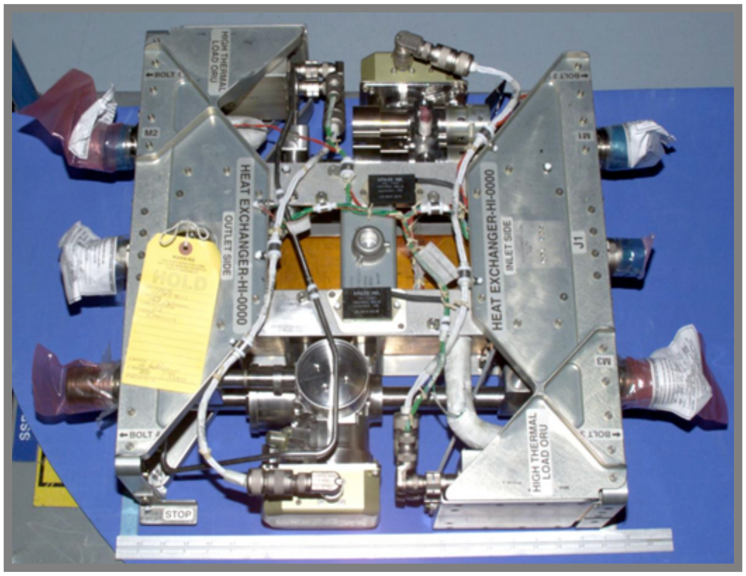


ISS Columbus Heat Exchanger Close Call Investigation Case Study

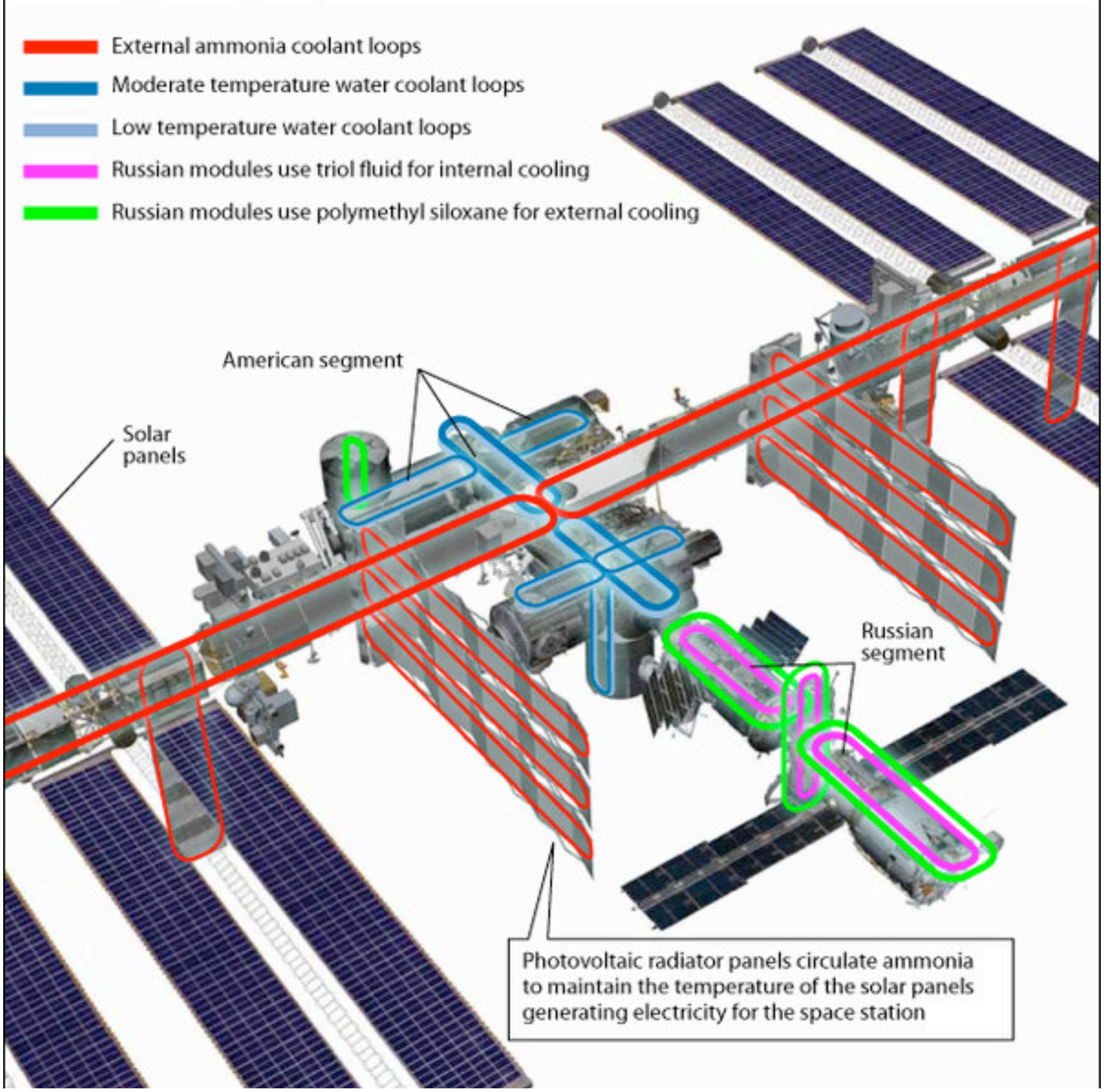
Summary

During International Space Station (ISS) Expedition 38, just days before Christmas 2013, the External Active Thermal Control System (EATCS) on the ISS Columbus Moderate Temperature Loop (MTL) Interface Heat Exchanger (IFHX) shut down due to low temperatures. Engineers on the ground scrambled for several days to troubleshoot a pump module Flow Control Valve (FCV) problem, however; no one recognized that the core temperature of the Columbus MTL IFHX was continuing to drop, to the point that water in the system could freeze. Freezing could rupture the core, resulting in high pressure ammonia entering the cabin of the ISS. With no way to clean up the ammonia, ISS crew would have to evacuate the U.S. segment of the station. Columbus MTL IFHX rupture is considered a catastrophic failure and could potentially result in a loss of crew/loss of vehicle. How did engineers miss this potentially catastrophic issue?

Background

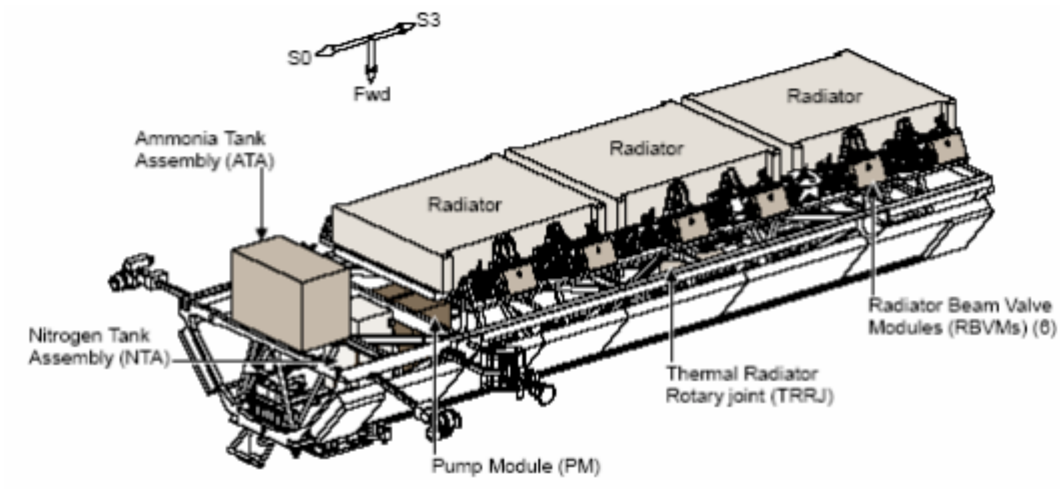
The space station's EATCS consists of two separate cooling loops – known as loop A and loop B. Both work together to transport heat away from electronic equipment and toward the radiators, which in turn dissipate the heat into space.

The International Space Station's active thermal control systems (ATCS) pump fluids through closed-loop pipes. A liquid-ammonia coolant loop along the station's main truss keeps the station's electricity-generating solar panels cool.



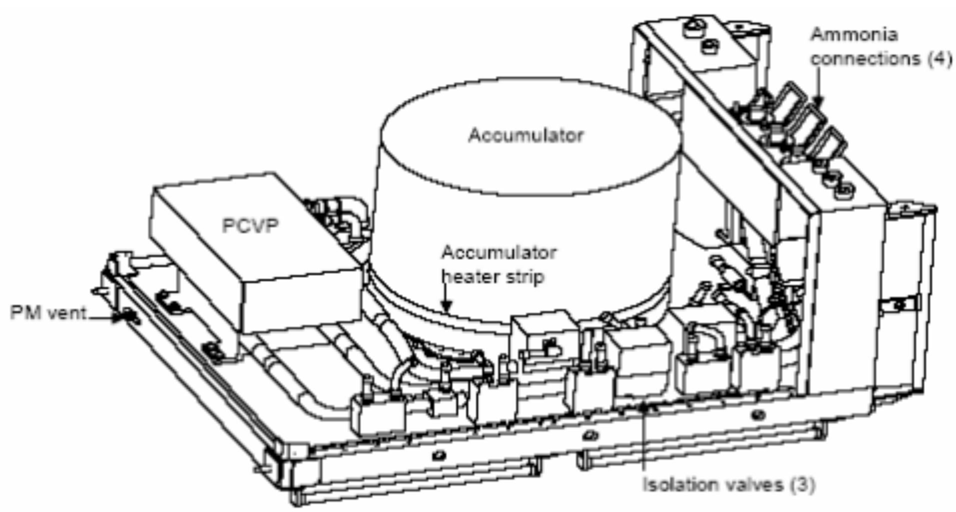
ISS Active Cooling Systems[1]

The ETCS loops use ammonia fluid as a coolant, while the Internal Thermal Control System (ITCS) cooling loops inside the ISS use water, to prevent a potential leak of toxic ammonia inside the ISS.



Loop A components on the S1 Truss segment[2]

The ITCS water loops transfer their heat to the ETCS ammonia loops via the use of an IFHX, which enables the external ammonia loops to transport the heat from the internal water loops to the external radiators. In addition, the external ammonia loops also provide cooling for all electronic equipment located outside the ISS.



Pump Module circulating liquid ammonia to coldplates and heat exchangers[3]

For the ETCS, ammonia is pumped around each of the two loops by an externally located component known as the Pump Module, with each loop having its own separate Pump Module. A FCV resides inside the Pump & Control Valve Package (PCVP) inside the loop A Pump Module.

The FCV controls the temperature of the ammonia in the cooling loops by mixing cool ammonia that is exiting the radiators with warm ammonia that has bypassed the radiators. However, the failure of the FCV means that it has allowed too much cool ammonia to enter loop A, which caused loop A to drop to a temperature that is far too low (around -32°C) for safe cooling operation.

Maintaining stable ammonia loop temperatures (typically around 4°C) is important. If the temperatures in the external ammonia loops are allowed to get too low, the water inside the IFHXs could freeze, causing the water pipes to crack and the IFHX to fail, which could allow toxic ammonia from the external loops to enter inside the ISS.

Toxic chemical release (in this case anhydrous ammonia) into the cabin atmosphere is one of the three major emergency scenarios identified on the ISS. Failure modes exist that could cause a breach within the IFHX which would result in high pressure ammonia from the EATCS flowing into the lower pressure ITCS water loop. As the pressure builds in the ITCS loop, it is likely that the gas trap, which has the lowest maximum design pressure within the ITCS, would burst and cause ammonia to enter the ISS.

The Flow Control Valve Takes Center Stage

On December 11, 2013, a Caution & Warning alarm sounded inside ISS when the TCS Controller sensed an off-nominal situation on loop A of the ETCS related to an under-temp reading. Mission Control determined that the FCV loop A was not closing properly causing a loss of thermal control on that loop. Too much cold ammonia was allowed back to the IFHX. Temperatures on the loop started dropping relatively fast and the system could no longer fulfill its purpose.

The ground team immediately started the process of transferring heat loads to loop B. It was decided to permit the loops temperature to increase above nominal, peaking at around 4.7°C. Some heat loads were shifted to loop B, and the loop B flow rate was increased to cope with the additional loads. However, since one cooling loop alone cannot handle all of the station's needs, several items of electronic equipment had to be shut down due to lack of adequate cooling. These included one of the two Multiplexer/Demultiplexer (MDM) computers in the Node 2 module, as well as three DC to DC Conversion Units (DDCUs) also in Node 2. Since the DDCUs provide power to many loads inside the Columbus and Japanese Experiment Module, many pieces of equipment inside those modules were also shut down. Additionally, internal equipment was shut down to minimize heat generation.

With loop A no longer available and equipment powered down, the ISS crew retired to their sleep areas. ISS was in a stable configuration and thermal control on Loop B was nominal. Due to the built-in redundancy in the system, there was no danger to the crew at any point.

On the ground, controllers and support personnel set about performing a number of steps to fully understand the problem with the FCV and recover it via ground commands, such as cycling the valve and using different command paths to verify whether an actual hardware issue was present.

Teams spent hours manually commanding the FCV through its complete range of motion in 5-degree increments to detect any changes in loop A behavior. Power jumpers were installed inside the US Lab to keep the Quest Airlock powered in preparation for an emergency Extravehicular Activity (EVA), should it be needed. A number of payload activities could not be performed due to the power-downs inside the USOS modules.

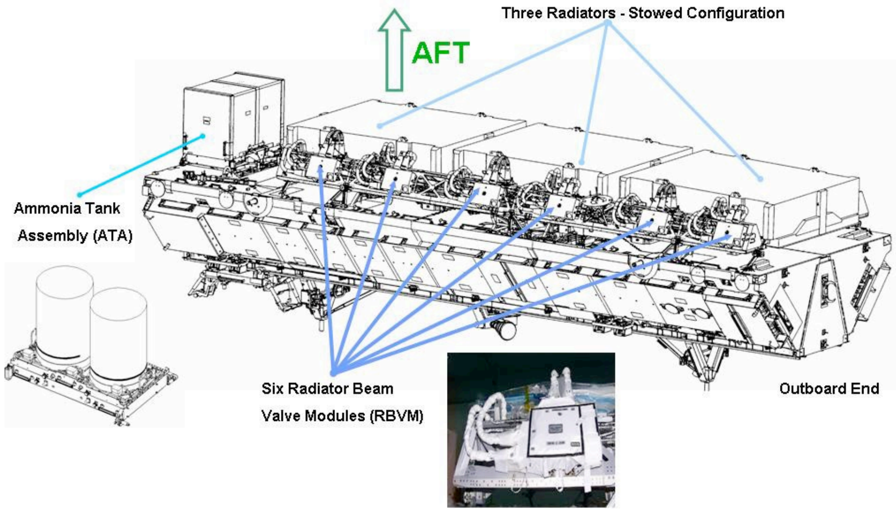
Additional troubleshooting steps included turning off the loop A pump to evaluate the performance of the FCV in low-flow conditions. The pump was powered up after assessments were complete. No improvement of FCV performance was noted. Specialists determined that valve firmware could not be modified to command it outside of set firmware limits.

Two different items were being worked in parallel - finding a way to regulate the loop A temperature using the loop heaters and manipulating other valves in the PM that normally fulfill other tasks but could also be used to somewhat regulate ammonia flow within the loop. This valve would be operated in a creative way because it is usually cycled between open and closed and does not normally have flow control capability.

The team was concerned that a low flow rate within the system could lead to undesired thermal gradients within the ammonia lines when using the heaters. It was verified that the flow rate would remain above the threshold in the current thermal conditions.

Evaluations of heaters and valve manipulation began. As controllers powered heaters on the loop in order to assess loop and the FCV response, the temperature of loop A began to rise to more than +10°C. Teams had to go through a number of tests using different valve settings in order to understand how to regulate the temperature without a functional FCV.

With the ISS in this configuration, launch commit criteria for the Cygnus resupply vehicle was violated. The first operational Cygnus mission to ISS was due to launch on December 19, but the “Go”/”No Go” decision by the ISS Mission Management Team (MMT) had been deferred to await the results of troubleshooting. If the ISS was to remain in the current thermal configuration, Cygnus would not be allowed to launch. Ironically, the Orb-1 Cygnus was carrying some internal cooling jumpers which would allow for better management of internal cooling loop temperatures in the event of an external cooling loop failure.[4]



Configuration of radiators and tank assembly[5]

While troubleshooting continued, Team 4 – a group of individuals of varied disciplines charged with developing a plan to account for an unexpected event during a mission - was called to begin planning the EVA needed to remove and replace the PM on the S1 Truss Segment holding the errant FCV. Mission Control told the crew that an EVA to replace the loop A pump module might be required if the valve could not be recovered by ground controllers.

While ground teams successfully managed to raise the temperature of loop A back into the nominal range, ISS program managers ultimately decided to proceed immediately with the EVA Removal and Replacement (R&R) of the loop A pump module and its failed FCV, rather than temporarily re-integrating loop A back into the IFHXs, and waiting to conduct the EVAs the following month.[6]

"We were working on a pump module issue… while that was going on we had this interface heat exchanger near freeze event that happened - in the middle of chaos. No one really recognized that this had happened until some point after the chaos subsided… we got really close to freezing interface heat exchanger, and then somebody realized that if it would have frozen, high pressure ammonia would have entered the cabin, and the crew would have had to evacuate."

Brian Derkowski, Mission Evaluation Room Manager

While the teams were working on recovery, water temperatures in the IFHX on the Columbus module dropped below zero degrees centigrade shortly after the loop A FCV failure. This could have caused a rupture of the barrier in the IFHX core which would result in pressurized ammonia entering the internal cooling system and habitable environment of the ISS. The crew would have to don emergency masks (evacuating the USOS), with the worst case impact being Loss of Crew/Loss of Vehicle. No rupture occurred, and a High Visibility Call was initiated (no damage or injury).

The Close Call Investigation

Mission Evaluation Room Manager Brian Derkowski had worked the FCV issue up to Christmas Day. After a brief break, management tapped him to lead a Close Call investigation on the near catastrophe. Derkowski was supported by Root Cause Analysis expert, Karon Woods. He was given one week to pull a plan together. Management approved the investigation plan, its boundaries and timeline. The investigation's objectives were to:

- identify the contributing factors, proximate and root causes leading to the close call
- identify and implement a corrective action plan to avoid a recurrence, and extrapolate lessons learned from the investigation
- identify other areas of the vehicle that could potentially be susceptible to similar risk

Derkowski outlined everything up front so that those involved in the investigation understood the goals and objective as well as their roles on the team. His investigation approach was to develop a set of focus areas and a detailed set of questions for each area.

Derkowski conduct semi-weekly team meetings to address each area in detail. Tasks included development of an Integrated Timeline, Causal Tree and Event Sequence Diagram. The investigation formally kicked off on January 21, 2014.

One challenge was to develop and achieve team consensus on findings. Each basic event was dispositioned; recommendations were developed as was a Corrective Action Plan Formal closure rationale.[7]

"From the very beginning I tried to set the tone - we were all there: the engineering community, the Mission Evaluation Room, the Ops community, the safety community. We were all there and we all missed it…we're all to blame, any one of us could have caught that. And everyone agreed. That set the tone for the investigation - all of us accepting the shared blame".

Brian Derkowski

Investigation Findings and Considerations

The investigation revealed much. In the Mission Control Center, the ITCS water side is monitored by Environmental and Thermal Operating Systems (ETHOS), the ammonia side is monitored by Station Power, Articulation, Thermal, and Analysis (SPARTAN), and the Columbus ITCS loops, (not the Heat Exchanger performance), is monitored by Columbus STRATOS - controlling the onboard power, thermal and environmental subsystems plus the onboard data and video subsystems.

The configuration at the time of the close call was that ammonia was being routed through the heat exchanger bypass line as a result of the initial EATCS loop A pump module failure. Water was not flowing through the heat exchanger on the ITCS side, and the heat exchanger heaters were disabled. The Columbus IFHX ammonia bypass and isolation valves were configured by the on-board automatic Fault Detection Isolation and Recovery (FDIR), routing ammonia through the IFHX bypass line. To protect the water in the IFHX core from freezing during an EATCS Large Leak Scenario, when the ammonia side is bypassed/isolated, the Columbus MTL IFHX Heaters were not enabled (controlled by MOD/ETHOS). Columbus IFHX heaters are nominally inhibited due to high setpoint. At the time, no Flight Rules/Procedures drove ETHOS to activate the Columbus IFHX heaters after IFHX water flow was terminated.

Analysis revealed several findings as to root cause(s), and recommendations/corrective actions were made.

- Cause 1: Hazard Reports (HRs) don't characterize the potential side effects of operating the ETCS in Startup Mode for an extended period of time. The ATCS models were insufficient to analyze a long term supply of cold ammonia through the bypass leg of the heat exchanger. And use of IFHX core heaters was not included in the Columbus IFHX bypass procedure. Recommendation: update the documentation (HRs, Flight Rules and Chits).
- Cause 2: The existing analytical tools are insufficient to support console decisions. Recommendation: update thermal models and procedures.
- Cause 3: System architecture deficiency fails to preclude freeze or does not give indication of freeze/rupture/thaw of Columbus IFHX. There is no formal requirement to protect the core from freezing in the event of cold ammonia flow through the bypass leg of the IFHX and current sensor locations can't directly measure the IFHX core temperature. No direct measurement of the IFHX core temperature exists given current sensor locations. Recommendations: Upgrade advisory to "Warning" based on IFHX temp. Assess on-board FDIR modifications to prevent an IFHX core freeze. Evaluate IFHX core heater set points, automated safeguards and operating limits and implement changes.
- Cause 4: Lack of institutional system knowledge to initiate correct actions to preclude the close call scenario. The procedures were wrong – the teams genuinely thought they were doing the right thing by stopping ITCS water flow through the Columbus IFHX, but in fact, this lead to the core reaching temperatures near freezing. Implementing Chit 11714 (to stop ITCS water flow through the Columbus IFHX) was deemed the correct action given what teams knew at that time. In hindsight, stopping Columbus ITCS flow through the Columbus MT IFHX led to the IFHX core reaching temperatures near freezing. Recommendation: update console training and procedures.

- Cause 5: Console teams (MER, MOD) failed to institute best practices of off-nominal operations. The operation of the EATCS loop outside experience base without scrutiny and having multiple teams working parallel efforts - Team 4 (EVA, PM Troubleshooting, Orb, etc.) - prevented focus on core temperature telemetry or considering the unique on-orbit configuration for a potential issue. The bigger picture went unseen. Recommendation: Assess updating FDIR, warning notifications and core heater set points. Update training for console teams.
- Cause 6: Ops Console and procedures were not available to prevent thaw of a frozen IFHX. Recommendation: Update procedures and Flight Rules.

An Investigation Final Out brief was held at Space Shuttle Program Control Board on April 8, 2014. Actions were assigned to assess if other areas of ISS are susceptible to common causes, including: surveying the ISS System Managers, the safety community reviewing existing ISS Integrated HRs with catastrophic consequences, and the Operations community reviewing operations organization controls of integrated catastrophic hazards.[8]

There are multiple considerations when undertaking such an investigation:

- **Being Thoughtful about Determining Root Cause or Proximate Cause.** Which is the objective? Understanding and knowing the difference between the terms root cause and proximate cause and whether to pursue a failure beyond proximate cause is crucial.
- **Have a clear goal**
  - What is being examined?
  - Is this critical?
  - If not critical, could it affect something that is critical?
- **Know the Right Questions to Ask without Attaching Blame.** There is no blame to be assigned; the intent is to fix the problem and make sure it doesn't happen again.
  - How did this happen?
  - Why was this not caught?
  - Were there signs that there was an issue?
  - How can this be avoided in the future?

- **Soft Skills Count.** Engineers are not considered adept at what are referred to as soft skills. Soft skills encompass character traits that decide how well one interacts with others: reading body cues, conflict management, and dealing with difficult people. It has been suggested that in a number of professions, soft skills may be more important over the long-term than occupational skills**.**
    - Create a hospitable environment for everyone so people are willing to participate.
    - Ensure everyone sees themselves as part of the solution.
    - Know how to talk to people so they don't feel attacked.
    - Listening skills count. Let interviewees speak without interruption.
    - Know how to successfully deal with uncooperative individuals.

References

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