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ISWE: A Case Study of Technology Utilization

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Acronyms List

BICS	Beam Impingement Control System
CAT	Cathode Alignment Tool
CC	Contamination Curtain
CDR	Critical Design Review
CP	Control Panel
CSD	Cable Stowage Device
CT	Coating Tool
DIB	Data Interface Box
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
EMU	Extra-vehicular Mobility Unit
EVA	Extra-Vehicular Activity
FT	Filler Wire Welding Tool
GOST	Russian State Standard
ISS	International Space Station
ISWE	International Space Welding Experiment
JSC	Johnson Space Center
MPE	Mission Peculiar Equipment
MPESS	Mission Peculiar Experiment Support Structure
MSDS	Material Safety Data Sheet
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NBS	Neutral Buoyancy Simulator
NSAU	National Space Agency of the Ukraine
NSTS	National Space Transportation System
PDR	Preliminary Design Review
PIB	Power Interface Box
PIP	Push-In-Place
PRR	Project Requirements Review
PWI	Paton Welding Institute
RID	Review Item Discrepancy
RSH	Rotating Sample Holder
SFR-R	Sliding Foot Restraint Rail
SFR-T	Sliding Foot Restraint Trolley
ST	Standard Tool
TB	Technological Block
TBE	Teledyne Brown Engineering
TQCM	Thermally Controlled Quartz Microbalance
TS	Test Set
TSA	Tool Stowage Assembly
UHT	Universal Hand Tool
UWS	Universal Welding System

Preface

The International Space Welding Experiment (ISWE) was a joint venture between the NASA George C. Marshall Space Flight Center (MSFC) in Huntsville, Alabama and the E.O. Paton Welding Institute (PWI) in Kiev, Ukraine. Manifested as an element of the United States Micorgravity Payload - 4 (USMP-4), ISWE was "to demonstrate the feasibility of welding as an operational maintenance process using equipment developed by the Paton Welding Institute (PWI)" (Russel, et. al. 1996). On December 6, 1996, ISWE was demanifested due to conflicts between various experiments vying for limited astronaut space walking opportunities. Current plans are possible manifesting on a shuttle flight to the Russian space station *MIR* for the welding process to be performed by Russian cosmonauts.

The paper contained herein was written before the demanifesting of ISWE and describes the ISWE project for operations on the Space Shuttle. It addresses selected issues that during hardware development. To keep the content of the paper from changing, the authors decided to publish the paper as is.

Introduction

The International Space Welding Experiment (ISWE) is a joint venture between the E.O. Paton Welding Institute (PWI) of Kiev, Ukraine and the National Aeronautics and Space Administration (NASA) of the United States government. Its purpose is to evaluate the Ukrainian developed Universal electron beam welding system as a contingency repair tool for the International Space Station (ISS) and to assess the capability for long term maintenance of space structures, including debris impacts to habitable modules and repairs of fluid line leaks (Rainwater 1995). Figure 1 depicts the current configuration of the ISWE.

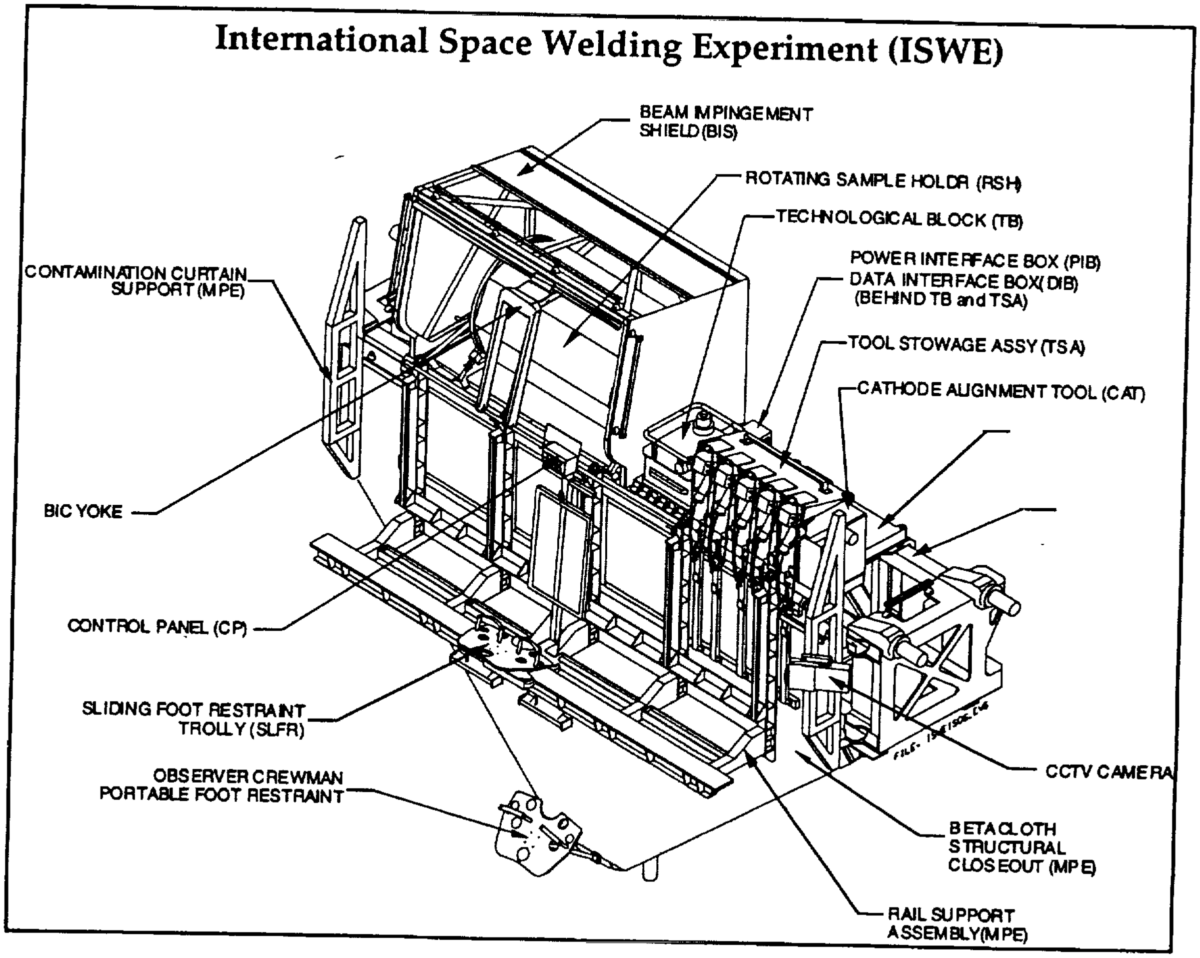


Figure 1. Current ISWE Configuration

PWI is providing the Universal welding system and supporting equipment and NASA is providing the vehicle, the Space Shuttle, the Mission Peculiar Equipment Support Structure carrier, and interface hardware, as well as engineering support at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Table 1 illustrates the different components of the ISWE as well as their provider and function.

With the introduction of an international partner several issues have arisen as to the way in which the experiment will be qualified as a flyable system aboard another agency's space vehicle. These issues are primarily due to the distinctly different technical standards and practices that NASA and PWI use in their respective space businesses, but issues of interagency communication and openness have also arisen. Together, these issues have significantly complicated what began as a small scale pilot project in international space cooperation. With other international projects likely in the future, it is imperative that a consensus of standards and practices for international cooperation be established for the 21st century and beyond.

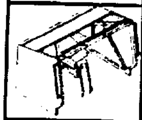
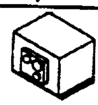
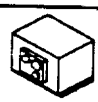
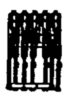
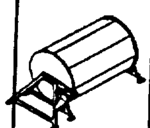
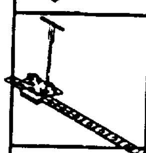
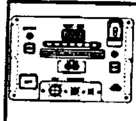
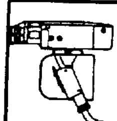
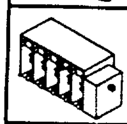
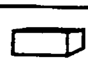
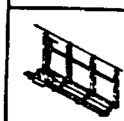
Section 1: Background

In this section the concept of welding in space is discussed. A historical look at space welding and the political foundation of ISWE is also presented as well as an ISWE experiment overview. This background includes a description of the process for qualifying ISWE to fly on the U.S. space shuttle.

Why Weld in Space?

In addition to initial construction tasks, long term operations in space will require performance of maintenance tasks such as repair of micrometeroid damage, leaking fluid lines, stuck instruments, contaminated surfaces, etc. These tasks will require welding or the development of alternative processes. Currently, space welding is considered a high risk endeavor due to unknowns about operational characteristics of such a process in the microgravity of space. Therefore, it is imperative that welding equipment and procedures be demonstrated in the space environment before welding operations can be included in the repertoire of routine space technology. With a metals processing system qualified for assembly, construction or processing of hardware in space and knowing appropriate welding techniques, restrictions, and weld properties, the aerospace design community can design for welding in space (Russell, et al. 1996).

Table 1. Components of ISWE

Component	Name	Provider	Function
	Beam Impingment Control System (BICS)	MSFC	To protect the orbiter and the rest of the USMP-4 experiments from contamination of the welding particles and impingment of the electron beam
	Power Inteface Box (PIB)	MSFC	Provides the following: electrical isolation from transients and noise to (or from) the TB, adds a third inhibit to guard against failues that could result in beam on condition
	Data Inteface Box (DIB)	MSFC	Provides signal splitting and conditioning to interface TB telemetry with the Spacelab and Orbiter data handling systems
	Control Panel (CP)	PWI	Provides EVA controls/feedback for: TB main power on/off, setting of beam power modes, and setting of filler wire feed rate
	Cable Stowage Devices (CSD)	PWI	Provides stowage for tool cables during launch/landing & when not in use during operations
	Rotating Sample Holder (RSH)	PWI	Structure which allows the drum mounted sample plates/samples to be manually rotated in front of the welder for ease of processing
	Sliding Foot Restraint (SFR)	PWI	Provides translation capability across the ISWE worksite with the astronaut secured in a standard PFR bootplate. Made up of the following: SFR-Trolley, SFR-Rail, SFR-T launch lock
	Technological Block (TB)	PWI	Main power source and controller for the Universal welding system
	Test Set (TS)	PWI	Provides IVA controls/feedback for: viewing telemetry from TB, TB main power off, TB main power on, cathode select, and beam test start
	Tool	PWI	5 modular hand-held electron beam welding tools; 1 Standard Tool (ST)- welding, cutting, brazing, 3 Filler Tools (FT) -filler welding, 1 Coating Tool (CT) -coating
	Tool Stowage Assembly/ Cathode Alignment Tool (TSA/CAT)	PWI	Provides the following: stowage for tools during launch/landing & when not in use by the astronaut, on-orbit alignment of filler wire feed mechanism to electrode beam if cathode changed
	EMU Protective Garment	JSC	Provide protection for the EMU during ISWE operations
	Visor Stowage Box	JSC	Stow the visors used on the shield of the EMU helmet
	Weld Samples	MSFC	Replicate typical weld configuration and potential ISS weld scenarios
	MPE	MSFC	to accomodate experiment hardware to the STS system

History of Space Welding

Welding in space is not a revolutionary concept. Since the 1960's the former U.S.S.R. and the United States have been conducting experiments in space welding. In 1969 the "Vulkan" automatic welder was launched on Soyuz 6 to compare three types of welding for potential space application: electron beam, low-pressure constricted plasma jet, and consumable electrode. As a result of the Vulkan project, the Soviet space program (including the Ukrainians at the time) concluded that electron beam welding was the most promising process for space welding due to its versatility and low power consumption (Avduyevsky, 1985).

Throughout the next two decades, the USSR continued to demonstrate electron beam welding in space. The "Isparitel" was developed by the PWI, and was launched to the Salyut-6 space station in 1979 to test production of vapor deposited coatings. Isparitel used an electron beam to heat the coating materials, causing them to evaporate. The vapor was condensed on multiple substrates, both metallic and non-metallic. Over two hundred samples of widely varying coatings were produced with this hardware during its three years aboard Salyut-6. An improved unit, Isparitel M, was developed and launched to the Salyut-7 space station in 1983. Tin-silver brazing alloys, and silver-germanium eutectic alloys, were among the samples processed the following year. The PWI also developed the "Yantar" unit which was launched to the Mir space station in 1988. This hardware used an electron beam to produce vapor deposited coatings on both metallic and polymeric substrates, and also allowed welding of very thin metallic specimens. This unit, like all of the preceding units mentioned above, was automated and therefore only produced samples where the parameters were well known and easily preset (Avduyevsky, 1985).

In an effort to provide a more flexible tool, the PWI developed the Universal Hand Tool (UHT) which was launched to the Salyut-7 space station in 1984. The UHT consisted of a power control electronics module and hand held electron beam gun. The 0.75 kilowatt (kW) UHT was first used to conduct Extra-Vehicular Activity (EVA) welding aboard Salyut-7 in July of 1984. The EVA lasted for just over three hours and involved two cosmonauts each performing a variety of welding, cutting, brazing, and coating operations with the UHT. This EVA was performed with ambient lighting and required approximately 3 months of crew training. The UHT electronics module and hand held electron beam welding gun were mounted to the exterior of the Salyut-7 station at the start of the EVA, prior to beginning the welding operations. Additional experiments aboard Salyut-7 were conducted in 1986 and involved welding truss structures and structural subassemblies representative of space station components. The UHT hardware had been in space since the initial testing done in 1984, and functioned flawlessly (Avduyevsky, 1985). A modified version of this 1984 UHT model, the "Universal Welding System" designed for use on the Russian Space Station *MIR*, was chosen for the ISWE project.

The United States began welding in space in 1973 on board Skylab 3 utilizing the electron beam concept. With the M512, astronauts on board Skylab demonstrated the capability to repair structures in space that had been exposed for long durations. Skylab's demise removed the need for a space welding capability and further U.S. research was halted.

History of ISWE

As design, construction, and maintenance plans were developed for the International Space Station (ISS), it became apparent that the need to weld in space was inevitable. But, since the last U.S. demonstration of welding was the 1973 flight of the M512, the NASA engineers felt that an operational system could not be developed in the short-term ISS schedule (and within allowable cost). Furthermore, with the collapse of the Soviet Union in 1991, various Soviet Union technologies (such as the Universal Welding System) and experience were becoming available to overseas countries. Prompted by the McDonnell Douglas Corporation, NASA, the PWI and the Clinton administration's desire for cooperative space ventures with the former Soviet states, the United States and the Paton Welding Institute began active negotiations to perform a joint flight demonstration of the Universal technology. This process, summarized in table 2, resulted in the development of the ISWE.

Table 2. Steps Toward ISWE Creation

Date	Occurrence
1992-1993	McDonnell Douglas Corporation and Ukrainians test UHT workstation in Neutral Buoyancy Simulator (NBS) tank
April 1993	Fourth Call for Flight Demonstrations from NASA Headquarters
September 1993	Space Act Agreement between MSFC & PWI - 1st project with the Ukrainians and MSFC - conduct demonstration of UHT on KC-135
October 1993	Ukrainians arrive for preparation of tests
November 1993	ISWE picked for further study as possible demonstration on shuttle
January 1994	KC-135 flight 130-150 welds processed
March 1994	President Bill Clinton goes to the Ukraine - talks of cooperation in space between the two nations
July 1994	Delegation from the National Space Agency of the Ukraine meets at NASA Headquarters in Washington, D.C. - 1997 flight demonstration of the UHT discussed

ISWE Experiment Overview

The ISWE will involve a single, two person EVA with a third IVA crew member in support at the aft flight deck. The heart of the ISWE is the Universal Welding System (UWS). The UWS is a hand-held electron beam welding gun with specialized attachments, and integral cable for connection to the Technological Block (TB). The electron beam is produced by heating a metal filament within the cathode to produce electrons which are then accelerated by the potential difference between the cathode and anode, and focused by the anode configuration. The power cable feeds into the tool through the base of the handle. The tools are designed to accept attachments which allow the operator to perform different operations, including welding with filler wire and coating by vapor deposition. Although the welding tools are designed for use as modular units, five electron beam tools are planned for use on this flight so that no on-orbit tool reconfiguration is necessary. The tools will simply be exchanged for the different tasks. Exchanging the welding guns will require removing power, disconnecting the integral power cable from the TB, stowage of the hand tool, and connecting the power cable for the new tool. The power cable connection is identical for each tool. Each electron beam tool weighs between 4.5 and 6.5 kg, including the integral cable, depending on the configuration. Each tool is equipped with a pair of green LEDs on the upper sides of the tool which indicate trigger position. All of the crew interface labels will be in English and Ukrainian.

The five tools to be flown include a standard tool (ST) for general purpose welding/brazing/cutting, three for welding with filler wire, and one for coating by vapor deposition. The 4.5 kg. ST is designed to weld aluminum, stainless steel, and titanium samples up to 2 mm thick, and cut samples up to 1.5 mm. The filler wire feed tools (each 6.5 kg.) include one with 2319 aluminum filler wire, one with 5356 aluminum filler wire, and one with 308 stainless steel filler wire. The 2319 filler wire is intended for use on 2219 aluminum samples. The 5356 filler wire is intended for use on 5456 aluminum samples. The 308 stainless steel filler wire is intended for use on the 304 stainless steel plates. The filler wire will be fed at a fixed selectable rate from a motorized spool attached to the side of the head. The filler wire feed rate is selected by the welding operator using the Universal control panel. The filler wire is necessary for welds where the joint is not very tight. It is also necessary for all welds of 5456 aluminum as this alloy will crack without filler wire. The motorized spools will dispense the filler wire at 10.83, 11.94, and 13.06 millimeters per second. Power for the spool motor is provided by the electron beam tool.

The experiment sample materials will include 2219 aluminum from which the U.S., Japanese, and European space station modules will be made, 5356 aluminum from which the Russian modules are made, 304 stainless steel, and Ti-6AI-4V titanium alloy. The welds will be performed at a rate determined by ground testing at MSFC. The coating experiments will involve the application of three optical coatings. The magnesium fluoride (MgF2), silver (Ag) and gold (Au) will be applied to the silica glass substrates using the hand tool with the vapor deposition attachment. The coating experiments will include three fixtures, each containing one inch diameter circular substrates. The coatings will be applied until they are visibly opaque, roughly just over one thousand angstroms thick.

ISWE Development

When an experiment has been chosen by NASA to fly on board the space shuttle the payload must go through a process to qualify its design and fabrication as flight-ready hardware. A standard development process is shown in Figure 2. As shown in Figure 3, ISWE's development process differs from the standard due to the additional UWS review and several delta Phase 0/1 Safety Reviews. Since the UWS was an existing design by PWI, the UWS review allowed NASA to evaluate the design in terms of safety and interfaces.

During each ISWE design review, issues arose due to the difference in standards and practices between NASA and PWI. For each issue, engineers at both the Marshall Space Flight Center and the Paton Welding Institute had to devise a solution that would minimize cost and schedule impact without jeopardizing safety of the astronaut crew or the orbiter. This paper details each design review and discusses some of the problems that occurred as well as the solutions that were devised by the ISWE team. Although many of the concerns initially seem small, they were amplified due to the philosophical differences of Ukraine and the U.S. in qualifying a payload to fly into space.

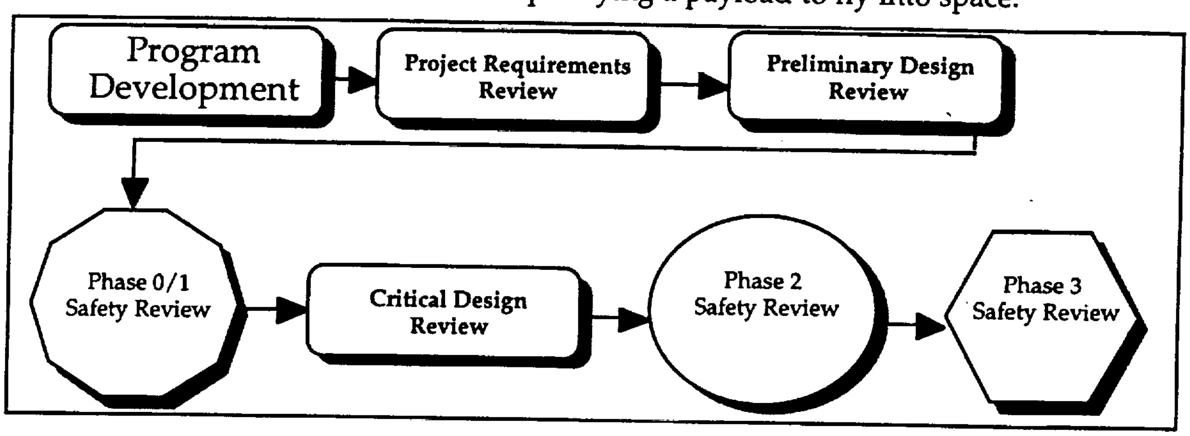


Figure 2. Standard Process for Payload Design/Safety Acceptance

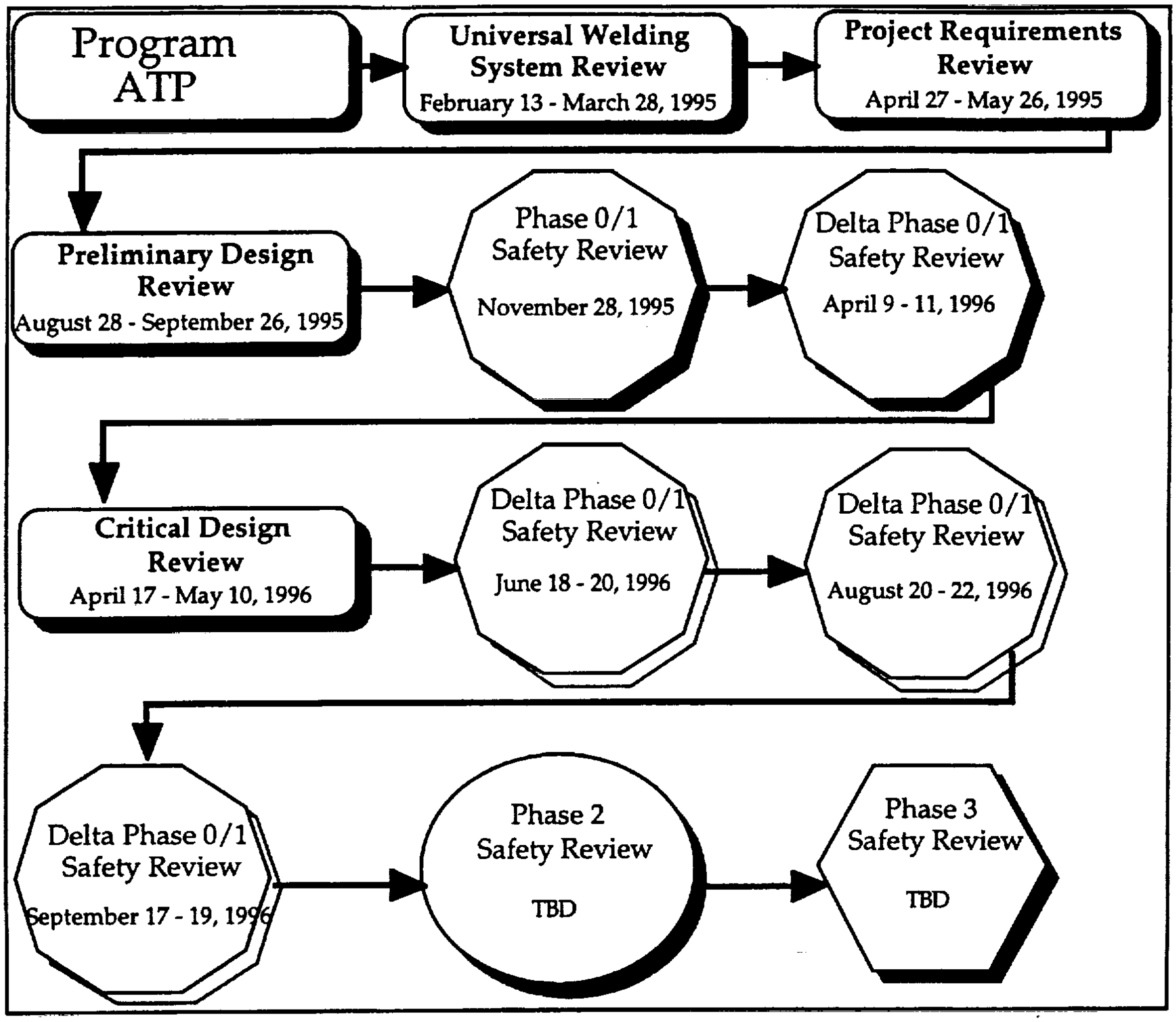


Figure 3. ISWE's Design/Safety Acceptance Process

Section 2: General Problems

Several general problems have plagued ISWE during the entire development process. These include: language barrier, willingness to share information, and limited analysis/testing data.

Language Barrier

With any effort being undertaken by international partners that speak different languages, problems are inherently possible and probable. With ISWE's partner being the Paton Welding Institute in Kiev, Ukraine, translators were required to speak between the two centers to enable the engineers to understand each other. Weekly telecons were held to discuss any problems of the week and to generally touch base with the other engineers. These conversations/telecons were time consuming because of the translation required between the two parties. But, there was still a risk of misinterpretation/mistranslation involved. Therefore, any agreements made during these telecons were usually written down and faxed or mailed to the other party to make sure the two sides were in total agreement. But, when those faxes or letters arrived, they would have to be translated causing an additional delay of several days. Over time both sides mutually adapted to this situation.

NASA should encourage and, in some cases, require the engineers with international projects to take classes to be able to better communicate with their foreign counterparts. This action would not eliminate the need for translation services, but would enhance the working relationship by showing the foreign counterpart a general interest in their culture and their language, making them feel a more integrated part of the team.

Openness

The U.S. and the former Soviet states have long been rivals in the space arena, each vying to be the preeminent space power of Earth. With ISWE, both of NASA and PWI were to become partners to achieve one common goal. Decades of rivalry had to be put aside to reach the completion of ISWE. Naturally, in the beginning there was apprehension on the part of both parties due to the unknowns of working together.

Initially, the Ukrainians were hesitant to disclose information vital to the integration and qualification of the Universal hardware. Unfamiliar with a free-market society, the Ukrainians were concerned that the information provided to NASA would become public domain and could therefore be taken by any interested American company. This false perception was allayed by conveying to the Ukrainians the content of Public Law #18-1905, "Whoever, being an officer or employee of the United States or of any department or agency there of, ... publishes, divulges, discloses, or makes known in any manner or to any extent not authorized by law any information coming to him or in the course of his employment or official duties or by reason of any examination or investigation ... shall be fined not more than $1000, or imprisoned not more than one year, or both; and shall be removed from office or employment." Under this law the Ukrainian hardware was labeled proprietary information, thereby protecting it from the American public. This action, in turn, gave Paton the confidence with which to proceed with the disclosure of their design.

Having taken this first step, the Ukrainians and NASA were now able to work more closely knowing that the other would secure their information. Trust is a vital part of cooperation that must be firmly in place if the space faring nations wish to effectively work with one another. ISWE can serve as a model of such cooperation. NASA and PWI both went through a time of building a working relationship of openness and trust. With this in place, future cooperative ventures with PWI will run more smoothly.

Limited Analysis/Testing Data

The UWS review brought out a major difference between NASA and PWI's approach to hardware development. For several decades NASA has moved toward utilizing computer analysis of designs to complement actual testing. This appraoch has continued to prove effective in qualifying hardware for space flight. However, the former Soviet Union states have a very different philosophy. They believe in overdesigning a system and then testing it to its limits (Zagrebelnij, 1995). This approach is initially more costly because two complete systems must be manufactured as well as the risk that the design fails to meet criteria and must be redesigned. The analysis method minimizes the risk to the project and maintains the life of the hardware. But, the analysis approach has its downfalls as well. Computational analysis cannot fully simulate the true environments that the hardware will be subjected to in space. If any design shortcoming appears after the system is on orbit, it is often too late if failures occur. There is a middle ground for hardware development. Performing some level of initial analyses to confirm the design's requirements are met and then testing to validate (or benchmark) the analysis, the hardware can prove qualification. With ISWE, several analyses were done as well as tests to validate the analyses.

Because of the lack of reliance on analysis by the Ukrainians and the fact that the UWS was designed as a portable unit that the Russians launched inside the crew cabin and transported outside to perform operations, it was decided that MSFC would do the analytical work of the qualification program. NASA has a specific analysis protocol that must be performed in order to qualify a payload for flight on the shuttle. This protocol is summarized in Table 3 along with the source document that requires them.

Table 3. Required NASA Analyses and their Sources

Analysis	Source
Thermal	SLP/2104-10, Appendix K
Stress	JA-081, JA-2294, NSTS 21000-IDD-MDK
Dynamic	JA-081, JA-2294
Human Factors	NASA-STD-3000, JSC 26626A
Fracture	JA-081, JA-276, NSTS 21000-IDD-MDK
Materials	JA-081
Venting	JA-081, ICD-2-19001, SLP/2104 Main Volume
Static Envelope	ICD-B-MPESS-A/MPESS-B, NSTS 21000-IDD-MDK, JA-2294

Once these analyses are performed, the hardware is then subjected in ground tests to the flight environments that the analyses predicts that it will see. By passing these tests the hardware is qualified for flight. From a safety standpoint, allowing Marshall to do these analyses resulted in a documented record that ISWE satisfied the requirements imposed on it.

Section 3: Specific Problems

NBS Lubricant

When a project involves extra-vehicular activity (EVA), Neutral Buoyancy Simulation (NBS) testing is recommended. By conducting NBS testing, astronauts, as well as the experiment's engineering team, can evaluate the functional and ergonomic design of the hardware. Since the ISWE calls for a six hour EVA to conduct the welding operation, a test was run to determine the crew interfaces acceptability. With NBS testing, moving parts within the experiment must have water-compatible lubricant. The lubricant that PWI was going to provide did not have a Material Safety Data Sheet (MSDS) which is required to assure no toxicity concerns exist when put in the water for the diver's safety. Therefore, MSFC had to provide the NASA approved standard lubricants to PWI so they could be incorporated before the NBS hardware was shipped from Kiev to Huntsville.

Threaded Fastener Preload

The threaded fastener preload issue is another example of the situations that occur due to the different NASA and PWI philosophies. Upon review of the ISWE design at PDR a major issue arose because there was no fastener preload indicated in the PWI drawings. Further investigation revealed that PWI does not apply preload in fasteners. It is standard U.S. aerospace industry practice to apply preloads to all fasteners loaded in tension. Both MSFC-STD-486 and NSTS 08307 require that NASA flight hardware to have nonzero preloads applied to all fasteners (Denniston 1995).

To solve the preload issue, a procedure developed by Marshall and approved by PWI, was introduced to determine the fastener preloads. Figure 4 shows the flow of work for establishing the fastener preloads. Note the complex set of decisions and actions required to rectify a basic issue of nonsimilar design practices. MSFC performed torque tension testing on fastener and joint configurations representative of those found in the PWI hardware. MSFC also provided PWI tooling (torque wrenches) to install the fasteners with the test determined pre-loads. MSFC also supplied thread locking compound (loctite) identical to that used in the testing so that all parameters remained the same as in testing.

This one issue caused a tremendous amount of unplanned work due to a small difference in design and manufacturing standards. If common standards were implemented this would not have had to happen. NASA and PWI could both feel that the design of the ISWE was safe and reliable from both sides.

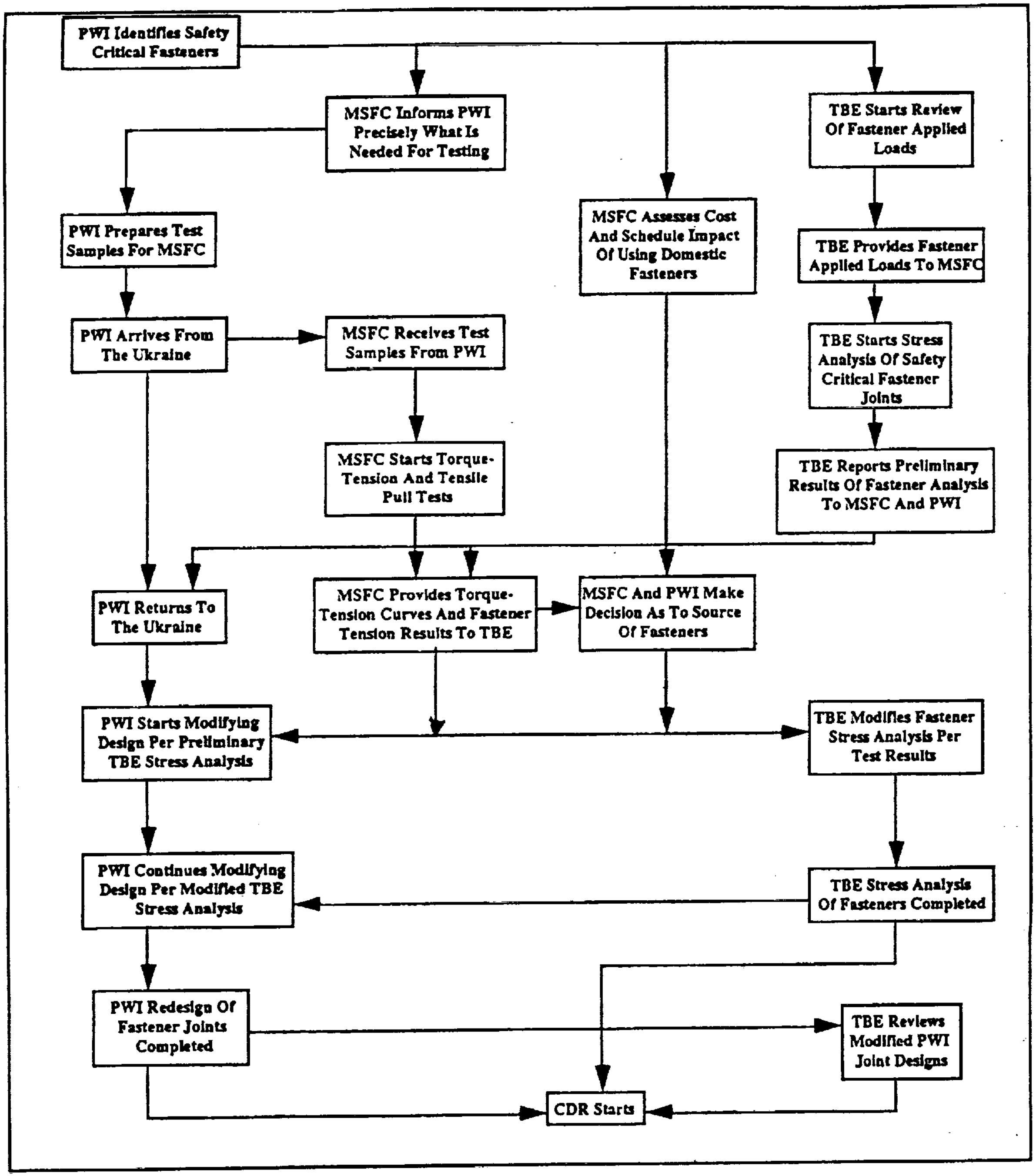


Figure 4. Flow of Work for Establishing Fastener Preloads

Materials

From the beginning of ISWE, materials were of great concern. During the UWS review, several Review Item Discrepancies (RIDs) were written against the design due to the differences between material characterization of the two agencies. Examples of the type of materials issues raised during the review are as follows:

1) All hardware located in the cargo bay of the orbiter is subject to contamination by thermally induced vacuum outgassing. There was no data to support that this was a common practice of PWI (Landers 1995).

2) No materials list was provided for the power cables, so the acceptability (flammability issues) for use on the shuttle could not be determined (Landers 1995).

3) All materials listed in the drawing packages referred to GOST standards, but did not contain them. To evaluate materials of construction in a stress analysis the GOST standards and material properties of the various materials were needed (Landers 1995).

The solutions to these problems proved to be very creative on the part of the Materials and Processes Laboratory as well as the entire ISWE team.

1) Hardware located in the cargo bay of the orbiter is subject to the thermal vacuum stability requirements of JSC-SP-R-0022. It was agreed that all of the hardware located in the cargo bay must go through a thermal bakeout period on the ground. By thermally baking the component, any impurity or residue will be offgassed before the component is flown on the shuttle. If this procedure is not carried out the shuttle's radiators could be contaminated or damaged. As a result, the ISWE team decided to conduct the thermal bakeout at Marshall with PWI supervising the process as well as agreeing to the temperatures the components would be baked at a pressure of 10 -6 torr or less and a temperature of 10∞C greater than expected maximum on-orbit while holding the Thermally Controlled Quartz Microbalances (TQCM) at 10 C less than expected minimum in flight).

2) The ISWE team decided to manufacture all flight cables at MSFC using appropriate, approved standards, with the exception of the UWS cables, to alleviate any questions from the material's experts about their composition. The UWS cables were made acceptable for flight by installing a braided zipper tubing and an overwrap of Mystic Tape.

3) To certify the material properties of the Ukrainian built components, the Materials and Processes Laboratory used the same procedure they had used with Russian built components on the Space Station. PWI provided the information from the GOST standards to the Materials and Processes Laboratory which then made an in-depth analysis of the material (i.e., chemical, physical properties, etc.). Rather than examine the multitude of different materials in the system, the most commonly used ten alloys were selected and compared to their U.S. equivalent to determine the acceptablility of the PWI supplied GOST standard properties. As a result of the analysis, eight of the ten alloys appeared to have mechanical properties that were similar to their USA equivalents. To provide a confidence level in the other alloys, the annealed properties were used. With this work complete, the stress analysis could be done with a high degree of confidence in the results.

EMI Testing

Within NASA there are several requirements for conducting EMI tests. To fly on the shuttle, ICD-2-19001 "Shuttle Orbiter/Cargo Standard Interfaces" states that the payload must provide documentation to prove compliance. This documentation takes the form of an EMI test report. EMI testing became a factor from the very start of the

ISWE project. Testing during the UWS review determined that the UWS was susceptible to the power bus voltage ripples and transients that are present on the orbiter's power bus (Clark 1995). This could have caused conducted interference and damage to the UWS hardware during on-orbit operations. Also, it was found that the UWS filler wire motor could interfere with the Extra Mobility Unit (EMU) radio. This posed great concern for the crew to be able to communicate with one another.

The Paton Welding Institute had never performed EMI testing. The Russian and Ukrainian system to determine on-orbit electromagnetic compatibility (EMC) is to have fully operational mock-ups on the ground. They simply turn everything on and see if it works together (Email from Tony Clark to Sonny Mitchell, March 2, 1995). EMI apparently was not a concern when the equipment was flown in the Soviet system. The UWS filler wire had never been operated on orbit. Conversely, NASA has established, governing requirements, especially in areas such as EMI, for tests of each unit, and then integration into the system. Because of these different philosophies, resultant designs are quite different. Generally, Ukrainian hardware is simple, but robust. American hardware is typically sophisticated and closer on margins due to the enormous costs of launching payloads. By being more sophisticated, American hardware can also often have more things to go wrong.

Another source of EMI problems was due to the differences in U.S. and Russian power buses. Aboard the space station *MIR* the Ukrainians/Russians utilize a vehicle power bus and a scientific power bus. The vehicle bus allows the normal operations of the space station without interfering with the experiments powered through the scientific bus. However, on the shuttle there are three redundant power buses, each supplying power to both payloads and the shuttle itself. The Ukrainians had not previously had to deal with EMI problems in the Russian bus architecture.

To fix the interference with the EMU radio, PWI added a braided zip shield and a line filter supplied by NASA to each tool. Also, a filter, called the Power Interface Box (PIB), was designed and built to prevent noise from the orbiter power bus from being transmitted to ISWE as well as preventing ISWE noise from being injected onto the orbiter and payload power bus. An interesting point to bring out here is that MSFC had to provide the line filters and zip-on shielding as well as build the PIB. This was due to the fact that PWI did not have a Russian/Ukrainian vendor for such devices and did not have the expertise to perform the operations (Clark, 1997). If a common standard had been in place, the required work to procure the necessary parts would have not been needed.

Temperature/Thermal

As with EMI testing, standards for temperature calculation and thermal analysis proved to be based on totally different philosophies at NASA verses PWI. The Shuttle

Payloads Accommodations Handbook (SPAH, Appendix K) specifies that a thermal analysis must be performed to define the maximum on-orbit temperature expected. The components must then be tested at a level 10°F (5°C) above this temperature according to MIL-STD-1540. The first thermal issue arose from the differences in the definition of temperatures. NASA has several different temperature categories: operational, non-operational, and survival. The corresponding range for each of these temperatures must be specified for each component. The Ukrainians had only one set of temperatures which were assumed to be the operating temperatures. The Ukrainians were not accustomed to non-operating and survival temperatures. Their philosophy is to design each component robust and durable enough to operate over a wide range of temperatures as shown by the thermal test performed on the tools by PWI in figure 5.

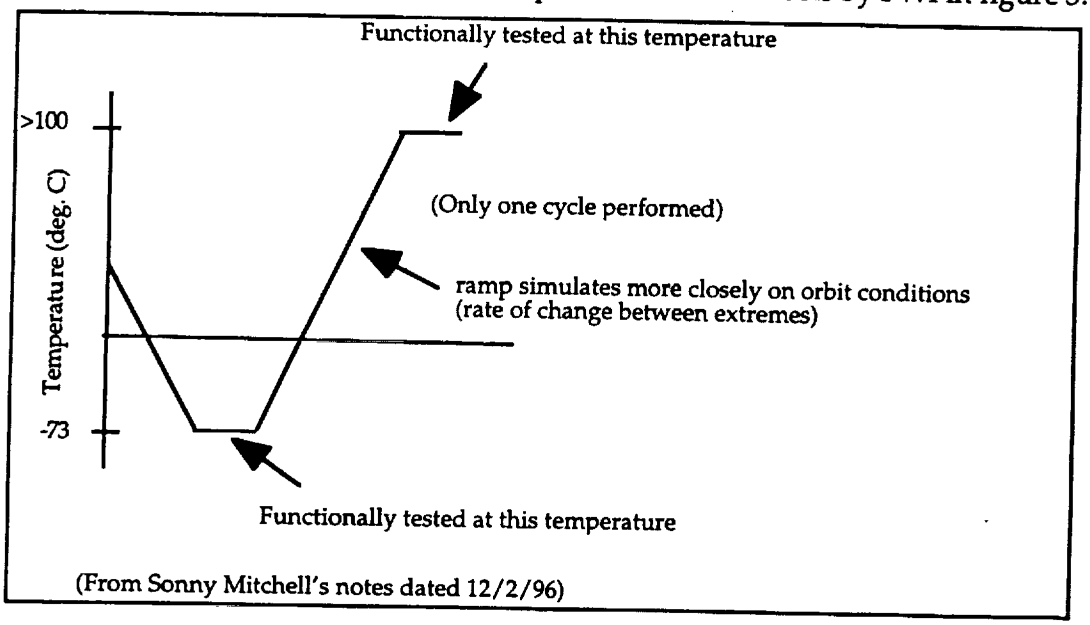


Figure 5. PWI Thermal Vacuum Test

Since the UWS was designed as a portable unit and the ISWE would launch the UWS in the cargo bay, it had never been subjected to the temperature extremes that the ISWE would undergo. Also, since the ISWE required an EVA, another set of temperatures had to be determined to evaluate the touch temperature extremes for the front and palm of the EMU gloves. To address both of these issues, a thermal model was developed using the orbiter attitude predicted during the mission to calculate the maximum temperatures that the ISWE would see on orbit. Utilizing these predicted temperatures, several tests were conducted to validate the hardware to those temperature limits or design operational work around which would maintain the Universal within its required temperature limits.

In addition, the operating temperatures supplied to MSFC by PWI were specified at the component level. At NASA, the temperatures are calculated as wall temperatures on the outside of the boxes. Without more information, the MSFC engineers could not relate the wall temperatures to the component temperatures to determine if the boxes could survive. To solve this issue, the ISWE team decided to perform a development test on the PWI hardware to determine the relationship between the wall and component temperatures. In addition to the developmental tests, the PWI hardware will undergo several other thermal tests as depicted in figure 6.

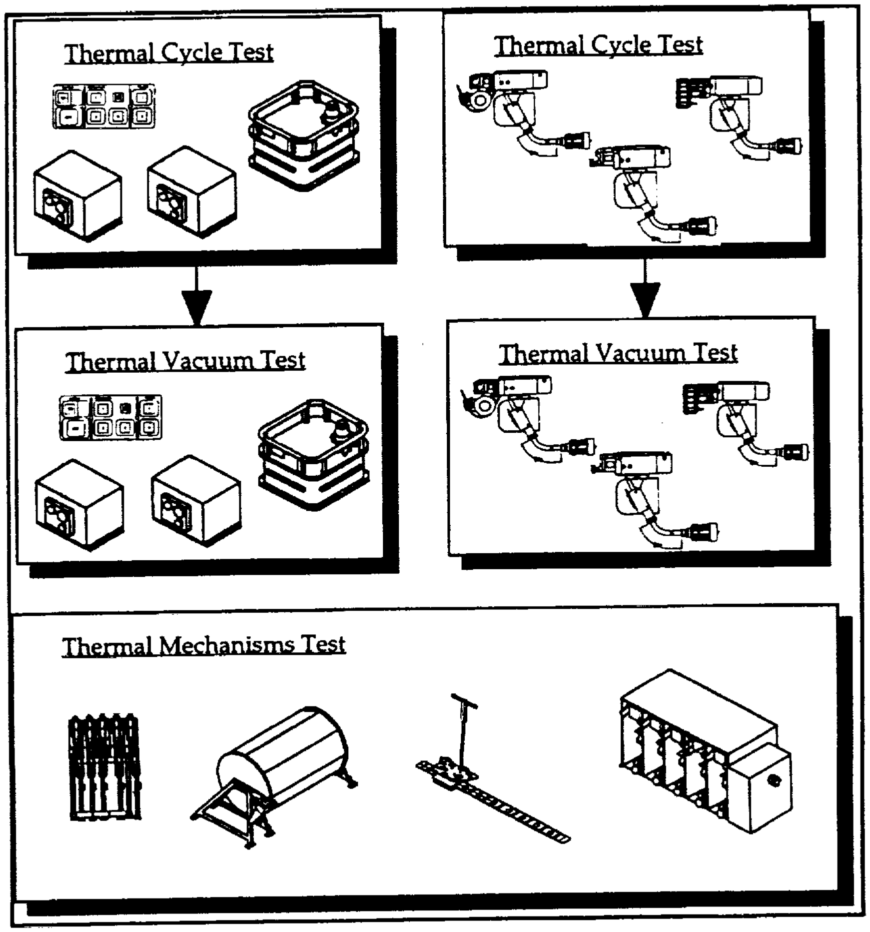


Figure 6. Thermal Tests

As one can see from figure 6, the hand tools undergo two separate thermal tests; thermal cycle and thermal vacuum. The first test is designed as a check or screening before the thermal vacuum test to pinpoint any workmanship problems in the design. The Ukrainians believed that twenty-four cycles in the thermal cycle test and eight cycles in the thermal vacuum test were too much on the tools. This issue brought forth another example of a fundamental difference in each institution's testing philosophy. The PWI subjected the tools to one thermal vacuum cycle, taking the tools to their temperature extremes and functioning them (figure 5) This thermal testing is in accordance with the guidelines established by Energia, the Russian Space Station *MIR* contractor, to qualify equipment to fly on the *MIR* (Sonny Mitchell's notes, December 2, 1996). However, NASA/MSFC adopted a different philosophy. Instead of taking the tools to an extreme temperature, the tools were subjected to the maximum expected on orbit temperatures plus 5 °C margin. They were then cycled twenty-four times at the fastest possible ramp rate (Figure 7). It was felt that the thermal cycle test would clearly point out any defects in the hardware before the expensive and complicated thermal vacuum test. This relatively small difference in thermal testing philosophy resulted in a significant issue of concern.

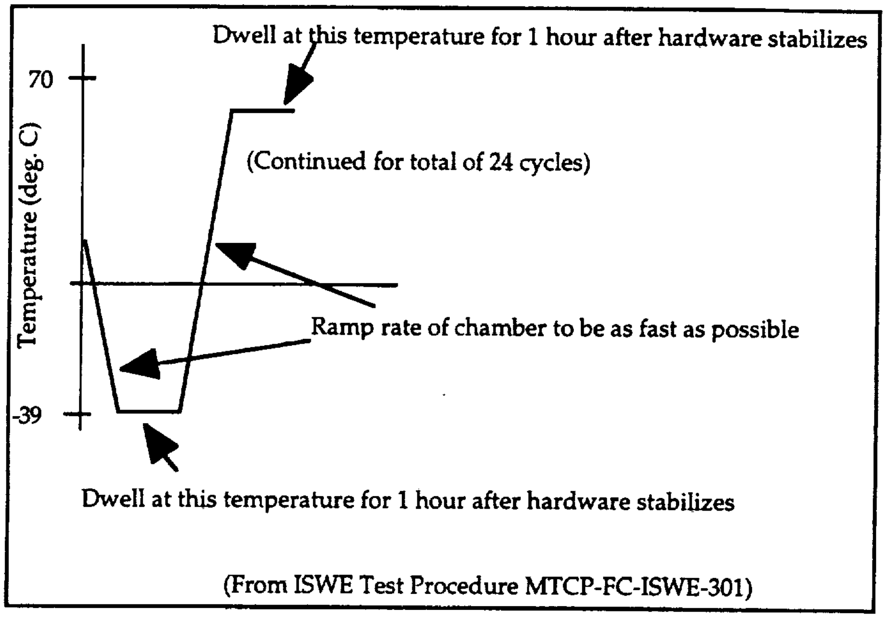


Figure 7. MSFC Thermal Cycle Tool Test

Test Procedures

To test and qualify a piece of hardware at MSFC, a procedure must be written to document the work to be done by a qualified test engineer. ISWE's hardware had to undergo this type of plan as well. A discrepancy was discovered during conversations between the MSFC test engineers and the PWI engineers. At MSFC if a piece of hardware must be changed out or reconfigured for another test, a procedure must be written to do that hardware change. If this is not written and the change is made, all prior tests done are invalid because the flight hardware configuration has been altered. In the case of ISWE, there were four such instances.

1) The cathode inside the UWS can be used up during the qualification tests and might need to be removed and a new one installed. Each cathode has a useful life of one hour and their are two cathodes per tool.

2) The filler wire inside the Filler Wire Tool might need to be changed or a new wire added.

3) The Coating Tool's crucibles and turret head might have to be removed and a new one installed.

4) The Technological Block would possibly need to be re-pressurized at Kennedy Space Center (KSC) or MSFC.

When the Ukrainians test their hardware and a part has to be changed they add a line to the test procedure saying that one of the engineers will change the part. No documented procedure on how to change the part was written. PWI had never documented these procedures before. Only standardized, documented procedures provide a level of assurance. After some discussion with PWI about this issue, they agreed to document their procedures for these four events.

Section 4: Safety

Risk is inherent in any space venture. When man is involved in the venture, the safety measures required to mitigate the risk increase tremendously. Within NASA, a Payload Safety Review Panel (PSRP) managed by the Johnson Space Center (JSC) in Houston, Texas oversees every project's safety compliance to fly on board the shuttle. This panel reviews the project's safety with respect to NASA requirements and provides feedback to the project team to help them comply. This panel meets at different times during the payload's development cycle to ensure a safe flight system is being prepared. These meetings are a Phase 0/1 review, a Phase 2 review, and a Phase 3 review. With ISWE being such a complex and potentially "hazardous" system, the safety panel met several times during the Phase 0/1 review to completely identify the hazards and safety controls of the ISWE. Figure 4 shows several meetings held by the safety panel during ISWE's review process.

In contrast, in the Ukraine there is no independent safety review commission/board. Payload specialists conduct their own reviews after which the final solutions are presented to the State Committee. However, the lead safety role belongs to the general designer. If he says yes to the risks, etc., then the whole issue is a go. The state committee is called a "Final Safety Commission". It is essentially similar to the PSRP, but less meticulous. Most of the discussions take place in working groups. Routinely, the commission will have the "yes-no" approach to most problems. Normally, no more than two to three questions for each topic are asked/answered during a session. The meeting of the committee normally takes one day instead of many (Zagrebelnij, 1996).

Contamination

When an experiment is flown on the orbiter, certain precautions must be taken to ensure the cleanliness and safety of the experiment. In the case of ISWE, the team had to ensure that the ISWE would not contaminate the shuttle, the EVA crewman's suit, the extra vehicular mobility unit (EMU), or other payloads. Unlike the previous missions of the UWS, ISWE welded more samples and at a higher power mode, therefore, it was expected that there would be more contamination than was experienced previously by PWI.

To provide this contamination free environment, the ISWE team had to design and manufacture several items necessary to ensure the cleanliness of the ISWE. When the ISWE is in operation, particulates can develop that could contaminate the other experiments in the cargo bay violating JA-081, "Payload Mission Manager Safety &

Interface Requirements Partial Payload Missions". Contamination of other payloads was not an issue to the Ukrainians because the system that flew on Salyut was mounted to the side of the spacecraft and allowed to expel vapor into space. Contamination is also important to the orbiter itself. If the shuttle's radiators become coated with material, they will not be able to reject the heat produced from the shuttle's internal systems causing an emergency de-orbit. Further, the aft flight deck windows would become covered by the vapor deposition resulting in a safety concern for the crew. To alleviate all of these concerns, a contamination curtain (CC) was designed and built by MSFC.

In addition, the EMU had to be protected from contamination. The EMU suits used by NASA are not expendable and must be reused. Also, the EMU's sensors and life support equipment are very sensitive and must be adequately protected to ensure the safety of the astronaut. A welding cosmonaut aboard the Salyut was provided no such suit protection (Zagrebelnij, 1996). After the welding operation, the suit was used again after a damage inspection. NASA was still insistent that the EMU be protected. JSC devised an EMU protective garment that would prevent the EMU from becoming contaminated. After the welding is complete, the astronaut takes off the protective garment and stows it in a garment stowage bag mounted on ISWE.

Further, the EMU helmet must continue to be contaminate free during welding operations. To give the astronaut complete visibility of the weld pool, expendable shields had to be designed to cover the visor. Once the shield becomes too contaminated for the astronaut to see, he will replace it with a clean one. When the Russians welded on Salyut, the cosmonaut had no other means of protection other that his helmet visor.

Light Intensity

Another hazard is associated with the weld pool being too intense for the astronaut's eyes. As with normal welding operations on Earth, welding in space requires eye protection from the intense light being emitted. If there is no protection provided, the retina in the eye would become damaged, with a resultant possible loss of sight. The standard cosmonaut's visor is made with a high optical density material to prevent this from happening. During their welding operations, their sun visor was used only when the titanium sample was being welded. This sun visor was also standard, with gold plating. The American counterpart, however, is of less optical density. To alleviate this problem a visor analysis was conducted to see if the sun visor provided on the standard EMU would be sufficient. Per Dr. Martin E. Coleman's memo to Mr. Curt Broussard, dated August 16, 1996, ". . .conduct of the ISWE in the space vacuum, while wearing an EMU with the standard sun visor, will not present an eye hazard from the bright light produced."

The above discussion is a prime example of the issues that arise during technology utilization. The system utilized was designed to meet another set of criteria and requirements. Once subjected to new criteria and requirements, obvious discrepancies occur, some of which may be quite serious. If the same standards were used, issues such as the one above would be resolved in a matter of minutes instead of days, or never occur.

Section 5: What About ISO?

The International Organization for Standardization (ISO)

ISO is a worldwide federation of national standards bodies, at present compromising 118 members, one in each country. The object of ISO is to promote the development of standardization and related activities in the world with a view to facilitate international exchange of goods and services, and to develop cooperation in the spheres of intellectual, scientific, and technological and economic activity. The results of ISO technical work are published as *International Standards*.

The scope of ISO covers standardization in all fields except electrical and electronic engineering standards, which are the responsibility of the International Electrotechnical Commission (IEC). ISO brings together the interests of producers, users (including consumers), governments and the scientific community, in the preparation of international standards.

ISO work is carried out through 2,856 technical bodies. More than 30,000 experts from all parts of the world participate each year in the ISO technical work which, to date, has resulted in the publication of 10,189 ISO standards.

ISO Standards and ISWE

Several of the issues encountered with ISWE would have been eliminated if ISO standards had been in place at both MSFC and PWI. Concerns over manufacturing processes, fastener strength and quality, and material property certification would have been eliminated with adherence to ISO standards in section 49, Aircraft and Space Vehicle Engineering. For example, Aluminum is the most common material used on ISWE, section 49.025.20 deals specifically with Aluminum alloys, their inspection, testing, and supply requirements, in aerospace construction. Section 49.030 of the ISO standards deals with the integrity of each fastener manufactured and even describes the process to test those fasteners. Adherence to this standard would have allowed for easier approval of the PWI process for their fasteners.

Concerns with ISO

Although several of the specific issues encountered by ISWE were unique, adherence to ISO standards would have potentially eliminated many of them as concerns. But several member nations, most notably the United States, have not fully embraced ISO jurisdiction in areas which would significantly impact its economic well-being. The first reason for this stand is the fact that although the U.S. drives a significant amount of the world's engineering activity, it has only a single vote among many in ISO decisions. Also, the near term cost of fully implementing current ISO standards would easily cost billions of dollars. Obviously, as engineering activity becomes more internationalized, especially in space, the long terms gains of uniform standards (in terms of reduced cost and effort) must be considered.

Conclusion

The International Space Welding Experiment was designed and submitted in the Fourth NASA Call for Flight Demonstrations. Although originally conceived to demonstrate the capability of welding in space as a possible repair scenario. ISWE became a larger demonstration of international space cooperation. Through ISWE, one-time rivals, the United States and the Ukraine, have come together to share technologies and lessons learned from three decades of flying in space. For many of the engineers at NASA Marshall Space Flight Center as well as the Ukraine, the ISWE experience has encouraged new ways of thinking and creative approaches to problem solving. But through the entire process, all of the engineers have been surprised at how differently the two parties operate. This shared learning experience can serve as an example of the pitfalls and successes faced when creating a truly international space program.

The history of ISWE redesigns which developed out a lack of common standards should serve as a catalyst for the development of a new set of standards. This process should at least begin with the current major space powers; NASA, the Russian Space Agency, the Japanese Space Agency (NASDA), and the unified European countries through the European Space Agency (ESA), convening a conference to develop a truly international set of standards for space technologies. Although NASA would normally seek to lead such a process, the authors feel that each nation should be given equal standing based on their cumulative years of experience. Standards should be assessed based on objective engineering judgment and not the bias of past practice. Creation of such a system would facilitate and promote future international partnerships and help to make space exploration and exploitation a truly international endeavor.

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APPROVAL

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The International Space Welding Experiment is a joint project between the E.O. Paton Welding Institute of Kiev, Ukraine and the George C. Marshall Space Flight Center in Huntsville, Alabama. When an international partner is involved in a project, differences in design and testing philosophy can become a factor in the development of the hardware. This report addresses selected issues that arose during the ISWE hardware development as well as the solutions the ISWE team made.

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