

Building Automation System Replacement and Improvements during Concurrent Integration and Testing for the Spacecraft Systems Development and Integration Facility

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Abstract

The Spacecraft Systems Development and Integration Facility (SSDIF), the premier cleanroom for NASA Goddard Space Flight Center (GSFC), has gone through multiple iterations of changes to its building automation system (BAS). NASA flight projects require more stringent environmental controls for temperature, humidity, air exchange rates, and pressurization. This led to increasingly difficult circumstances with replacing and improving the BAS during Integration and Testing (I&T) operations.

The SSDIF was transitioned to a new BAS in segments, from November 2023 to July 2024. Transition occurred in a live environment, while regular I&T activities resumed for the Roman Space Telescope. This resulted in the development and execution of a comprehensive method of procedure. Strategies such as sequencing equipment transition, and using temporary controls for critical equipment, avoided detriments to cleanroom environment.

While the new BAS was being built, data points on the previous system would become obsolete, leading to data gaps and uncertainties. Critical data points were distinguished and trended on the new system, providing key insights on equipment functionality, while the BAS was completed.

Control hunting and environmental deviations were persistent cases with the SSDIF. In some instances, proportional-integral-derivative (PID) tuning was implemented on current logic to bring smooth PID loop hunting. In other situations, controls logic was completely altered by changing setpoints or sequences. This provided greater laminar flow, more stable pressurization, and improved temperature and humidity controls.

This paper documents the transitionary procedure to a new BAS, the improvements made, and challenges faced when altering a BAS during I&T operations.

1. Introduction

1.1 SSDIF Overview

The Spacecraft Systems Development and Integration Facility (SSDIF) is a horizontal unidirectional flow cleanroom, located at NASA Goddard Space Flight Center (GSFC) and managed by Code 549. Known as the world's largest cleanroom, the SSDIF is 38.1 m (125 ft) in length, 30.48 m (100 ft) in width and 27.13 m (89ft) in height. It has the capacity to bear two space shuttle payloads simultaneously. The facility is designed to support the Integration and Testing (I&T) of spacecraft hardware and has played an integral role in the development of flight projects, such as Hubble Space Telescope, the James Webb Space Telescope, and the Roman Space Telescope.

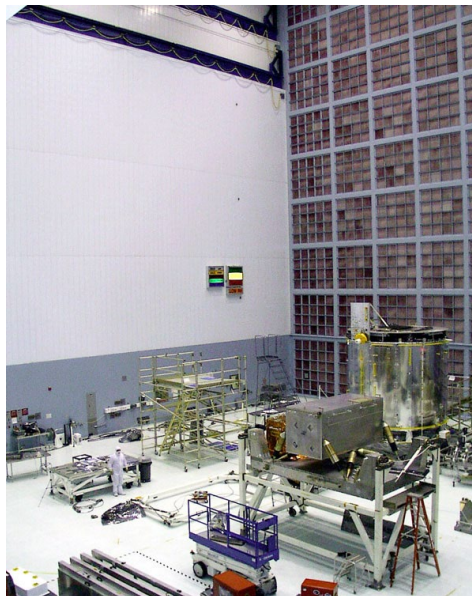


Figure 1. Space Craft Systems Development and Integration Facility (Credit: NASA)

The SSDIF is an ISO 7 (class 10,000) cleanroom, maintaining air cleanliness levels of a maximum 10,000 particles (greater than or equal to 0.5µm in size) per 0.0283 cubic meters (1 cubic foot). NASA flight projects require more stringent environmental controls for cleanrooms. These further deliverables (detailed in Table 1) include temperature, relative humidity, airflow, and differential pressure (between the inside of the cleanroom and the adjacent high bay).

Table 1. SSDIF Cleanroom Deliverables

Cleanroom Deliverable	SI Units	Imperial Units
Particle Count	353,000 particles/m ³	10,000 particles/ft ³
Temperature (T)	20 °C +/- 1.111 °C	68 °F +/- 2 °F
Relative Humidity (RH)	45% RH +/- 5%	45% RH +/- 5%
Airflow	424.7 m ³ /s	900,000 ft ³ /min or cfm
Differential Pressure (DP)	37.33 Pa	0.15 in. WC

1.2 SSDIF Environmental Control Systems

Multiple heating, ventilation, and air conditioning (HVAC) systems work in unison to maintain all cleanroom deliverables. Air handling units (AHU) or air conditioning systems (ACS) are a primary form of controlling the properties of the air provided to SSDIF. 029-ACS006 (referred to as ACS6) is the dedicated outside air unit, providing preconditioned air and pressurization to the cleanroom. 029-ACS007 (referred to as ACS7) serves as a redundant AHU, conditioning return air from the cleanroom. The chilled water (CHW) system provides cleanroom temperature control by regulating the CHW supplied to four stories of heat exchangers. Air recirculation fans maintain clean airflow through the cleanroom and particle count requirements.

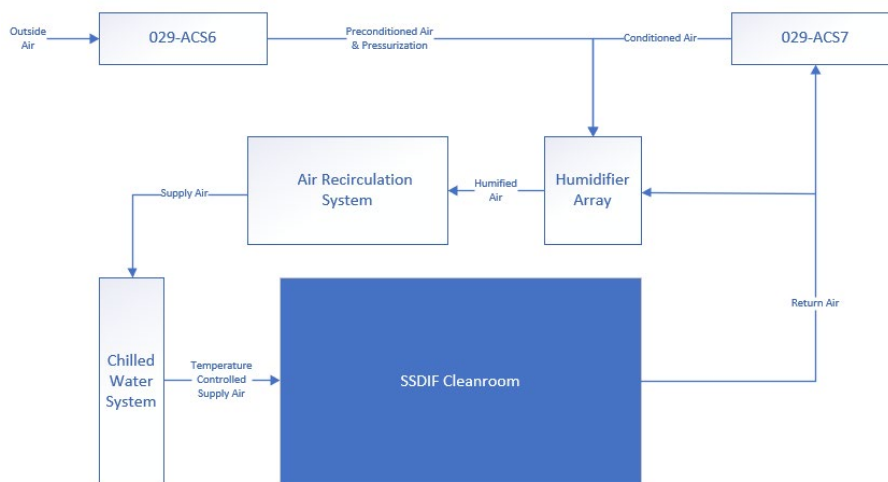


Figure 2. SSDIF Environmental Control Systems Flow Diagram

Table 2 lists the systems and their corresponding equipment that preserve the SSDIF environmental conditions. (Table 2 does not encompass all equipment that serve SSDIF but shows an overview of pertinent equipment).

Table 2. SSDIF Environmental Control Systems and Subsystems

System	Subsystem/Equipment	Qty	Function/Description
ACS 6	Steam Coil	1	Freeze protection for unit
	CHW Coil	2	Dehumidification of outside air
	Direct Expansion (DX) Coil	1	Secondary dehumidification of outside air
	Supply Fan	4	Pull in outside air and cleanroom pressurization
ACS7 + Humidifier Array	CHW Coil	1	Dehumidification of return air
	DX Coil	1	Secondary dehumidification of return air
	Steam Coil	1	Heating of return air
	Supply Fan	4	Pull in return air through the unit
	Humidifiers	5	Humidification of cleanroom supply air
	Cleanroom Humidity Sensors	10	Monitor cleanroom humidity and modulate humidifiers
CHW System	Pumps	2	Maintain CHW flow to coil wall
	Control Valves	3	Control CHW temperature supplied to coil wall
	Cleanroom Temp Sensors	10	Monitor cleanroom temperature and modulate control valves
Air Recirculation System	Recirculation Fan	6	Maintain airflow or air change rates in cleanroom
	Airflow Station	6	Monitor airflow and control recirculation fan speed

1.3 Building Automation System Upgrade

A Building Automation System (BAS), a network of hardware and software that manages various control systems, is utilized to maintain cleanroom environmental deliverables. The SSDIF BAS operates all HVAC equipment, preserves cleanroom conditions, trends relevant data, and generates alarms conveying system discrepancies. Code 549 monitors the BAS, responds to alarms with any corrective actions, and utilizes data to implement functionality changes.

In 2018, Code 549 submitted a report to the NASA Engineering and Technology Division (ETD) risk board on the cleanroom control BAS for the I&T complex. The issue was twofold: First, the system was not Federal Information Security Modernization Act (FISMA) compliant from an IT perspective. Second, the system was aging, and the controls logic was proprietary. These two issues posed a risk to both ETD and flight projects since they exposed the system to hacks and IT workarounds, made it difficult to meet flight project environmental controls, and delayed responses to needed changes because controls logic was proprietary.

The original system was designed prior to Federal Information Security Modernization Act (FISMA) standards were required for federal facilities. After the implementation of FISMA, the BAS was installed behind two firewalls, NASA's onsite network and what ETD calls the Secure Lab Environment (SLE). Code 549 was also required to apply for an Authority to operate exemption from NASA GSFC IT division on an annual basis. This IT risk, and technical risk, was the driving force to getting this system replaced with a compliant one.

The new BAS system was built by Mid-Atlantic Controls Corporation (MACC) in collaboration with Code 549, utilizing the Niagara Framework®. The Niagara framework is an open integration platform that leverages the latest cyber security technology and supports multiple open protocol integrations as well as drivers for proprietary protocols. Normalizing data across multiple protocols, powerful reporting, and analytics. Multiple other cleanrooms at GSFC had previously been transferred to the Niagara built BAS. These iterations all served as predecessors and lessons learned for the SSDIF transition.

2. Procedure Development

2.1 Limitations Imposed

A critical variable that was considered in the development of the SSDIF BAS transition Method of Procedure (MOP) was cleanroom activity. Transition of the BAS occurred in segments partially during November 2023 and the remainder during July 2024, while the Roman Space Telescope (RST) occupied the cleanroom. Throughout this time regular I&T activities occurred in the SSDIF for RST, including the transportation of space flight hardware. This live environment transition imposed increasingly difficult circumstances, as cleanroom deliverables needed to be maintained.

Normally during a startup or upgrade of a BAS for HVAC systems, the transition occurs while the environment is unoccupied or not live. This allows the systems and associated equipment to be inactive while they are brought under the new BAS control. Furthermore, not having imposed environmental limitations, allows for free range equipment modulation. This gives critical insight on system behavior which can be used to implement controls changes or tuning. In the case scenario of the SSDIF BAS transition, neither of these liberties were present. Pertinent equipment needed to remain in operation, leading to the use of temporary or manual controls. In addition, stringencies on cleanroom environmental ranges, caused limitations in implementing precise equipment controls.

2.2 Systems Transition Sequence

Before developing an MOP, the sequence in which each SSDIF environmental control system was transitioned was planned. The major consideration for this was the risk associated with each system. Table 3 highlights the Risk Matrix used to evaluate the SSDIF systems. Probability of failure was measured by accessing how likely a subsystem is to fail or operate incorrectly during or after the transition of it. Severity quantification accounts for multiple inputs, such as redundancy, cleanroom deliverables impacted, equipment or system failure, and complexity. For instance, a subsystem with little redundancy that is prone to controls issues is deemed more severe than a very redundant and simple subsystem. Table 4 shows generated Risk Analysis based upon the Risk Matrix. (Table 4 reflects the assessed risk before transition occurred; it does not reflect any corrections from post-transition lessons).

Table 3. Risk Matrix

		Severity				
		1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
Relative Probability of Failure	5 Very Likely	5 Medium	10 Medium	15 High	20 Critical	25 Critical
	4 Likely	4 Low	8 Medium	12 High	16 High	20 Critical
	3 Moderate	3 Low	6 Medium	9 Medium	12 High	15 High
	2 Unlikely	2 Low	4 Low	6 Medium	8 Medium	10 Medium
	1 Very Unlikely	1 Low	2 Low	3 Low	4 Low	5 Medium

Table 4. Risk Analysis for SSDIF Systems and Subsystems

System	Subsystem/Equipment	Probability	Severity	Risk
ACS 6	Steam Coil	4	5	20
	CHW Coils	4	4	16
	Direct Expansion (DX) Coil	4	2	8
	Supply Fan Array	3	4	12
				Avg: 14
ACS7 + Humidifier Array	CHW Coil	4	2	8
	DX Coil	4	2	8
	Steam Coil	4	2	8
	Supply Fan Array	3	2	6
	Humidifiers	4	4	16
	Cleanroom Humidity Sensors	3	3	9
				Avg: 9.17
CHW System	Pumps	2	3	6
	Control Valves	3	4	12
	Cleanroom Temp Sensors	3	3	9
				Avg: 9
Air Recirculation System	Recirculation Fan	2	4	8
	Airflow Station	3	4	12
				Avg: 10

An overall approach was taken to incrementally increase risk with each system transition. Thus, the least risk adverse system would be transitioned first, with the most risk adverse being completed last. This was done so that any early issues could be mitigated easier and consequentially build project confidence. A final consideration for the sequence was the role each system plays with one another. For instance, the CHW system controls cleanroom temperature but that is secondarily managed by ACS7. Furthermore, ACS7 and the Humidifier Array provide cleanroom humidity control, but this is also managed by ACS6. Thus, these three systems are intertwined and must be transitioned sequentially. The finalized system transition sequence, considering both risk and system role, was as follows:

- 1) CHW System
- 2) ACS7 + Humidifier Array
- 3) ACS6
- 4) Air Recirculation System

3. Transition Procedure

3.1 Preliminary Work

Preliminary work was first completed to both alleviate tasks during the actual transition and mitigate potential risks. Initial drawings were created diagraming each system and its corresponding control panel layout, providing a detailed overview of equipment functionality and a mapping of controller inputs/outputs. This aided the transition process by giving the MACC and NASA team a reference point of drawings. Proper controller power and network connection was verified to ensure the controller would not be lost during upgrade. Any temporary or new control wire and new equipment, including the controller, were positioned near their respective permanent locations to ensure quick install. Lastly, controls logic was preemptively programmed, allowing immediate equipment functionality after transition. Table 5 highlights an overview of equipment logic, by detailing control points and values. (Table 5 does not reflect final controls logic, but merely the logic that was in place initially during transition).

Table 5. Control Points and Values for SSDIF Equipment

System	Subsystem/Equipment	Control Point	Control Value
ACS 6	Steam Coil	Coil discharge dry bulb	7.222 °C (45 °F)
	CHW Coil 1	Coil discharge dewpoint	11.78 °C (53.2 °F)
	CHW Coil 2	Coil discharge dewpoint	8.278 °C (46.9 °F)
	DX Coil	Coil discharge dewpoint	6.111 °C (43 °F)
	Supply Fan Array	Cleanroom pressure	37.33 Pa (0.15 in. WC)
ACS7 + Humidifier Array	CHW Coil	Coil discharge dewpoint	4.667°C (40.4 °F)
	DX Coil	Coil discharge dewpoint	6.111 °C (43 °F)
	Steam Coil	Cleanroom average temperature	20 °C (68 °F)
	Supply Fan Array	Unit airflow	9.44 m ³ /s (20,000 cfm)
	Humidifiers	Cleanroom average humidity	45%RH
CHW System	Pumps	CHW flow to coil wall	32 L/s (500 GPM)
	Control Valves	Cleanroom average temperature	20°C (68 °F)
Air Recirculation System	Recirculation Fans	Total calculated airflow from airflow stations	424.7 m ³ /s (900,000 cfm)

3.2 CHW System Method of Procedure (MOP)

The CHW system is the primary cooling and temperature control system for the SSDIF. It consists of two secondary pumps (SWP-001 and SWP-002), that are secondary to primary building CHW pumps. They operate in a lead/lag configuration and maintain flow of the CHW that is supplied to cooling coil wall. The temperature of the supplied CHW modulates based upon the average of the cleanroom temperature sensors and is controlled by three control valves. Valve 1 (V-1) provides building return CHW (nominally 10-12.22 °C or 50-54 °F), Valve 2 (V-2) provides return CHW from the cooling coil wall (nominally 17.78-19.44 °C or 64-67 °F), and Valve 3 (V-3) provides building supply CHW (nominally 6.111-7.778 °C or 43-46 °F).

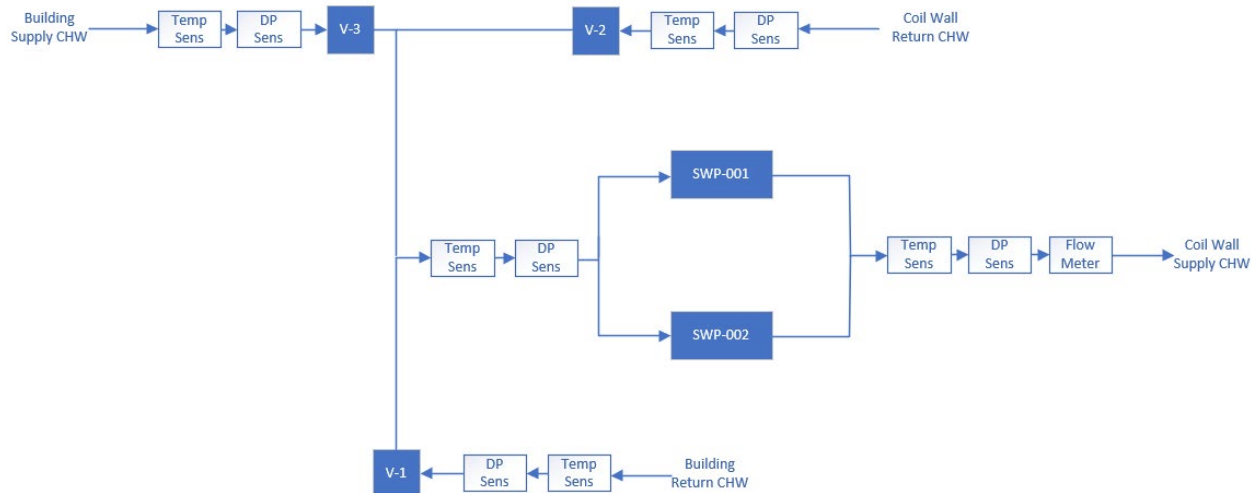


Figure 3. CHW System Flow Diagram

Below is the developed MOP for the CHW system transition.

- 1) The control valves will be commanded to their most recent position on the old BAS.
- 2) The temperature sensor inputs will be transitioned.
- 3) The controls valves will be transitioned and released to auto. Proper cleanroom temperature control will be verified.

- 4) The lag secondary CHW pump (SWP-001) will be transitioned while the lead pump (SWP-002) remains in operation on the old BAS.
- 5) SWP-001 will be commanded on the new BAS to maintain CHW supply flow and operate as the lead pump.
- 6) SWP-002 will be transitioned.
- 7) The CHW flow meter will be transitioned, and the pumps will be released to auto. Proper flow and cleanroom temperature control will be verified.
- 8) Remaining monitoring points for the CHW system will be transitioned.
- 9) A failover test will be performed on the pumps.
- 10) The pneumatic actuators, that control the valves, will be swapped with new electric ones. Valve actuation and cleanroom temperature control will be verified.
 - This was done because of NASA's ongoing effort to transition away from pneumatic dependent systems.
- 11) Confirm all points, alarms, trends, and graphics are operational.

3.3 ACS7 and Humidifier Array MOP

ACS7 is an AHU that conditions the return air of SSDIF, providing dehumidification and heating. Both its CHW and DX coil modulate to maintain their respective coil leaving air dewpoint. The steam coil provides heating and modulates based on the average of the cleanroom temperature sensors. It is mostly an unutilized coil, as there is already heat generated by the system fans. For this reason, the steam coil was able to remain out of operation while the temperature sensors were on the new BAS. A supply fan array, consisting of 4 fans, maintain airflow through the unit. The humidifier array does not exist in the unit, but is located in the SSDIF supply plenum, to provide humidification to the entirety of the supplied air to the cleanroom. The array's controls, however, are in the same control panel as ACS7. Although comprised of five individual humidifiers (Humidifier 1 – Humidifier 5), the units share a common output command.

Since ACS7 is a redundant unit, that only treats return air, its effects on the cleanroom were diagnosed as minimal. For this reason, it was deemed that ACS7 could remain offline throughout the transition process. However, the humidifier array, especially during winter months, is critical in preserving SSDIF humidity control. Therefore, temporary control wire was installed parallel to the permanent wire for the array, to allow automatic control of the humidifiers while ACS7 was offline. (The humidifier array flow diagram is shown in section 3.5, with the Air Recirculation System, as they are physically in the same location).

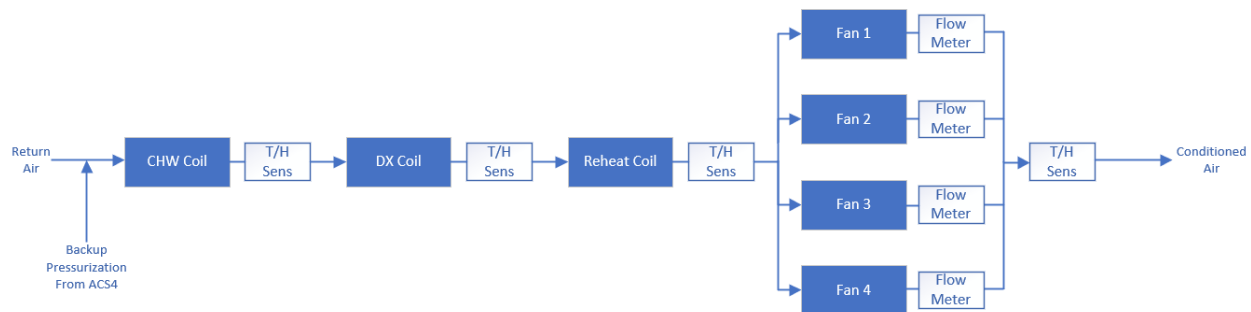


Figure 4. ACS7 Flow Diagram

Below is the developed MOP for the ACS7 and Humidifier Array transition.

- 1) Humidifier 1 will be commanded to its most recent position on the old the BAS.
- 2) Humidifier 1 will be transitioned to the temporary configuration and stay at its most recent position.
- 3) Steps 1-2 will be repeated for Humidifier 2 to 5.
- 4) The humidity sensor inputs will be transitioned to the temporary configuration.
- 5) The humidifiers will be released to auto. Proper cleanroom humidity control will be verified.
- 6) ACS7 and its associated equipment will be shutdown.
- 7) All control and monitoring points for ACS7 will be disconnected from the old controller.
- 8) The control points for the CHW coil will be transitioned. Modulation and functionality will be verified.
- 9) Step 8 will be repeated for the DX coil, steam coil, and supply fan array.

- 10) Remaining monitoring points for ACS7 will be transitioned.
- 11) Humidifier 1 will be commanded to its most recent position on its temporary configuration.
- 12) Humidifier 1 will be transitioned to the permanent configuration and stay at its most recent position.
- 13) Steps 10-11 will be repeated for Humidifier 2 to 5.
- 14) The humidity sensor inputs will be transitioned to its permanent configuration.
- 15) The humidifiers will be released to auto. Proper cleanroom humidity control will be verified.
- 16) ACS7 and its associated equipment will be restarted. Proper cleanroom temperature and humidity control will be verified.
- 17) Confirm all points, alarms, trends, and graphics are operational.

3.4 ACS6 MOP

ACS6 is the dedicated make up air unit for the SSDIF, providing conditioned outside air and cleanroom pressurization. Its steam coil preheats the outside air to maintain a dry bulb temperature above freezing. This is imperative to not expose the CHW coils to below freezing air, which could lead to potential equipment failure. Both the CHW coils and the DX coil modulate to maintain their respective coil leaving air dewpoint. The supply fan array modulates fan speed to maintain cleanroom differential pressure.

The decision was made to transition ACS6 while it was not in operation for two reasons. One, a backup pressurization source exists from another air handler, ACS4. Although, ACS4 is not a Code 549 controlled unit, it does have a pathway that feeds into ACS7. When the damper to this pathway is opened, minimal cleanroom pressurization (4.977 Pa or 0.02 in. WC) can be maintained. Thus, the pathway was planned to be utilized to maintain positive pressurization in SSDIF, while ACS6 was shut down and transitioned. The second reason was due to the fact the transition was occurring during the winter season. Dehumidification capabilities are widely unused during cold and dry weather, so ACS6 conditioning capabilities were deemed unnecessary during the time of transition. By shutting down the unit, the use of a temporary configuration for ACS6 was nullified, which reduced any unforeseen risk of equipment operation under partial control.

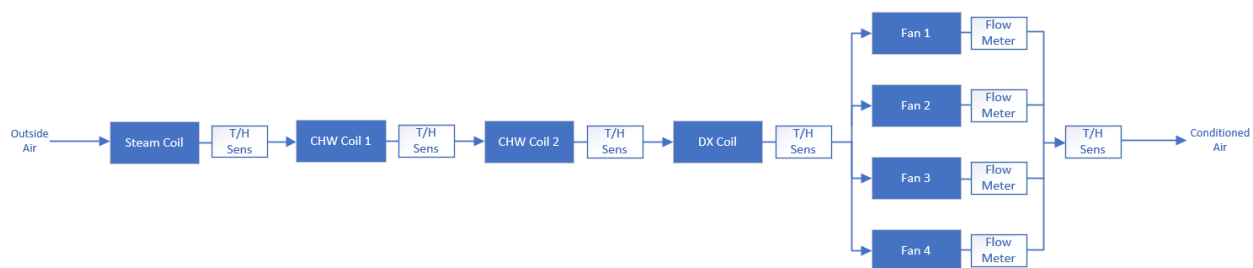


Figure 5. ACS6 Flow Diagram

Below is the developed MOP for the ACS6 transition.

- 1) The damper to ACS4 will be opened to provide cleanroom pressurization.
- 2) ACS6 and its associated equipment will be shutdown.
- 3) Cleanroom pressurization will be verified positive.
- 4) All control and monitoring points for ACS6 will be disconnected from the old controller.
- 5) The control points for the steam coil will be transitioned. Modulation and functionality will be verified.
- 6) Step 5 will be repeated for CHW coil 1, CHW coil 2, the DX coil, and the supply fan array.
- 7) ACS6 its associated equipment will be restarted. Proper cleanroom temperature and humidity control will be verified.
- 8) Remaining monitoring points for ACS6 will be transitioned.
- 9) The damper to ACS4 will be closed. Proper cleanroom pressurization will be verified.
- 10) Confirm all points, alarms, trends, and graphics are operational.

3.5 Air Recirculation System MOP

The Air Recirculation System consists of six vane axial recirculation fans (Recirc Fan1 – Recirc Fan6) that maintain airflow or air change rates in the SSDIF. Airflow is deemed the most critical cleanroom deliverable, as not only does

it maintain particle count levels but without airflow there is no temperature or humidity control. Each fan's rated maximum airflow is 84.95 m³/s (180,000 cfm) and each has a respective variable frequency drive (VFD), allowing the fan speed to vary. One common fan speed is commanded to each fan based upon the deviation from total airflow setpoint. Total airflow is ascertained from the summation of each fan's individual airflow, which is monitored at their respective airflow stations. To maintain proper particle count control, Code 549 contamination control ascertained that 40 air changes per hour must be maintained. Based off the volume of SSDIF, this roughly translates to a minimum required airflow of 354 m³/s or 750,000 cfm. From using each fan's rated maximum output, it was calculated that only five fans need to be operational at a time to fulfil air change rate requirements. Thus, it was deemed that a recirculation could be transitioned while it was offline, given that the other five remained in operation.

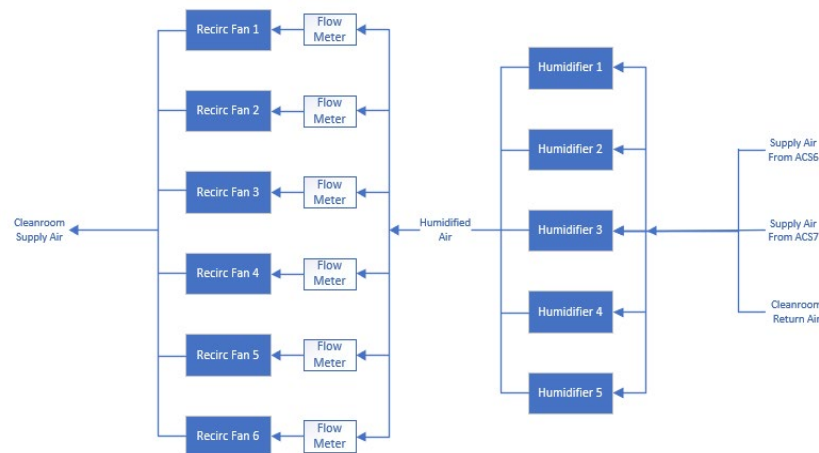


Figure 6. Air Recirculation System and Humidifier Array Flow Diagram

Below is the developed MOP for the air recirculation system transition.

- 1) Each recirculation fan will be commanded to their most recent position at their respective VFDs. Total cleanroom airflow and stability will be verified.
- 2) Transition the Recirc Fan 1 airflow station. Total airflow will be verified by manually calculating the sum of Recirc Fan 1 airflow on the new BAS and Recirc Fan 2 – 5 airflows on the old BAS.
- 3) Step 2 will be repeated for the airflow stations of Recirc Fans 2 – 5.
- 4) Recirc Fans 2 – 5 will be commanded to 100% at their respective VFDs and Recirc Fan 1 will be taken offline. Minimum cleanroom airflow will be verified.
- 5) Recirc Fan 1 and its associated drive will be transitioned.
- 6) Recirc Fan 1 will be commanded to 100% at its VFD and Recirc Fan 2 will be taken offline.
- 7) Recirc Fan 2 and its associated drive will be transitioned.
- 8) Steps 4 – 6 will be repeated until all recirculation fans have been transitioned.
- 9) Remaining monitoring points for the air recirculation system will be transitioned.
- 10) A failure test will be conducted on each fan to show fan functionality in the case scenario of a failure.
- 11) Confirm all points, alarms, trends, and graphics are operational.

4. Transition Results and Challenges

Each transition posed different challenges in maintaining cleanroom deliverables. In some cases, detriments to SSDIF presented themselves right away and required immediate intervention. In other cases, discrepancies were more subtle or not noticeable until well after a system had been transitioned. This resulted in rigorous investigative work to pinpoint the equipment or controls issue. Various corrective actions were utilized to amend cleanroom control. For critical issues, equipment would be manually commanded to a certain position for immediate results. But this posed future risk to the system, as without automatic control and response, cleanroom deliverables may further skew from setpoint. Another option is changing control point values for equipment. As documented in Table 5, equipment control point values were set before transition occurred but in certain situations, these values needed to be altered as they did

not result in proper cleanroom control. Furthermore, control points themselves could be completely changed. By altering the control point, equipment behavior changes, resulting in new modulation. This is known as a controls change – the altering of an equipment’s or a system’s sequence of operation. An equipment’s PID (Proportional-Integral-Derivative) controls parameters can also be adjusted or tuned to ensure precise modulation. This was done in cases of oscillation or overshoot with cleanroom deliverables.

4.1 CHW System Transition and Adjustments

Temperature instability was the largest risk during and after the transition of the CHW system. Flow of CHW supplied to the cooling coil wall was largely stable as the transitioned pumps settled on an output speed. Issues were however faced with modulation of the control valves. Usually, CHW systems input a fixed temperature of CHW, and a control valve modulates the flow entering a coil or multiple coils. This situation only contains one variable: the flow of CHW. In the case scenario of the SSDIF CHW system, flow is set to a constant value and the temperature of CHW varies by modulation of the three control valves. This allows for more precise temperature control, but introduces three variables to the system, resulting in greater controls complications. Consequently, modulation of the control valves was unstable after transition, resulting in multiple incidents when cleanroom temperature fell out of range. Although these instances were infrequent and the controller would quickly adjust temperature back within spec, corrective measures still needed to be taken.

The first action taken was tuning of the PID. Due to the tight range of temperature control, the control loops for the valves were initially evaluated and tuned for fast responses to conditions. This allowed for valve positions to quickly change based upon cleanroom temperature. However, this led to large fluctuations in valve positions, as the valves would modulate between fully open (100%) and closed (0%) commands within short periods, causing temperature overshoot. The PID parameters of the control valves were changed to allow both fast recovery and smooth output control. This resulted in cleanroom temperature remaining within range.

Although temperature was within designated parameters, oscillations were still prevalent. An evaluation of the entire CHW system controls sequence was conducted, specifically the use of the cleanroom average temperature as a control point. Since temperature is a defined cleanroom deliverable, it was initially believed to be the best control point. However, there is a large physical distance between the control valves and temperature sensors, which was leading to a lag in valve modulation versus cleanroom conditions. To remedy this lag, a controls change was initiated to alter the control point of the valves to the temperature of CHW supplied to the coil wall. In order to still adhere to cleanroom temperature, the control point would not be a stagnant value but operate as a “modulating control point” and vary its value with regard to average cleanroom temperature. This resulted in the dampening of SSDIF temperature oscillation and the supply CHW temperature settling to value near 15.55 °C (60 °F) at nominal conditions.

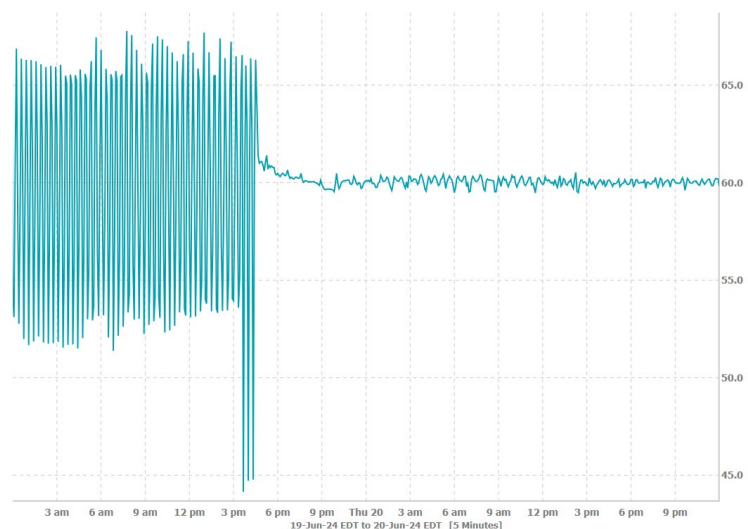


Figure 7. Supply CHW Temperature Before and After Controls Change

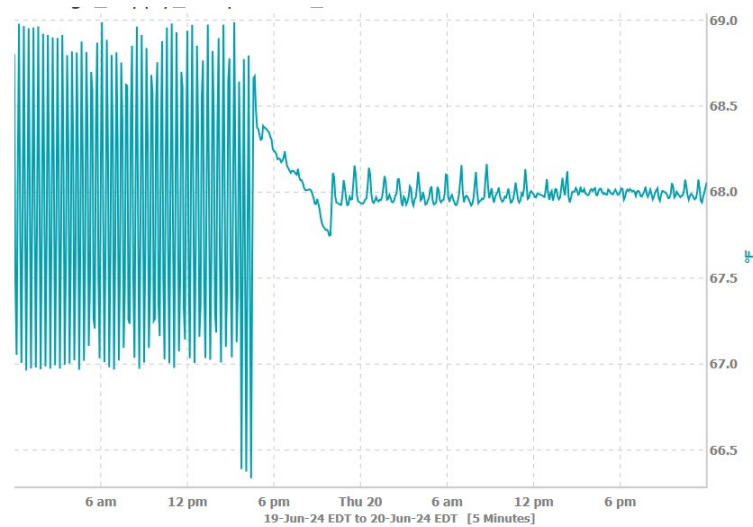


Figure 8. SSDIF Average Temperature Before and After Controls Change

4.2 ACS7 and Humidifier Array Transition and Adjustments

No negative events occurred during the transition of ACS7 and the Humidifier array. Although humidity control could have been compromised during the temporary control and transition of the humidifier array, relative humidity remained within specification. This was largely due to the simplicity of the system as humidification was only controlled by one variable: the output of the humidifier array. Transition and control of ACS7 resulted in no detriment to SSDIF, as its effects are minimal. PID tuning and controls changes were implemented for ACS7, but this was done after successful control of ACS6 (see section 4.3).

4.3 ACS6 Transition and Adjustments

Two cleanroom deliverables, relative humidity and pressurization, can be comprised by improper operation of ACS6, making it the most risk adverse system. The first challenge was faced during the early stages of transition, with the performance of the steam coil. ACS6 contains freeze stats, after the steam coil and both CHW coils, that operate independent of the BAS. If any freeze stat detects an air temperature value below 2.222 °C (36 °F), it will trigger a shutdown of ACS6, which can only be reset manually. Although the control value of the steam coil (7.222 °C or 45 °F) was well above this low limit, there were multiple instances of freeze stats tripping. Consequently, ACS6 would shutdown during these instances leading to depressurization of the cleanroom. Temperature readings were taken using a calibrated sensor, to verify readings of the freeze stats and leaving coil sensors. It was discovered that the leaving steam coil sensor, due it being installed high in the ductwork, was detecting a much higher temperature than then freeze stats, which were located low in the ductwork. To ensure ACS6 operation, a short term solution was implemented post initial transition, where the steam coil control value was raised to 21.11 °C (70 °F). After the winter season, when the steam coil would not be needed, a long term solution was implemented, where a new averaging sensor, that would account for air temperature stratification, was installed.

Proper humidification control was the second challenge encountered. Since transition of ACS6 occurred during the winter season, dehumidification and use of the CHW and DX coils, was widely unneeded then. However, humid outside conditions were soon prevalent, showcasing the deficiencies in ACS6 equipment control. Cleanroom humidity went out of range for nearly a 5 hour period, with conditions as high as 57.4%RH.

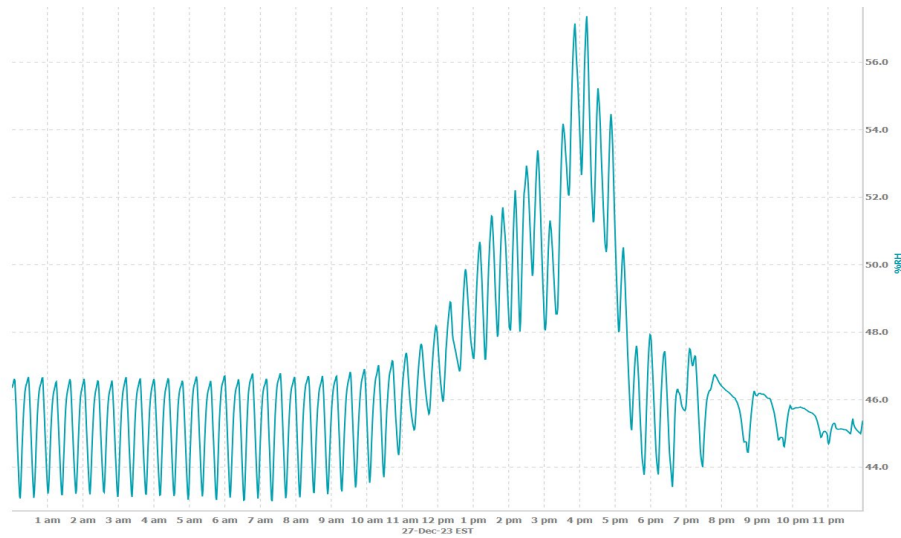


Figure 9. SSDIF High RH Incident and Recovery

One initial cause was the inability to use the DX coil. Due to continuous high pressure trips on the refrigerant circuit, the DX coil was inoperable. Thus, the total outside air dehumidification load was placed on the CHW coils. Initially, both CHW coils were commanded to 100%, to bring the cleanroom back within range (see Figure 9). To place the system back in automatic control, the dewpoint control values of CHW coil 1 and 2 were changed to 8.278 °C (46.9 °F) and 6.111 °C (43 °F), respectively and their PIDs were tuned. Even after several PID tuning iterations, large fluctuations and out of range instances were still prevalent with cleanroom humidity. Upon further investigation, it was determined that the use of dewpoint as a control value was a major fallacy. The leaving coil sensors did not measure dewpoint, but calculated it based upon measured values of temperature and relative humidity. This made it a far more complex control variable, that was leading to difficulties in its control. To simplify CHW coil operation, a controls change was initiated to alter its control point to leaving dry bulb of 7.778 °C (46 °F) and 6.111 °C (43 °F), for CHW coil 1 and 2 respectively. This resulted in cleanroom humidity dampening and the elimination of out of range incidents. After successful verification, the same dry bulb controls change was also applied to ACS7, to enact similar equipment logic and modulation.

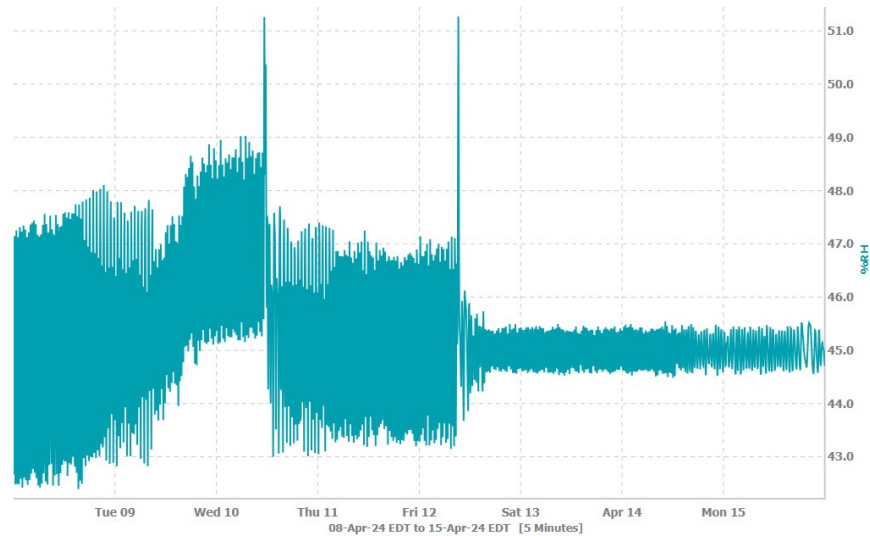


Figure 10. SSDIF Humidity Before and After Controls Change

4.4 Air Recirculation System Transition and Adjustments

No negative events occurred during the transition of the Air Recirculation System, as airflow maintained over the minimum required value. Similar to the humidification array, this was largely due to the simplicity of airflow control as it was only controlled by one variable: the speed of the recirculation fans.

5. Discussion

5.1 Lessons Learned

Although overall transition had occurred successfully, there were clear challenges in the maintenance of cleanroom deliverables, specifically with the CHW system and ACS6. This was largely due to improper controls of equipment from unrefined PID control and incorrect control values and points. Although avoiding discrepancies is very improbable when taking control of a new system, three critical actions could have been taken to help circumvent cleanroom detriments. The first is reassessment of system risk with regard to equipment control difficulty versus cleanroom deliverable complexity. For instance, humidity is a more difficult point to maintain than temperature, and for this reason the Humidifier Array (and ACS7) transition was deemed higher risk than the CHW system. However, due to the Humidifier Array only modulating one variable for humidity control, it is less complex and lower risk than the CHW system, which modulates three variables for temperature control. This same logic can be applied to the Air Recirculation System, as it was assessed to be a high risk transition, due to the importance of airflow. But due to its simplicity in maintaining airflow, its risk is lesser. Table 6 reevaluates the initial risk analysis, accounting more for control variable complexity. Regarding this new risk analysis, while still accounting for system role, the reevaluated system transition sequence would be as follows:

- 1) ACS7 + Humidifier Array
- 2) CHW System
- 3) ACS6
- 4) Air Recirculation System

Table 6. Reevaluated Risk Analysis for SSDIF Systems and Subsystems

System	Subsystem/Equipment	Probability	Severity	Risk
ACS 6	Steam Coil	4	5	20
	CHW Coils	4	4	16
	Direct Expansion (DX) Coil	4	2	8
	Supply Fan Array	3	4	12
				Avg: 14
ACS7 + Humidifier Array	CHW Coil	4	2	8
	DX Coil	4	2	8
	Steam Coil	4	2	8
	Supply Fan Array	3	2	6
	Humidifiers	4	3	12
	Cleanroom Humidity Sensors	3	3	9
				Avg: 8.5
CHW System	Pumps	2	3	6
	Control Valves	4	4	16
	Cleanroom Temp Sensors	3	3	9
				Avg: 10.33
Air Recirculation System	Recirculation Fan	2	3	6
	Airflow Station	3	3	9
				Avg: 7.5

A secondary fault that led to cleanroom discrepancies, was reliance on previous controls logic. Largely, the same control points and values from the previous BAS were transcribed to the new one. This was done in an effort to not implement changes while transition occurred and reduce the likelihood of cleanroom detriment from new controls logic. The misguidance in this however, is the assumption that a previously tuned controls logic would be the best starting point for a new system. Previous controls should have been evaluated preemptively, and only implemented if assessed to be a simple and effective methodology. For instance, the use of dewpoint control for ACS6 and ACS7, although prevalent in the old BAS, should not have been implemented in the new system, as it is a difficult (and later deemed unnecessary) variable which to control. If instead, earlier concurrence had been reached that dry bulb would have been a more functional control point, cleanroom humidity detriments could have been avoided.

A last action that could have been taken is the full utilization of trends. Per NASA requirements, trends were immediately enabled on cleanroom deliverables after each point had been transitioned. Trends were not initially enabled for other control and monitoring points, such as a valve position or coil's leaving air conditions. At the time of transition, efforts were geared toward more critical actions. However, not having these trends made it far more difficult to perform PID tuning or controls changes, as imperative data showcasing equipment or system functionality was not available. If trends had been enabled for all points originally, it could have resulted in less speculation and trials for proper controls.

5.2 Key Accomplishments and Takeaways

The SSDIF BAS transition did not occur without challenges and incidents, but still yielded great improvements to the BAS. All control points have been properly transferred to the BAS interface, allowing easy adjustability from a user level. An alarm console was built into the interface, permitting the user to make alarm configurations. Furthermore, new alarms and trends can easily be added in under different classifications, detailing more data to the user. Although many iterations of changes were needed to stabilize SSDIF environmental control, this showcased the ease and quickness at which changes can be made.

SSDIF automation and environmental control continues to be an ongoing endeavor. Even if cleanroom deliverables are presently met, that does not cease the improvement of the BAS. New and present challenges, such as changes to cleanroom deliverables or equipment failure, constantly require adjustments to the BAS. Lastly, any further cleanroom BAS transitions can utilize the lessons learned from SSDIF.