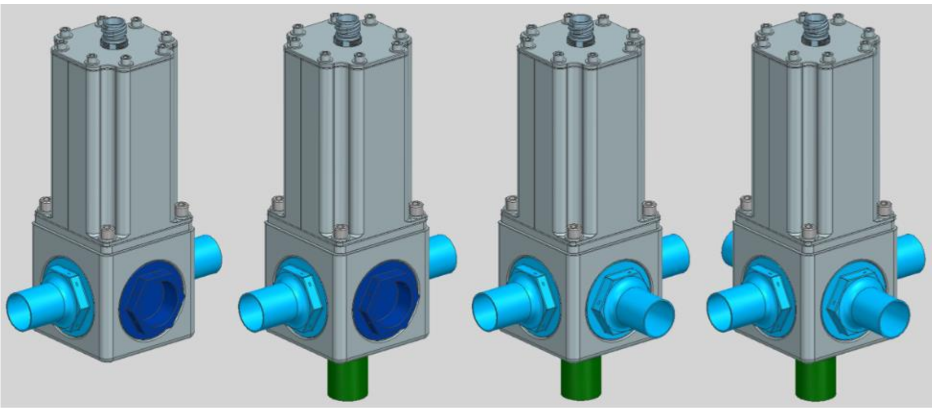

Figure 7. Two- to five-port valves created by only replacing tail pieces with tube stubs.

In addition to moving the outlets to be co-linear, removing the motor output shaft from the flow path, having a fully integrated actuator package that includes absolute position sensing rather than end of travel switches, and making the tube stubs and valve body into separate parts, there were several other lessons learned from the Dream Chaser valve. These include moving away from Nitronic 40 material due to darkening of the heat affected zone (HAZ) during welding that contributed to extensive inspection investigations and designing for increased fastener size to ensure they will pass NASA-STD-5020 requirements for threaded fastening systems without additional retention methods.

Sierra Space ball valves generally follow the same internal geometry design formula across many line sizes (approximately 0.5 inch (1.27 cm) -5.0 inch (12.7 cm)), which enables straightforward extensibility across different vehicles with different TCS line sizes. Additionally, it extends the use cases past TCS into environmental control and life support system (ECLSS) applications. Though different fluids for ELCSS applications may require material changes, Sierra Space has developed multiple ECLSS ball valves and understands what variable tweaks are needed to account for such. Some examples of Sierra Space ECLSS ball vales that were developed for programs before LIFE include the 3 inch (7.62 cm) Vacuum Isolation Valve and the 1.5 inch (3.81 cm) Positive Pressure Relief Valve, see Figure 8.

To extend the commonality of the new generation of LIFE ball valves, the ECLSS valves are being upgraded to follow the same standards as the TCS valves, allowing them to use the same common actuator. Among many, these include a 5 inch (12.7 cm) Ascent Pressure Relief Valve (APRV) and a 2 inch (5.08 cm) Debris Tolerant Valve (DTV), see Figure 9.

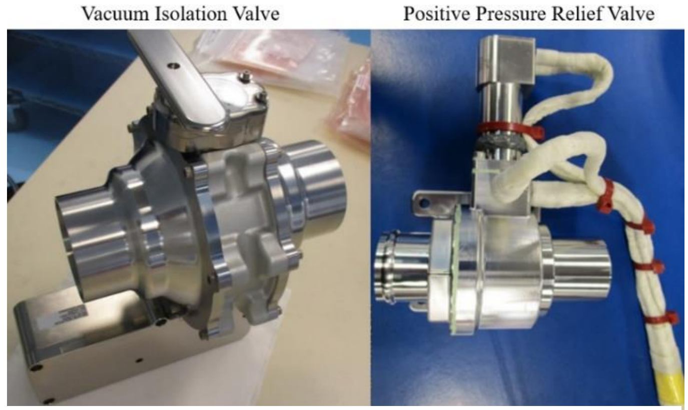

Figure 8. Images of the Sierra Space Vacuum Isolation Valve (VIV) and Positive Pressure Relief Valve (PPRV). *The VIV is 3 inch (7.62 cm) line size and the PPRV is 1.5 inch (3.81 cm) line size.*

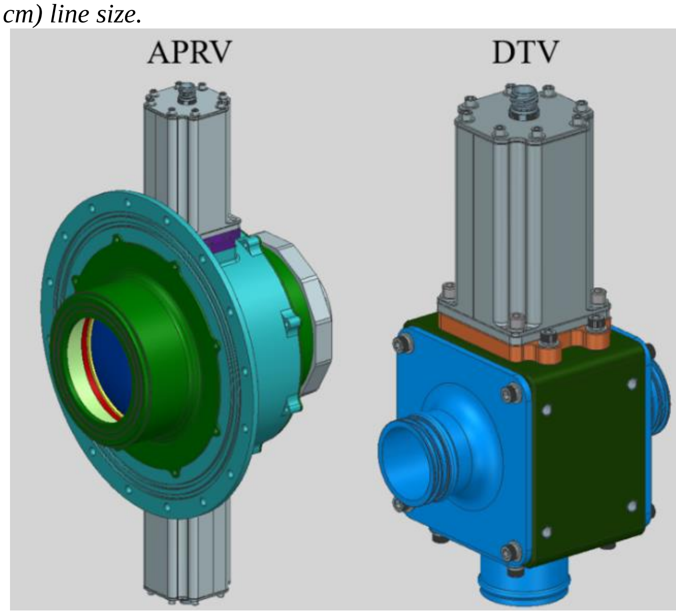

Figure 9. Images of the LIFE Ascent Pressure Relief Valve (APRV) and the Debris Tolerant Valve (DTV).

IV. Conclusion

Choosing the correct valve style is imperative for effective performance in a thermal control system, but design, manufacturing, and cost concerns must also be balanced. Though there are many types of valves used for flow control, ball valves have a wide breadth of advantages for TCS because they can effectively throttle and isolate flow, have a low loss factor while maintaining a low actuation torque, and can be modular, all of which aid the restrictive pressure, power, and mass budgets of a thermal control system. The modularity of ball valves contributes to lower costs across a system to be competitive in the modern commercial space market and is a driving factor as to why Sierra Space is developing a new generation of ball valve. This valve is the Three-Way Proportional Coolant Valve and is multipurpose for use in its LIFE habitat TCS. The TWPCV has a larger control authority range, lower pressure drop, and improved manufacturability than its predecessor. This valve will proportionally control flow along with isolating, bypassing, and splitting flow throughout the LIFE system. All sizes of the TWPCV are designed to interface with an integrated common actuator package that can be removed without exposing the fluid. ECLSS applications also use the general ball valve design of various sizes and use the common actuator package for commonality. The Sierra Space ball valve is designed to be modular for extensibility to future systems.

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