ANALYTICAL ASSESSMENT OF A GROSS LEAKAGE EVENT WITHIN THE INTERNALTIONAL SPACE STATION (ISS) NODE 2 INTERNAL ACTIVE THERMAL CONTROL SYSTEM (IATCS)

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ABSTRACT

Results of the International Space Station (ISS) Node 2 Internal Active Thermal Control System (IATCS) gross leakage analysis are presented for evaluating total leakage flow rates and volume discharge caused by a gross leakage event (i.e. open boundary condition). A Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA85/FLUINT) thermal hydraulic mathematical model (THMM) representing the Node 2 IATCS was developed to simulate system performance under steady-state nominal conditions as well as the transient flow effect resulting from an open line exposed to ambient. The objective of the analysis was to determine the adequacy of the leak detection software in limiting the quantity of fluid lost during a gross leakage event to within an acceptable level.

INTRODUCTION

Within the pressurized elements of the International Space Station (ISS), requirements exist to ensure a safe, habitable environment for the crew. Internal Active Thermal Control Systems (IATCS), typically pumped coolant loops utilizing a non-hazardous working fluid, have constraints on touch temperature, maximum design pressure and leakage. This paper addresses "gross" leakage, or leakage that is much greater than normal, specification leakage. Node 2 is required to limit the internal heat transport fluid leakage to no greater than one gallon per gross leakage event[1].

The quantity of fluid expelled during a gross leakage event is clearly defined, however the duration is only bounded in general terms by the "event." Node 2 utilizes software to control IATCS functions, and thus, hardware and software response times must be taken into account to quantify the leakage "event." The applicable software time constraints for gross leakage failure detection, isolation and recovery (FDIR) are as follows[2]:

Time Averaged Accumulator Quantity Sensor Data	1.7 seconds
Data Transfer Latency to INTSYS	1.0 seconds
INTSYS Command to Node 2 Latency	2.0 seconds
Pump Package Assembly (PPA) Response	0.5 seconds
Total Time	5.2 seconds

Therefore, an "event" of 5.2 seconds must be analyzed to determine compliance of the Node 2 IATCS hardware and software (FDIR) designs with the gross leakage requirement. This paper presents an analysis of a gross leakage event for the Node 2 IATCS.

NODE 2 IATCS DESCRIPTION

The Node 2 IATCS consists of two separate single-phase, water coolant loops. The function of the IATCS is to provide heat rejection for subsystem avionics equipment, for the environmental control system and for subsystems and payloads within elements attached to Node 2. The two IATCS loops consist of a Low Temperature Loop (LTL), that provides coolant temperatures in the range of 38-43 °F, and a Moderate Temperature Loop (MTL), that provides coolant temperatures in the range of 61-65 °F. The Node 2 IATCS is schematically shown in Figure 1.

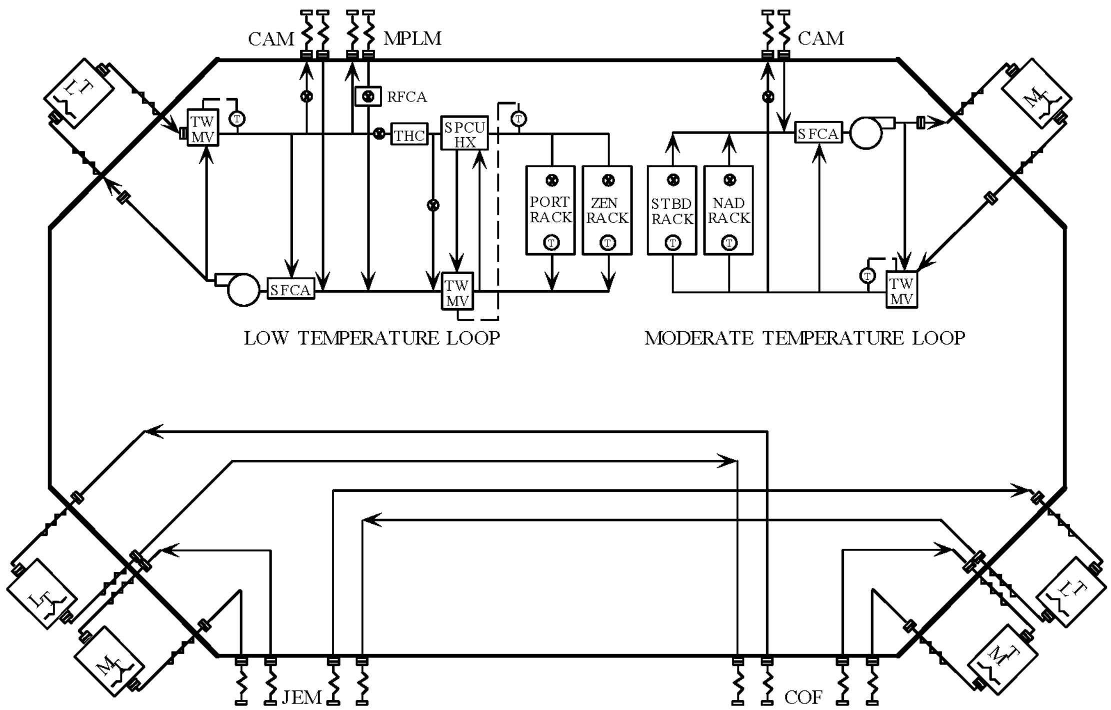

Figure 1. Node 2 IATCS

Each loop contains a Pump Package Assembly (PPA), capable of providing a mass flow rate of 3000 lbm/hr, and a System Flow Control Assembly (SFCA) that maintains a constant differential pressure across the system. Thermal control components include an ammonia/water heat exchanger, a Three-Way Mix Valve (TWMV), which controls the water supply temperature to subsystems and attached elements, and a regenerative heat exchanger (LTL only).

The PPA contains a centrifugal pump and an accumulator that maintains sufficient pressure at the pump inlet to avoid cavitation. The bellows within the accumulator is pressurized by gaseous nitrogen, actively controlled by a Nitrogen Interface Assembly (NIA). As will be presented, the accumulator plays a significant role, in addition to the pump, to the total fluid leakage during a gross leakage event. The accumulator has a gas side maximum design pressure of 35 psia, and a nominal operational pressure in the range of 18 to 30 psia. The accumulator has a fluid capacity of 680 $in^3 \pm 30$ in^3 (2.8 gal. to 3.1 gal.)[3]. An accumulator quantity sensor indicates the level of water within the accumulator, and at 59%, prompts the software to initiate the shutdown procedure[4].

SINDA85/FLUINT THERMAL HYDRAULIC MATHMATICAL MODEL

The gross leakage analysis is based on the Node 2 Design Review 1 (DR1) SINDA85/FLUINT IATCS Thermal Hydraulic Mathematical Model (THMM) developed by Alenia Aerospazio[5]. In order to analyze the transient, gross leakage event, a plenum at ambient pressure was added downstream of the leakage location, and inertia effects were added for all fluid lines. The most significant change to the model was logic added to simulate the transient pressure within the accumulator.

The mathematical model fluid network is constructed of "lumps" and "paths" and a set of governing equations are developed and solved within SINDA85/FLUINT. Three types of "lumps" exist within SINDA85/FLUINT: tank, junction and plenum. The Node 2 IATCS model primarily consists of tanks (finite volume) and junctions (zero volume), with a plenum (infinite volume) added to provide a "pressure" sink for the leakage location.

The algebraic forms of the mass and energy conservation equations for junctions are:

$$\sum \dot{m} = 0$$

$$\sum h\,\dot{m} + \dot{Q} = 0$$

where:

$\dot{m}$ mass flow rate
h donor enthalpy
$\dot{Q}$ lump energy source or sink term.

Similarly, the governing equations for tanks are differential forms of the mass and energy conservation equations:

$$\sum \dot{m} = \frac{dM}{dt}$$

$$\sum h\,\dot{m} + \dot{Q} - P\left(\dot{V} + \frac{dP}{dt}VC\right) = \frac{dU}{dt}$$

where:

M lump mass
P lump pressure
$\dot{V}$ volumetric flow rate
V lump volume
C tank wall compliance factor
U lump internal energy term.

The governing differential equation for tubes is a form of Newton's second law:

$$\frac{d\dot{m}}{dt} = \frac{\mathrm{A}}{\mathrm{L}}\left(\Delta P + HC + FC\,\dot{m}\left[\dot{m}\right]^{FPOW} + AC\,\dot{m}^{2} - \frac{FK\,\dot{m}^{2}}{2\rho A^{2}} \right)$$

where:

ΔP	pressure difference
A	tube flow area
L	tube length
HC	head coefficient (pressure, body force)
AC	tube recoverable loss coefficient
FC	tube irrecoverable loss coefficient
FK	tube head loss coefficient
FPOW	flow rate exponent for FC; function of flow regime (ranges from 0,laminar, to 1, fully turbulent)
ρ	fluid density.

Connectors can change flow rate instantaneously, and are governed by a linear algebraic constraint equation:

$$\dot{m}^{\,n+1} = \left(\frac{\partial \dot{m}}{\partial(\Delta P)} \right)^{n} \left(\Delta P_i - \Delta P_j \right)^{n+1} + \left(\dot{m}^{\,-n+1} - \dot{m}^{\,n} \right)$$

where:

i, j	upstream and downstream lumps
n	current time step
n+1	next time step.

The accumulator pressure can vary between 35 psia and 18 psia during operation. The accumulator pressure has a significant effect on the quantity of fluid expelled during a gross leakage event[6], and must be modeled as a function of time to accurately predict the fluid expulsion. The accumulator is modeled as a reversible isothermal process, represented by the equation:

$$\mathrm{PV} = \text{constant} = \mathrm{P_1V_1} = \mathrm{P_2V_2}$$

where:

P	nitrogen pressure
V	nitrogen volume
1, 2	nitrogen pressure and volume at t and t+Δt.

The nominal pre-charge accumulator volumes are 80% water and 20% nitrogen. Based on the variation of the volume specification (680 in^3 ± 30 in^3), the resulting $PV_{constant}$ differs and must be considered.

The volumetric increase of nitrogen, compensating for the volumetric water expulsion, is calculated by:

$$\mathrm{V_2} = \mathrm{V_1} + \dot{V}\ \Delta t$$

where:

$\dot{V}$ volumetric flow rate of water expelled from the system
Δt computational time step.

The transient nitrogen pressure is then calculated by:

$$P_2 = PV_{constant}/V_2$$

ANALYSIS

Leakage scenarios were developed for both the MTL and LTL. These scenarios assume a critical Quick Disconnect (QD) seal failure at the Node 2 to attached element(s) IATCS interface. The scenarios analyzed were:

- Leakage at Node 2 to CAM MTL supply interface
- Leakage at CAM to Node 2 MTL return interface
- Leakage at Node 2 to MPLM LTL supply interface
- Leakage at MPLM to Node 2 LTL return interface
- Leakage at Node 2 to CAM LTL supply interface
- Leakage at CAM to Node 2 LTL return interface.

Steady state and transient simulations were performed for each leakage scenario. FASTIC and STDSTL solution routines were used to establish nominal, steady-state conditions prior to analyzing the gross leakage event. The FWDBCK solution routine was used for the transient analysis of the event. The computational time step was limited to no greater than 0.1 seconds[7].

SINDA85/FLUINT analysis results for the aforementioned scenarios showed that the "leakage at Node 2 to CAM MTL return interface" provided the most severe leakage path in which to assess the IATCS system[6]. This scenario was considered for the purpose of this paper.

LEAKAGE AT CAM TO NODE 2 MTL RETURN INTERFACE

This scenario assumes that leakage occurs at the Quick Disconnect (QD) located on the Node 2 side of the CAM MTL return line. The QD on the CAM side of the return line is assumed to "seal" upon disconnection. Figure 2 depicts the IATCS MTL nodal network and leakage area. At the onset of the leakage event, nominal flow through the CAM from the supply line is "shut off" due to the sealed QD on the return line. The leakage area for the failed QD is calculated based on 100% exposure of the line cross-sectional area (0.3872 in^2). The failed QD is exposed to an ambient pressure of 14.25 psia which coincides with the U. S. Laboratory (USL) module nitrogen introduction threshold.

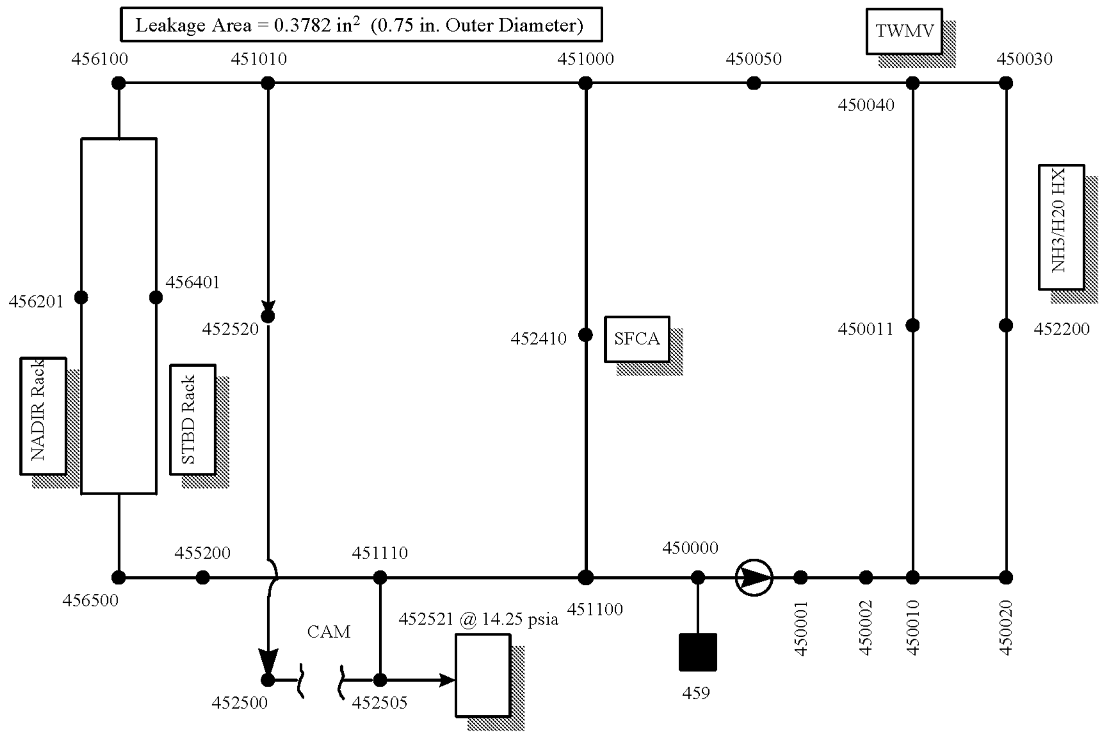

Figure 2. MTL Leakage at CAM to Node 2 Return Interface

Two cases were analyzed to assess the effects of accumulator volume on leakage quantity. The minimum and maximum accumulator volumes (650 in^3 and 710 in^3) were analyzed assuming a nitrogen pre-charge pressure of 35 psia.

Leakage detection is based on a 59% accumulator water level. PPA shutdown is complete at 5.2 seconds after detection. If the accumulator pressure drops below 18 psia and remains under 18 psia for 6 seconds prior to PPA shutdown, re-pressurization from the NIA will occur. However, for these analyses, re-pressurization was not considered.

RESULTS

Results for the two cases are summarized in Table 2 and shown in Figures 3 through 5 and Figures 6 through 8.

Case Number	Total Accumulator Vol. (cu. in.)	Initial Gas Volume	Initial Gas Pressure (psia)	Time at Leak Detection (sec)	Volume Leaked at Pump Shutdown (gal)	Accumulator Pressure at Pump Shutdown (psia)	NIA Re-press Before Pump Shutdown
1	650	20%	35	3.0	0.91	14.25	No
2	710	20%	35	3.3	> 1.0	N/A	Yes

Table 2. Results of Leakage at CAM to Node 2 MTL Return Interface Analysis

Figures 3 through 5 show the transient accumulator pressure, total leakage flow rate and total volumetric leakage for an accumulator volume of 650 in^3. From Figure 4, the leakage contribution from the PPA is constant. However, the contribution from the accumulator (back-flow) decays rapidly after the initial spike as a result of the decreasing accumulator pressure. Figure 5 shows that the total quantity of fluid expelled during the event is approximately 0.91 gallons, which is in compliance with the requirement.

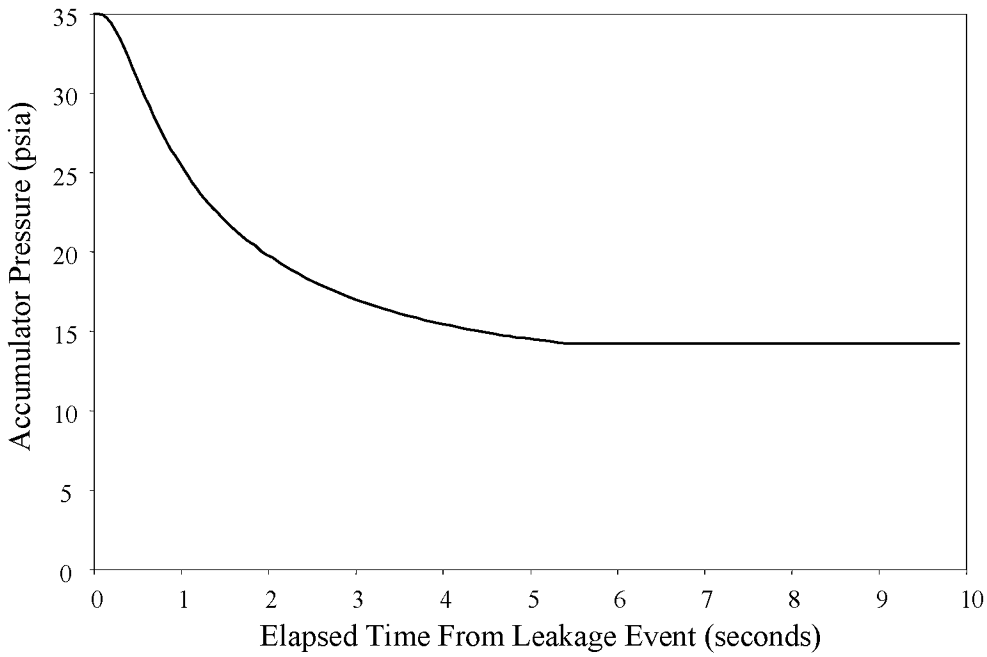

Figure 3. Transient Accumulator Pressure

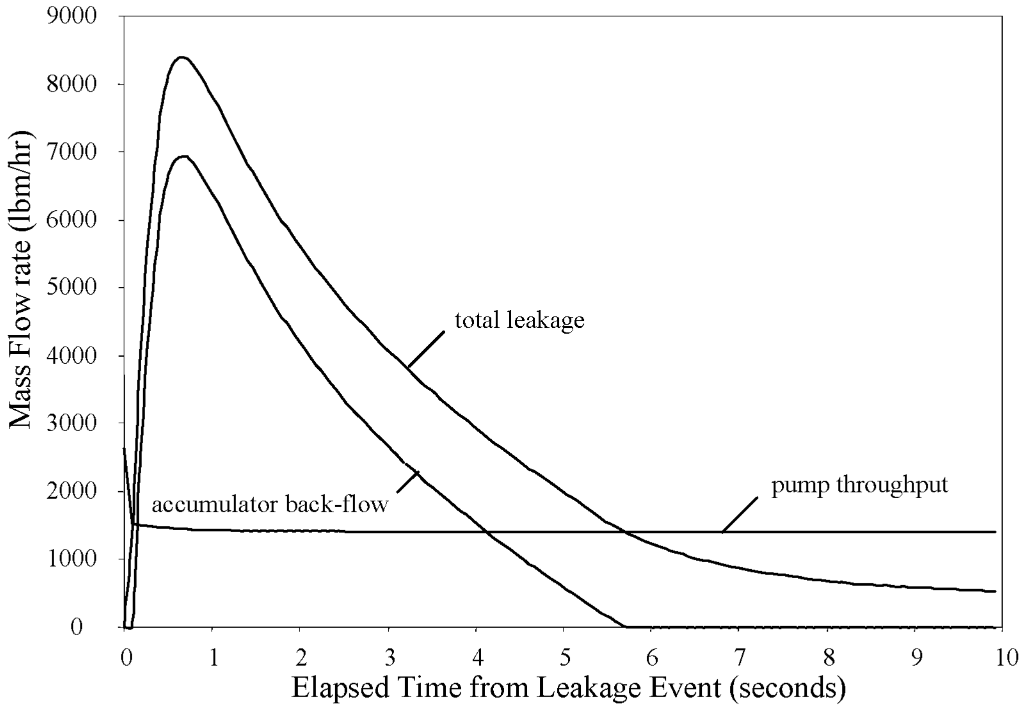

Figure 4. Total Leakage Flow Rate

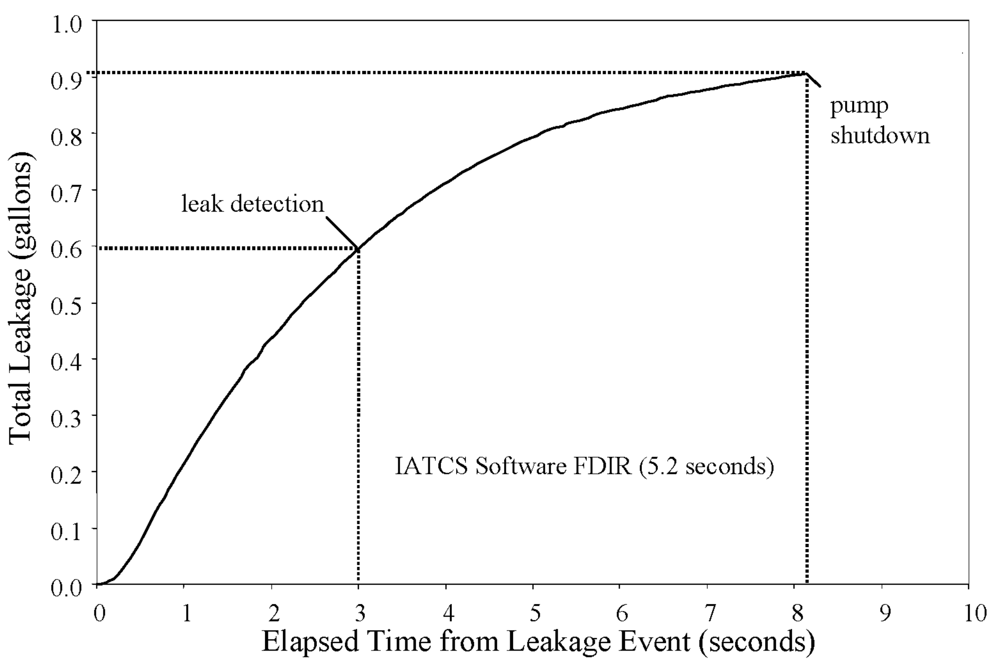

Figure 5. Total Volumetric Leakage

Figures 6 through 8 show the transient accumulator pressure, total leakage flow rate and total volumetric leakage for an accumulator volume of 710 in^3. As from the previous results, the trends are identical. From Figure 6, the leakage contribution from the PPA is constant. Again, the contribution from the accumulator (back-flow) decays rapidly after the initial spike as a result of the decreasing accumulator pressure. Figure 8 shows that the total quantity of fluid expelled during the event is approximately 0.92 gal, which is in compliance with the requirement. However, from Figure 6, the accumulator pressure is below 18 psia for more than 6 seconds prior to PPA shutdown and re-pressurization of the accumulator must occur. If re-pressurization has been accounted for, the total quantity of fluid expelled would exceed 1.0 gal.

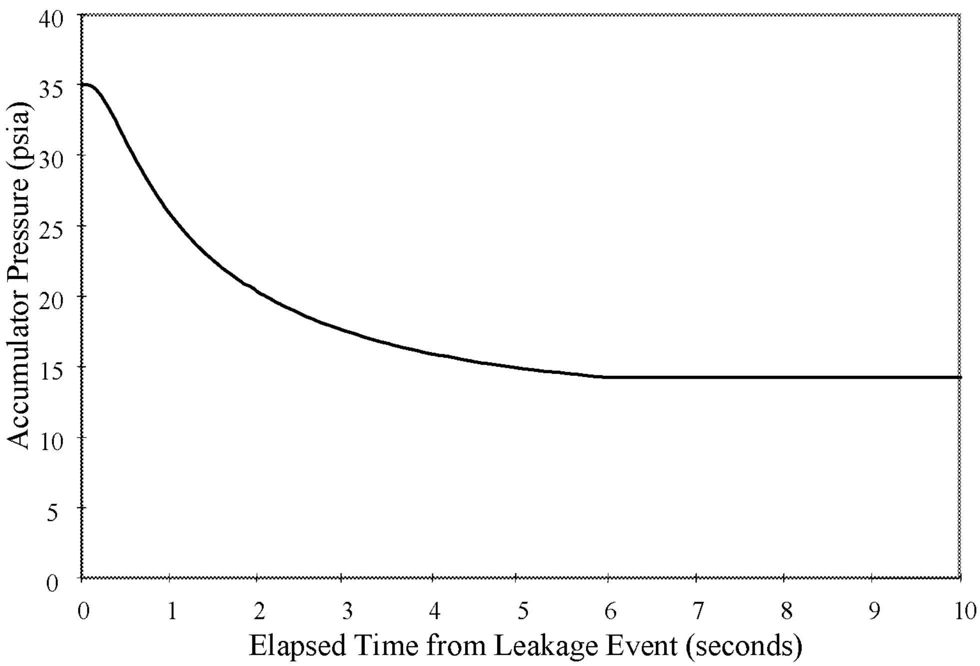

Figure 6. Transient Accumulator Pressure

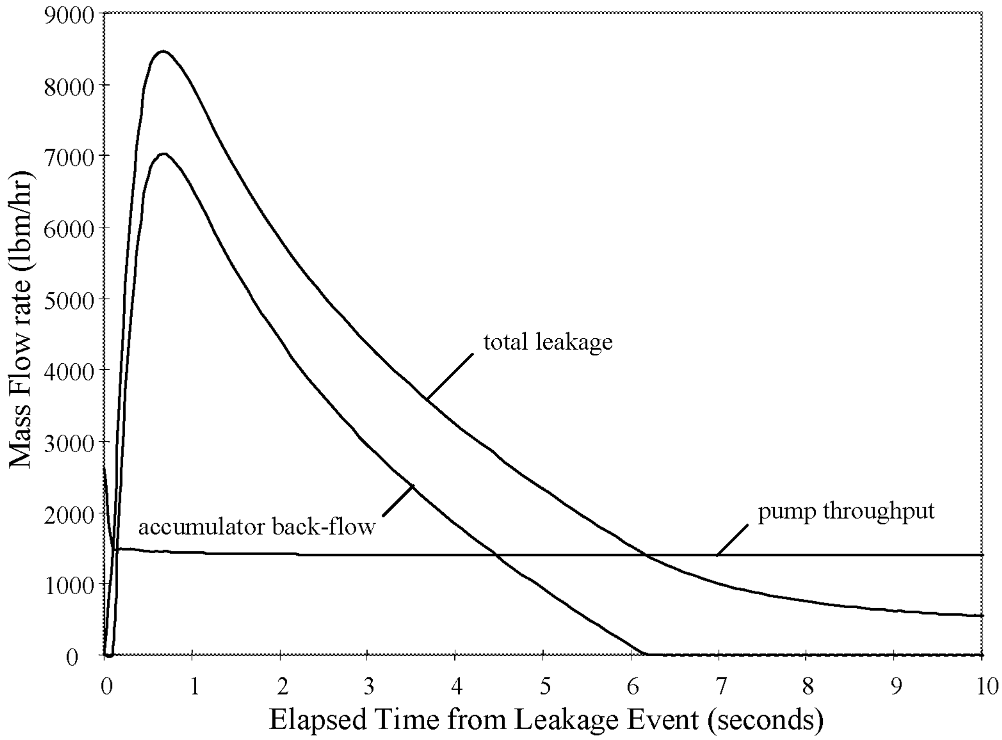

Figure 7. Total Leakage Flow Rate

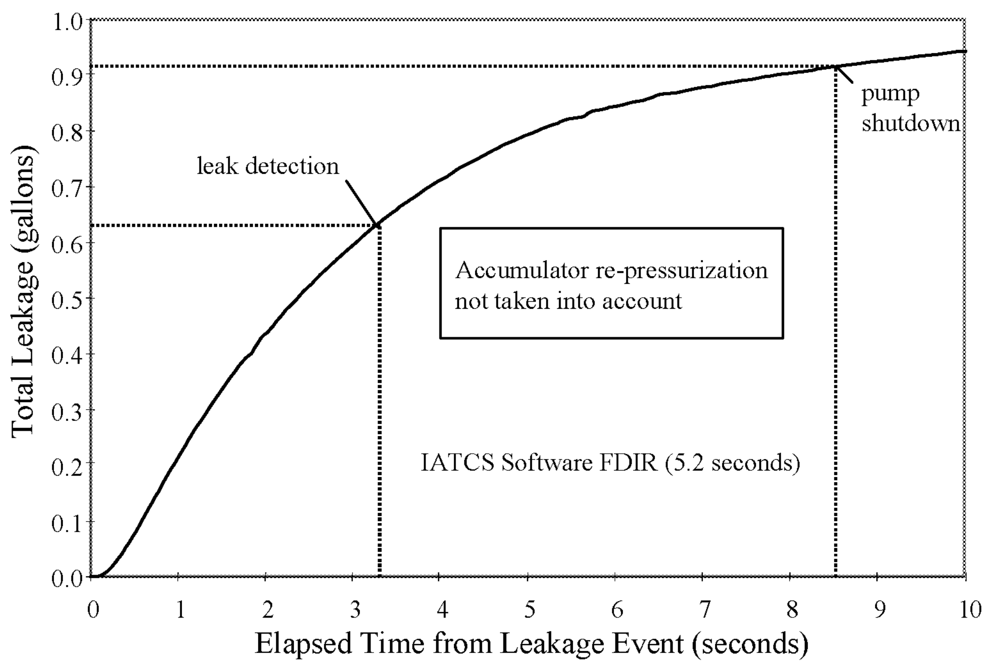

Figure 8. Total Volumetric Leakage

CONCLUSIONS

For an accumulator pre-charge ratio of 80% water and 20% nitrogen and a pressure of 35 psia, an accumulator of 650 in^3 (minimum hardware specification) is in compliance with the gross leakage requirement with the current FDIR software. However, for the same pre-charge conditions, an accumulator of 710 in^3 (maximum hardware specification) does not satisfy the requirement. Since the accumulator volume variation is a consequence of the manufacturing process, either the pre-charge water volume (80%) or the software leak detection threshold (59%) must be altered to insure that the requirement is not violated.

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