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AIMS and SCOPE

The Journal of Space Safety Engineering (JSSE) provides an authoritative source of information in the field of space safety design, research and development. It serves applied scientists, engineers, policy makers and safety advocates with a platform to develop, promote and coordinate the science, technology and practice of space safety. JSSE seeks to establish channels of communication between industry, academy and government in the field of space safety and sustainability.

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ISSPRESSO DEVELOPMENT AND OPERATIONS

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ABSTRACT

The ISSpresso is a small aisle deployed payload developed to demonstrate the capability to brew quality espresso coffee in the environment found on the International Space Station (ISS) as well as in the conditions that would be experienced on possible future human exploration missions beyond Low Earth Orbit (LEO) to the Moon or Mars. A number of design challenges are presented by microgravity and low-gravity environments. In addition, the ISS program has a number of safety and interface requirements that any payload needs to adhere to. For ISSpresso each requirement was fully met as documented by the verifications submitted to NASA, including those required by the Payload Safety Review Panel (PSRP) to demonstrate compliance with ISS safety requirements for transportation, on-orbit operation, and return or disposal NASA Certification was obtained at the end of 2014. ISSpresso is currently onboard ISS having been successfully operated for the first time during Expedition 43.

1. INTRODUCTION

The food system for long-duration space missions not only provides nutrition to the crew, but it also provides a form of psychological support by providing a familiar element in an unfamiliar and hostile environment [1].

The ISSpresso project was already in progress when Luca Parmitano said from the ISS, "I miss my espresso". Argotec and Lavazza partnered to develop an espresso maker that would work in space as well as meet the requirements for flying on the International Space Station. Bringing together the experience Lavazza has with coffee and the experience Argotec has with space engineering and operations provided a unique opportunity to deliver to the crew of the ISS an improvement over the previous food systems onboard.
Argotec and Lavazza did not work alone, the Italian Space Agency (ASI) acted as the sponsor for the payload with NASA.

Prior to the ISSpresso, the crew only had access to instant coffee. The instant coffee is in a drink pouch which is then filled with hot water to produce their coffee. The hot water is provided by the Potable Water Dispenser (PWD). The ISSpresso however, infuses coffee grounds with hot water under pressure to extract the espresso as would be done on Earth. The espresso is provided inside commercial capsules conveniently modified to prevent burst if exposed to vacuum, and properly packaged to avoid coffee grounds dispersion in case of capsule accidental rupture. All equipment on the station is required to sustain decompression and recompression as nominal condition.

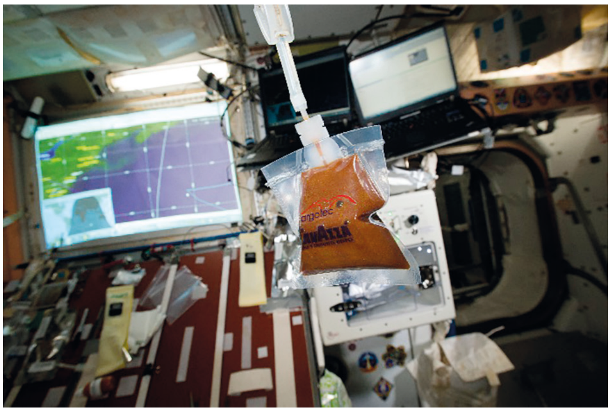

Figure 1 ISSpresso pouch with espresso on the ISS

ISSpresso does not brew only espresso, it can also produce hot beverages and consommé (such as chicken broth) for food hydration, depending on a wide selection of capsules.

2. COMMERCIAL HERITAGE

In the seventies there was a general understanding in the industry that instant coffee would see the end of coffee machines. The invention of coffee in capsule was meant to be an alternative to instant coffee that is quick to prepare and as tasty as traditional espresso. Eventually, it matured to a perfect combination of oxygen pressure mixed with packed coffee to extract all the aromas and tastes [2]. In early capsule designs, each capsule contained a filter that was made largely of aluminum. Then the filter was moved outside the capsule such to be reused on each capsule as part of the machine. The use of coffee capsules has dramatically changed the espresso market worldwide. It is no longer necessary to have all of the equipment that was previously required: grinders, tampers, and related skills in using those tools. The advent of the capsule allows a user to insert the capsule and after the machine does its work quality espresso is ready for consumption.

A typical home espresso machine consists of a reservoir of water that is heated and pressurized to extract the espresso from a capsule. The capsule is a small plastic container with an aluminum foil lid sealed to the top of the capsule. When closed in the brew chamber, the capsule lid is perforated by small spikes. This allows the heated and pressurized water to flow into the capsule. The combination of heat and pressure causes the capsule to deform. This deformation pushes the other end of the capsule into a second set of spikes. These spikes puncture the capsule completing the path for water flow through the capsule. After the capsule the espresso flows out of the brewer.

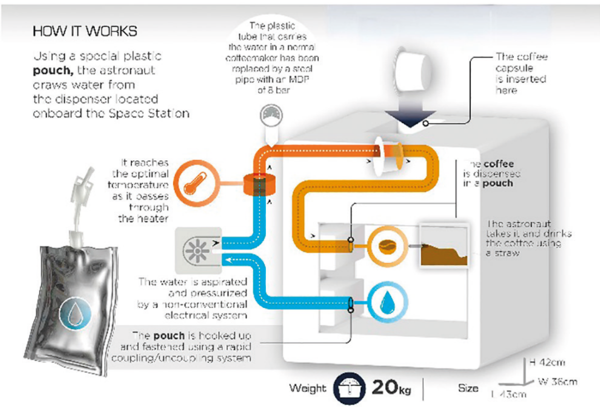

Figure 2 ISSpresso brewer and brew chamber

The brewer (and brew chamber) for the ISSpresso has the same functionality as a commercial machine on the ground. However, the materials and individual components were made entirely new for the ISSpresso, in order to increase their strength to mechanical and pressure loads and to reduce the residual water produced during the brewing cycle. A different design of the brewer outlet is introduced in the ISSpresso. It allows the used capsules to be removed from the chamber providing enough volume to accommodate micro-switches in charge of detecting the position of the capsule in each phase of the ISSpresso operations. Furthermore, an aluminum plunger has been integrated in order to push the capsule out of the brewer chamber replacing the effect of the gravity acting in the terrestrial machines.

3. APPLICABLE REQUIREMENTS

In order to be approved for transportation to and operation on-board the Station, the ISSpresso system had been analyzed and verified for compliance to all the applicable requirements for payloads. These requirements are collected in the ISSpresso PIRN (basically a tailoring of SSP57000 [3]) and in the Flight Safety Data Package extensively reviewed and approved by NASA Safety Review Panel. The number of requirements documents that are applicable is rather long, we present in Table 1 a shortened list of main applicable documents that were referenced in the development and safety review of the ISSpresso.

Many of the technical requirements in SSP 57000 provide for safety and well-being of the crew and vehicle. Some are more related to human factors, such as the strength required to flip a switch, or naming conventions for hardware. It is possible to obtain exemptions for certain requirements, but it is generally cheaper and faster to design in compliance with the requirements than seeking approval of deviations.

Table 1 Reference requirements documents

SSP 57000	Pressurized Payloads Interface Requirements Document
SSP 57059	Standard Payload Integration Agreement for Pressurized Payloads
SSP 50005	International Space Station Flight Crew Integration Standards
SSP 30559	Structural Design and Verification Requirements
SSP 30599	Safety Review Process
SSP 30243	Space Station Requirements for Electromagnetic Compatibility
SSP 30245	Space Station Electrical Bonding Requirements
SSP 30237	Space Station Electromagnetic Emission and Susceptibility Requirements
SSP 50008	International Space Station Interior Color Scheme
SSP 50076	NASA/ASI Joint Management Plan
SSP 50102	NASA/ASI Bilateral Integration & Verification Plan
SSP 50254	Operations Nomenclature

4. ISS ENVIRONMENT

While adapting an Earth based machine to operate in the microgravity environment of the space station a number of factors were taken into account. The thermal conditions are different since lack of gravity is not helping cooling by convection (i.e. hot air does not rise as on the ground). Liquid spills do not behave as would be expected on the ground and care was taken to determine what would happen in the event of a liquid spill from (or inside) the ISSpresso.

Once installed the ISSpresso is in fairly benign environment in terms of loads and vibrations. However, during launch there are a number of forces acting on the machine. Foam packing was used to damp vibrations and shocks, and its effectiveness was verified by a test campaign. Shown below is the Power Spectral Density (PSD) curves for Dragon and Cygnus launch vehicle that we used during testing.

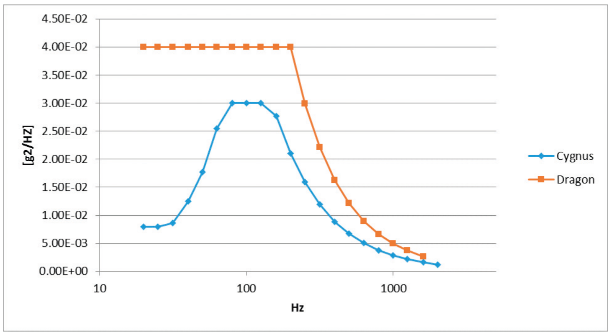

Figure 3 Dragon and Cygnus PSD curves

As mentioned, during all phases of operation the ISSpresso must be able to sustain depressurization of the station to vacuum and return to standard atmospheric conditions without causing damage to the station and other payloads. We designed ISSpresso to remain operational after such an event, however the ISS requirement is just to be safe and not to cause damage to anything else.

In addition to the physical differences experienced on the station there are ISS program requirements that the ISSpresso must adhere to in order to preserve the crew environment. For example the ISSpresso limits thermal, gas, light, and electromagnetic emissions to levels acceptable to the ISS program. The ISSpresso keeps temperature of all surfaces that can be touched by the astronaut under 45 °C, in nominal conditions as well as in case of an anomaly such as a runaway of the heather. In order to limit the vibrations generated by the ISSpresso that could spoil the microgravity environment required by some experiments, a vibration pump was not used as is frequently done for ground based models. The water pressurization is achieved by a double-effect linear pressurizer moved by a stepper motor and able to increase the water and air pressure up to the deign values.

5. CONSTRUCTION

The ISSpresso was built and tested on the basis of 4 models. Each successive model showed an increase in fidelity and functionality until the final flight model was assembled.

The first model, was a breadboard of the hydraulic and pneumatic system which we called the "2-D model". The lines were laid out in a flat fashion. The pump and brewer used in this model were commercial versions of those items and not those selected for the flight model. The intent of this model was to demonstrate a proof of concept before continuing to develop the hardware further. The most flight realistic components in this model were the drink pouch adapter and the needle for dispensing the beverage into the drink pouch.

The second model was of increased fidelity "elegance model" with a version of the pump we selected for the flight model. We had an early version of the brewer. Ultimately this design was changed prior to inclusion in the flight model. The housing and the structure were the same as the flight model. The surface coating was not the same as we intended to use for the flight model, but it was not required at this stage of development. The electronics were a crude mockup of the flight version. There were no safety devices installed in this version of the hardware. That is to say, the hardwired controls we utilized for safety were not applied in this version of the hardware.

The third version of the ISSpresso was the "ground model". The ground model was functionally identical to the flight model with the exception of two additional relief valves being included in the flight model for safety of the pressure system. In the event of out-of-nominal overpressurization. The ground model was used to perform a number of tests where appropriate.

The protoflight model, was the final version incorporating everything we learned from each of the previous stages. It was used to perform those final tests that could only be performed on the flight configuration to ensure safety and mission success. The protoflight model included, the two additional relief vales as previously mentioned, but also included the appropriate surface coating as required by NASA and the prescribe labels as per SSP 50005 "International Space Station Flight Crew Integration Standards".

6. HAZARDS & CONTROLS

The ISSpresso had a number of requirements to meet for safety certification. Many of the requirements are standard for hardware intended to be flown on the ISS, for example non-flammable materials, low off-gassing, radiated EMC limits, sharp edges, touch temperature, etc. There were four unique hazards that required to be documented in Unique Hazard Reports for the NASA safety panel. These reports identified the hazard, what causes there were for the hazard, how the hazard would be controlled, and finally how that hazard control would be verified.

Table 2 Unique Hazard Reports

Hazard Report Number	Hazard Report Name	Causes
UHR-01	Rupture/Leakage of fluid loop and/or release of hot liquid	• Inadequate design • Improper material selection • Improper on-orbit operations • Improper manufacturing and assembly
UHR-02	Water dispenser needle sharp points	• Crew member touching needle
UHR-03	Electrical shock	• Inadequate design • Improper operations • Exposed contacts or terminals
UHR-04	Drink Pouch Touch Temperature	• Improper operation • Improper design

For those causes which were related to design, materials selection, or manufacturing and assembly control was provided for and verified by review of design, hardware inspection, and where necessary testing of the hardware. Review of design involved examining the drawings to verify that design controls were in line with those documented in the hazard reports. Hardware inspection required examining the as built hardware to ensure it was in compliance with the drawings as well as determining that the hardware was functionally capable of controlling the hazards. Finally, testing involved subjecting the hardware to flight like conditions, with safety factor margins included, to demonstrate with test data that the hardware was physically capable of controlling the hazards.
For the concerns that were operational, or related to crew action, notes were added to crew procedures to remind them of the safe method for performing the related steps. The NASA safety panel reviewed and approved the hazard controls as well as planned verification for each of the controls.

7. TESTING & CERTIFICATION

Safety, design, and functional requirements have been verified according to the verification plan negotiated with ASI (Italian Space Agency) and NASA. To help make the hardware reliable, we decided to include in the ISSpresso design Space/MIL rated EEE components as much as possible. This allowed us to select the Proto-Flight qualification process conducted at a system level as the best approach to follow for the flight unit. Despite the efforts driven by the engineering team to use the above components in the ISSpresso design, some exceptions have been included and verified at the subsystem level. This is the case of the linear pressurizer which drives the water and the air in the hydraulic and pneumatic circuits respectively. This mechanical component was entirely designed and developed by Argotec to address specific functional and safety requirements. The same for the electronics and other mechanical elements such as the brewer and the pouch connections.

We used the Ground Model as a test bench to assess the response of the hardware to the most critical safety aspects as main outcomes of the safety analysis, such as over pressure and over temperature of the water/air in the hydraulic/pneumatic lines and an high temperature on the external walls due to the presence of the heating element. Furthermore, we tested it extensively to assess the maximum number of brewing cycles the machine can operate at a system level. This number, multiplied by a large safety factor, was considered as an indication for the design lifetime. We also conducted a preliminary EMC/EMI test campaign as an indication of the hardware response to the electromagnetic compatibility and interference.

The preparatory test campaign performed on the Ground Model revealed a few relevant working and compatibility issues which were fixed on the Proto-Flight Model (PFM) at all stages of the development process (from the design to the integration). The PFM followed the entire qualification and acceptance process aimed at verifying the requirements applicable to the ISSpresso hardware such as the tightness of the hydraulic and pneumatic lines under the prescribe Maximum Design Pressure (leak and proof pressure test), the structural integrity of the entire system under the defined launch loads (vibration test), the proper working of the safety devices, the compatibility with the applied electrical requirements (grounding, bonding, isolation, and EMC/EMI), the response of the hardware to thermal cycles (thermal cycling test), the heat distribution and thermal dissipation along the entire system (thermal interface test). In particular, the tightness of the hydraulic and pneumatic lines and the safety devices have been tested before and after the vibration test to ensure their integrity and to demonstrate they worked nominally.

Following the test procedures written during the hardware design phase, each individual safety device has been tested on ground in a specific sequence and the results have been extensively discussed with the NASA Safety Panel at Payload Safety Review Panel (PSRP) Phase II/III Safety Review, successfully passed on the 28th of January 2015.

Other than the relief valves, the pressure switches, the thermal switches, and the hardwired end switches acting as main safety controls, three of the ISSpresso elements have been reviewed deeply for safety by the NASA Mechanical System Working Group (MSWG) and they are the brewer, the pouch adapter (containing a stainless steel needle which allows the connection with the pouch) and the compartment door. These mechanical elements have been discussed with the MSWG during the Phase II and III Safety Reviews and they have been finally approved at the end of the tests carried out on each single flight mechanism.

Finally the PFM has been inspected by the Human Factor Integration Team (HFIT) for compliance with the Human Factor requirements and approved for flight.

8. OPERATIONS

For operations on board the ISSpresso is mounted to a surface inside the USOS module, in the American segment of ISS. The mechanical connection is provided for by using four straps to secure the machine to the rack seat tracks. Each strap provides a connection for one corner of the machine. Electrical power is provided from a Utility Outlet Panel (UOP) supplying 120 Volts DC.

Much like a commercial brewer, once installed operation of the ISSpresso requires a water supply, a capsule of coffee grounds, a container to dispense the espresso in, as well as crew manipulation of switches and buttons to control the brew process.

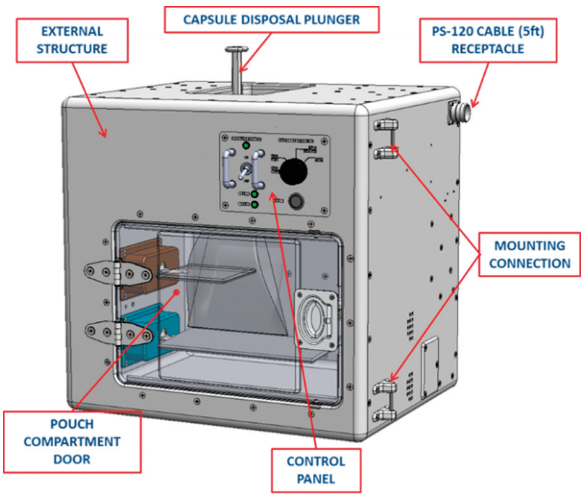

Figure 4 ISSpresso

The new espresso capsules are stored in stowage bag attached with Velcro to the right side of the ISSpresso. The bag contains drink pouches and flush capsules as well. The flush capsules are used in nominal operations to clean the hydraulic lines with hot water after long periods of ISSpresso inactivity.

Once on board the Station the hardware is installed and the hydraulic circuit filled with water, as per the dry to wet transition procedure. The execution of this procedure represents the first operational step since ISSpresso is launched in the dried configuration to prevent possible internal damages due to the water (thermal) expansion occurring during the transportation to the ISS.

ISSpresso makes use of a NASA standard water bag filled by 250 ml of water from the potable water dispenser (PWD) and connected to the ISSpresso adapters (the ISSpresso adapters are blue for water and brown for coffee). The bag attachments (both water and drink where the coffee is collected at the end of the brewing cycle) are designed to provide a standard interface with the drinking pouches already used on the Station and to increase the crew safety by securing the pouch in place with a spring loaded mechanism.

The pouch connection to the ISSpresso is the first step to brew the coffee on orbit and it is followed by the machine power activation and the selection of the desired volume of hot beverage. ISSpresso provides the choice of 30, 60, 120 ml of hot beverages depending on crew preferences. Part of the preparatory steps is the capsule insertion in the brewer chamber, conceived to be as much as possible similar to the commercial machine. The closure of the brewer chamber lid assures the proper insertion of the capsule and starts the brewing process. When the water reaches the right pressure and temperature inside the lines, the brew button becomes green and if pushed enables the coffee production. At the end of the espresso extraction, a small volume of pressurized air is released in the last branch of the hydraulic line to clean and empty the tubes from residual coffee. The espresso is than ready to be tasted by using one of the NASA standard straws available.

The ISSpresso operations are continuously monitored and controlled by the On-Board Controller (OBC) and all the telemetry is written to two SD Cards installed on the right side of the ISSpresso main housing. The acquired telemetry is used for troubleshooting operations to determine failure causes and allow the engineering team on ground to provide the proper corrective actions. All the on-orbit operations are supported by NASA certified personnel at the Argotec Control Center, located in Turin.

9. CONCLUSIONS

The ISSpresso team was able to provide the machine in less time than is normally taken to develop a payload. This was due, in part, to a dedicated team of engineers who put in a tremendous amount of effort. It was also due to the team taking into account many of the safety requirements prior to, and during, the design. Iterative steps in the design and development phase strove to take into account all known, and some only suspected, safety and design requirements that would be levied on the final version of ISSpresso. A great deal of time and effort was saved by having a safe design prior to having even the first preliminary meetings with the NASA safety panel. This was most beneficial in the development of ISSpresso in that no redesigns were required as a result of PSRP reviews and their inputs to the machines design.

One of the big challenges undertaken by the engineering team was to design ISSpresso as an ISS system and not only as a payload and extending the ISSpresso functionalities and capabilities. It does make espresso, which can provide a psychological benefit to the crew that is away from home for months at a time, but it also has the ability to expand, or modify, the crew menu. The ISSpresso can make teas as well as consommé. These additional options provide flexibility to the crew menu that is not currently available. For example, a dish of rice may have a variety of broth added to it for different tastes. As it is currently, the crew would need to make that selection months before flight and would not have the option to modify that choice on board. With the ISSpresso that choice could be made at the time of preparation on the ISS. This improved selection ability can provide additional psychological support to the crew by providing them more control over their menu selection at a time that is more relevant to them.

It is known that fluid shift in microgravity results in crewmembers whose tastes change on orbit versus what they preferred on the ground. Typically, this is towards more spicy food with additional flavor. The additional flavor is thought to overcome the loss of taste resulting from the additional fluid that has shifted up into their heads. The ISSpresso shows the possibility to provide an increased functionality to the crewmembers, not only on the space station, but to other future manned human exploration efforts.

10. REFERENCES

[1] *Food systems on space exploration missions* https://en.wikipedia.org/wiki/Food_systems_on_space_exploration_missions

[2] *A Life Encapsulated* - GCR Magazine Cover Story November/December 2011

[3] SSP 57000, *Space Station Program, Pressurized Payloads Interface Requirements Document*

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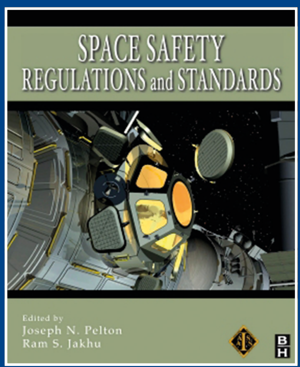

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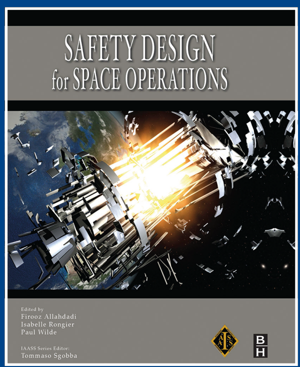

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