The Kentucky Re-Entry Universal Payload System (KRUPS)

To increase the TRL of a small re-entry spacecraft to TRL 7 by demonstrating data acquisition, communication, and TPS designs.

James Nichols, Collin Dietz, Kirsten Ford, Joshua Laredo, Shelley Williams

Dr. Alexandre Martin, Dr. William Smith, and Dr. Suzanne Smith

University of Kentucky

September 30, 2019
1.0 Mission Statement

Participating in the RockSat-X project helps increase the Technology Readiness Level (TRL) of a small reentry spacecraft from TRL 5 to TRL 6 by demonstrating data acquisition, communication, and TPS designs in a space environment. Even though the environment of the project does not replicate the exact conditions expected with orbital fights, this suborbital fight can test the subsystems involved with the Kentucky Re-entry Universal Payload System (KRUPS) in microgravity conditions helping to ensure the success of the project. This fight helps test and demonstrate communication and TPS design so that it can be applied in future research, activation reliability in space environment, and the newly developed parachute release mechanism’s (PRED) reliability. The fight demonstrates what works in the experiment and what needs to be examined with more detail before proceeding to orbital flights.

2.0 Mission Requirements and Description

This mission aims to launch a small (11-inch diameter) re-entry capsule out of the sounding rocket. During the entry phase, the on-board circuitry records the data of thermocouples, accelerometers, a gyro-meter and magnometer. The main focus of the mission is to record thermocouple data at different depths of the Thermal Protection System (TPS). Successfully recording thermocouple data at the stagnation point will help provide fight data for validation of numerical models created by Dr. Alexandre Martin and his lab. Because of the small size of the capsule, retrieval has proven to be an issue on previous flights. Therefore, the primary method of obtaining the data is transmission to a ground station via the Iridium satellite network. An overview of the fight can be seen in Figure 1, with the Concept of the mission Operation (ConOps).

Figure 1: Concept of Operations
As seen on the figure, the capsule is transported by the sounding rocket to apogee. At T+240 the capsule is powered on and begins to attempt to transmit data. Five seconds later, the doors are opened and the cameras in the ejection mechanism are powered on. At T+250 seconds, the rocket reaches apogee (~150 km) and the capsule is ejected. The capsule is separated from the rocket, and both fall back on earth. During the entry and descent phase, the capsule records and transmits the scientific data using the Iridium satellites. Around 30 km, the connection becomes stable, and the bulk of the transmission begins. The parachute is then deployed once the capsule reaches and altitude of approximately 2 kilometers. As it drifts down to the water it will continue to transmit data. Since the capsule is expected to survive splashdown, transmission is expected to continue until all the data is transmitted. A GPS system was also incorporated to help locate the capsule if deemed possible during recovery of the rocket.

For the mission to succeed, the following requirements must be met:

- The KREM shall protect the capsule so that it reaches apogee undamaged to obtain accurate data.
- The KREM (with the capsule inside) shall be 40 ± 1.5 lbs.
- All communication and electrical components shall fit within the 11-inch diameter capsule.
- The capsule shall be ejected close to rocket apogee.
- The capsule shall be radio transparent to allow data transmission.
- The capsule shall have a center of gravity so that it is self-stabilizing.
- The TPS shall be able to mitigate the heat enough to protect the internal components.
- The capsule shall be able to withstand the impact forces of parachute opening and splashdown.
- The KREM shall successfully activate the capsule before deploying.
- The communication system shall transmit data to the Iridium satellite system after ejection until all data is sent.
- The capsule is to be water resistant to protect the internal electronics upon splashdown.
- The parachute release device shall deploy at the appropriate time.

3.0 Payload Design

Various missions with similar concepts of a re-entry were explored to evaluate what systems have worked in the past and what areas need to be improved for all objectives to be achieved. From this research it was determined that the best capsule design for the KRUPS project should be based on the Deep Space 2 capsules, utilizing a self-stabilizing 45-degree nose cone. This mission sent two entry capsules to the surface of Mars as a part of the Mars Polar Lander mission in 1999 [1]. Over the years, other capsules have successfully borrowed this design, such as the Reentry Breakup Recorder (REBR) [2], designed by The Aerospace Corporation. REBR was used to collect data during the re-entry and breakup of a
massive space debris or launch stage. The first reentry flight tests occurred in 2011 from the International Space Station. The first test was a success, while the second test was not. Two more REBRs were successfully tested in 2012, where the capsules self-stabilized, transmitted data, and survived impact. Considering the success of these missions and the added benefits of self-stabilization, this geometry was selected for the KRUPS vehicle. The relative dimension of the capsule is shown in Figure 2.

![Figure 2: REBR Dimensions](image)

All the dimensions are expressed as a function of parameter D, the overall diameter of the capsule, making it easy to scale the capsule to a desired size.

Two previous sounding rocket flights have been conducted to test the KRUPS vehicle, the KRUPS Deployment and Communication System (KUDOS) and KRUPS Operational Reentry Experiment with Veterinary Aspects (KOREVET). Analysis of the results of these missions played a very significant role in the designs utilized during this flight. Important design changes to both the capsule and ejection mechanism occurred as the team moved from one mission to the next, learning from the successes and failures of each one. The KREM module, shown in in Figures 3 and 4, was designed to hold the capsule in place and prevent any damage to the vehicle during ascent. The mechanism was constructed out of aluminum plates that were skeletonized to conserve weight and assembled in a hexagonal shape to maximum capsule size. Filler material was machined to the profile of the capsule out of nylon to allow it to be secured while minimizing risk of damage to the TPS. Two spring loaded doors held the capsule in KREM on ascent and were held closed by a linear pull solenoid. When this solenoid was activated it would retract pulling a pin that held the doors in place where the springs would then allow the doors to open fully, as shown in Figure 3. An activation pin was used to power the capsule on when the rocket reached apogee as well as provided a means to prevent the capsule from rotating out of place. The bottom filler pieces were secured to a linear push solenoid that when activated would gently push the capsule off the activation pin and out of KREM. The KREM was secured to the payload plate via 3 vibration isolating mounts, which reduced the vibration forces experienced by the payload. The ejection mechanism also contained 2 GoPros that were used for verification of events after flight.
The KRUPS capsule was instrumented with a variety of sensors to achieve mission objectives. The primary sensors were the K-Type thermocouples placed in thermoplugs within the TPS. Two side plugs were outfitted with four thermocouples and a single stagnation plug contained eight thermocouples making sixteen in total. Each plug contained one thermocouple at the tip, one a tenth of an inch (0.1”) from the inner surface of the TPS, and each of the remaining ones were spaced a tenth of an inch from each other starting from the tip of the plug. The stagnation plug is pictured in Figure 5. These thermocouples were connected to a sensor board that would then be read by a central flight computer, both of which were designed in house. This data was then compiled with data from the other sensors, compressed, and transmitted via an Irdium modem and antenna to the ground station. A functional block diagram depicting the sequence of events during the experiment is shown in Figure 6. All capsule power was provided internally through Li-Ion batteries. Finally, Analysis of the first flights revealed stabilization and impact as high potential failure points. Therefore, a parachute release device (PRED) was implemented to help mitigate
these issues. PRED will allow for stabilization below transmission altitude orienting the Iridium antenna upwards and therefore successful transmission. PRED will also allow for survival upon impact and therefore have a higher potential for recovery of the capsule. PRED consisted of an annular parachute integrated into the top portion of the capsule. The layout of PRED is depicted in Figure 7.

![Figure 5: Stagnation Plug (Left) and X-Ray (Right)](image)

![Figure 6: Function Block Diagram](image)
In order to model the expected trajectory and entry condition, the KTMP code [3] was used. KTMP is a six-degree of freedom trajectory code that uses the Sutton-Graves empirical relation to calculate the expected heat flux. The velocity at apogee was estimated at 315 m/s, at an altitude of 155 km. Using these values, the estimated heat flux is 17.9 W/cm². The results can be visualized in Figure 8, where the estimated trajectory is shown with the purple line. The other two lines (green and red) illustrate the difference in heat flux at different altitudes.

Figure 8: Expected Heat Flux Data

4.0 Student Involvement

Many groups of students have worked on the development of the vehicle and ejection mechanism over the past several years. Undergraduate senior design teams have worked on the different subsystems while a core team has been responsible for integrating all systems for flight. The organizational chart is shown in Figure 9.
5.0 Testing Results

The payload went through a series of tests to ensure the experiment was ready for the rocket launch. Some systems such as the ejection mechanism, camera system, embedded control (software and hardware), capsule design, base communication (Iridium), and GPS all had flight heritage and required less testing than the newly implemented systems. The first major tests conducted were vibration tests performed at Yokohama Industries in Versailles, Kentucky. The vibration table and set up used for these tests can be seen in Figure 10. The profile provided in the RockSat-X Guidelines was used to perform these tests and verify key components: verify the integrity of the KREM module, ensure that the capsule remains engaged with the activation pin, the door solenoid remains engaged, and that the capsule stays properly oriented. The sinusoidal and random test in the z-direction were the only profiles used as the shaker table did not allow to test other axes. The vibration tests verified that the capsule stayed properly oriented, remained on the activation pin and verified that KREM was ready for flight. However, the first tests revealed a potential for the solenoid pin to disengage due to the vibrations. Therefore, a stronger spring was placed on the solenoid and vibration testing was repeated. These final tests did not reveal anymore issues with the pin and all other systems passed.
Each of the electrical subsystems were tested individually before integration into the payload. As majority of these systems are flight verified majority of testing was completed quickly and easily with few minor bugs. Each system was then integrated, and multiple full simulation tests were conducted to ensure reliability. Full system tests were also conducted directly after vibration testing to ensure all systems functioned as designed after experiencing the vibration forces. All full simulation tests went smoothly with very few minor issues to address mainly with software.

Impact and waterproof testing were also conducted with a test vehicle to ensure survival upon splashdown. These tests were conducted at the Seaton Aquatic Center at the University of Kentucky. Analysis was conducted to determine impact speed and force for comparison to these tests. The test vehicle was then instrumented with sensors to detect water at various locations inside. The vehicle was then dropped from the high dive at several speeds and angles. After each drop the capsule was allowed to dry and water measurements were evaluated. Each drop was also recorded with high speed cameras in order to determine capsule speed. These tests verified the capsule would survive splashdown and that data could continue to be transmitted even after the capsule reached the ocean.

The final set of tests conducted were for inspection and verification of the parachute release device, PRED. The main concern with PRED was the opening forces the housing structure of the capsule would experience at the anchor points when the parachute deployed. After seeking advice from entry, descent, and landing experts at NASA JPL analysis was conducted to determine the magnitude
of these forces. A model of a single anchor point was then developed for implementation into a tensile test machine. Multiple anchor point models were then produced and several tests at varying angles were conducted on the tensile test machine. The set up for the test is shown in Figure 11. The results of the tensile test were then compared to the calculated forces to determine if the capsule could manage these forces. After evaluation it was determined that a single anchor point could withstand all forces experienced during parachute deployment and having 4 anchor points would be more than sufficient to ensure PRED reliability.

![Figure 11: Tensile Test Set-Up](image)

6.0 Mission Results

Many issues in the design of the KRUPS payload came to light during this mission. Unfortunately, due to the sequence of issues experienced no data was received. However, analysis of the failures revealed valuable information that will improve designs for upcoming missions and lead to successful collection of data. The first was revealing that a mechanical redesign of the system must be conducted in order to mitigate risks or doors bending, binding, or opening early and causing mission failure. Upon analysis of the GoPro footage it was revealed when the cameras powered on the doors were already open and pointing at wrong angles. Once the ejection mechanism was received off the rocket visual inspection showed both the hinges and doors were bent. It was determined this was due to the impulse force experienced on launch pushing the capsule into the doors causing them and the hinges to bend. This bending most likely shifted the solenoid pin out of place, allowing the doors to open and the capsule to come off the activation pin. The team
has consulted with ILC Dover in the past and one of their suggestions was to create a KREM that fully opens removing the need for doors that hold concentrated loads like the current design. Another major change will be with the sequence used to activate the capsule. In this flight, as well as all previous KRUPS missions, activation of the capsule was achieved through an electrical signal provided by a timer event once the rocket reaches apogee. However, it was pointed out that the capsule could be activated before launch utilizing the GSE lines and put into a dormant mode. The timeline of the launch could then be incorporated into the control of the capsule to ensure data collection did not begin until after it was ejected. This change would mitigate the risk of the capsule disengaging from the activation pin during the launch. Finally, the last major change will be in the replacement of the linear pull solenoid utilized to hold the doors closed. While the KREM design will not utilize doors some sort of device will be needed to hold KREM closed during ascent and release the capsule once given the appropriate signal. The team is currently evaluating the use of a device called a PinPuller from TiNi Aerospace. This device remains rigid and in a locked position until given a signal to retract. It also has a significantly higher pull force and higher rating for shear loading than that of the solenoid.

7.0 Conclusions

In evaluation of this mission the KRUPS team was able to determine a path forward to ensure a successful KRUPS flight in the future. Even though data was not transferred, the team was able to learn valuable lessons, evaluate what worked well and devised strategies to mitigate the problems for the next mission. The major takeaways included was the need to redesign the ejection mechanism, evaluation of the activation sequence, and replacement of the linear pull solenoid holding the doors closed. Below is a summary of the mission.

The following were successful in the mission:
- The events were captured by one camera
- Camera footage was successfully retrieved

The following is a list of the main items that did not work as planned:
- Doors and hinges bent during ascent
- One camera did not power on
- Capsule was not activated
- Doors opened prematurely
- PRED was not verified
- No data was received

8.0 Potential Follow-on Work

The ultimate goal of the KRUPS project is to launch multiple capsules from the International Space Station (ISS). In order to do so, future projects aim at raising the Technology Readiness Level (TRL) until the systems are mature. With the launch discussed here, the team was able to test the subsystems in suborbital conditions. Although an orbital entry is vastly different this flight is beneficial in
providing an evaluation of subsystem functionality in relevant environment. Because data was not transmitted in this flight the TRL of the experiment remained at TRL 5. Improvements to the system are needed to have a fully successful suborbital flight. KRUPS is scheduled to fly on a high atmospheric balloon in spring of 2020 with another suborbital flight potentially scheduled for RockSat-X 2020. A few design changes will be made as each of these flights are conducted. The first being the change of the solenoid to a device that will have an appropriate pull force while also not move during ascent. One such device currently being evaluated is the PinPuller developed by TiNi Aerospace. Following this a mechanical redesign of the ejection mechanism will be conducted for the upcoming RockSat-X 2020 flight. This will mitigate the risks of doors bending and binding the capsule preventing a successful ejection. Finally, a reevaluation of the experiments sequence of events will be conducted to help mitigate risks of the capsule not being activated before deployment.

9.0 Benefits to the Scientific Community
As stated previously, the overall goal of this project is to provide a technology testbed for experiments that need to re-enter the atmosphere. Once the capsule is fully successful in orbital flights, it will have achieved that goal, and will have reach TRL 9. To achieve its purpose, the capsule must be versatile and easily accommodate a variety of onboard experiments. For the flight tests, the experiment consists of measuring the temperatures within the TPS, using thermocouples. However, this is only one usage of the capsule amongst many potential applications. For example, a company could test their heat flux sensor in orbital re-entry flights. In order to make the capsule universal for any type of experiments, the electronics inside the capsule use a molex connector. Using this molex connector for the base board and other sensor boards allows to stack multiple boards on top of each other. This makes it easy for third parties to simply incorporate their sensor board into the flight computer. All in all, once this project is complete and has reached TRL 9, the capsule will be a fully functional and tested technology testbed. The testbed will be used to advance other aerospace and re-entry technologies that require atmospheric re-entry experimentation.

10.0 Lessons Learned
The RockSat-X experience has been very beneficial for the KRUPS team at the University of Kentucky. Several key lessons were learned through the flights conducted with the program. This mission allowed the team to realize the need to re-evaluate the mechanical design of KREM in order to produce a successful mission with data in the future. While data has not yet been collected each flight has proved valuable in improving the subsystems to ensure a successful mission when orbital flights are conducted. The mission also allowed students who recently joined the team to experience the design process of the payload. They were able to see the design work, manufacturing, testing, integration, launch procedures, and analysis that goes into producing a payload. This will prove to be invaluable for the continuation of the KRUPS project as older team members graduate and younger members move to take leadership roles.
11.0 References