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MMaJIC, an Experimental Chamber for Investigating Soldering and Brazing in Microgravity

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ABSTRACT

An E-1 payload, the Microgravity Materials Joining Investigative Chamber (MMaJIC), was designed and built for use aboard the International Space Station to investigate soldering and brazing phenomena in a microgravity environment. MMaJIC is a self-contained unit employing a microcontroller that runs a pre-programed experiment, monitors safety sensors, and supports temperature and video recording. MMaJIC uses individual experiment trays that can be easily modified for a specific investigation. The trays, which include a temperature/video data acquisition card, can be easily changed out and returned to Earth for evaluation. Simple operation of MMaJIC minimizes astronaut time while ensuring maximum sample throughput. It is expected that the results will shed considerable light on soldering and brazing in low-gravity environments, information that is important for NASA in conducting comprehensive repair and/or fabrication operations during long duration space missions.

Key words: Soldering; Brazing; Microgravity Science Glovebox; International Space Station; ISSI (In-Space Soldering Investigation)

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INTRODUCTION

Only a few soldering-related experiments have been conducted in a microgravity environment (Winter and Jones, 1996; Pettegrew et al., 2002; Pettegrew et al., 2003; Struk et al., 2004). These were followed up by the In-Space Soldering Investigation (ISSI) which was conducted as "Saturday Science" in the Maintenance Workbench Area (MWA) onboard the International Space Station (ISS) in 2004 (Grugel et al., 2006). During these tests, 86 total solder samples were made. Seven different wire configurations were employed to observe how the microgravity environment affects the behavior of solder during melting, flow, and solidification. Figure 1 shows ISS Science Officer Mike Fincke conducting a set of melting experiments within the MWA. The samples were video recorded during processing and, upon return to Earth, micro/macroscopically examined and metallographically prepared to examine the internal structure.

Figure 2 presents a cross-sectional view of one of the samples shown in Figure 1. The equilibrium "football" shape results from the lack of buoyancy forces. Considerable porosity is seen at the solder-wire (joint) interface. During the experiment, a temperature gradient occurs through the sample as heat is applied to the wire from below. As buoyancy (gravity-driven) effects are essentially eliminated in microgravity, other gravity-independent forces such as thermocapillay convection become dominant. This convection, in conjunction with the temperature gradient, effectively moves bubbles (likely flux generated) to the joint interface. The resulting porosity compromises thermal and electrical conductivity of the solder joint and reduces mechanical strength. In short, solder joints made in microgravity were found to be inferior to their Earth counterparts.

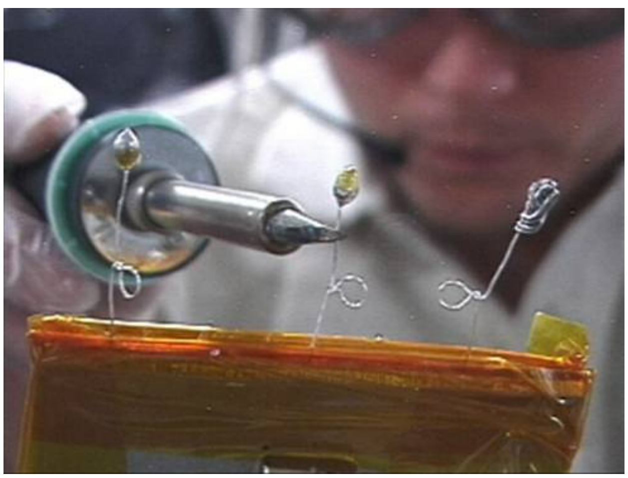

Figure 1. Photograph of ISS Science Officer, Mike Fincke, conducting a set of melting experiments within the Maintenance Work Area. The sample on the left was just completed, the central one is being melted, and the one on the right shows 10 cm of solder wrapped about the top of the wire prior to melting. The yellow material is rosin from the solder-wire core.

Soldering protocols that ensure structural integrity are needed if repairs or joints will be made in reduced gravity environments on future space missions. Additional studies are needed to understand and mitigate the impact of microgravity phenomena in material melting and solidification that are detrimental to the solder joint. The intent of this work is to design and construct an apparatus, the Microgravity Materials Joining Investigative Chamber (MMaJIC), in which a diverse number of soldering/brazing experiments could be conducted in an efficient and safe manner onboard the ISS.

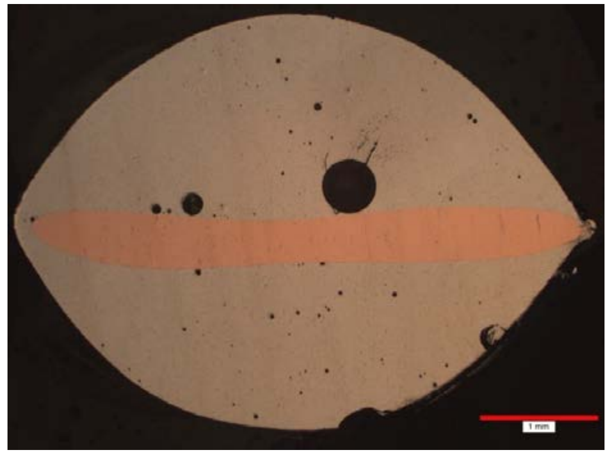

Figure 2. An optical micrograph from one of the ISSI samples processed in Figure 1. Flux bubbles (porosity) are seen at the solder/copper wire (joint) interface. This porosity compromises thermal and electrical conductivity as well as reduces mechanical strength.

DESIGN RATIONALE AND IMPLEMENTATION

MMaJIC was designed in accordance with E-1 payload requirements. As such, it should serve as spaceflight hardware, be aligned with identified needs on the ISS Exploration Technology Roadmap (NASA, 2015), not duplicate existing efforts, and be ready in a short (~1 year) period of time. Furthermore, the flight hardware must be accommodated within present ISS research facilities, and existing processes and culture (i.e., time and money) in its development should be challenged as well.

The requirements development and design of MMaJIC considered containment (for particulate and smoke generated during payload operation), electronics/software, science, and safety/risk. The apparatus was designed to fit within the Microgravity Science Glovebox (MSG) or the MWA, interface with the available power, and be operable by a crewmember with gloved hands. The payload utilizes interchangeable sample trays to maximize throughput and incorporate visibility so the experiments can be video recorded while also allowing the astronaut to observe operations. Safety considerations included incorporating levels of containment and sensors. Owing to limited crew availability, ease of use and autonomy were among the most important considerations in designing MMaJIC. Therefore, human factors were a high priority in each subsystem design to ensure operation was smooth, simple, and fast.

Containment

A simple box geometry (~27 cm × ~20 cm × ~16 cm) was chosen to house the sample cartridge, electronics, and video camera. Windows were included on the front wall and door of the containment box to allow the attending crewmember to view the samples and ensure the experiment is running nominally. A high definition GoPro® camera was placed inside the box, enabling a direct close-up view of the samples. The electronics fit on the inside of the box's removable lid. The electronics suite includes indicator light-emitting diodes (LEDs), a power switch, a push (start) button, a digital liquid crystal display (LCD), the microprocessor, and circuit board. The removable lid enables easy access to modify wiring modifications or upload revised firmware to the microprocessor. The interior volume is large enough to permit considerable variation in sample cartridge design if needed for a specific investigation. The finished apparatus is shown in Figures 3A and 3B.

Figure 3. Photographs of the Microgravity Materials Joining Investigative Chamber (MMaJIC) containment box. 3A shows the box with an inserted sample tray and the door open. 3B is a close-up of the removable top showing the indicator LEDs, power switch, start button, and LCD panel.

The sample cartridge was manufactured additively with acrylonitrile butadiene styrene by a Fortus® 900mc FDM machine. A 1.6 mm thick neoprene seal was placed around the sample bay, and a 3.175 mm acrylic window was cut to cover the cartridge and provide a seal around the sample bay to retain particulates. Copper blocks were used to support the kanthal wire heating element. The sample cartridge was designed to contain the experiment, control thermocouples, and house the data acquisition (microSD card). The SD card can be easily interchanged. Flexibility in cartridge design was an important consideration. As a potential multi-user facility, MMaJIC needs to accommodate different sample geometries and heating element arrangements in order to conduct a wide range of experiments. At the rear of the cartridge there is a power and signal plug that routes the current for heating as well as up to 24 signal lines from the microprocessor. Figure 4 shows a photograph of the cartridge tray.

Electronics/Software

Primary design considerations emphasized reliability and ease of use to minimize set-up and experimental time on the ISS, while remaining robust enough to recognize off-nominal situations and shut down automatically, an important safety feature of the payload. The electronics must also reliably and autonomously start the system when powered on in the MSG.

MMaJIC is powered by the glovebox's 28 V circuit, which limits current to 7 A. This powers the heating wires and is regulated to 12 V to power the controller and box lighting. All signals and power from the housing to the cartridge pass

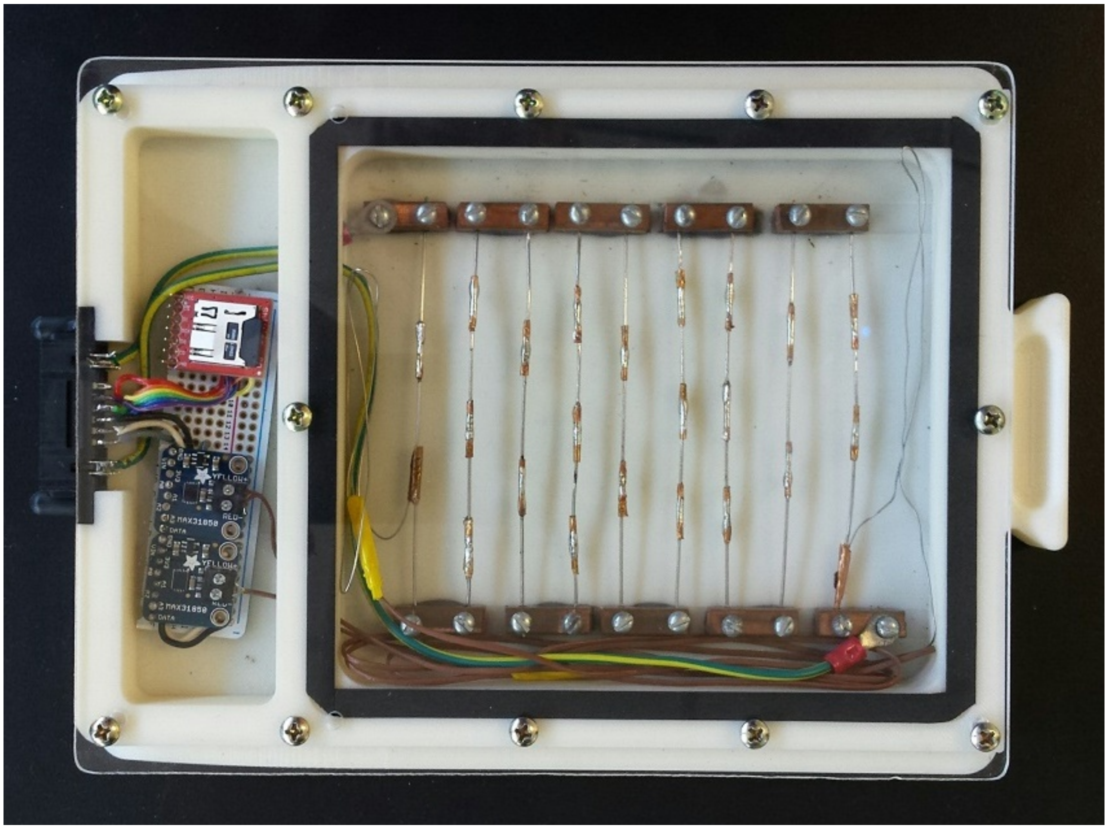

Figure 4. Photographs of the Microgravity Materials Joining Investigative Chamber (MMaJIC) sample tray. Dimensions of the tray are, including handle and plug, approximately 23 cm × 16 cm × 20 cm. The left, smaller chamber houses experiment-specific electronics, including the data acquisition card. The chamber on the right shows the kanthal heating wires. The 20 samples consist of a small copper foil, tightly wrapped around the wire, around which 10 cm of a lead-tin rosin-core solder was then added. Two control thermocouples are seen at the bottom of the left and right wires.

through a pin and blade connector consisting of 24 signal pins; 13 are used for the cartridge's communication and power. Four pins are used to configure the experiment to run at different temperatures. The system is controlled by an Arduino Mega® that enables execution of a stored program once the system is powered. This also eliminates the need for a crewmember to directly interact with the program to execute an experiment. The electronics are divided into two subsystems: cartridge sensing/control and user input/output. These subdivisions come naturally from the need to route all signals through the Arduino before sending commands or information to the cartridge and crew.

Cartridge sensing and control

The experimental operation is fundamentally simple: the relay controls power to the heating wires, thermocouples monitor the temperature until a set point is reached, and the Arduino turns off the relay. A micro-SD card records the thermocouple output, and an infrared particle sensor monitors the cartridge for potential containment failure. The diagram shown in Figure 5 provides a subsystem overview of the components and their interaction with the microcontroller. The heating wires are made of 20 Gauge Kanthal A1 wire, a Fe-Cr-Al alloy capable of reaching temperatures up to 1400°C. The wires are monitored by K-type ungrounded thermocouples connected to the electronics through a MAX31850® breakout board. This allows one-wire data communication with an arbitrary number of breakout boards, permitting an experiment to support several thermocouples in each cartridge.

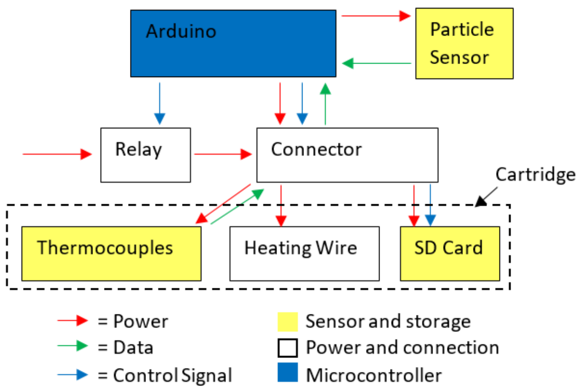

Figure 5. Microgravity Materials Joining Investigative Chamber (MMaJIC) system block diagram.

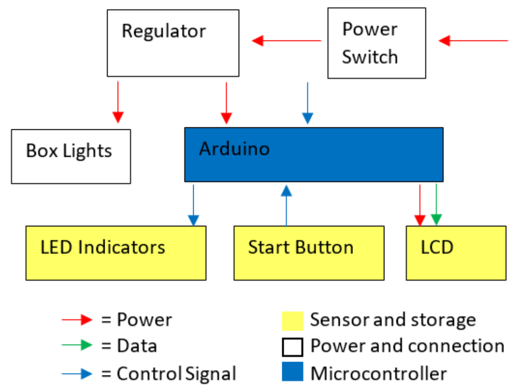

Figure 6. Microgravity Materials Joining Investigative Chamber (MMaJIC) user interface block diagram.

Thermocouple output is temporarily stored in the Arduino for display to the crew and to determine if shutdown criteria have been satisfied. Shutdown occurs if: i) the thermocouples have reached the target heating temperature, ii) if any thermocouples rise above a defined shutoff temperature, or iii) if the experiment has been on for longer than 30 seconds. The last two shutoff conditions are safety features. After shutoff, the microcontroller switches to cooling mode, which waits for the thermocouples to reach and fall below the safe touch temperature before prompting the crew to switch out trays.

User input and output

MMaJIC's user interface is designed for simplicity and ease of use. As detailed in the system diagram in Figure 6 (with reference to Figure 3), the user interacts with the experiment via the green start button on the front, and receives feedback from an LCD screen and three colored LEDs. A power switch allows for emergency shutdown if needed and is also used to reset the electronics if an unknown state is reached.

The LCD and LED lights combine to clearly indicate the state of the system at a glance while supplying more detailed information as needed. The LED lights change as the experiment moves from standby (yellow), to heating (flashing green), to cooling (steady green). During this time, the LCD displays the same information and additionally indicates the current highest and lowest thermocouple temperature recorded. If the electronics detect an error that will prevent operation, the red LED illuminates and an error message is sent to the screen. If the error is not experimentally critical, such as a failure of the SD card, the crewmember will be prompted to override the error by pressing the start button if desired.

Until an error is overridden or resolved, the software will prevent operation of the experiment. Currently identified errors include loss of cartridge signal, thermocouple failure, and leak detection, which all lead to immediate shutdown of heating power. Each of these off-nominal situations results in an uncertain experimental state, and the electronics will not allow the experiment to progress until the error is resolved. Failure of a SD card does not represent a potential safety risk; thus, the electronics allow this error to be overridden.

RESULTS AND DISCUSSION

During initial testing, MMaJIC demonstrated successfully its ability to meet the core requirements for the payload. Figure 4 shows 20 solder test/demonstration samples were simultaneously and successfully processed in the cartridge with only a pushbutton start. Thermocouple data and video imaging were recorded, and the experiment safely shut down after exceeding the shutoff temperature. The recorded temperature data from the cartridge thermocouples are shown in Figure 7. Note that

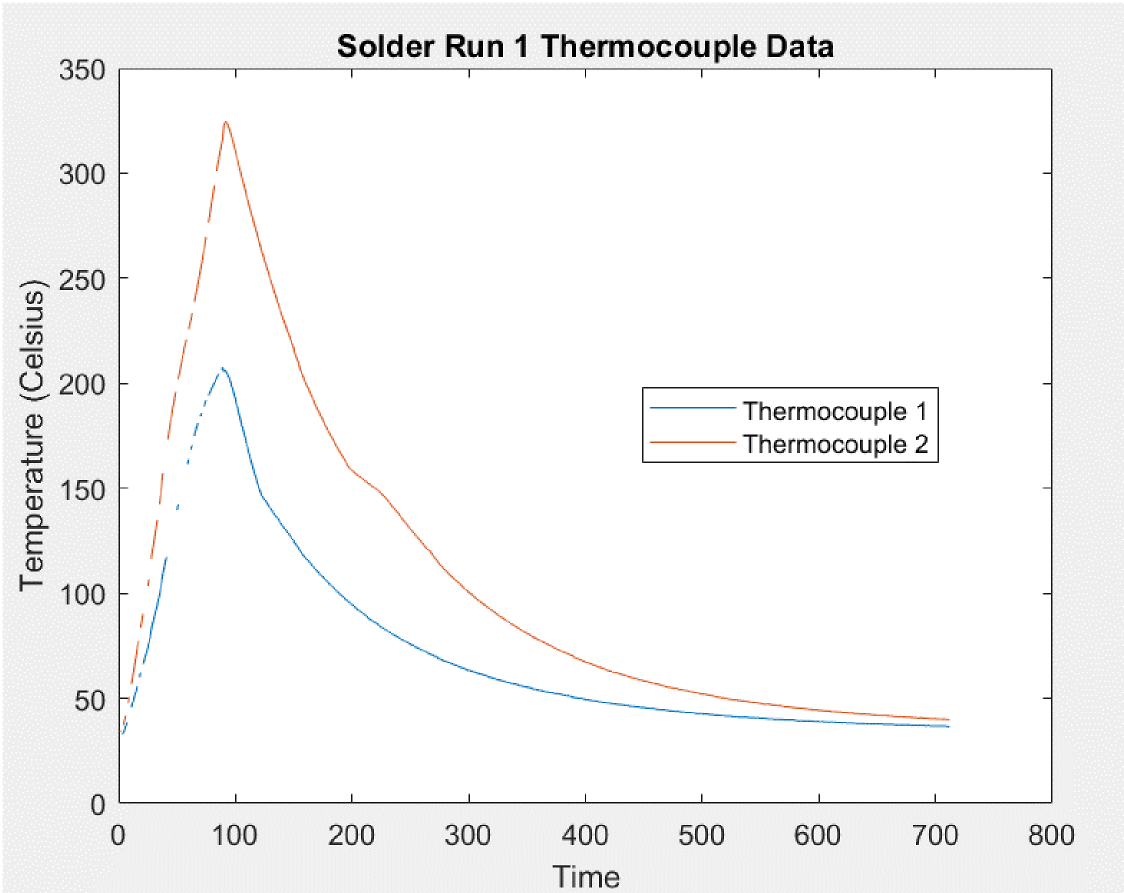

Figure 7. Plot of thermocouple data showing heating and cooling of the nichrome wires from which heat is conducted to melt the samples during the experiment. Note that the tip region of theromocouple 1 was not in contact with the heating wire.

thermocouple 1 reads significantly below thermocouple 2. This resulted from the thermocouple tip not being in contact with the heating wire. Despite this anomaly, the experiment successfully demonstrated the redundant shutoff conditions capability in the software and elucidated the need for sound and sustained contact with the wire. The sample tray itself can be modified easily to accommodate a wide range of experimental parameters. For instance, it could be built to a height of 10 cm, which would enable combustion experiments. Finally, the chamber and the sample cartridge each represent levels of containment.

While MMaJIC performed as expected, several modifications could be made. For instance, diffusing the internal lighting would improve imaging. The camera and processor could also be upgraded, more robust connectors installed, and design of the electronic systems revisited.

CONCLUSIONS

The Microgravity Materials Joining Investigative Chamber demonstrated its capability as an experimental platform for conducting soldering/brazing experiments in a microgravity environment. MMaJIC is compact in size, lightweight, user friendly, and compatible with the MSG. It consists of a single chamber and the unit is designed to accommodate/process many samples of varying geometries over a wide range of temperature/time scales. Combustion-type experiments using the hardware can also be envisioned. It is anticipated that the results from this apparatus will aid NASA exploration goals related to developing procedures for electronic component repair and fabrication during extended space missions.

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