LIQUID NITROGEN TESTING OF AN INTEGRATED REACTION CONTROL SYSTEM

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ABSTRACT

Integrated Reaction Control Systems (IRCS) are considered an enabling technology for future human exploration of the solar system. An IRCS uses the same fuel and oxidizer as the main propulsion system, allowing for increased performance and simplified cryogenic fluid management operations. The IRCS team at Marshall Spaceflight Center is currently evaluating an IRCS system that uses a combination of electric pumps and pressure-regulation devices to provide a constant flow of conditioned propellant to a thruster bank during operation. In contrast to accumulator and gasifier designs, the recirculation loop design is less massive and can provide large, sustained flowrates to the thruster inlet.

In the summer 2021 test series presented herein, the feasibility of this concept was evaluated using liquid nitrogen as a simulant for liquid oxygen. The goals of this test series were to demonstrate the ability of the pump and pressure regulator to maintain adequate thruster inlet conditions during transient operation, and to demonstrate the ability for the system to operate in an "idle mode" that maintains system chill between activations. During test operations, the back-pressure regulator responded more slowly than the opening/closing of valves in the thruster simulant, but it was still able to attenuate the pressure fluctuation at the pump discharge and ensure a stable flowrate through the pump. Similarly, the pump was able to be run far below its nominal operating point and successfully flow sufficient fluid to maintain chill conditions.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

BPR Back Pressure Regulator

GTO Ground Test Objective

h_{fg} heat of vaporization

HLS Human Landing Systems

iRCS Integrated RCS

LN2 Liquid Nitrogen

$\dot{m}$ mass flow rate

MSFC Marshall Space Flight Center

$\dot{Q}$ heat rate

RCS Reaction Control System

TRL Technology Readiness Level

INTRODUCTION

In the summer of 2021, the Human Landing Systems (HLS) ICELAB project performed a test campaign on an integrated Reaction Control System (iRCS). This system was built to prove the feasibility of iRCS architecture and explore system operations. The iRCS test article consisted of a large tank for holding liquid nitrogen (LN2), a recirculation loop driven by a pump, banks of solenoid valves to serve as thruster simulants, and a back pressure regulator to provide pressure control within the recirculation loop. The test article was constructed at Marshall Space Flight Center's Propulsion Research and Design Laboratory. Assembly of the test article components began in 2019 and continued until the summer of 2021 when the test series commenced.

The motivation for building this test article and performing this series of tests was to advance the Technology Readiness Level (TRL) of the iRCS concept. Previous work had focused on modeling, but full-scale system testing had not been performed at NASA. The HLS program backed this work as part of its risk reduction efforts, as this new technology has potential to enable significant mass savings and reduce operational costs for future space vehicle designs.

Liquid nitrogen was selected as a propellant simulant, since the scope of this test series was limited to the process of supplying propellant to RCS thruster inlets. A bank of six solenoid valves imitated the pulsing action that would be expected of a typical RCS valve. The tests were conducted at a range of tank fill levels to characterize system performance under different potential mission phases. Facility nitrogen systems controlled the ullage pressure.

Another goal of the tests was to explore the operational scenarios envisioned for an integrated RCS. iRCS operation can be classified under two modes: idle mode, and active mode. Idle mode (sometimes referred to as "standby mode") refers to when the system recirculates propellant through the iRCS recirculation line with none of the simulated thrusters firing. This is to imitate the spacecraft maintaining a state readiness for the system to respond to the vehicle's attitude control needs. During idle mode, the flow rate is maintained by the pump at lower speeds, compared to an active firing mode. This is to maintain chilled-in conditions in the recirculation loop. To transition to active mode, a short pump ramp-up transient would be required.

The ground test objectives (GTO) were to characterize ambient heat load to the tank when filled with liquid nitrogen, determine idle mode performance, and assess system performance under steady state and puled thruster firing conditions. These objectives are summarized in sections GTO-1, GTO-2.1, GTO-2.2, and GTO-2.3 respectively, below.

A schematic of the test components is shown in Figure 1. The storage tank is designated as CTB-2. The two clusters of four solenoid valves on the right are the thruster pods. BPR-1 is the back pressure regulator.

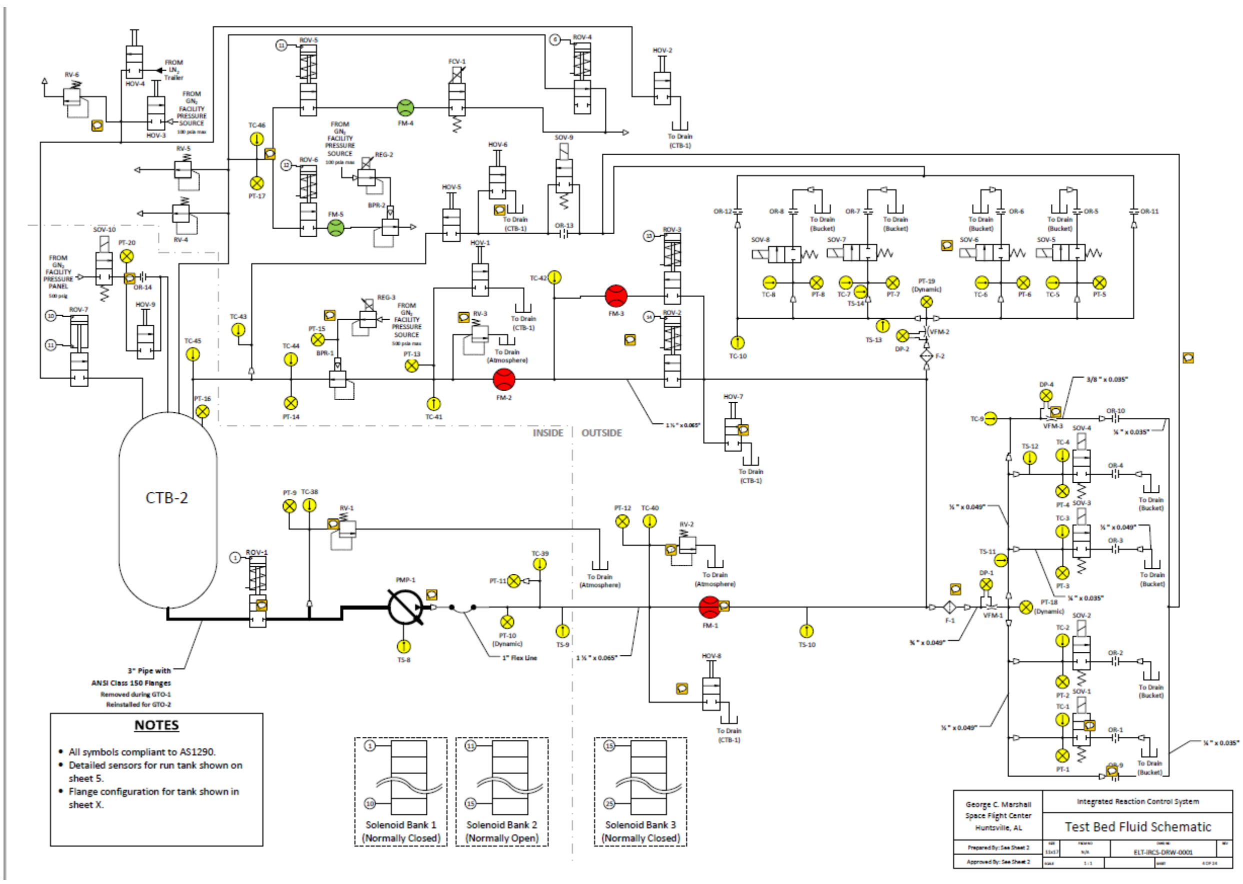

Figure 1: Test System Fluid Schematic.

GTO-1

The first test objective was to characterize the ambient heat load to the liquid nitrogen tank, as it would be necessary to assess the feasibility of the iRCS system concept. The ambient heat load provides a useful point of comparison for the two operational modes of iRCS that were tested in later in the campaign. Comparison of these data to the ambient load determines the additional heating to the propellant from iRCS operation.

Our tests indicate that the ambient heat load to the liquid nitrogen tank, when loaded with liquid nitrogen at saturation conditions under atmospheric pressure, is 1010 Watts. This was calculated from the heat of vaporization of LN2 and the mass flow rate of boiloff gas leaving the liquid nitrogen tank under steady-state conditions (see equation 1.) Figure 2 shows the data used to measure the inputs for the calculation.

$$\dot{Q} = \dot{m} h_{fg} \tag{1}$$

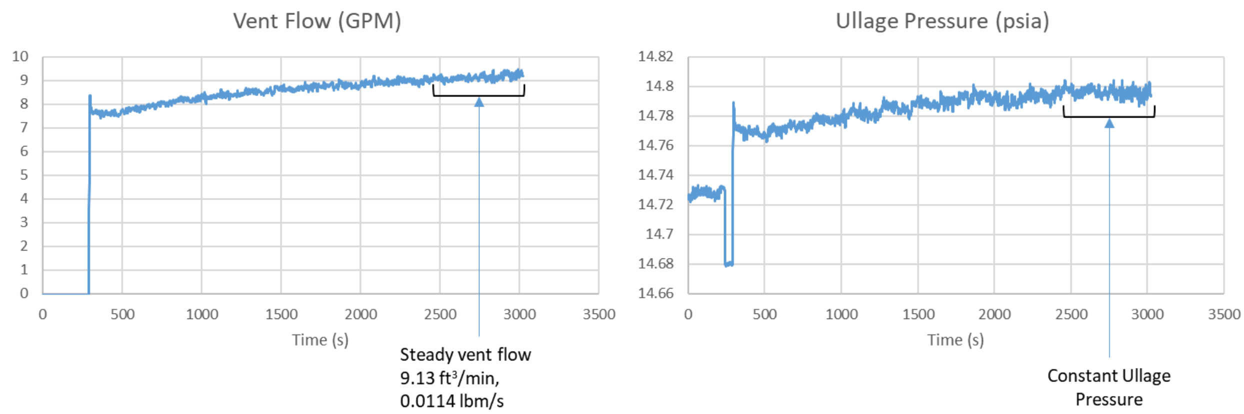

Figure 2: Vent Flow and Ullage Pressure for GTO-1.

GTO-2.1

The purpose of this test objective is to characterize the conditions of the propellant during idle mode while being recirculated through the system loop, and then reduced back to tank conditions by the BPR. The driving concern in this objective was to check for the possibility of two-phase flow downstream of the BPR, which would put the tank at risk of rapid rises in pressure. The tests for this objective consisted of 6 cases, at varying pump speeds from 12 Hz to 43 Hz, with a minimum duration of 5 minutes for each test. The tank pressure was maintained at 45 psia for all idle test cases.

Our data indicate that there was no two-phase flow for all 6 test cases. We also analyzed the additional heat input to the LN2 by watching the rise rate of the bulk LN2 temperature in the tank. There were issues with data fidelity that prevented us from analyzing the heat load in the recirculation line via instrumentation. Figure 3 shows the calculated heat load compared to the baseline ambient heat load.

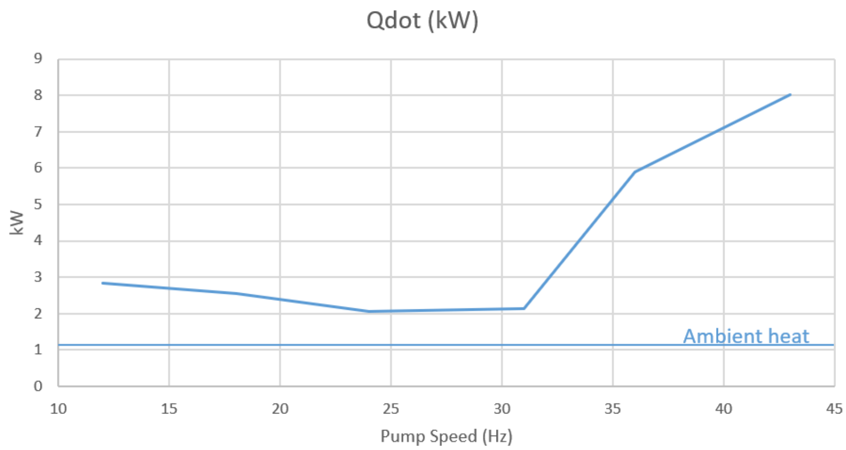

Figure 3: Additional Heat Load from Pump.

GTO-2.2

The focus of this test objective was to characterize system performance under steady-state thruster firing conditions. The recirculation line was pressurized to about 350 psig, and then thruster valves were opened to flow LN2. The goal was to show this iRCS concept can deliver steady-state conditions to thruster inlets. Data from 4 flow meters indicated that the system could maintain steady-state conditions to the thruster inlets. Figure 4 below shows data from the 6-thruster case, where steady conditions were achieved near the 140-second mark.

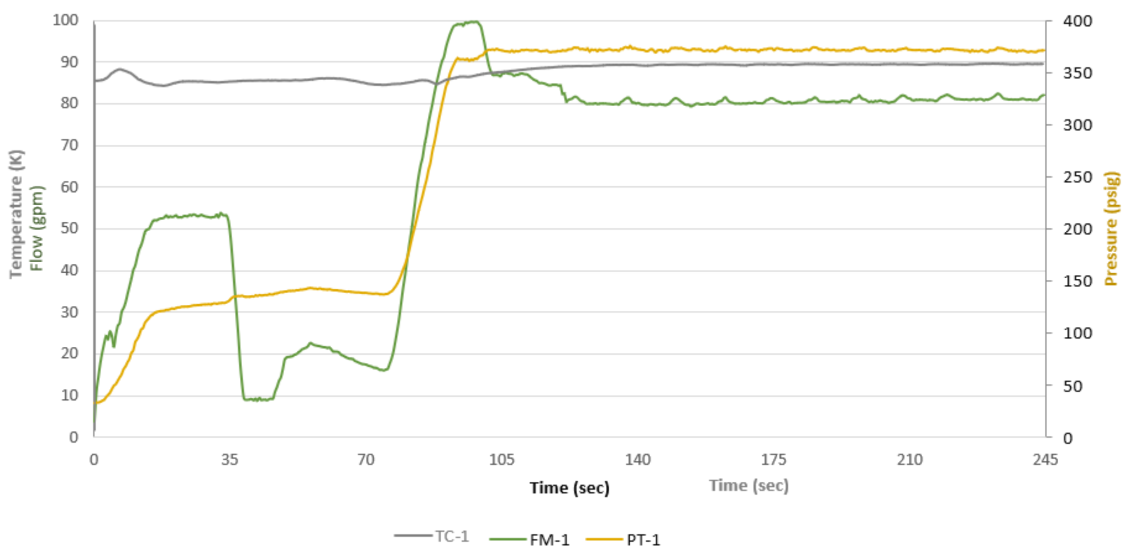

Figure 4: 6 thrusters, steady flow.

Further work is needed to refine the operational steps to achieve steady-state flow conditions to the thrusters. However, the time to achieve steady-state flow was not a parameter for success of this objective, so this is only noted here for the purposes of future concept development. The startup transient may be shortened with a pump more suited to the system size.

GTO-2.3

This test objective focused on characterizing the system under conditions of pulsed thruster fire, as may be encountered during landing or other main engine operation scenarios. The team selected 16 different pulsing scenarios, varying the number of active thrusters, pulse width, duty cycle, and number of pulses. The pulse firing of the thrusters did introduce measurable pressure spikes into the recirculation loop, but these transients were attenuated once they reached the BPR. This system's attenuation would need to be compared to other pump designs and power levels to determine the best method for dampening out these fluctuations. This gives the team guidance for developing test objectives for future test efforts of this concept.

Figure 5 shows the inlet pressure for one of these pulse cases, and the valve actuation current. Figures 5, 6, and 7 below depict data from a single test case which pulsed two thrusters 30 times, each pulse lasting 200 msec with a 25% duty cycle. Five of these pulses are shown in the figures.

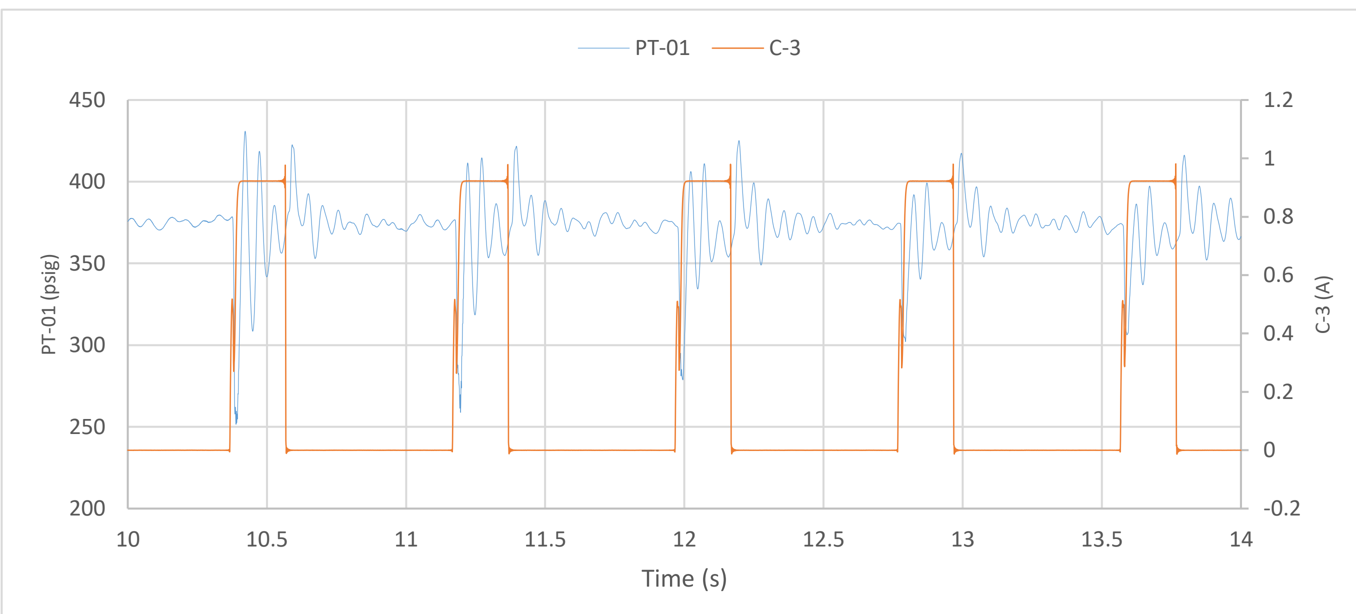

Figure 5: Pulse Profile and Pressure Response.

Figure 4 has data taken from the same test as that in Figure 3 and shows the reduced magnitude of pressure spikes by the time they reach the BPR inlet. During this test, the pump was able to maintain flow without cavitation.

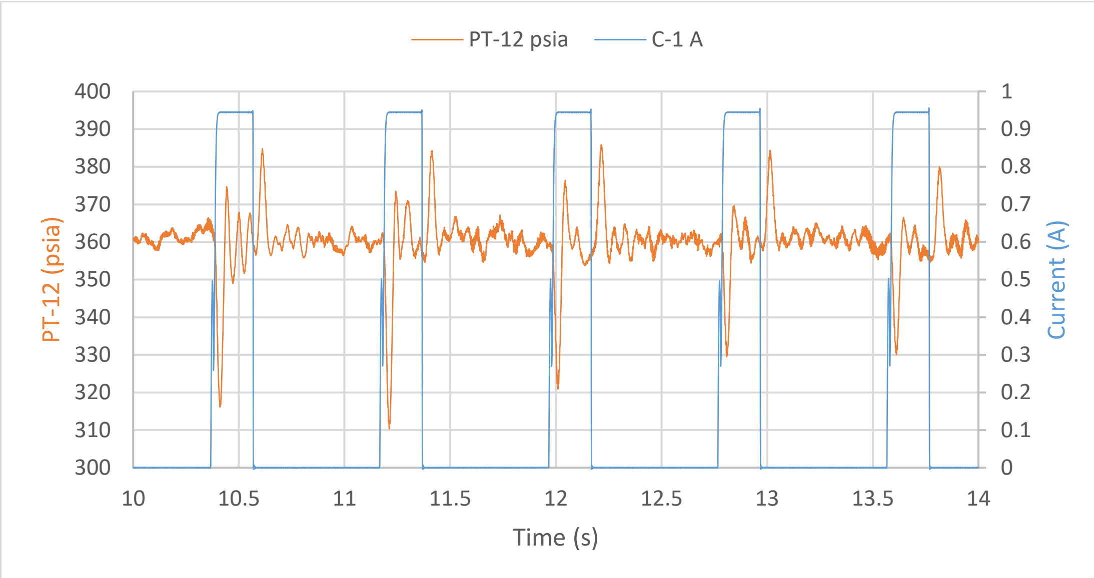

Figure 6: BPR Inlet Pressure and Pulse Profile.

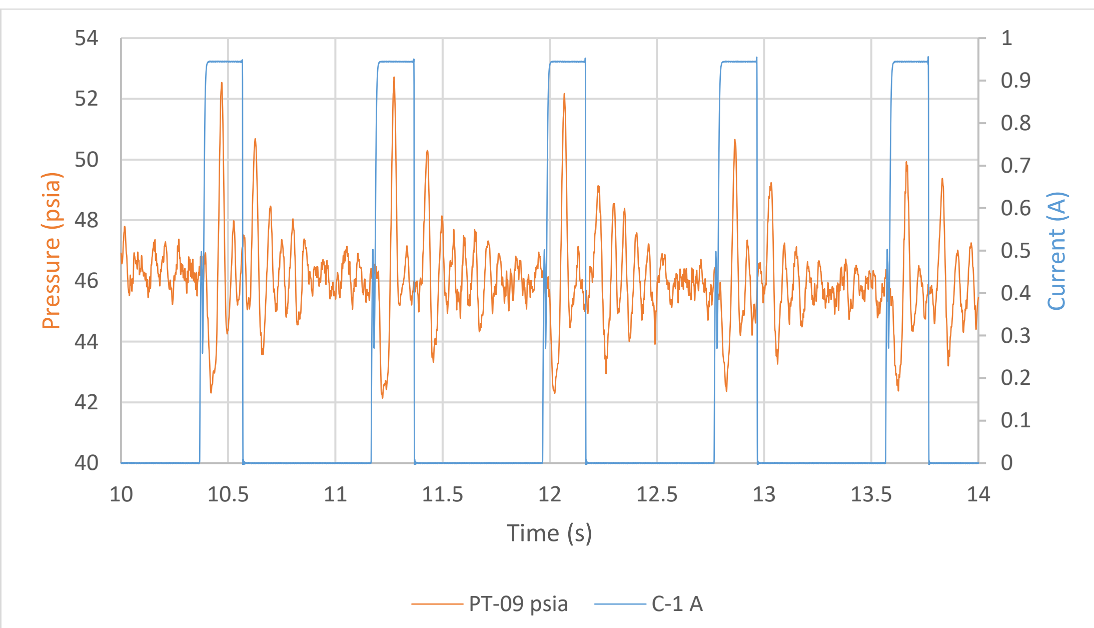

Figure 7: Pump Inlet Pressure.

Figure 7 shows the pump inlet pressure as affected by the valve pulsing. With all six valves pulsing, the pressure spikes were small enough such that they did not impede pump operation.

The largest pressure spikes were less than 10 psi, and decreased over the course of the test, as shown by the significant magnitude attenuation observable over the 4-second span shown in Figure 7.

CONCLUSIONS

This test series has given further insight and clarity into iRCS as an operational concept and provides useful data for determining its feasibility for application to cryogenic in-space propulsion systems. Further testing would be valuable to determine if alternative pump designs could provide longer operational times. Some test cases required the team to adjust tank ullage pressure to prevent pump cavitation. The pump was oversized, so this is not considered a detriment to the iRCS concept's feasibility.

The BPR showed decreased capability under cryogenic conditions and was therefore not able to control flow rates as anticipated. Some test cases called for flow rates around 7 GPM, while the system would flow 70 GPM through the recirculation loop. Part of the reason for this was the pump head curve being relatively flat across a wide range of flows, but some contribution is from the BPR diaphragm losing responsiveness when chilled to cryogenic conditions. The system was not able to reliably control pressures above setpoints of 65 psig. In these cases, the driver for pressure in the system was the pump, and the BPR was not able to dial in the flow rates called for in the test matrix. The testbed would benefit from a different pressure control device, such as the digital valve also under development at MSFC.

These tests have shown promise for the iRCS concept and underscore the need for further investment and investigation into this novel propulsion system concept. Future tests are pending.

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