48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico
ICES-2018-297

The ISS TCS System Manager Experience

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The experience of being a System Manager (SM) during the early years of the International Space Station (ISS) Program is probably similar to the experience a future SM will have in an international exploration or commercial space program. Thus; it is relevant to provide an overview of the ISS SM experience to inform future SMs of the scope and nature of the role. Overviews of the connection to the Space Station Freedom (SSF) Program and the political environment at the start of the ISS program are provided. The scope of the ISS Thermal Control System SM role is then described via the system architecture. How the ISS program was initiated, what the SM roles were and how those roles evolved as the program proceeded are addressed as are interactions with US contractors, NASA centers, and International Partners (IPs). The SM involvement with the Russian Mir Program is described with some of the lessons learned during that NASA/Russian program. The interactions with IPs are described with several anecdotes of how interacting with counterparts in Russia, Europe and Japan was accomplished. Several challenges to the technical content of the TCS system are provided as examples of how the ISS TCS design evolved to address problems. Finally, some lessons learned are provided along with recommendations on how to prepare to be a SM for a future program.

Nomenclature

ARC = NASA Ames Research Center – Moffett Field, CA
ATCS = Active Thermal Control System
CAM = Centrifuge Accommodation Module
CDR = Critical Design Review
C&DH = Command and Data Handling (system)
CTSD = Crew and Thermal System Division (of NASA JSC)
COF = Columbus Orbiting Facility
DCAA = Defense Contract Auditing Agency
EATCS = External Active Thermal Control (System)
ECLSS = Environmental Control and Life Support (System)
EEATCS = Early External Active Thermal Control (System)
EPS = Electrical Power (System)
ESA = European Space Agency
EVA = ExtraVehicular Activity
FCS = Flight Crew (System)
FGB = Functional Cargo Block – Russian module developed for Boeing
GN&C = Guidance, Navigation and Control (System)
GRC = NASA Glenn Research Center – Cleveland, OH
GSFC = NASA Goddard Space Flight Center – Greenbelt, Maryland
HQ = NASA HeadQuarters – Washington, DC
HX = Heat Exchanger
HW = Hardware
IATCS = Internal Active Thermal Control (System)
ICES = International Conference on Environmental Systems
INIK = IATC(I) Sodium-Hydroxide(N) Injection Kit
IP = International Partner
ISS = International Space Station
JAXA = Japanese Aerospace Exploration Agency
JEM = JAXA Experiment Module

JEM LM = JEM Logistics Module
JEM EF = JEM External Facility
JPL = (NASA) Jet Propulsion Laboratory – Pasadena, CA
JSC = NASA Johnson Space Center – Houston, TX
JTWG = Joint Technical Working Group (for Space Shuttle and ISS integration)
KSC = NASA Kennedy Space Center - Florida
LeRC = NASA Lewis Research Center (now GRC)
LESC = Lockheed Engineering and Science Company
MDAC = McDonnell Douglas Astronautics Company
MEIT = Multi-Element Integration Testing
MMOD = Micro-Meteoroid and Orbital Debris
MSFC = NASA Marshall Space Flight Center – Huntsville, AL
NaOH = Sodium Hydroxide (used to raise pH in water coolant systems)
NASA = National Aeronautics and Space Administration (USA)
N2 = ISS Node 2
PDR = Preliminary Design Review
pH = percent Hydrogen
PPCO$_2$ = Partial Pressure of Carbon Dioxide
PTCS = Passive Thermal Control (System)
PV = PhotoVoltaic
PVATCS = PV Active Thermal Control (System)
RID = Review Item Disposition
RSOS = Russian Segment Operational System
SM = System Manager
TCS = Thermal Control System
TCSR = Technical, Cost and Schedule Review
TIM = Technical Integration Meeting
SSF = Space Station Freedom
SSP = Space Shuttle Program
S&M = Structures and Mechanics (System)
USOS = United States Operational System (US, European and Japanese parts of ISS)
USL = United States Laboratory
USSR = Union of Soviet Socialists Republics
WP = Work Package (Assignment of the development of parts of the Space Station to a NASA center and associated contractor organization)

I. Introduction

THe experience of being chosen to lead the development of the ISS TCS, then leading the design and development and implementation of the system was challenging, invigorating, and critical to success of the ISS program. NASA planning for future missions includes international projects to explore the moon and Mars. Such programs will involve many of the challenges and processes that the ISS program experienced and implemented successfully. Additionally, commercial space programs will include many processes that the ISS program used to implement commercial space exploration and exploitation. There are many changes in the ways programs are implemented now versus those used during the ISS program. Also tools available to engineers have evolved and those will be used in accomplishing program objectives. However, the scope of work that needs to be accomplished and the experience of being proactive to establish what needs to be done and how to get it done will be similar to how the ISS program system managers accomplished development of their parts of ISS. Related to that connection between the past ISS and future international exploration programs, it is appropriate to provide an overview of what the experience of designing, developing and implementing the ISS TCS be provided to those that may perform the system manager role for future programs.

The intent of this paper is to provide an overview of the experience of being the focal point for developing the ISS TCS. It is hoped that those reading this paper will have a clearer perspective of what the role of such a system lead will be like in future exploration programs.

The first 10 years of the ISS program are addressed during which the ISS

1) program initiation,
2) concept definition,
3) the mode of operation to define design details and manufacturing processes,
4) integration with the shuttle launch system,
5) planning for assembly of the ISS elements,
6) integration with International Partners (IPs)

was accomplished.

That period from 1994 to 2004 included the first 6 years during which the author was the lead for ISS TCS and a period from 2000 to 2004 during which the author was deputy system manager for ISS TCS.

The circumstances leading to the start of the ISS program will be provided along with the status of the author going into the ISS program. That will provide a perspective of events leading to selection of the author for the role and how the role was defined and implemented.

Most of the experiences from the development of the ISS TCS will be relevant to future programs since the design, manufacturing, management, contractor integration and international space organizations interactions will be required of any future major space exploration program.

II. History and Environment at the start of the ISS program

The ISS program was initiated in 1994 after the prior space station program (the Space Station Freedom (SSF)) program had been canceled. The SSF program had established a design but was primarily a study program. The SSF design had evolved but the SSF TCS system (still in definition at the end of the SSF program) was to implement a two-phase central TCS system. The author had participated in the SSF program by supervising a group of system specialists contributing to evaluation and definition of the concept and selection of technologies to be used.

The SSF program was organized into a Level I organization that established the concept, a Level II that addressed content, and 4 Work Packages (WPs) that split work into logical blocks. WP1 was based at NASA MSFC and employed Boeing to develop a US laboratory; WP2 was based at JSC and employed McDonnell Douglas to develop the integrated truss and connect elements, power systems; WP3 was based at NASA GSFC and addressed payload definition and integration; WP4 was led from NASA GRC (then LeRC) and employed Rockwell Rocketdyne to develop power systems.

The SSF program had participation from the US, Canada, the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency(JAXA). The role of the NASA JSC part of the SSF program included level II integration with IPs to ensure compatibility of IP element's TCS with the central ATCS to be provided by the USA.

Meetings held at NASA HQ had established that the ISS TCS would use a single phase External Active Thermal Control System (EATCS) since the two-phase options were thought to be too challenging to be successful.

A. The International Political Climate

A remarkable transition was taking place in 1994 involving the dissolution of the Union of Soviet Socialist Republics (USSR) into separate countries and the end of the cold war between western blocks of countries and USSR connected countries. Russia had developed significant space faring capabilities including operating the Mir space Station. The USA was operating the Space Shuttle Program (SSP) and was operating in space routinely.

The Mir space station provided an opportunity to gain long term on-orbit experience and a spacecraft construction approach that included a building block of a core module that was self-sufficient onto which other elements could be connected. The Russian space expertise developed by the USSR was viewed as a capability that should be integrated into the new ISS program both due to the technical capability it offered, and to make use of that capability by terrorist organizations less likely.

The independent module used to start the Mir program was employed by ISS as the starting block. Other ISS modules could be devoted to the purpose they were designed for without the burden of including systems needed to exist in space while other elements are in delivery. NASA obtained the Functional Cargo Block (FGB) module from the Russian company Energia by purchasing it via Boeing.

B. ISS Organization

The ISS program assimilated the work package organization used in the SSF program with substantial changes (notably for TCS, the change to a single phase EATCS instead of the SSF two phase concept). Level II and WP2 were merged at JSC to form the ISS Headquarters office located at JSC. The author joined the ISS program office at JSC as the System Manager (SM) for ISS TCS. The role of System Managers was to understand and approve the technical content of their system and confirm that the resources proposed to build it were adequate.

The author's deputy was then Gerald Esquivel but later Tim Bond became the TCS Deputy and Marie Kowal joined to manage the ISS Passive Thermal Control Systems (PTCS). That small cadre of engineers was responsible for NASA guidance of the development of the ISS TCS. We were supported by a prime contractor, Boeing who was responsible for implementing NASA plans for ISS development.

Bartering became a mode of operation for international partners to provide parts of ISS in exchange for US launch of their parts of ISS in the Shuttle.

C. Author history and situation going into the ISS program

There will be some similarities between the career path followed by the author and that of a future program SM. There will certainly be differences but in some ways parts of the career path will overlap.

The author had recruited a team of engineers to support SSP TCS subsystem managers and had been involved with all design reviews and even organized Technical Interchange Meetings (TIMs) with IPs from ESA and JAXA. However, in the Fall of 1993 the author's company Lockheed Engineering and Sciences Corporation (LESC) won a recompetition for the NASA JSC engineering and sciences support contract and after the win, the author and many others on the proposal team received layoff notices! The author's response was to identify some 17 alternative career paths including accepting a temporary lower salary while pursuing alternatives. It's interesting how things work out because the lower salary made it feasible to accept a comparable NASA salary to be the program lead for development of the ISS TCS.

The author had been involved with the International Conference on Environmental Systems (ICES) for many years at the start of the ISS program. During the summer of 1993 the author had agreed to lead the parts of the ICES conference related to TCS. That meant that the author was committed to attending the 1994 ICES which was to be held at an international venue for the first time (Friedrichshafen, Germany). When the author accepted the NASA ISS TCS SM role he announced that he was committed to international travel and thus was going to need to have an expensive international trip early in his ISS role. The response was "As ISS TCS lead it was very appropriate to travel to an international conference to lead TCS parts of the 1994 ICES". An awkward situation was easily resolved.

III. The ISS program startup

The 9 ISS systems SMs got started communicating with the new ISS program organization. Since all the ISS program was getting underway, there was little direction to the SMs, so we were very proactive in our efforts. We knew we were in charge of our parts of ISS but exactly what that meant was to be clarified over the next few years.

We moved into the new JSC building 4 South as the initial occupants (along with the astronaut corps) as the NASA Level II headquarters organization based at JSC. The ISS program office was intentionally very lean to limit cost. The TCS team consisted of the author and 1 support engineer.

We had been selected because each of the 9 SMs had knowledge of the SSF program, had exposure to what system managers did (via the SSF and Space Shuttle (SSP) programs); knew the content of the SSF program, knew the management structure of the SSF program and we all had some management experience. We knew we had to be proactive to figure out what to do.

D. ISS Proposal Evaluation

The evaluation of a semi-truck size proposal from contractors to do the United States Operational Segment (USOS) part of ISS work began immediately. The proposal was an integrated response to the NASA ISS Level II call for ISS work. Each of the SSF WP organizations provided proposals for the scope of the work that had been their part of the SSF program – but tailored for the technology content of the new ISS program.

The author had been involved with 11 contractor proposals to NASA and thus had experience with proposals to NASA. But this NASA role was new since the author was serving as the source evaluator for NASA for the ISS TCS. We evaluated the proposals from Boeing for the prime contract for today-to-day management of the ISS program and for the United States Laboratory (USL)(WP1); from MDAC for the WP2 truss structure (but with a single-phase ammonia system for External Thermal Control Systems (EATC)); from Rockwell for the WP4 power systems; and from Grumman for payload systems (deemphasized early in ISS to focus on more critical ISS systems).

The ISS TCS system encompassed all thermal systems of ISS – all actively and passively controlled systems for the USOS parts of ISS (including ESA and JEM modules) and the Russian Segment Operating Systems (RSOS). The initial focus was the US parts of the USOS and after 2 months of proposal evaluation the author had concluded that the nearly $1 billion cost of the USOS proposed TCS could be reduced by nearly $200 million dollars. Some proposed work was viewed as not essential and some work proposed by the WPs and the prime contractor overlapped. With that position established; the team of ISS SMs hit the road to negotiate with WP contractors to determine what reductions could be accepted and what parts would need to be kept as bid. We met at the major contractor sites at Huntsville, AL for WP1; Huntington Beach, CA for WP2; and Canoga Park, CA for WP4. We also worked with Boeing the prime contractor at JSC and later worked with major subcontractors on issues.

At the end of the contract negotiation process the cost of the TCS was nearly $200 million dollars reduced and the total ISS cost was reduced from nearly $10 billion to $8.4 billion to manufacture the USOS elements and systems and integration of such. Much larger cost numbers related to ISS integrate the development of equipment (the $8.4B of the core ISS work) with the launch and operations cost.

Congress approved the ISS plan and budget by a 1 vote margin!

E. Changes to the design

We had agreed to the ISS cost and scope of work – however; no organization had ever attempted such a large and complex development. Even with 7 years of a relatively low level of SSF as the basis for ISS we started realizing via review of design details and operational plans that:

1) things didn't work together as seamlessly as envisioned (but we knew that would be the case – realism),
2) some planned operations couldn't be accomplished via the top-level plans,
3) new levels of sophistication were required to make systems work and meet evolving requirements,
4) IP contributions needed changes to be compatible with the USOS,
5) ISS needed to do more than initially planned to accomplish goals.

As of 2018, over 13,000 changes have been approved and implemented. Most of those were small but some were really large with one TCS change costing over $32M.

F. ISS Organization

In 1994 the ISS was organized with TCS as one of 9 systems and also launch packages to integrate parts of ISS that would be launched on each shuttle or Russian launch. The 9 systems were: TCS; Power (Electrical Power Systems (EPS); Command and Data Handling (C&DH); Structures and Mechanisms (S&M); Communications, Tracking, Guidance, Navigation and Control (GN&C); Propulsion (Prop); Environmental Control and Life Support (ECLS); Flight Crew Systems (FCS) and ExtraVehicular Activity (EVA). Each of the 9 ISS systems addressed development of equipment within that system and integration across systems. Interfaces between systems were established and documented so that responsibilities were well defined.

TCS, EPS and C&DH were connected to nearly all other parts of ISS and relied on each other to implement their system function. Those 3 systems were thus the focus of an ISS systems study to address stringing (interdependency) of systems. That information was used to organize each system to prevent a failure in one string of any of those systems from resulting in failures in the other systems. The system modifications made to ensure system interoperability was one of the significant changes early in ISS development.

G. TCS System Functions

Since this paper focuses on the experience of being the TCS SM during the Early ISS design and development and because the ISS TCS has been described in many earlier ICES papers; only a top-level description of the ISS TCS is offered here.

The function of thermal control is to maintain thermal conditioning and applies to all parts of ISS. The TCS SM role is to ensure that all parts of ISS accomplish that requirement during all phases of operation (pre-launch processing, the launch and assembly environment, during assembly and for each phase of operation as part of the ISS). The ISS TCS accomplishes the maintain thermal conditioning function by passive thermal control when possible and active thermal control involving acquiring waste heat, transporting the heat to heat rejection systems that reject the heat to space. The ATCS of ISS was divided into:

1) An independent ATCS for Russian elements,
2) Internal Active Thermal Control Systems (IATCS) for US, ESA and JAXA parts of the USOS,
3) EATCS to accept heat from each module and transport the heat to radiators for rejection to space (an Early EATCS (EEATCS) to address heat rejection from the USL before truss elements were launched to provide the final EATC capability), and
4) PhotoVoltaic (PVATCS) to maintain conditions in power producing wings of ISS.

PTCS was implemented when possible via coatings, orientation of parts with low heat loads and a semi passive heat pipe network for equipment in the first truss element. The following schematics are offered as examples of the connectivity of systems that accomplish the ATCS function.

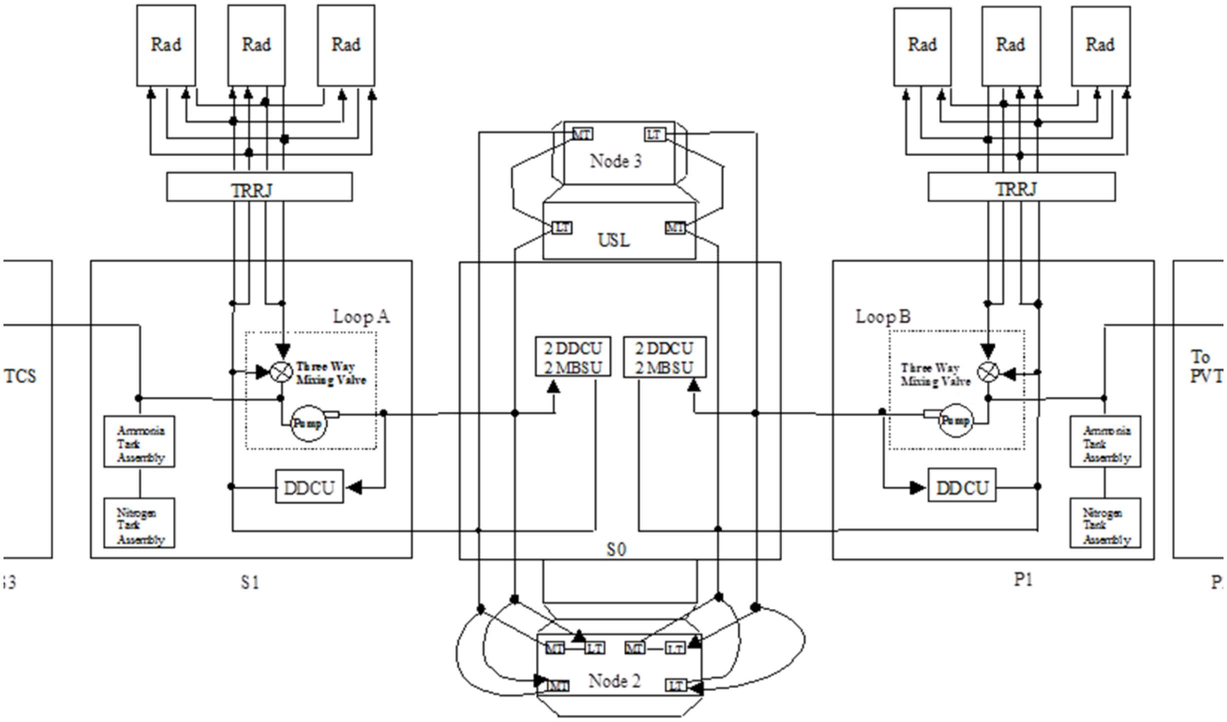


Figure 1 - Simplified External Active Thermal Control System Schematic

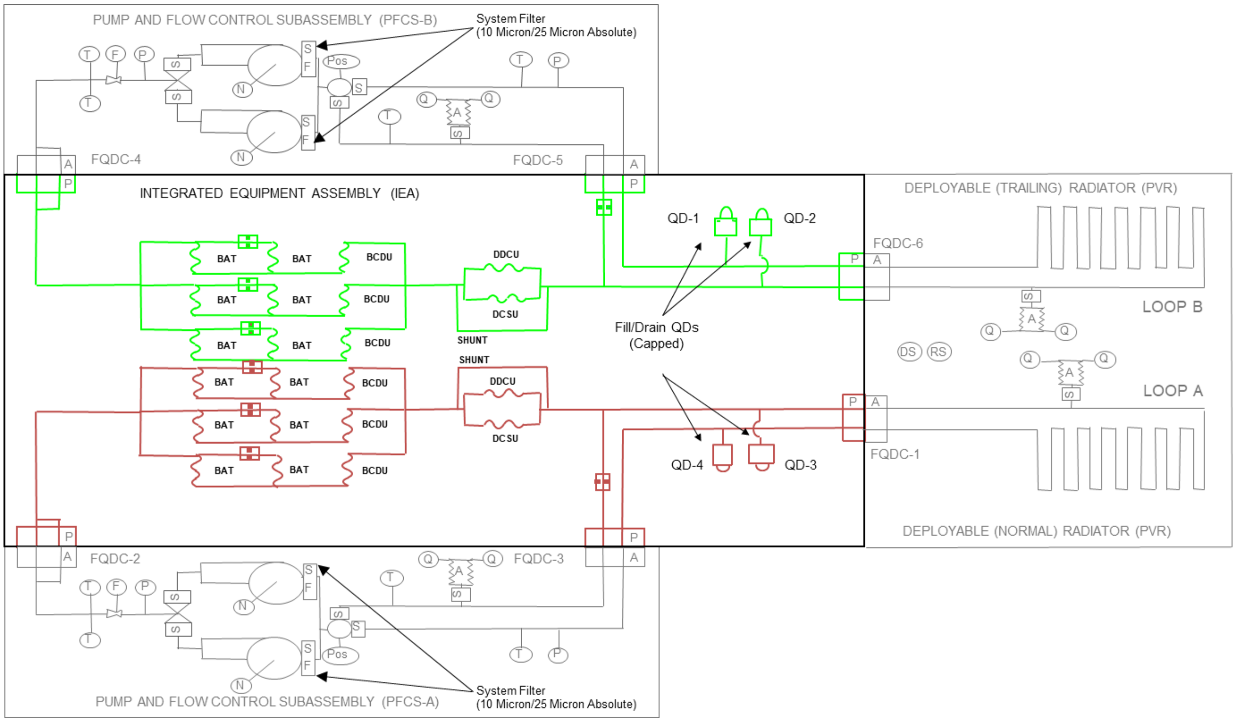
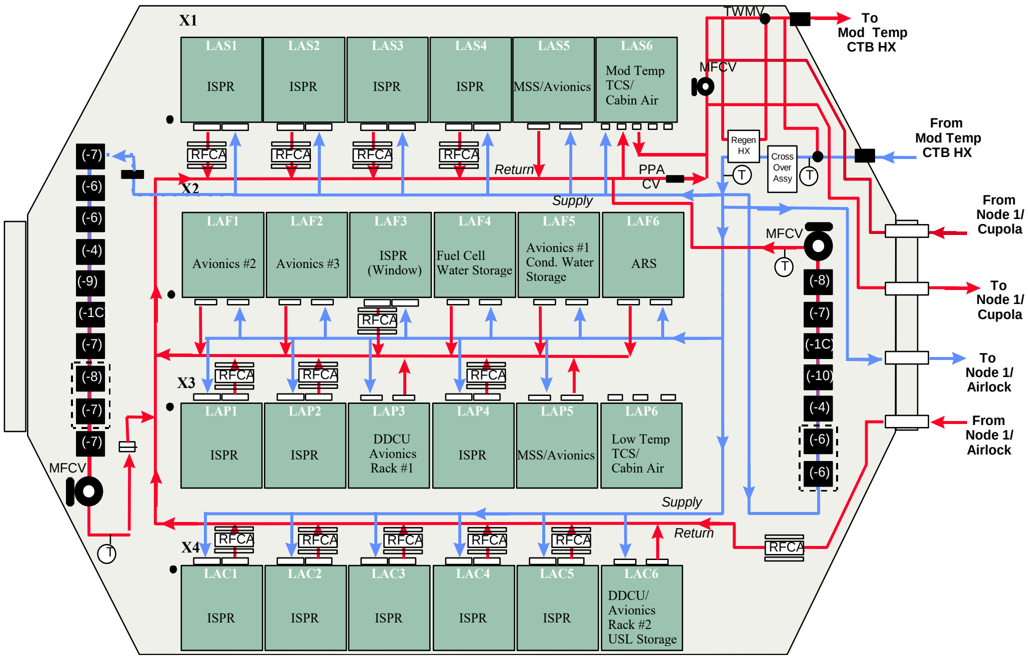


Figure 2 – Schematic of a PV ATCS Subsystem (one of 4)



ARS: Atmosphere Revitalization System
CTB: Central Thermal Bus
CV: Check Valve
DDCU: DC to DC Converter Unit
ISPR: International Standard Payload Rack
MFCV: Manual Flow Control Valve
MSS: Mobile Servicing System
QD: Quick Disconnect
PPA: Pump Package Assembly
RFCA: Rack Flow Control Assembly
TWMV: Three Way Mix Valve
Ⓣ Temperature Sensor

Figure 3 – Schematic of the USL IATC Moderate Temperature Loop

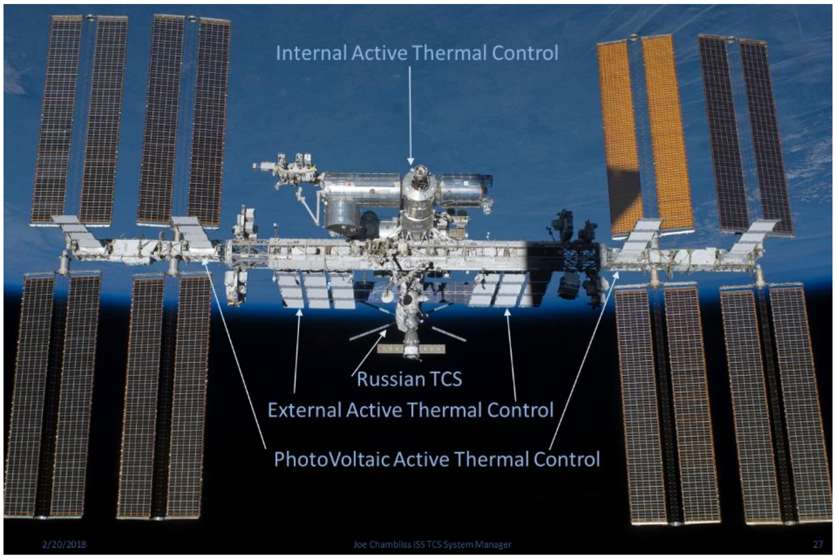


Figure 4 – Location of major parts of the ISS TCS

IV. How SMs got the job done

Communication is the key to getting integration and design and development work done. As TCS SM the author communicated with ISS management, contractors, subcontractors, and international partners. SMs interacted with ISS management to understand overall requirements and the mission plan. We worked with contractors to evaluate designs, get the plan implemented via manufacturing parts then integrating parts to build the system.

For TCS; the JSC ISS program office led the development as part of the HQ level II organization but we worked with other NASA centers for parts that those centers did the day-to-day management for. At JSC we continued to work with JSC engineering for support of WP2 parts of ISS and for integrated testing of the EATCS. We worked with MSFC on the IATCS for the USL and PTCS for the USL and Node 1 and on integrated IATCS. At KSC, as the launch processing center, on receiving equipment and prelaunch hardware processing and conduct of important Multi-Element Integration Testing (MEIT). Integrated testing was also done at NASA GRC (then LeRC) for both the PV ATCS and the EATC radiators. ARC was involved with technology development and the Jet Propulsion Laboratory was involved in leak location technology development. The Photo in Figure 4 illustrates the location of parts of the ISS TCS.

The NASA project management approach was used – the concept was established via the call for proposals; periodic data releases are used to track progress, each work package and each system used formal reviews (design reviews (Preliminary, Critical, and Acceptance) then Operational reviews for integration with the Shuttle, each launch and each stage of assembly.

H. Involvement with the Russian Mir Program and working with the Russians

As part of the plan to integrate Russian elements into the ISS; NASA got involved with the Russian Mir program in many ways. NASA extended US knowledge of long duration microgravity operations by interacting with Russian counterparts to understand the Mir design and by having US astronauts visit Mir for long duration stays. As ISS TCS SM, the author's role was to learn about the Mir TCS system via interacting with Russian counterparts. We established how the Mir TCS functioned and learned of problems that were experienced in the Mir.

On return from his mission on the Mir; Astronaut Mike Foale called the author to a meeting on his experience and outlined problems experienced with coolant leakage and condensation in the Mir after which the Mir TCS had to be shutdown. That meeting was used to establish lessons learned with the intent to prevent the possibility that ISS could have such problems. Mike had been inside Mir when a Progress vehicle failed on approach of the Mir and collided with Mir. That caused substantial damage of the Mir and almost led to abandoning Mir. Recovery of Mir functions included TCS changes to address damage.

Understanding of the nature of the Mir TCS was essential because that vehicle design was to be used for much of the ISS RSOS elements. Getting connected with the Russian TCS engineering organization during the Mir program made work on the ISS RSOS elements much more easily accomplished.

As the ISS TCS lead, the author had to approve the launch readiness of the Russian elements of ISS before each launch and that approval was based on knowledge of the Mir history and the ISS element design.

Until the ISS program, the last time NASA had worked with the Russians was during the Apollo Soyuz rendezvous mission in 1975. ISS established Russia as a key player in development of the ISS. Many TIMs were held at JSC to exchange information between NASA and our Russian counterparts. Follow-up telecons were held between the author and Russian counterparts to continue the process of each understanding the design and function of the other's systems. Due to the time zone difference telecons were generally held at around 6:00 AM US central time or 4:00 PM in Moscow. The prime contractor Boeing was integrated in the interactions both as support of NASA TCS efforts and as the owner of the development of the Russian FGB element that was being purchased from Russia (but was to be launched via Russian Proton rocket).

NASA was the most respected and accomplished space organization in the world but; the Russians were very accomplished also. Russian counterparts were the only ones that viewed their space efforts as independent of NASA's. However, in the ISS program, the Russians were in a contributing role while NASA was the ISS program lead organization. That arrangement led to interesting interactions.

As ISS TCS SM, one facet of the author's role was to approve the Russian elements for launch. Just 3 months before the launch of the first ISS element (the FGB) the Russians announced that they were going to use a coolant in the internal FGB ATCS that was not the coolant used on Mir. As TCS SM the author needed to know that the coolant would work; but the Russians wouldn't provide details of the new coolant because they considered it a trade advantage. The week before launch, NASA got the Russians to provide a limited release of information on the new coolant only to the NASA safety team. Based on qualified information only, the author was able to approve launch of the FGB.

In interacting with Russian counterparts, it was established that Russian TCS development was connected to US developments when the Russian reference for ATCS technology contained many references to ICES papers on US technology developments.

Russian interactions were followed usually by celebrations one notable one was held at a Russian testing installation around 60 miles north of Moscow. See the author if you want to understand more on Russian celebrations.

Interactions with Russian engineering counterparts was always open and productive; however, Russian management had other objectives including obtaining funding from NASA when possible.

I. Interactions with ESA

ESA interactions with NASA on ISS used the agreements and plan established during the SSF program as a starting point. The Columbus Orbiting Facility (COF) TCS design continued to evolve in the ISS program. The COF engineering team consisted of representatives from ESA HQ, Germany and Italy (with contributions from other ESA nations also). Several TIMs with ESA contributed to maturing the COF systems and the integration of COF systems with NASA provided parts of the USOS. As the design matured, meetings were held at the prime ESA contractor for the COF, Alenia in Italy. Alenia had participated in the Spacelab program as provider of the module that was flown several times in the space shuttle and the expertise developed and associations made during the Spacelab program were important to establish the credibility of the engineering provided by Alenia. Those meetings were a delight to participate in due to the competent engineers of Alenia and the organization of the TIMs and the celebrations of the accomplishments. Torino was a lovely and historic city and having meetings there occasionally provided the opportunity to tour that part of Italy. Running along the Po river in Torino with fellow NASA and Alenia engineers was great for bonding.

In the late 1990's a decision was made on building Node 2 that had dramatic implications for TCS. NASA was near the final stages of awarding the contract for building Node 2 to a US company when a barter agreement was reached with ESA. The agreement was that for future launch services for ESA provided parts of the USOS; ESA would provide Node 2. Node 2 was the hub of ISS for the TCS systems since it was to contain the Heat Exchangers (HXs) for the TCS for N2, the ESA COF and the JAXA Japanese Experiment Module (JEM). The author initially resisted the transfer of the development of such a critical part of ISS to ESA but the agreement was made at a top level and was complete. Working with Alenia on development of N2, the author became sold that ESA and specifically Alenia were very competent providers of N2. Most spoke fluent English and many were bikers and/or runners.

N2 development came with some dependencies for NASA USOS parts of ISS. Specifically, much of the N2 IATCS equipment was provided by NASA (contractors) to Alenia for integration. Additionally, the 6 water-to-ammonia interface HXs were provided to ensure commonality with the EATC system. Additionally, the IATC coolant to be used was to be common with the rest of the USOS. Since the development of the USL was well underway; the thinking was that any issues in developing the EATC and IATC systems of the USL would ensure that the design would be mature for use in the COF and JEM and N2.

During the first few months of operations of the USL problems were encountered that made the reliance on the NASA IATC systems a source of growing concern (see a following section on the IATC coolant problem). That made the job of the ISS SM very interesting when working with ESA and JAXA and continuing to assure them that the US would solve the coolant problem and they should continue to base the success of the TCS in their modules on the future US solution of the problem.

Driving in Turin was an experience. Going to Alenia in the mornings one would be going 4 cars abreast down a 2-lane city street going fast. Driving in Torino is challenging and fun. Turin is very close to the Italian, French and Swiss Alps. One morning during a TIM we were alerted that Alenia was going on strike; several of the NASA team and the author got in the author's rent car and the author drove to the Italian side of the Matterhorn. We hiked a while then learned that the strike was over at the end of the morning and speeded back to Turin for afternoon meetings.

NASA influences the curricula at several universities; but, in Turin, Alenia determines the curricula for many university courses and graduates become Alenia employees.

I attended several TIMs as one of the NASA system managers during vehicle design reviews but several others were devoted to the TCS design; and in those cases, I was the NASA lead for the TIM and I would bring a team of engineers from Boeing Prime and NASA MSFC IATC engineering.

J. Interactions with JAXA

Interactions with the Japanese intensified during the ISS program. Many of the JAXA engineers had participated in the SSF and the JEM design was conceptually established at the start of the ISS program. The Japanese were very enthusiastic but their program didn't initially recognize the benefit of a jet lag day. Thus, for the first days of TIMs in the US, we would notice that the Japanese would be fighting to stay alert. But they learned quickly and during the ISS program they became a spacefaring nation with not only their ISS developments but in their launch capabilities.

The Japanese Experiment Module (JEM), JEM Logistics Module and JEM External Facility represents one of the most capable parts of ISS.

Design reviews held in Tsukuba japan were intense with volumes of design data to address and only a week or two to have the reviews. Those events were very productive and we identified issues and worked on the solutions with our Japanese counterparts. Celebrations at the end of reviews were special – the Japanese offered an impressive buffet of Japanese foods many of which were completely outside the normal experience of those of us from the US.

When the author returned to the JSC engineering directorate in 2000 (along with all other system managers) part of the author's assignment was to be the first deputy branch manager of the EC2 branch of the Crew and Thermal Systems Division (CTSD). In that capacity the author was part of the management for the branch that included a brilliant engineer that later became an astronaut – Karen Nyberg. She is the only astronaut that the author can claim (kind of) worked for the author. The author was delighted years later when Karen became the first astronaut to enter the JEM during its activation. Later the author was the ICES lead in getting Karen to be the Plenary speaker for the Tucson ICES. The author advocated successfully for Karen to become one of the University of Texas Distinguished Alumni after her return from her long duration mission on ISS.

As lead for ISS TCS; the author got the assignment to coordinate engineering efforts of JAXA, NASA Ames and NASA JSC to address a condensation concern for the Centrifuge Accommodation Module. Under a barter, JAXA was awarded the role of provider of the CAM and NASA ARC was the lead center for the development of the module. The author led a team of engineers mainly at JAXA to address the problem of providing low temperature cooling to the rotating part of JEM wherein low temperature cooling was required for animal support. The team had telecons and several conceptual designs before arriving at a solution that the team took to ISS management for implementation. Shortly after solving the problem, the CAM project was canceled due to lack of funding. Nicky Williams/NASA supported the team with passive thermal control engineering and analysis and that experience was one factor that lead her to become a branch chief in CTSD.

K. IP language and Culture

NASA offered all SMs training in languages and customs of our IPs. Part of that training included insights into the context that individuals see their selves and their counterparts in their organizations. We learned in that training and then experienced the contextual thinking in interacting with our IP counterparts. The Europeans and Russians have what is thought of as high context wherein an individual is important because of his/her family or history. ESA and Russia saw importance as only obtained after years of experience and younger NASA leads had difficulty getting response from their ESA or Russian counterparts. The US and Japanese have what is thought of as low context in which an individual is important because of his/her accomplishments.

The Russian language has very few ambiguous sounds in their Cyrillic alphabet and, once the alphabet is learned; the author found that one can sound out words and actually correctly interpret Russian signs.

Gender acceptance is different in IP organizations. NASA has been a leader in recruiting and integrating female engineers into organizations. IP organizations (at the time of ISS development) had only recently started considering female engineers as capable of contributing to their organizations (at the start of ISS). Several of the very capable female engineers of the NASA team had difficulty working with their counterparts in IP organizations. During the ISS program progress was made in NASA and IP organizations in integrating female engineers into our organizations.

Similar progress was experienced in IP organizations when they experienced NASA counterparts that didn't smoke. Many of our counterparts smoked at the start of the ISS program but smoking was rare as interactions continued.

L. Interactions with Contractors

NASA SMs interacted with US contractors at several levels with the prime contractor Boeing, the work package contractors, and we would interact directly with companies on many levels. For major products like PDR, CDRs and acceptance reviews we would go to contractor locations. We led teams of engineers to review the large data packages and determine if there were any flaws with the design or implementation plans. Once Review Item Dispositions (RIDs) were resolved; the approval to proceed with final design (for PDRs); manufacturing (for CDRs); or accept products (for acceptance reviews) was granted for each system. Some integration reviews were held at JSC since several WPs or contractors had to be involved.

We also had many focused reviews to resolve problems or address technical issues.

The author developed a good connection with several Defense Contractor Auditing Agency (DCAA) representatives. Those on-site engineers would monitor the day-to-day operations and expenditures of the major contractors and subcontractors and would share their reports with the author as the SM for TCS. In addition to many plant visits; the DCAA reports provided essential information on the conduct of ISS work without the need to travel.

At the start of ISS; 4 work packages were with 4 contractors, Boeing for the Prime ISS contract and WP1, McDonnell Douglas for WP2, Grumman for WP3 and Rocketdyne for WP4. As the ISS organization matured; Boeing acquired Rockwell then MDAC thus interactions became only with the larger Boeing organization. That simplified interactions but reduced alternatives and thus the price of changes went up. TIMs and design reviews were held at the contractor plants or at JSC. We also had lots of interactions with major subcontractors which for TCS included Hamilton Standard, Ling-Tempco-Vought and Honeywell and even with sub-sub-contractors for important and problematic equipment such as valves and Quick Disconnects. Several of these companies changed their names during the ISS development and SMs had to keep up with the changes to correctly interface with each.

The closest support for the ISS TCS development was the prime contractor. According to the plan NASA was to remain very lean with very few engineers and much of the development was to be coordinated by the prime contractor Boeing. The author worked very closely with the prime contractor team and at times the boundaries between NASA and prime contractor work became blurred since we worked as a unified team. Especially important was deferral of most of the work to interact with the Russian organization Krunichev in developing the Functional Cargo Block (FGB) starting module of ISS. Boeing was funded by NASA to purchase the FGB from Krunichev to be the building block to start assembly of the ISS. Only rarely did the author get involved with the FGB development while the prime contractor lead (Roberto Duffy) spent months in Russia interacting with Krunichev.

The author met with the prime contractor weekly and participated in all the prime contract Technical, Cost, and Schedule reviews (TCSRs).

M. Interactions with the Operations, Astronauts and the Space Shuttle Teams

To translate the Concept of Operations for ISS into the details it takes to get it built and operate the systems, the details of handling the TCS equipment from manufacture, to delivery, to integration for launch, then deployment from the shuttle to become part of the ISS, and initiate operations required that every detail of each step be addressed and planned. As TCS SM, the author led teams in discussing how to address handling of the equipment and the steps required to get the parts integrated into modules or truss structure and then flown to and attached to ISS and finally initiate operation of the equipment to start to provide the thermal control the ISS needs. Teams to address those facets of ISS assembly included the engineering team, operations team members assigned to support TCS, management and the astronauts that would accomplish the final assembly and initial activation of the parts of the TCS.

As leader of several teams to address assembly processes and resolve issues one has to imagine the details of each process including each move and operation that an astronaut would make; the operations that come from the C&DH system and the operations done from ground controllers (via telemetry). Results of team activities would be brought to ISS program boards both for ISS and for the shuttle program that played a very important part in the process. Many of the plans resulted in checkout of the feasibility of the plan and training to implement the plan in such simulations as the Neutral Buoyancy Laboratory testing. The TCS team was involved in all those processes. All astronauts on those teams have subsequently flown to ISS and helped to implement the plans.

To address the many interactions that ISS had with the shuttle, particularly for the TCS system, a Joint Technical Working Group (JTWG) was formed. The author was the ISS lead and a good friend (that the author worked with for many years in the shuttle program), Rick Miller, was the Shuttle program lead. We held weekly meetings on the operations and interactions between ISS and Shuttle for nearly all of the 10 years this paper addresses. We addressed operations, identified issues and called for analyses, developed teams to conduct assessments and model the interactions. Results were presented at ISS boards and at Shuttle boards and at joint boards on occasion. The shuttle was the way most of ISS arrived in orbit and started assembly and it was important to address the details to confirm plans would work.

Interactions with the astronauts was a highlight of being the TCS SM. There was a lot to address and that required a lot of work with the astronauts. The author reviewed a list of those that have flown in space and identified well over a hundred astronauts, cosmonauts and other international astronauts that the author has worked with. Most of those were crew that the author worked with during times he led the ISS TCS but some were from times the author worked with astronauts to develop shuttle flight procedures.

V. Examples of TCS problems addressed during the early ISS development period

There were several hundred changes to the TCS plan for ISS that addressed things as mundane as a change in the testing to prove a part could tolerate the extreme ISS environment, to solving the most critical of ISS failure modes - the possibility of leakage across the single barrier inside the interface HXs that would result in high pressure ammonia entering the IATC coolant loops and then leaking into the habitable parts of ISS making the atmosphere toxic to the crew. In this paper, the author will provide an overview of a few selected issues as examples of some of the issues we addressed.

The possibility of a HX rupture was one of the top ISS issues

As the top issue to ISS operations the HX rupture failure got attention at all levels of ISS management. One change addressed implementing controls that would make the likelihood of such a failure tolerable cost $32M. The author addressed that issue many times with ISS management including many meetings with then Vehicle Office manager (now late) Jay Greene. Many will probably agree that Jay was difficult to work for due to his intimidating style of management. The author will agree with that view but also acknowledges that such a personality had its place in an organization that needs a forceful approach to getting things done.

Probably the most stinging failure of the author was the inability to get the interfacing HXs replaced with a design that has two barriers to prevent HX rupture. The team pursued development of the dual barrier HXs and got as far as completing development units. When pressed to accept changing the operating HXs on ISS with the dual barrier HXs; ISS management wouldn't fund the change. Future spacecraft should start with a dual barrier HX design as a requirement to eliminate the possibility of a catastrophic failure.

MicroMeteoroid and Orbital Debris (MMOD) protection of exposed TCS parts

A top concern for the TCS system was that the exposed parts of the system might sustain damage due to impact from MMOD. We engaged parts of the ISS organization tasked to quantify the MMOD risk and likelihood of such an event. They conducted testing using simulated MMOD fired at samples of TCS equipment to understand the risk of failure should such an event occur. Based on that information, models were developed and those were used to predict the likelihood and rate of events. The TCS has to have parts of the system exposed to the MMOD environment to reject heat to space. Using the information from the MMOD team, we changed several parts of the design to protect critical tubing to the extent it was possible. In addition, we planned how to address such a problem should it occur. The author had provided the plan in an ICES paper presented in San Antonio in 2002[1].

The planning of how to respond was beyond the scope of any of the work packages and thus NASA became the agent to develop and implement a design and development ways to fix such a problem. The author led those efforts. Part of that plan included getting precise data on the implementation of the TCS system. Another part included getting data on the system as implemented. The author joined by KSC and Boeing engineers led an effort to enter the truss structure and USL as they were being readied for flight at KSC to conduct a survey by actually entering those parts of ISS and having a photographer document the final configuration before those elements of ISS were launched.

Fortunately, the predictions of MMOD hits were conservative and the rate of bombardment has not occurred at the rate predicted. However, MMOD has hit the ISS many times and some of those hits could have caused damage. Figures 6 and 7 show how the operations TCS team has evaluated a MMOD hit on a radiator panel and confirmed that the penetration of the radiator panel did not hit a flow passage.

Figure 6 – MMOD damage to an ISS radiator panel

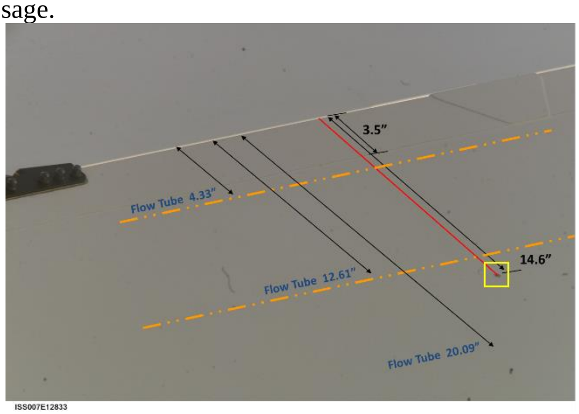


Figure 7 – Dimensional assessment showing that the MMOD hit missed radiator flow tubes

Sea level atmosphere in ISS didn't control CO_2 pressure to sea level

Having designed the IATC system to function in the advertised sea level atmosphere inside all of the ISS modules seemed straight forward and testing concluded the IATC design was functional in a sea level atmosphere. In 2000, the USL was launched and became part of the ISS. Part of the HX risk reduction mentioned earlier included developing a way to test the IATC coolant to confirm that no small leaks of ammonia were occurring and that IATC coolant remained within specifications and thus equipment would operate as planned. The first sample taken during that mission showed coolant was within specification. Flights after the USL was launched, were frequent and thus we had opportunities to return samples of coolant frequently. Results were not expected and quickly caused alarm as the coolant was quickly becoming more acidic. The issue quickly became the top issue of ISS because the coolant going out of specification meant that the risk of corrosion of system parts leading possibly to HX breach jeopardized the operation of the centerpiece of the ISS, the USL. Expertise that the author or the TCS organization didn't have was needed. Experts from all over the US, inside NASA, in the contractor community and in US academic organizations were called to task to determine what was happening and how to address it.

It was quickly determined that the Teflon hoses used to connect and enable easy replacement IATC plumbing to all the racks was permeating CO_2 into the coolant. Results didn't match ground testing because ground testing was at sea level conditions whereas inside the USL the Partial Pressure of CO_2 ($PPCO_2$) wasn't maintained at sea level (because CO_2 collection equipment functioned more efficiently at higher CO_2 levels). More CO_2 was permeating into the USL IATC all the time and pH levels were continuing to go out of specification.

An IATC coolant chemistry team was assembled, led by the author, to address the situation, conduct additional testing and develop a solution. Working with ISS management the author quickly got the resources needed to assemble the team and conduct the research needed to isolate the problem and develop a solution. The team met frequently and developed many possible approaches to address the problem.

One partial solution was to chemically adjust the pH of the coolant by adding Sodium Hydroxide (NaOH) (as is done on the ground). That approach was approved and a project was initiated in the fall of 2000 within the NASA JSC CTSD. The need was urgent and the team assigned to develop an IATCS NaOH Injection Kit (INIK) got to work. In probably the most expedited effort ever in the space industry, the team got underway and developed a concept, built the space qualified HW, and addressed all the safety concerns of carrying a toxic chemical within the space shuttle within 3 months. The INIK was cleared for launch in the shuttle and was delivered to KSC for launch in early spring. The INIK was integrated into the shuttle cabin and readied for launch.

In parallel at MSFC, testing of the IATC with increased CO_2 around flex hoses was underway. Once conditions had been established to be like the coolant in the USL the final test was conducted to test the solution of using the INIK to increase the coolant pH. Good fortune was with the program because the final test happened around 1 week prior to launch of the INIK. The test produced immediate precipitation of corrosion products in the coolant and caused the ground IATC test loop to fail as precipitation products clogged several components.

The INIK wasn't the solution and couldn't be used on ISS. But launch processing was too far along to remove the INIK from the shuttle. The INIK was launched and stored on ISS until a return flight could return it to the ground.

The author had the role of keeping ESA and JAXA informed of progress since they were to use the same IATC coolant.

The IATC coolant chemistry team continued to meet and eventually developed products to remove the corrosion products; adjust the coolant chemistry and develop and implement a new coolant chemistry to address ISS conditions. Those developments happened just in time to be implemented in the COF and then the JEM.

$PPCO_2$ mattered to the IATC of ISS! A system integration problem escaped recognition as a problem until flight!

IATC Pump Failure and the Columbia Disaster Recovery Team

Early in 2003 the author volunteered to be part of the search and retrieval team to recover parts of the Columbia shuttle following the disaster over east Texas. The IATC was in stable operations after many steps to recover from the coolant chemistry issue were implemented. On arriving in Lufkin, Texas on Sunday afternoon to join the team for 2 weeks, the NASA recovery team leads notified the author that the USL Low Temperature Pump had just failed. The author was still the NASA team lead for the IATC at that time so the author had to work the solution and failure recovery from the forests of east Texas. The recovery teams had set up temporary cell phone towers over East Texas for use during the recovery and those enabled the author to communicate with the IATC team periodically to organize the IATC pump failure solution. On return to JSC two weeks later, the author finished the clearance for launch of a spare IATC pump via the next Russian Progress launch (quite a feat and a demonstration of the robustness of the international ISS organization). Corrosion products had contaminated parts in the pump causing it to fail. Nickel removal components were deployed to remove corrosion products from the coolant.

VI. Workload of an ISS SM

The workload of an ISS SM during the early days was intense. The proactive approach identified things that needed to be attended to and insights into the flow of activities going on in the ISS program provided a sense of the time criticality of work. Many parts of the ISS organization were also developing schedules for products needed to support ISS milestones. There was always a combination of self-generated actions to guide the TCS team and actions other parts of the organization imposed. Early in the ISS program, reviewing and developing a posture on the proposals was the focal point and the need to get that accomplished so that the program could get started was the top priority. Later getting details on the design and evaluating and critiquing the design became a priority. Once the content and design were established the focus of SM efforts was on monitoring the progress toward developing, and the resources needed to produce, ISS products.

Scrubs of mass, power, cost

The budget of the ISS was constrained and staying close to the approved budget was critical to the continuing approval of the ISS budget by the US congress. Management approached the inevitable budget increases (as the ISS design became more mature) by conducting what were referred to as Scrubs of the ISS content. Around one-half year after the ISS program was approved the scrubs started. First mass was critical and each system manager was required to task the system team to reduce the amount of mass of their system by a percentage determined by ISS management. Around one-half year later, a scrub of how much power was required to operate the system was initiated. The next scrub focused on cost. A year or two later the cycle of scrubs would repeat. For SMs that were trying to get the system built with all the resources we thought it would take; each scrub was a difficult process. But each scrub resulted in reduction of content or processes that met the programmatic need. Asking for more resources to resolve an issue was particularly difficult during this period – but it was essential to solve issues.

ISS Assembly

As assembly of the ISS approached, efforts refocused on the reviews and processes leading to launch of TCS parts of the ISS. Each launch was proceeded with launch readiness reviews and each ISS SM had to certify that the parts of their system to be launched were ready. Additionally, the operational readiness of each part of the system needed to be certified by the SMs. Serious, success related calls were required from each SM for each launch.

During a one-year period, 7 launches were conducted and thus many launch processing approvals were required in a very short period. Many times, launch readiness reviews overlapped operational readiness reviews. The USOS development was ready to go when the Russian elements were finally launched. As shown in Table 1, Node 1 was launched within 2 weeks of the Russian launch of the Boeing FGB. Then, after a long period of 1.5 years, the first truly Russian element, the Service Module, was launched. The Service Module was the module needed to support independent crew operations in space. Permanent occupancy of ISS began shortly after the Service Module launch. As shown in Table 1; six USOS launches were achieved during the 1year period after the Service Module was launched.

1A/R	20-Nov-98	Zarya (FGB)
2A	4-Dec-98	Unity (Node 1),PMA-1 & PMA-2
1R	12-Jul-00	Zvezda (Service Module)
3A	11-Oct-00	Z1 Truss & PMA-3
4A	30-Nov-00	P6 Truss & Solar Arrays
5A	7-Feb-01	Destiny (US Laboratory)
5A.1	8-Mar-01	External Stowage Platform-1
6A	19-Apr-01	Canadarm2 (SSRMS)
7A	12-Jul-01	Quest (Joint Airlock)

Table 1 - The launch rate during early ISS assembly

Travel

Travel was required at times to have face-to-face interactions with teams doing the work of designing and manufacturing ISS TCS equipment. During one week the author traveled to KSC to address launch processing, then to Los Angeles to work with the EATC team, then to Cleveland to meet with the team developing the TCS for the power systems of ISS. The author managed to run at each location and thus ran on the East Coast, West Coast, North Coast and (in Houston) on the South Coast of the US during a one-week period.

Jet lag is real but mostly tolerable. During another period of time the author attended a one-week CDR in Torino, Italy; then returned to JSC for a week; then attended a week long CDR in Tsukuba, Japan before returning to JSC. Each stay was long enough to acclimate to the difference in time zones but at the end of that period the author could really notice that jet lag was a real phenomenon.

The author (like other SMs) learned to become a little critical of travel so that, only when the business of getting the system built required his presence, would he travel.

Verification required TCS SM involvement and extended periods were required to get ready for integrated tests. Arrangements for testing required SM involvement to assure verification goals were addressed so that the design was confirmed to be practical and operational. The author was involved with the interaction with ISS contractors and with host centers of companies for integrated system testing. To be cognizant of the test results, the author participated in testing of the PVATCS in Lockheed Martin Denver, CO test facilities. Testing of the PVATCS and the EATC radiator deployment mechanisms and heat rejection capabilities used NASA GRC facilities at Plumbrook, OH. The EATC integrated system testing was performed at JSC.

Multi-Element Integrated Testing was done at KSC to test the interfaces between some of the elements to be launched as the only time element-to-element testing could be done prior to each element arriving for connection on-orbit. The MEIT testing was complex as illustrated in Figure 5.

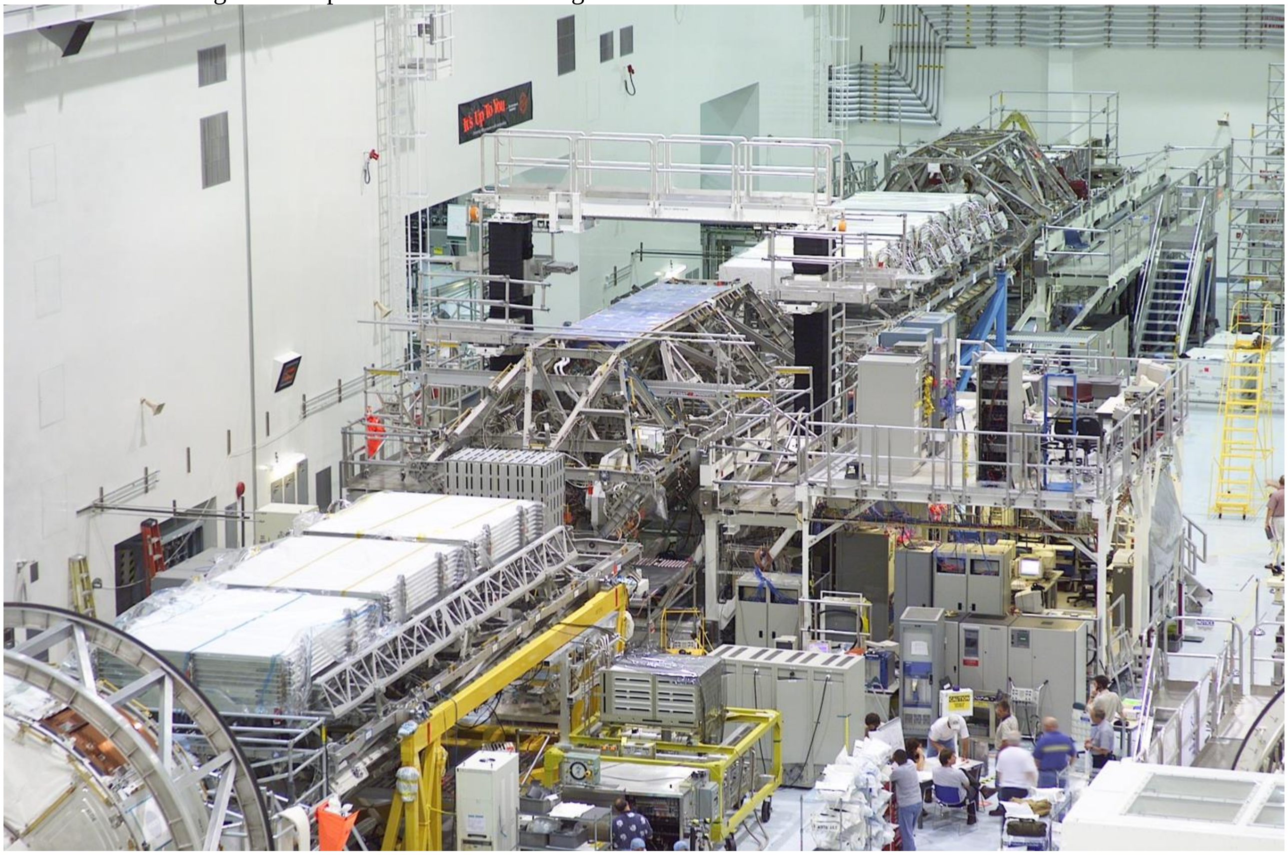


Figure 5 – The layout of ISS elements used in Multi-Element Integration Tests to confirm interfaces worked as planned (at the KSC Space Processing Facility)

Other jobs of the TCS SM as relevant

The prime contractor was doing most of the coordination and integration activities but was understaffed. As part of the team of SM and prime contractor for TCS; the author provided several products that were actually Prime contractor products for the ISS program including the first ISS TCS Architecture Description Document.

The TCS SM also served as the focal point (the NASA Change Engineer) for all changes associated with the TCS system. There were hundreds of changes that the author had to certify as relevant and essential to development of the ISS TCS. Each change required a change review and, in many cases, review at ISS program board meetings.

A method of coping with the high demand for TCS SM approvals was required. A method the author used during this and other periods to maintain a balance was to approach each day with a maximum effort to get things done and at the end of each day leave the office with a feeling that the day was productive. Using that approach; the feeling of being overwhelmed with the work load was tolerable and the needed rest could be obtained.

VII. Conclusion – Lessons from being the ISS TCS SM

Getting prepared to fill such a role; the following were relevant and important for the author in order to enable those that select program leaders to select him.

1) Get educated as well as you can for the role you want to fill
2) Develop an experience base that qualifies you to lead in the job you want
3) Get involved with technology development related to the role
4) Pay attention to program developments and the direction of progress
5) Use your leadership skills to develop management skills
6) Participate in proposals to understand how the business side works
7) Establish your technical leadership position

Preparing for the role of ISS TCS SM required a background that included; technical work, management, proposal development, flight techniques involvement, analysis, test and team leadership.

Leading a major program requires a manager to be proactive and use of all the knowledge one has to evolve the job to accomplish what is needed. One has to get involved in all parts of the organization to figure out how to interact and what is needed at all levels. One has to be resilient because there is a lot to do and it can be overwhelming. Keep everything in perspective by taking the time to think about the big picture of how your efforts matter and contribute to the program. Know what is going on but delegate when possible – rely on great leaders in the organizations developing your system.

Staying healthy during a long program is very important. One has to balance work and family and health so that one's body isn't abused by overworking. The author mentioned running at various locations and that was part of balancing mental and physical workloads. The author recommends that future system managers keep up with health news to organize your life to establish and implement the best plan to stay healthy and productive.

VIII. Paper Review Considerations

This paper doesn't include any export sensitive materials. Illustrations or schematics used to illustrate the scope of the system have been released in prior publicly released technical papers.

Acknowledgments

The author would like to acknowledge Jenny Stein who put her faith in the author by selecting him for the ISS TCS SM role. The ISS TCS SM job required an infrastructure of organizations to enable accomplishing the design, development and implementation of the ISS TCS. Without the management at the program level, in the contractor organizations and in the international organizations that participated in the ISS program; development of the TCS would not have been possible. The Shuttle program was essential in the development and implementation of the ISS plan. The astronaut corps and mission operations teams provided the world class capability to implement such a program. Finally, to all the hundreds (maybe thousands) of TCS engineers, analysts and technicians at NASA, US contractors, and international partners, thanks for making it happen.

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