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Considerations for Crew Rescue from the ISS

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The design and development of crew emergency response systems, particularly to provide an unplanned emergency return to earth capability, requires an understanding of crew performance changes in space. The combined effects of psychological and physiological adaptation during long-duration missions will have a significant effect on crew performance in the unpredictable and potentially life threatening conditions of an emergency return to earth. It is therefore important that the systems to be developed for emergency egress address these challenges through an integrated program to produce optimum productivity and safety in times of utmost stress.

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1. Introduction

The physical and psychological hostility of space, and the environmental support required to live and work there, places great demands on the adaptive capacity of the crew members. In particular there are significant effects on the ability of a crew, either individually or as a team, to perform well in unpredictable and potentially life threatening conditions.

Such a situation will occur in the event that a crew has to make an unplanned return to earth in the emergency escape vehicle. The crew may not be in good physical or psychological shape, and may have the additional burden of injured colleagues and a damaged vehicle to contend with. During the un-docking, re-entry and landing phases, the crew may be simultaneously subjected to acceleration, vibration, noise, heat, shifts in atmospheric composition, and emotional stress.

There are particular difficulties for the pilots in the event that the automated systems fail to fully function. Control of the spacecraft may require a number of human abilities including arm-hand steadiness, finger dexterity, hand-eye co-ordination, perceptual speed, and rapid reaction time, against a background of the effects of prolonged confinement, decreased motor function, and weightlessness. Additionally the skills and procedures needed by the crew may not have been practised for many weeks, or not at all, and the ground support may not be fully knowledgeable about the condition of the crew.

2. Background

Safety of the International Space Station crewmembers is the prime concern of NASA and the participating nations in the operation of the ISS. Studies on the process of escape from an orbiting space station have continued from the early 1960's and included many innovative concepts ranging from Apollo type capsules [1, 2] to a vehicle based on the HL-20 lifting body [3], and the European Space Agency Hermes [4]. The aim of the lifeboat studies carried out in the early 1990's was to develop an Assured Crew Return Vehicle (ACRV) for Space Station Freedom, which was simple to operate, reliable and available to de-orbit the Space Station crew [5, 6]. With the advent of the ISS, the plans developed have been amalgamated into a dual vehicle approach using the Soyuz and the X-38 Crew Return Vehicle (CRV). Historically all the manned space stations to date have had a vehicle permanently attached in standby mode for use in case of an emergency.

3. Mission

Three missions have been identified which will require the deployment of the ISS crew rescue system, based on a crew complement of seven [7].

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(1) Mission I - Medical Emergency (Design Reference Mission DRM-1) requires evacuation within 24 hrs, due to serious injury or illness in a crewmember;

(2) Mission II - Station Emergencies (DRM-2) would require immediate evacuation due to structural and/or life support failure;

(3) Mission III – Logistics interruption, (DRM-3) is a planned evacuation due to re-supply failure.

The NASA requirements for a crew module and seats are to accommodate 95th percentile American male crewmembers through 5th percentile Japanese females, as defined by NASA in Mil-STD–3000. Present figures put the likelihood of utilizing the CRV, in the event of a DRM–I scenario, and the inability of the Soyuz to accommodate the crewmembers, at 1 evacuation deployment every 12.5 years of ISS operations [8].

4. Crew Condition

To design an effective and safe crew escape vehicle, it is important that the designers have an understanding of the likely condition of the crew in the event of a worst case scenario, i.e. of an unplanned immediate escape from the station with one or more injured crewmembers. The effects on human physiology and psychology, of exposure to the space environment have been well documented [9 to 12]. There are many key technical issues to address in the system definition of a crew recovery vehicle from the perspective of degraded crew performance, and the relevant effects of microgravity. In an emergency situation crew members are additionally called upon to act with decisive, clear and correct actions to prevent a crisis deepening and preserve their own lives and the lives of their colleagues.

4.1 Biomedical Changes

Microgravity causes a number of physiological changes which effect performance in emergencies. Additionally the environment is deprived of the usual sensory and motor stimulation, and subject to constant noise, and confinement. These can jeopardise the health and functioning of crews and, if no countermeasures are in place, reduce the physical capacity of crews in emergencies.

During the first phase of flight, less than one week, several significant physiological changes occur in the interactions among sensory systems resulting in the development of sensory conflicts. With the addition of fluid redistribution this is the phenomenon known as space adaption syndrome. Significant changes also occur in the accuracy of psychomotor performance, and posture, with the adoption of a fetal like position, and a tendency to overshoot until adaption occurs. However as a result of this, accurate grasping responses are not typically included as mission critical tasks, especially in the early phases of a mission. The decrease in dexterity, due to adverse effects on fine motor movement, can pose potential problems for the manipulation of control panels, particularly in urgent situations with an increase in anxiety.

Cardiovascular changes result in fluid redistribution towards the head, with diminished tolerance of orthostatic and physical loading on exposure to one-g, while bone density is decreased by approximately 1% per month of exposure to microgravity. A significant health hazard is the long and short term effects due to exposure to radiation. Together these changes will clearly have greater implications with the increased length of a mission.

The problems of space sickness pose an immediate threat to performance in space. For this reason EVA activities are normally not programmed in the first 48 hours after launch. This may however become a serious problem where a crew has to make an emergency return almost immediately on arrival at the ISS.

Part of the process of designing for crew escape is to ensure the provision and use of effective countermeasures, currently focused on an exercise regime, to maintain the physical performance of the crew at an optimum level.

4.2 Psychological Concerns

The isolation of space can lead to sleep disturbance, headaches, irritability, anxiety, depression, boredom, restlessness, anger, homesickness and loneliness. On the other hand sensory overload has also occurred through the excitement and uniqueness of the environment, the volume of work, and the disruption of circadian cycles. Significantly, temporal and spatial disorientation likened to the ‘break-off’ phenomenon reported by jet pilots flying under monotonous high-altitude conditions may occur. This in particular is significant, in that it may result in delayed response and low performance in emergency situations [13].

These findings are particularly relevant to the actions and performance of crews in emergency situations, where time is of the essence and effective leadership and decision making are paramount. However the major difficulty in understanding any of these effects is that they may also be due to physical or psychological stressors, the phase of the flight or undisclosed underlying psychiatric illness. A key to the maintenance of psychological health is ensuring the correct crew is selected both at the entry to the astronaut corps and for specific missions, based on a profile of the attributes considered to be fundamental to mission success. This is particularly important with the multicultural, mixed gender, civilian and military crew make-up.

An important component of designing for emergency procedures is understanding the decision making process, and the recognised causes of human error in the aviation environment [14]:

(1) Unfamiliarity with the task;
(2) Time pressure;
(3) Poor signal:noise ratio;
(4) Poor human:system interface;
(5) Irreversibility of errors;
(6) Information overload;
(7) Negative transfer between tasks;
(8) Crew mismatch;
(9) Hostile environment;
(10) Work over/underload.

In addition there are concerns about the effects of group versus individual behaviour when survival is threatened, and the effects of latent acts arising from system design [15].

A space based escape and recovery system will also need to consider the daily routine of a crew so that the procedures and actions required in an emergency are an evolution of the normal daily routine. Such an approach will enable an easier more accurate and faster response from the crew, thereby enhancing their safety, and increasing the likelihood of a successful outcome to their predicament.

5. Emergency Actions

Once an emergency occurs which necessitates activation of the crew rescue system, significant threats to success at dealing with the problem may come from sources such as:

(1) Effects of stress, fatigue, sleep loss, reduced motivation, inadequate ability and/or training;
(2) Reduced vigilance and alertness in responding to slowly changing events or low event-rate displays;
(3) Problems of monitoring and diagnosing system failures;
(4) Excessive workload and decision making in multiple high demand tasks;
(5) Damage to the ISS and/or degraded environmental life support;
(6) Poorly designed escape system;
(7) Disorientation due to ISS configuration changes;
(8) Difficult access to X38 CRV.

The design team will also need to clarify and address the process of a crew's response to an emergency and accommodate this in the system. When a problem does occur, the tasks in a space station emergency can be summarised as:

(1) Response to an alarm;
(2) Move to workstation information panel in a compartment;
(3) Switch off the alarm;
(4) Read comprehend and identify the necessary action/s to be taken;
(5) Collect and don protective clothing and respiration equipment;
(6) Collect and assist injured personnel;
(7) Move to the crew escape vehicle as necessary and initiate recovery procedure.

Therefore in designing for unplanned escape from the ISS, the crew rescue systems and vehicles need to reflect the expected capacities of the crewmembers both as individuals and as a team.

6. ISS Considerations

There are many factors to consider in the environment and layout of the ISS for a safe and efficient evacuation procedure.

6.1 Internal Structure and Escape Routes

A significant difficulty will be progress through the ISS. The size of the US, ESA and Japanese modules is similar in cross-section, whilst the Russian Service Module has a variable internal diameter, with the FGB being the most narrow. Trials aboard the NASA KC 135 aircraft in 1991 demonstrated the need for mobility aids, such as handrails, kick pads, and footholds to enable safe egress during emergencies [16]. Features such as these will facilitate initiation in translation, and changes in direction.

Minimum translation dimensions have been set at 32 inches /81 cm, however this may present problems with injured crew members, particularly if launch and entry (LES) suits are needed, as with Soyuz. This is the minimum acceptable width specified in Mil-STD-3000, with a required depth of 72 inches for passing, and 45 inches for a single crewmember turning. Equipment deployment and stowage may conflict with these requirements, therefore maintenance of a clear unobstructed escape route is of paramount importance. Direction indicators and lighting strips to indicate the path to the rescue vehicle would help the crew to overcome the effects of spatial disorientation, particularly in the event of a degraded life support system.

6.2 Crew Information

The aim is to ensure that the crews have access to information necessary to effect a safe and speedy escape. There is a tendency in aviation and space systems to overload the user with unnecessary information, simply because it is available. In planning CRV displays the aim should be to provide the minimum necessary information, with the crew having access to more detailed information should they require it. The system may have to be operated with a degraded life support system, inadequate lighting and excess noise, requiring redundancy and backup.

6.3 Activation Mechanisms

Remote CRV activation from all major consoles within the ISS, both with touch displays and with voice commands, is a desirable feature. This ideally should be possible with a single button or voice command start-up procedure to initialise the on-board systems, such as those in common use in the military. This is presently not possible with the Soyuz TM, and not currently planned with the CRV.

6.4 Ground Support and Direction

It may be appropriate to facilitate full control of the escape procedure from the ground in addition to CRV activation. This could be, as a result of injury to a key crew member, particularly the commander, or a life support system so degraded that the crew have no capacity left beyond preserving their own lives. Improved safety margins would come from an integrated information system, allowing exchange of data between the rescue vehicle and ground control.

7. Crew Recovery Vehicle

Crew Rescue planned for the ISS is based on a dual approach with the Soyuz and the experimental NASA X-38 CRV.

7.1 Requirements

The vehicle has a mission requirement duration of 9 hours, which allows de-orbit opportunities to at least two landing sites at all times. The vehicle must be deployable from a non-functioning or tumbling Space Station, return to Earth day or night and under variable weather conditions, and land on unprepared ground and/or at a foreign site with no navigational aids [17].

8. Limitations to Current Vehicles

Ground based studies have shown that it is difficult to place an unconscious or incapacitated crew member in a Russian Launch and Entry suit (LES). As such in a suited environment at best only 60% of the medical mission can be accommodated using Soyuz [7].

8.1 CRV Ingress

In 1998 seven astronauts, ranging from the 5th to 95th percentile American male, participated in successful CRV ingress tests using a mock-up installed in the NASA KC 135. The test results showed that the astronauts were able to pass quickly and easily through the tunnel adapter mock-up in any orientation either with or without the LES and helmets [18, 19]. This mirrors earlier zero-g testing aboard the NASA KC-135 in June 1991, which showed that an entire crew of eight stationed at a mock-up of the original SSF Assured Crew Recovery Vehicle(ACRV) node, could reach their seats and close the hatch in less than 20 seconds, with a planned system activation time of 3 minutes [20]. Similar tests were carried out in 1991 with a human factors analysis of the HL-20 [21].

It is essential that the crew be able to move easily and readily through the connecting tunnels to the CRV. This task will change as the position of the vehicle is changed as the ISS grows. However, in principle, the pathway and route must be accessible, obvious and unambiguous.

As with the ISS itself, handholds will be required in front of the astronauts during travel through the tunnel, regardless of the astronaut's orientation (i.e., facing bottom, side, or top or tunnel). Handholds may need to be placed on both sides of the hatch, immediately surrounding the hatch opening, depending on testing. To enable recognition they should contrast in colour to the cabin interior, and where possible be independently illuminated for visibility.

8.2 Internal Layout

The design of the CRV vehicle itself must recognise the physiological de-conditioning of the crew and the potential for spatial disorientation, confusion, and lack of mobility as gravity takes hold during reentry procedures. This requirement will be met with the provision of horizontal seating, arm rests and overhead displays placed in a 30 deg cone of visibility.

The internal layout will accommodate up to seven crew including an injured individual. The design of the seats will directly affect crew survival, volume available in the CRV's interior cabin, crew to CRV interfaces, and ingress and egress capability. In addition the crew require access to emergency equipment, and access to injured crewmembers. There may be a need to restrain an injured crewmember for their own safety, or due to incapacitation, with the Crew Medical Restraint System (CMRS). The CMRS is designed to be compatible with the crew module providing a restraint/interface system for advanced life support packs, defibrillator, ventilator, oxygen supply and IV support.

This presents problems with the Soyuz vehicle in that the CMRS cannot be fitted to a crew member who needs to be transported, while recent tests with the X-38 mock-up showed the CMRS cannot be used with the present hatch diameter due to turning restrictions from the hatch to the seats. The injured crewmember will have to be detached from the CMRS prior to being moved into the CRV.

8.3 Flight Controls

The pilot position in particular needs to ensure that he or she can operate all aspects of the vehicle with as little head and body movement as possible, and with fixed reference points to minimise disorientation and illusions. The use of active voice activated and miniature head-set mounted displays may considerably ease these problems.

Additionally space system engineers need to ensure that switches are easy to manipulate, do not require unnecessarily delicate tuning, and are positioned to allow maximum individual access without the likelihood of accidentally changing one setting while altering another. Current requirements are that common display standards derived from those used in the ISS will be used where possible. ISS status will be capable of being monitored from within the CRV.

9. Skill Maintenance in Orbit

One particular problem in long-duration spaceflight is the difficulties associated with maintaining essential skills for extended periods [22]. Currently some training for the Shuttle Remote Manipulator System (RMS) is conducted in the Virtual Laboratory. This enables the crewmembers operating the RMS, and the crewmember on its virtual arm to see and interact with each other as they would in flight. It is well regarded by crewmembers and trainers as providing a high fidelity training experience.

In the future, the use of in-orbit virtual reality training to simulate the likely events and actions necessary in an emergency may considerably ease training difficulties. This would have the advantage, over ground based training, of the crew being exposed to the microgravity environment during the exercise. This would also increase the level of fidelity of the training and thus the confidence levels of the crew in the event of a real time on-board emergency requiring evacuation.

10. Conclusion

To date the overall incidence of serious accidents in spaceflight, which is low, has been attributed to the rigorous selection and training procedures of crews, as well as the high levels of crew motivation. The application of simulation and virtual reality technology will enhance the safety of a crew in orbit by enabling training for emergencies in microgravity conditions.

What appears to be most needed at this time is a recognition that Human Centered Systems are an integral part of Manned Space missions. This requires a more integrated view of manned space mission design and operations, including mission objectives and requirements definition, spacecraft design and development, to the implementation of mission operation concepts and support, in the context of human capabilities.

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