AUTOMATIC TEMPERATURE CONTROL OF A HYDRAULIC SYSTEM VIA STEPPED PRESSURE MODULATION, A DUAL STAGE VALVE OPTIMIZATION

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ABSTRACT

The AW 609 will be the world's first civilian tiltrotor aircraft, and the full triplex redundant FBW hydraulic system is a key technology that will make this unique aircraft possible. The majority of aircraft actuation systems rely on constant pressure hydraulic power generated by variable displacement, mechanically actuated and pressure controlled hydraulic pumps. One of the possible failure modes of the hydraulic systems is associated to pump pressure regulator hardover, where the delivery pressure and flow of the pump reach the highest possible value due to inability of the regulator to correctly close the mechanical loop and reduce displacement. The state of the art of aerospace hydraulic circuit technology during this failure scenario does not grant pressure preservation and a proper control of temperature excess; therefore it is an objective of this design to provide a hydraulic system in which solenoid operated shut off valves and oversized heat exchangers are not required to manage such condition. Results evaluation shows that unloading of nominal pressure will reduce the energy transferred to the fluid converted in heat, placing the system within the safe temperature operating envelope and permitting a temperature limiting control of the circuit with the pump failed. In case of temperature decrease or recovery of pump functionality, the system can return to its normal functions. This paper reviews the AW 609 automatic temperature control requirements, design, and development test results.

ACRONYMS

URTV	Unloader Relief Thermal Valve
URV	Unloader Relief Valve
TV	Thermal Valve
GPM	Gallons per Minute
PSID	Pounds Square Inch Differential

1. INTRODUCTION

The AW 609 will be the world's first civilian tiltrotor aircraft, and the full triplex redundant FBW hydraulic system is a key technology that will make this unique aircraft possible.

The majority of aircraft actuation systems rely on constant pressure hydraulic power generated by variable displacement, mechanically actuated and pressure controlled hydraulic pumps.

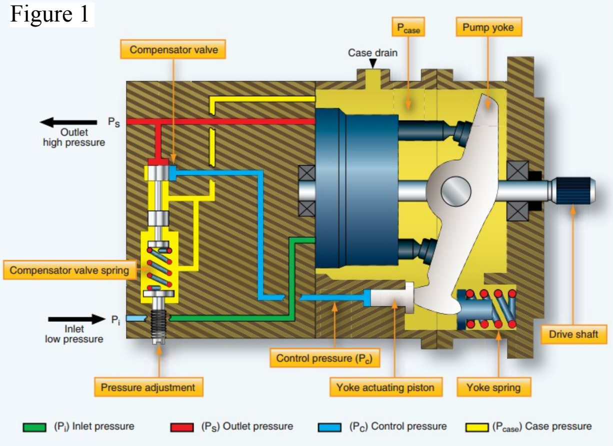

Figure 1

During operation, system hydraulic pressure is maintained at a constant value under variable flow demand conditions through the use of pumps equipped with pressure-controlled displacement regulating mechanisms that adjust the pump displacement as a function of system pressure.

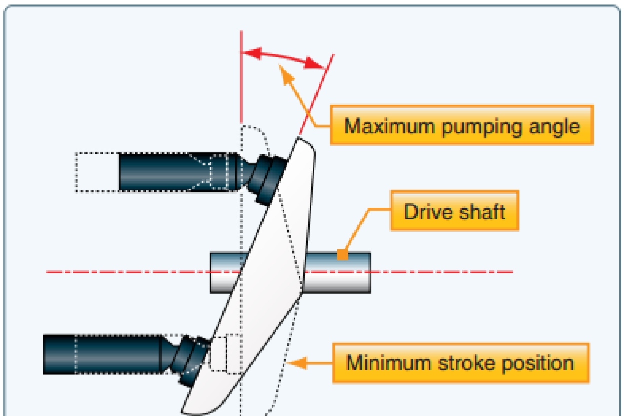

Figure 2

One of the possible failure modes of the hydraulic systems is associated to pressure regulator hardover malfunctions where the delivery pressure and flow of the pump reach the highest possible value due to inability of the regulator to reduce displacement.

Under these conditions, the ability of the system to perform its actuation function is compromised.

Since in most aircraft there is usually no way to correct a failed pump, under failure conditions the affected pump is taken off-line and a second hydraulic system or a backup pump are used to restore the actuation function.

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The risk of consequential failure for the system components exposed to the high pressure condition is normally mitigated by means of pressure relief valves that bypass part of the flow across the loads providing a localized head loss through the opening of a parallel flow path to the one associated with the load itself.

This solution, when employed under the high flow conditions associated to regulator failure, converts significant amounts of hydraulic power in thermal energy that increases the temperature of the circulating hydraulic fluid, to the point that damage can incur on seals, gaskets, tubes and other thermally sensitive parts of the system, in addition to the increased potential for fires when flammable fluid is used.

There are basically two methods to cope with system overheating as a result of hydraulic pump compensator failures. The first one is to oversize the hydraulic system heat exchanger capacity by about 40—50% to account for the additional heat resulting from the failure. This method requires additional space and adds a sizeable amount of weight to the aircraft.

The second method is to install a solenoid operated bypass valve or shut-off valve that allows the operator to manually isolate the pump from the hydraulic system.

This method has several drawbacks. Once the valve is activated, the system loses all hydraulic power and with it all its functionality while the overheat condition is still present in the section of the system (pump-reservoir-heat exchanger) upstream of the valve. The addition of the valve reduces the overall system reliability and requires an external electrical power source with dedicated control. Finally, pilot intervention is required to activate the valve.

The state of the art of aerospace hydraulic circuit technology does not grant pressure preservation and a proper control of temperature excess; therefore it is an objective of this design to achieve this goal and to provide a hydraulic system in which solenoid operated shut off valves and oversized heat exchangers are not required.

The aim of this study is to offer a lightweight, reliable solution to the overheating condition by means of an automatic way to achieve hydraulic pressure and temperature control by self-regulation of the hydraulic circuit under abnormal flow conditions.

2. CONCEPTUAL DESIGN

The failure scenario described is considering two adverse effects that the proposed design shall be able to control and limit: excessive pressure and excessive temperature while avoiding a full shutoff of the affected system.

These objectives are achieved by providing a hydraulic system having a two-stage unloader relief thermal valve (URTV), the definition of 'two stage valve' refers to an assembly capable of regulate it's functioning at two different pressure levels by means of two internal poppets divided into main poppet and pilot poppet. The presence of two poppets which can work in a combined way to achieve at least two stabilized pressure levels explains also the functions available: relief as first one, to cope with a high pressure protection functionality and a pressure unload, to manage the pressure reduction to limit the thermodynamic heating generated by the pressurization of a high volume of oil at high pressure for a sustained length of time.

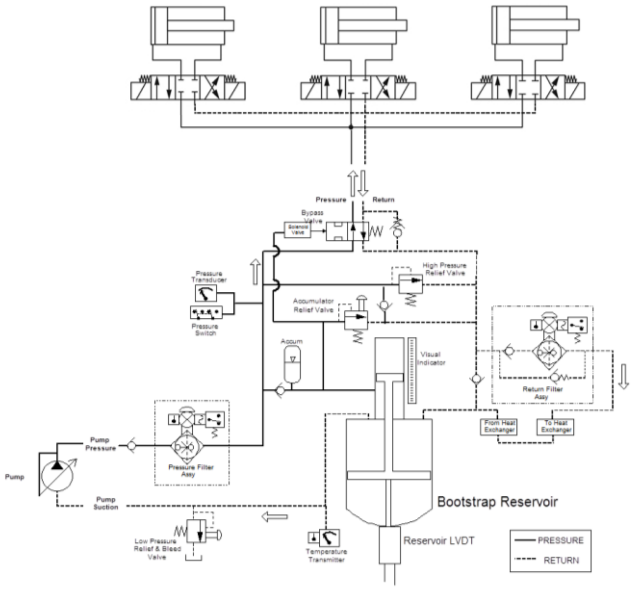


Figure 3

PRIOR ART

The statement above relevant to 'at least' two stabilized pressure levels refers to the possibility that one of the two poppets could be shaped in order to achieve a variable continuous regulation depending on its displacement.

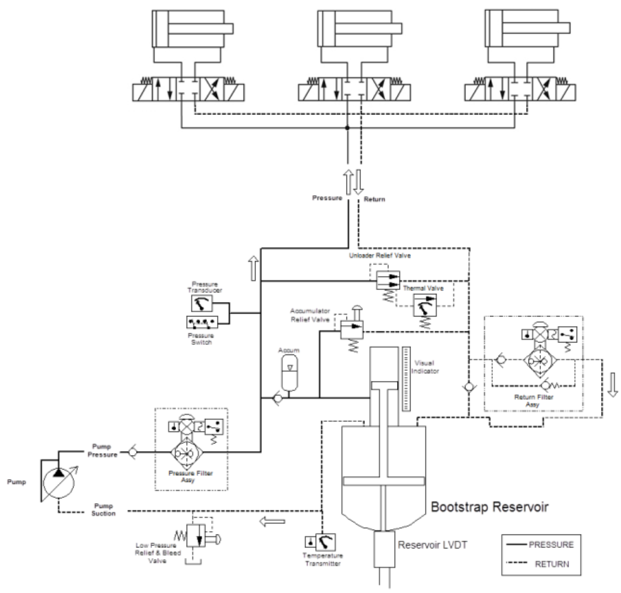


Figure 4

PROPOSED INVENTION

The over-pressure failure case is managed by designing the main and pilot poppet in order to relieve the extra flow by limiting the maximum pressure for any value of pump flow.
The over-temperature failure case is managed by reducing the hydraulic system pressure to a pre-selected reduced operating pressure value for any value of pump flow when the system temperature exceeds a safe value for continuous operation. This pressure value is below the normal operating pressure but is a value that is sufficient to achieve two aims:

- Maintain an adequate pressure in the system in order to allow the affected system to provide power to the control actuators
- Reduce the overall power transferred to the hydraulic oil by the hydraulic pump thus reducing the maximum temperature that could be reached.

To better explain this last point, the unloading of nominal pressure will reduce the energy transferred to the fluid converted in heat by thermodynamic heating, placing the system within the safe temperature operating envelope and permitting a temperature limiting control of the circuit with the pump failed and still running. This energy reduction at the input side of the system will result in having less energy to be dissipated via heat exchangers thus leading to a self-regulation of the system.
The URTV intervention is reversible, in fact in case of temperature decrease to safe values or recovery of pump functionality, the system can return to its normal functions providing full power as prior the failure condition.

3. UNLOADING RELIEF OPERATION

An aerospace Class II Hydraulic system iaw SAE AS5440 shall be able to operate at a rated pressure of 3000PSI between x and y temperatures. The system has to be equipped with safety feature to provide protection from overpressure preventing to exceed the proof pressure that is defined as 1.5 times the rated pressure. The URTV embodies this safety feature plus an active temperature control for stepped pressure reduction. The specific scenario starting from the URTV has been conceived is the variable displacement pump compensator hardover failure.

NORMAL MODE
The unloading relief valve operates as a standard system relief valve during short endurance pressure excursions and as an unloading valve during extended periods of pressure elevation. During normal operation, when system pressure remains below 3650 PSI, the valve sits closed, as depicted in figure 5. A small annular orifice between the pilot poppet stem and the main poppet allows pressure on both sides of the main poppet to remain equal and the combination of differential area and spring force holds the poppet against the seat. Likewise, the thermal valve poppet also remains seated.

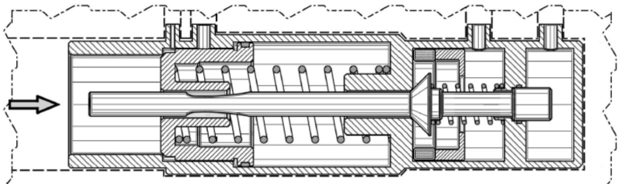


Figure 5

For pressure spikes damping control purposes only the first return hole is used, as depicted in figure 6.

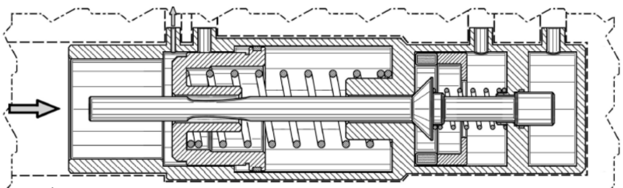


Figure 6

RELIEF MODE
When system pressure reaches 3650 PSID above return, the force on the small area of the pilot poppet is sufficient to overcome the pilot spring force. The pilot poppet unseats and creates a pilot flow path from supply pressure, through the annulus around the poppet stem, past the seat and into the area below the pilot poppet conical head. This flow creates a differential pressure across the main poppet, unseating it and relieving the system pressure to return as depicted in figure 7. In order to relieve the full 17.3 GPM at 3650 PSID, the main poppet travels ~.100 in. to open the large drillings to return. A drilling in the pilot poppet seat allows flow into an annulus in the main poppet seat. The oil flows from this area into the bottom of the thermal valve poppet. While the temperature is low enough, there is pilot flow into the area before the unloader stage that remains closed.

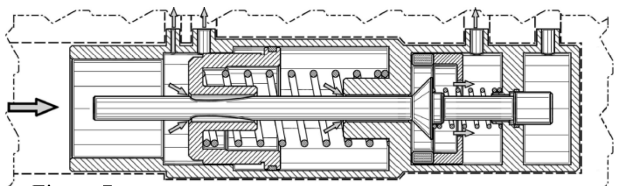


Figure 7

UNLOADER MODE
In the case of temperature increase exceeding 120°C (250F), the thermal sensitive element expands letting the thermal valve poppet to fully travel, it stops the flow to get out from the pilot poppet stage forcing it to escape into the unloader stage by pressing on the head piston of the pilot poppet, as shown in figure 8. The pilot flow is

through a small orifice of the thermal valve poppet, sized to provide pressure under the pilot poppet conical head to provide a helping force in addition to the system pressure on the small area of the pilot poppet stem. Pressure under the pilot head is maintained by a close fit between the poppet head and the pilot poppet seat. This additional force on the pilot poppet changes the force balance such that the main poppet now meters at 2000 PSI versus 3650 PSI. Immediately after the thermal poppet displacement, the main poppet will lift to meter at lower differential pressure to balance 2000 PSIg at the 17.3 GPM flowrate, Figure 8.

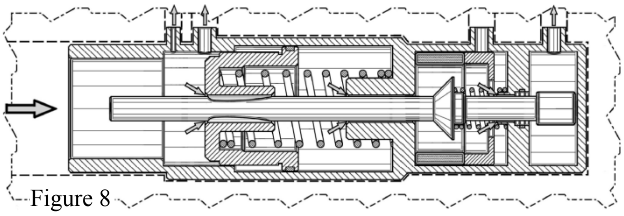


Figure 8

RESEAT

As flow decreases, the valve will maintain 2000 PSI system pressure at flows down to 6 GPM, Figure 8. The main poppet will remain lifted above the seat in order to relieve 2000 PSI down to 6 GPM.

As flow decreases towards 6 GPM, the main poppet moves back towards its seat. The main poppet will travel back to seal off the large drillings in order to maintain the 2000 PSI drop, leaving only the 6 GPM orifices open. When flow decreases below this, the main poppet travels farther to fully seal the flow from the system and causing the reseat of the pilot poppet too.

4. DESIGN EMBODIMENT

The valve is a standard cartridge design, this means that the valve can be installed or removed by screwing or unscrewing the valve body from the reservoir manifold. The valve is a self-contained design containing two concentric poppets, main and pilot, each one grounded via mechanical spring to the body frame. The valve is designed with four plenums, as depicted in figure 9, starting from the left side is possible to define: the pressure plenum, which is the hydraulic circuit side where the pressure is sensed and from which the flow is relieved (11).

There are two pressure sections, the central is the section that pushes and move the pilot poppet (2) while the annular outer section is the main poppet active area (3).

The movement of the main and pilot poppet is independent one with respect to the other and they act on different openings. The pilot poppet spring is preloaded with a force equivalent to 3650PSI acting on the central area. The main poppet spring is also preloaded but at an higher threshold value of equivalent pressure acting on the minimum area when is in closed position. This allows the pilot poppet to be always the first to move after a change in pressure in the pressure plenum in order to trigger and regulate the main poppet displacement.

The main poppet acts on two kind of ports connected to return (4), when the equivalent pressure in the pressure plenum is over the pilot poppet spring preload the first of the two outlets is completely open while the second one is partially overlayed by the main poppet side surface. This position is equivalent to the relief mode, in which the valve is relieving the flow, as long as it is necessary, in order to maintain constant maximum pressure in the system of 3700 PSI. On the other hand the main poppet design comprises a step next to the 45° chamfer that realizes the sealing between the pressure plenum and return, this step on the side surface of main poppet creates a recess and thus a chamber that is in direct connection to the first outlet hole as soon as the main poppet starts to move. This chamber that creates a sudden connection is used to relieve instant pressure spikes that can happen in the hydraulic system avoiding for a complete opening of the valve main poppet.

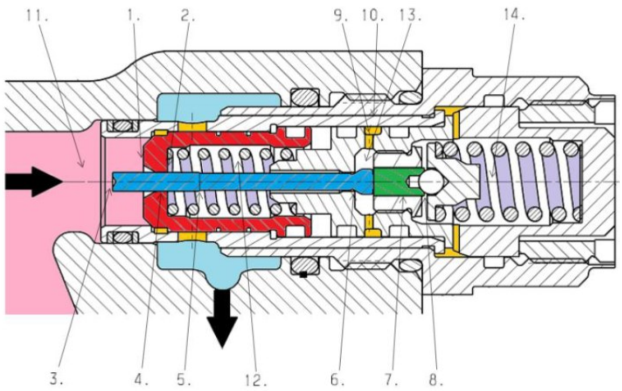


Figure 9

Behind the main poppet there is the balance plenum (6): the oil flow in this oil volume is regulated by the conical head (7) displacement that forces a flow thru the calibrated annular orifice created by the coupling of the main poppet inner hole and the pilot poppet outer diameter. This controlled flow can guarantee a backpressure differential on the main poppet capable of regulate and balancing its lift and thus the discharge rate from the pressure plenum. The balanced lift obtained regulates the overlay of the second outlet port allowing for the relief mode operation. The main poppet spring rate is key in defining the flow that is discharged with respect to the pressure applied in the pressure plenum and moreover the area ratio of the main poppet forward and backward hydraulic sections is critical for dynamic stability.

The main poppet, as it has been described previously, is designed as a hollow cylindrical spool that has the key characteristics listed:

- Precision inner diameter coupling with pilot poppet in order to create a flow calibrated annular orifice
- Front and back hydraulic sections areas designed with a suitable ratio to provide stability during operation
- Stepped interface between the two outlet holes to give pressure spikes dampening capability

On the right, after the conical head, there is the thermal relief plenum, this stage contains the thermal active element and a return outlet; this plenum is normally open to return causing the valve to operate in relief mode if there is an overpressure in the pressure plenum. Otherwise in case of high temperature of the oil, the heating will cause an expansion of the thermal element and the port to return is closed by sliding of a ring connected to the thermal element itself. At this stage the flow thru the conical head will result as a pressure buildup in the thermal relief plenum that will push onto the piston head causing a further displacement of the pilot poppet letting the flow to escape to return thru the hole in the unloader plenum. The further displacement of the pilot poppet will result in a greater flow exiting from the balance plenum and thus a lower backpressure on the main poppet, causing a further travel in order to uncover completely the second port to return in the pressure plenum. This action will relieve more flow from the system leading to a drop of the system pressure down to 2000 PSI. In this condition the valve is operating in unloader mode.
The pilot poppet, as it has been described previously, is designed as a cylindrical spool that has the key characteristics listed:

- Precision diameter coupling with main poppet in order to create a flow calibrated annular orifice
- Conical head that acts as closure of the balance plenum to return
- The conical head is also shaped with a profile in order to act as a stabilizing lifter when is open both in relief and unloader mode
- Piston head that creates a sealed coupling when in relief mode and actuates open when is needed to switch in unloader mode.

5. NUMERICAL MODEL

The URTV design has been modeled and simulated in order to check and fine tune all the key parameters in order to achieve the final performances desired.
Past designs of such type of dual stage valve failed to achieve specified requirements due to lack of dynamic stability of the poppets under regime operating conditions. In particular here are listed some of the problems encountered:

- Valve spools resonance against hydraulic pump forcing tones with consequent lack of performance
- Pilot poppet instability at high flow discharge with consequent high frequency oscillation and conical head profile destruction
- Main poppet hydraulic sections ratio unfavorable to handle stabilization after pressure transients with consequent erratic behavior of the valve discharging
- Main poppet sealing lip geometry generating jet flows when starting to displace with consequent lack of poppet lifting force.

In order to achieve a working design was clear from the beginning that the design parameters with an impact on the valve dynamics should be investigated and reviewed; this analysis effort has been carried out with use of AmeSim software. The software package is a suite of tools used to model, analyze and predict the performance of mechatronics systems. Models are described using 1D nonlinear time-dependent analytical equations that represent the system's hydraulic, pneumatic, thermal, electric or mechanical behavior. Compared to 3D CAE modeling this approach gives the capability to simulate the behavior of systems before detailed CAD geometry is available, hence it is used earlier in the system design cycle or, as in this case, when design fixes are needed on order to optimize specific performance requirements.
The fact that a design embodiment to start from was already available allows creating a very detailed model, focusing on changing specific parameters rather than

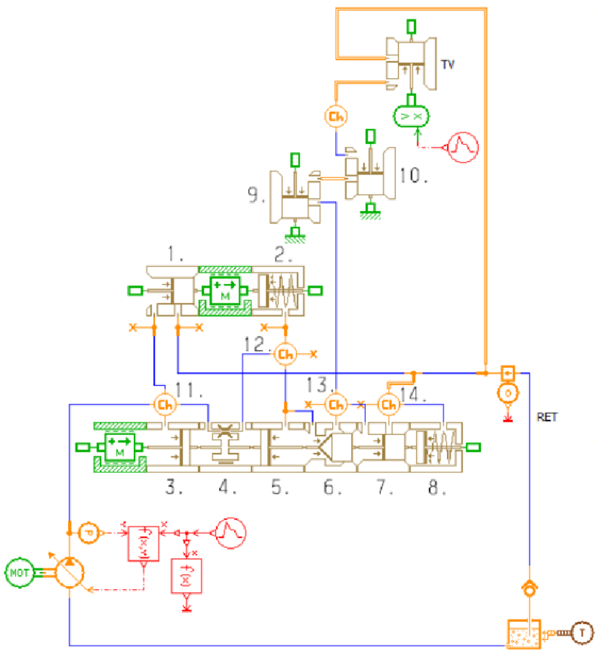


Figure 10

trying to find a completely new set of design parameters.

The URTV model considers a dynamic system merging mechanical and thermo-hydraulic components:

1. Main poppet annular pressure section
2. Main poppet backpressure section plus spring preload
3. Pilot poppet circular pressure section
4. Main-Pilot poppet calibrated annular orifice
5. Pilot poppet undercut section
6. Pilot poppet conical head
7. Pilot poppet piston head
8. Pilot poppet reacting section plus spring preload
9. Series of four circular discharging holes
10. URV discharge screen holes to TV
11. Pressure plenum oil volume
12. Balance plenum oil volume
13. Thermal relief plenum oil volume
14. Unloader plenum oil volume

To these components that represent the URTV, within the model are considered also:

- Variable displacement pump
- Thermal valve
- Reservoir

The dual stage valve can be modeled from a dynamic perspective as two sliding masses connected to independent springs and both fixed to ground. In addition to the inertial and spring forces, damping forces, both viscous and frictional, and fluid pressures shall be considered as part of the system model.
According to the components list reported above, each model subassembly is here described: the main poppet comprises the frontal hydraulic section (1) that receive a fluid flow from the pressure plenum (11) and can uncover an hydraulic port to return, a sliding mass with friction plus travel endstops, and the hydraulic backpressure section plus spring that is connected to the balance plenum (12). Each block transfers, sums and updates at every iteration inertial, frictional and fluid forces along the axis which is solved for position.
In parallel is hydraulically connected the pilot poppet model comprising: a sliding mass with friction plus travel endstops, hydraulic thrust sections from the pressure plenum and balance plenum (3) and (6). In between the hydraulic sections there is the annular orifice model (4) porting the flow from pressure (11) to balance (12) plenums; this block is actually the physical interface between main and pilot poppet but since the annular section in not function of the relative displacement of main and pilot poppet it can be considered as just part of the pilot poppet model.
Additionally in series are connected the conical head model (6) and the piston head hydraulic section (7), both capable of porting the flow from balance (12) to thermal relief (13) and unloader (14) plenums, and backpressure section plus pilot poppet spring (8). Also in this case each block transfers, sums and updates at every iteration inertial, frictional and fluid forces along the axis which is solved for position.
The calculation of both main and pilot poppets positions allows for flow update, and thus pressures, hydraulic forces and temperature at every iteration.
Exiting from thermal relief plenum are modeled three hydraulic ports stages: stages (9) and (10) are needed to model the internal pressure drop due to filter screens present in the actual URTV design while the stage (TV) is actually a commanded hydraulic spool open-closed model to replicate the actuation of the thermal active element ring.
All plenums and hydraulic stages are connected to return and reservoir in accordance to the design; in the model is also present a variable displacement pump model representative of displacement and rpm of the system pump that can be triggered to deliberately simulate a compensator failure and activate the URTV.
The model described above is thus capable to perform results predictions according to the following features:

- Each block contains local thermal and hydraulic or mechanical initial parameters
- Each block substantiate local thermal and hydraulic or mechanical state variables
- The blocks are capable to interact in order to perform a global calculation update
- All the links between the blocks are processed to create a time variant non-linear 1D system.

The solution has then the following characteristics:

- Is capable to predict the moving mass dynamic
- Is capable to predict the hydraulic dynamic
- Is capable to predict the combined effect of both mechanical and hydraulic stiffness
- Is not capable to predict local geometry flow effects

6. REFERENCE CASE STUDY SIMULATION

The results reported refers to the following test case input; the test case is imposed to the model by acting on the pump compensator to achieve an artificial modification of the pressure regulation setting in order to simulate normal and failed operation of the pump:

a) Step 1: 0,05s compensator set to increase the working pressure to the regime value of 3000 PSI (URTV not yet engaged)

b) Step 2: 0,2s compensator maintained at 3000PSI to wait system response transitory (URTV not yet engaged)

c) Step 3: 0,4s compensator set to obtain system pressure increasing above valve cracking pressure up to 4350 PSI (URTV first stage engaging at 3650 PSI in relief mode)

d) Step 4: 0,6s compensator maintained at 4350 PSI and valve thermal stage actuation to close position (URTV second stage engaging and transition to unloader mode)

The test case is showed for clarity in figure 11, the red line is the pump pressure setting profile as described above and the green line is the step actuation from open position to closed of the thermal stage.
This case study is aimed to let the valve dynamic system to initially ramp up and stabilize at the rated working condition of 3000PSI and temperature lower that 120°C, 0s-0.2s.
As soon as the system is stable the pressure setting is increased to an overpressure condition only in order to simulate a pump compensator failure and evaluate the dynamic characteristics in relief mode, 0.2s-0.4s is the failure injection and 0.4-0.6 is the sustained failure period.
At 0.6s the thermal stage is closed to let the valve switch to unloader mode and evaluate the stability during pressure transition down to 2000PSI and the continued operation in this condition, 0. 6s-1s.

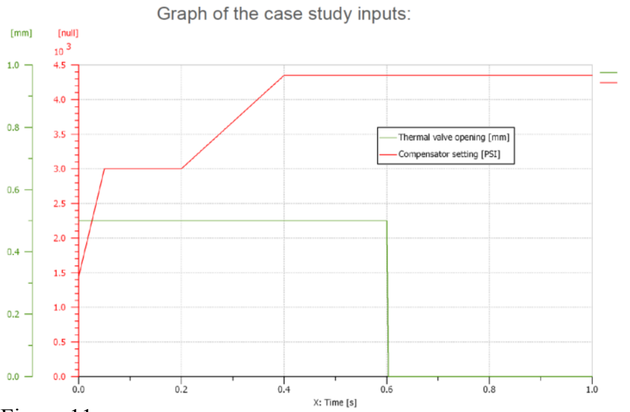


Figure 11

Simulation results showed a solution with some peculiarities as reported in figure 12; the results are in accordance with the experimental measurements of the URTV first prototype showing a main instability in relief mode, three features repeat in both numerical and test cases:

- The relief stage is unstable and the unloader stage is stable
- The instability has an amplitude of ca. 2000PSI
- The period of oscillations is comparable, 41ms and 38ms

From the bullets above some conclusion can be made. Being the relief stage unstable, while the unloader stage is not, is reasonable to conclude that the oil flow in the thermal relief plenum is rather turbulent than laminar; this possibility is also enforced by the fact that the conical head lifting force is very sensible to pressure variations.

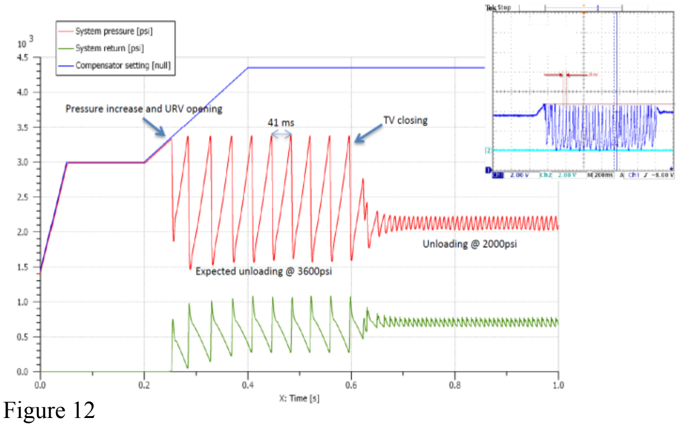


Figure 12

This disturbance under the conical head area results in slight oscillations of the pilot poppet that are amplified by the high sensitivity of the main poppet due to its frontal-backward area ratio of approximately 80%. This fact means that opening the main poppet requires 20% less force than closing leading to a full opening caused by small disturbance of the pilot poppet. The amplitude of the instability also confirms what supposed above, an unstable rapid switching between relief and unloader mode caused by the main and pilot poppets cross interference.
The desired approach was to change the minimum number of parameters in order to find and act just on the design parameters that could be controlled and realized with great level of precision, this led to:

a) Increase the area ratio 100% equalizing closing and opening forces
b) Profile and increase the conical head diameter to gain laminar flow, more lift and less sensitivity to disturbances

Exploring the design, by changing in the model the key

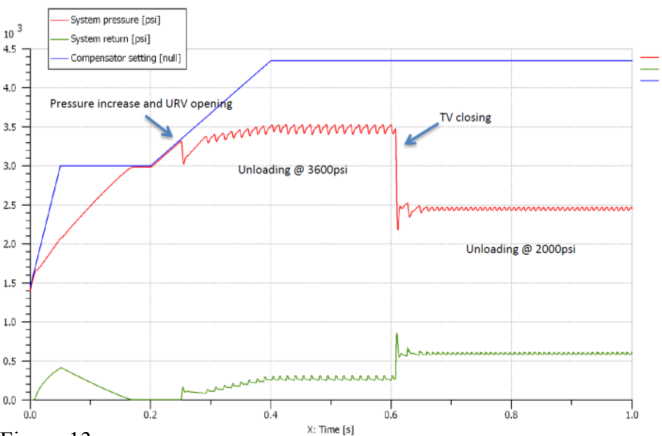


Figure 13

parameters identified, lead to find a stable balance of main and pilot poppets dynamics under fluid forces.

The solution obtained, figure 13, from the updated model with the same input showed eventually stabilization with the following notes:

- The instability is no more present in both stages
- The stability allows oscillations but confined in a narrow band, as the typical relief valve response
- The valve global performances are, at first glance, not affected

The evaluation made after the first unstable simulation revealed to be correct from a numerical perspective and gave the possibility and the confidence to step to an experimental verification, since, as said before, a test article would be already available, by changing the two poppets with their modified versions.

7. EXPERIMENTAL CONCLUSION

A test case of a similar fashion has been full scale tested on a prototyped URTV valve to confirm and validate the analysis results. The test case explanation of previous section applies also to the test results here reported.
In the validation test steps from 1 to 4 are repeated, even if with a different duration and the addition of two others step:

e) Step 5: compensator maintained at 4350PSI and valve thermal stage actuation to open position (URTV first stage engaging and transition to relief mode)
f) Step 6: compensator set to obtain system pressure reduction below valve reseat pressure down to 3350PSI (URTV first stage closure at 3350PSI and return to normal mode)

Test recordings, figure 14, shows a confirmation of the expected results showing a less sensitive response and in other words shows that the two working regimes are achieved in a stable manner at the specified pressure levels throughout the full flow interval.

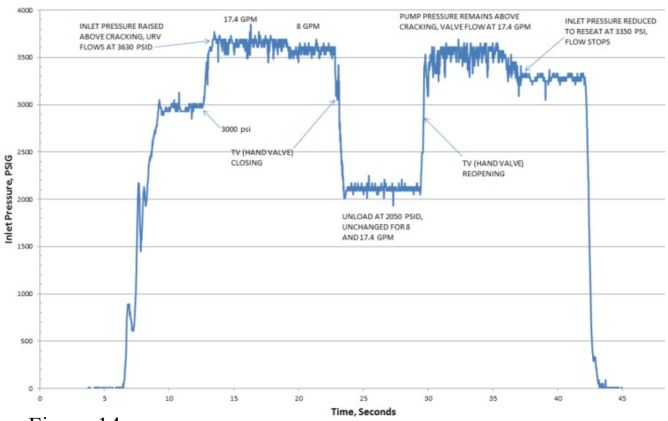


Figure 14

Since steps 4 and 5 required thermal valve actuation, for testing purposes has been simulated via manual valve and not actually with a temperature in the test system. A due check on the repeatability of the thermal actuation has then been carried out in order to validate its functioning, in particular if the minimum stroke of the thermal element to open and close the sliding ring is achieved at the specified temperature.
The chart in figure 15 shows the actuation characteristic curve compared to the open and close stroke threshold of the thermal-relief plenum that is represented with a red line. Three different repetitions showed consistent results.

A full scale test without manual activation of the thermal stage was then performed with the objective to benchmark the thermal performance of the URTV and with the aim to be the proof of concept test. Test details are here reported:

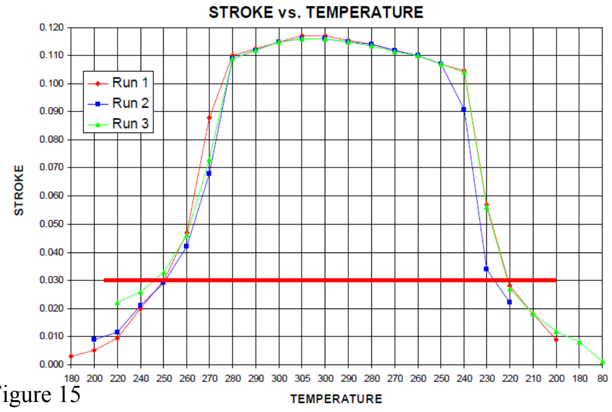


Figure 15

- the URTV starts in relief mode, the oil is supplied at constant flow thru a fixed displacement pump with unbalanced compensator and then a constant heat rejection resulting in a temperature rate of 6°F/min
- the URTV is allowed to stay in the initial condition until the temperature threshold of 120°C (250F) is reached switching the valve in unloader mode
- the valve continues to receive flow up to the moment the inlet temperature rate is null or negative
- the pump compensator is reset to a normal operating value to allow the URTV to reduce temperature below 120°C (250F) and switch to normal mode

Test results reported in figure 16 shows the expected URTV operation:

- switching at the correct temperature thresholds
- capability to decrease down to null and negative value the temperature gradient of the inlet oil

- recover of normal operation after temperature decrease
- maximum temperature at rated flow does not exceed maximum design temperature of the hydraulic system

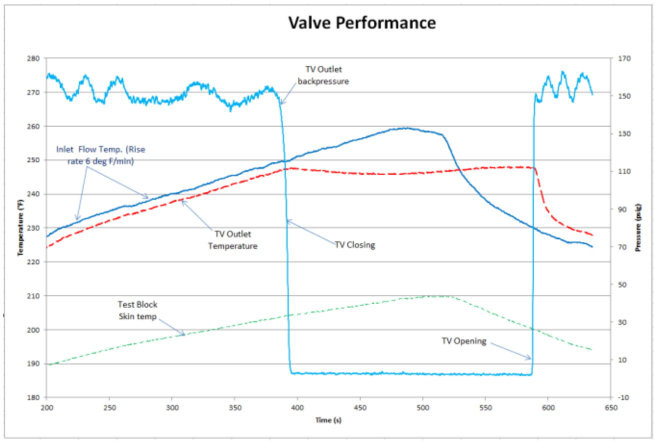


Figure 16

As a conclusive statement is possible to say that the URTV valve has been evaluated and tested extensively to fine tune the design parameters identified as drivers to achieve stability of the studied dynamic system. Initial design relying on common technical solution were not able to deliver the desired performance and functionality until detailed analysis showed the need of additional features to create internal balanced thrust sections and profiled conical head with jet flows features to generate local forces that allow to achieve system stability and performances for the first time.

8. REFERENCES

[1] US Patent, US 7,165,950 B2 – Two-Stage Pressure Relief Valve – Fenny et al.

[2] EU Patent, E5673/17-EP/daz – Safety valve and method for controlling an hydraulic circuit – Bacchiega et al.

FIGURE REFERENCE APPENDIX (A)

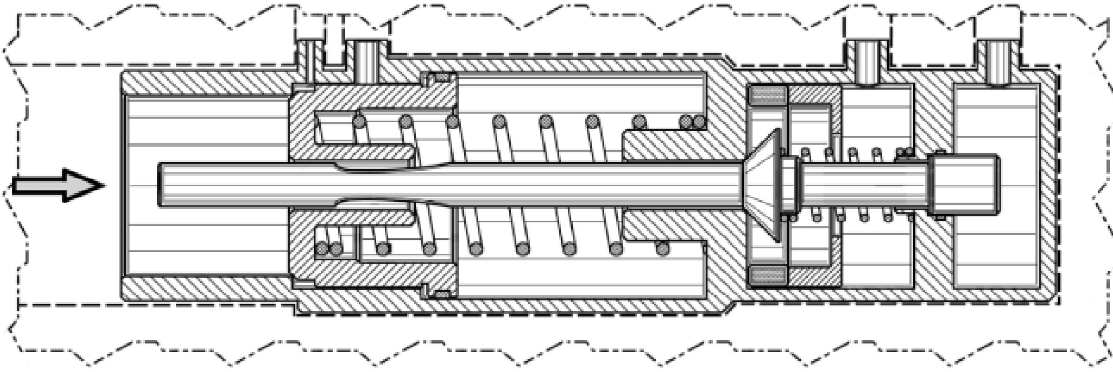


FIG. 1

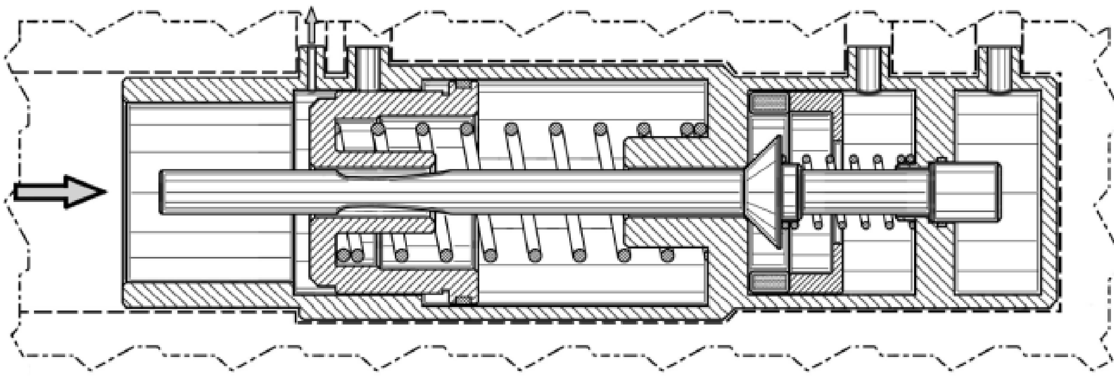


FIG. 2

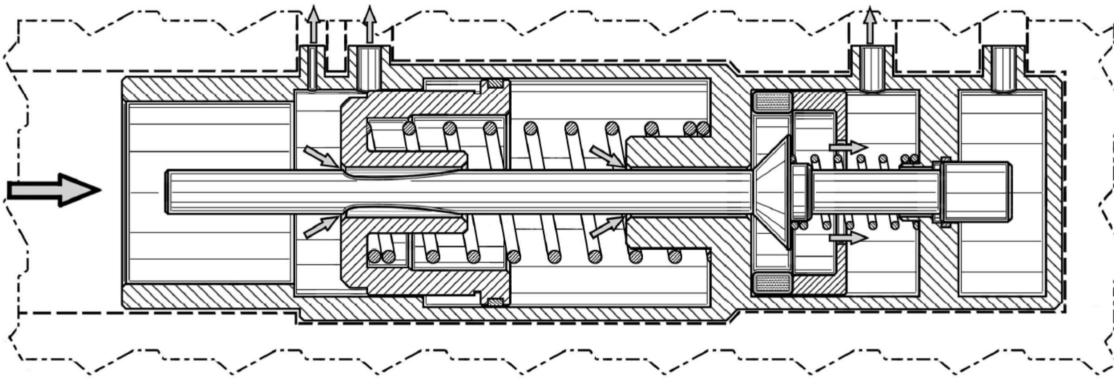


FIG. 3

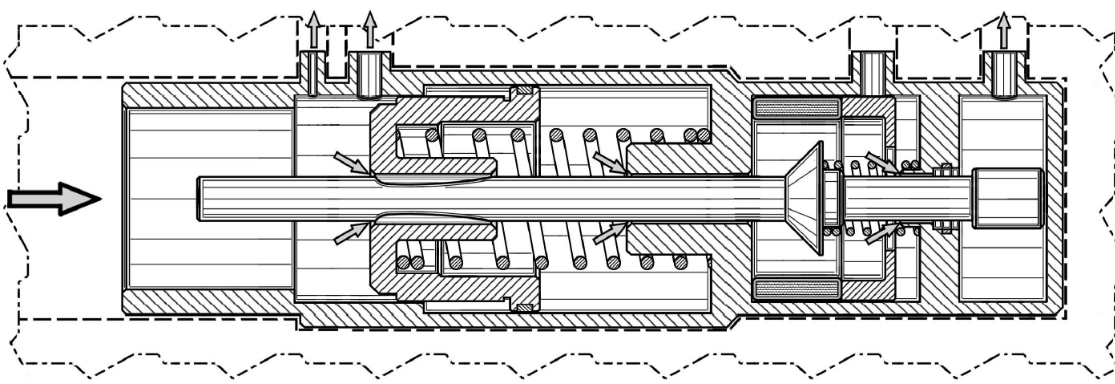
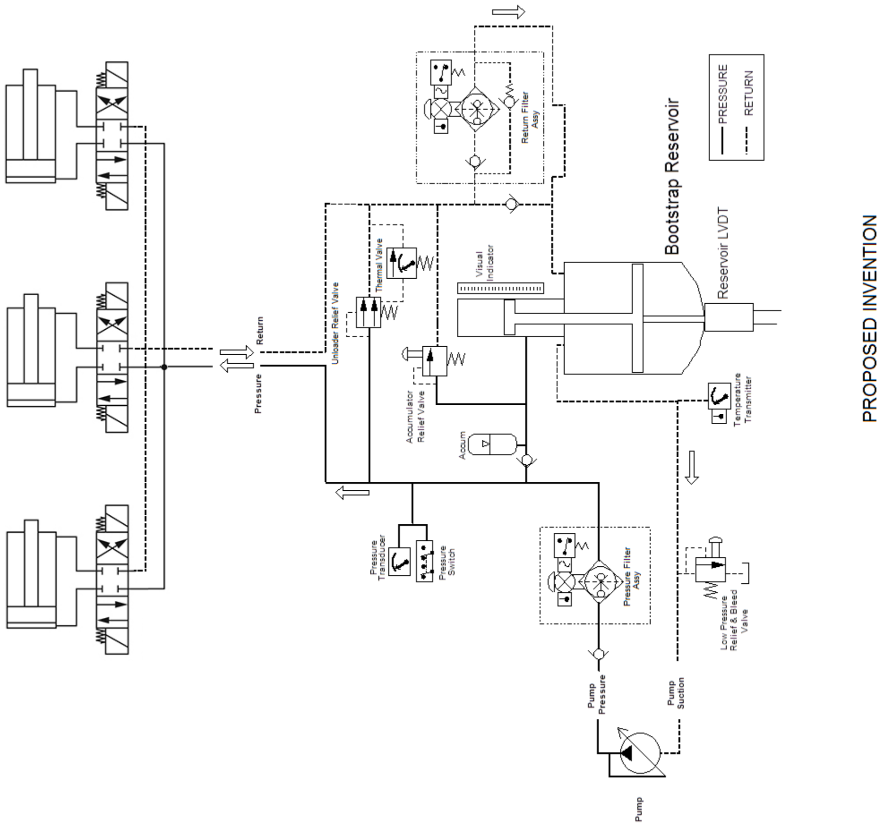
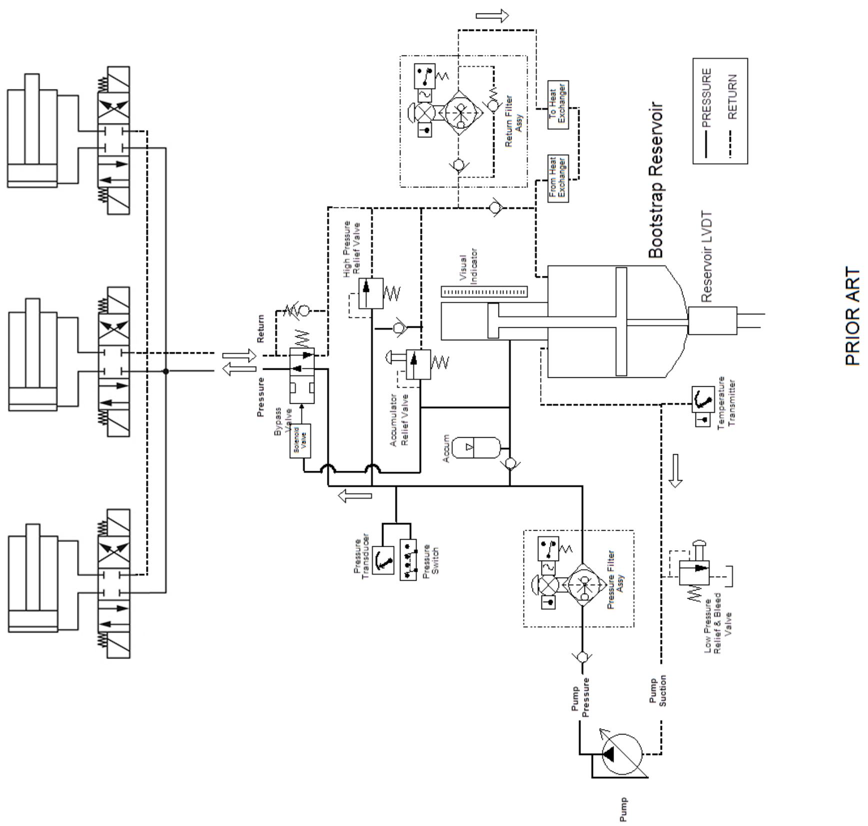


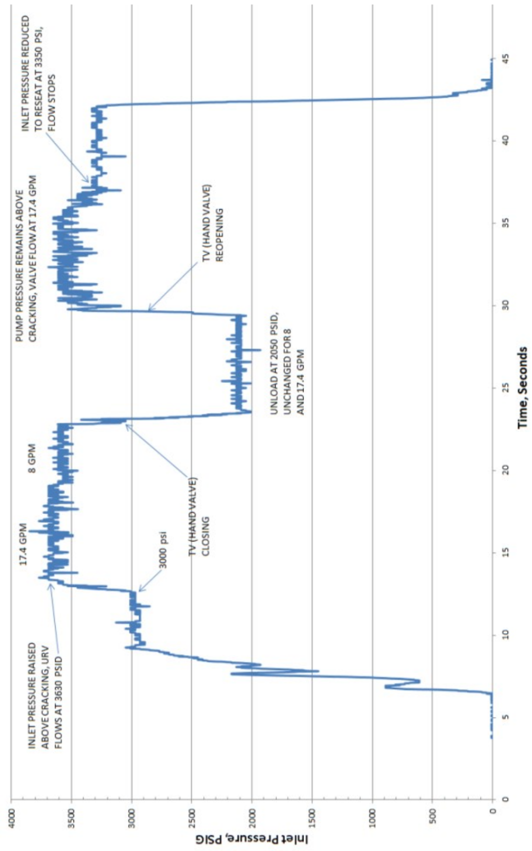
FIG. 4

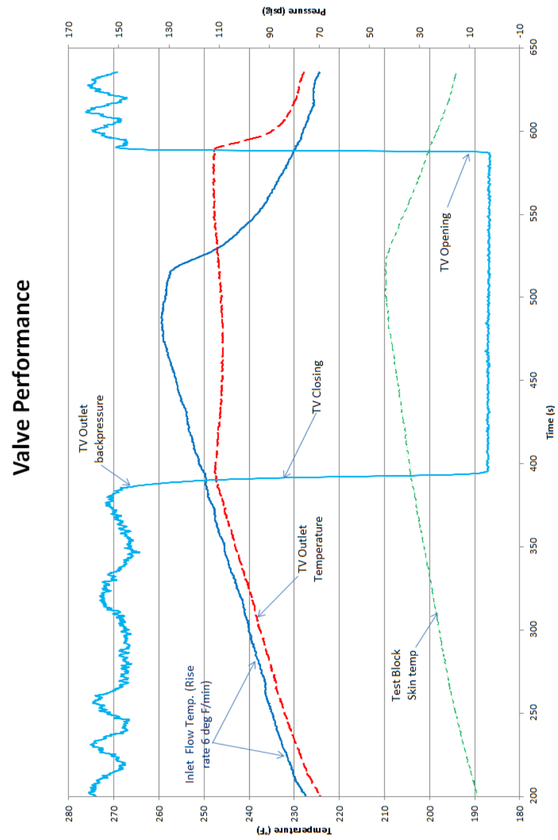
Figures from 5 to 8



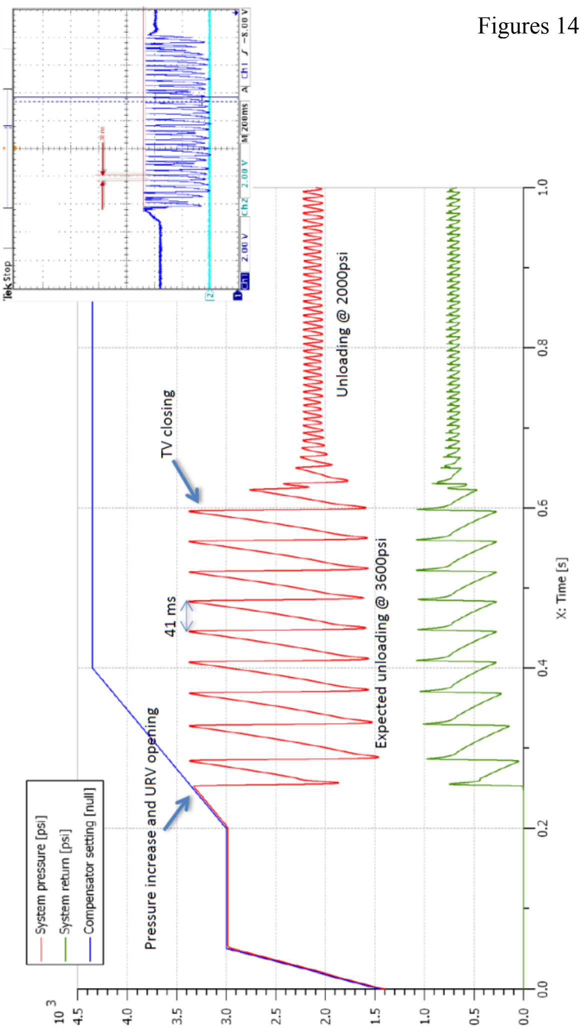


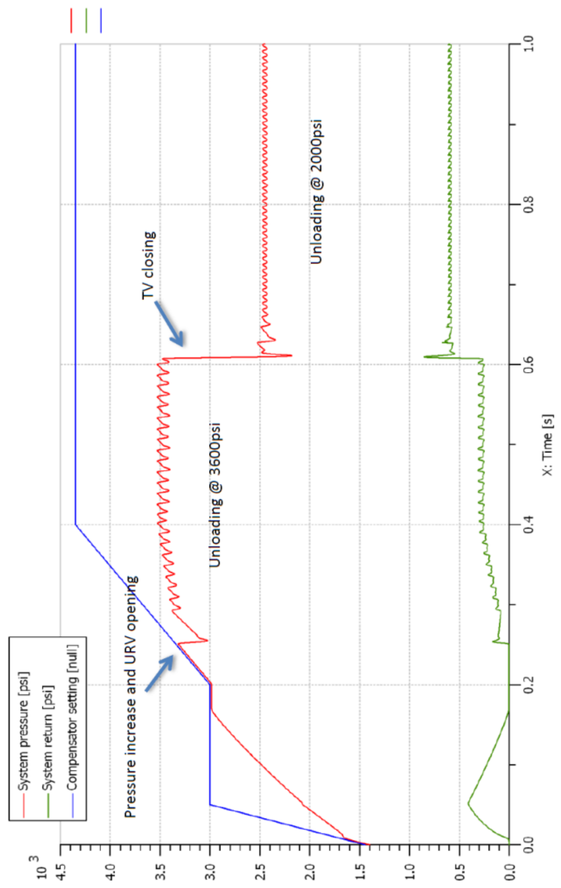
Figures 3 and 4





Figures 14 and 16





Figures 12 and 13