History of the Assured Crew Return Vehicle and Spaceflight Medical Evacuation

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There has always been a concern about spaceflight medical evacuation of an ill or injured crewmember.[1] Besides the possibility of shock due to sepsis or hemorrhage and limited medical care while in transit, there will also exist cardiac deconditioning, loss of plasma volume, and musculoskeletal deconditioning from a long-duration spaceflight. Neurovestibular effects and orthostatic hypotension will also occur upon landing even with well crewmembers. Add to this the reentry G forces experienced and, in some cases, flight termination with a hard landing on Earth causing impact acceleration.[2] G_x reentry forces (chest to back) are tolerated well, but G_z reentry forces (head to foot with decreased brain perfusion) are difficult even in well crewmembers.

Research with primates (that were not deconditioned) involving controlled hemorrhage followed by centrifugation to mimic atmospheric reentry forces ($+G_x$) has shown that exposure to reentry acceleration forces[3] has no adverse effects unless the hemorrhage is severe (class III or IV, or 30–50% loss of blood volume) or the forces are excessive (8 G_x instead of 1.8 G_x). Since uninjured but deconditioned crewmembers returning to Earth typically display many of the hypovolemic characteristics of a class I hemorrhage [15% loss of circulating blood volume (750 mL blood loss)] manifested as minimal tachycardia and orthostatic hypotension, a true class I hemorrhage in space may respond more like a class II hemorrhage on return to Earth (i.e., 15–30% blood loss), manifested as tachycardia, tachypnea, and decreased pulse pressure. Therefore, a trauma patient in space is likely to have a decreased ability to tolerate the return to 1 G during a medical evacuation. Although aggressive resuscitation onboard the International Space Station (ISS) before a medical evacuation is initiated would be important, there is a limited ability to provide volume expansion on the ISS as only several liters of crystalloid are available. In the future, lyophilized plasma or "walking donors" might be used.

Designs for crew recovery from disabled manned space vehicles, including the concept of a space "lifeboat," were first proposed as early as 1957.[4] The United States first proposed a permanently manned space station in 1984 that would be serviced by the Space Shuttle every 2 mo. There was a concern that the station could become incapacitated and a Shuttle rescue would not immediately occur. A concept was developed of a "safe haven"—a part of the station that could shelter the crew until a rescue Shuttle arrived.

In 1988, the station concept was better defined to now be multinational and was to be called Space Station Freedom. It was still dependent on servicing by the Space Shuttle every 2 mo. A health maintenance facility was proposed in 1986 that would provide for medical and surgical care of the crew with a surgically capable crew medical officer since medical evacuation might not be available for 45 d. The health maintenance facility was eventually defunded by 1995 as the option of medical evacuation was considered essential.[5]

An Assured Crew Return Vehicle (ACRV) was proposed that could be used for medical evacuation or return of the crew if the Shuttle became incapacitated or if the station needed to be abandoned because it could no longer provide life support.[6] The HL-20 Personnel Launch System (**Fig. 1**) was designed by NASA Langley in 1988 and based upon the U.S. Air Force Dyna Soar and HL-10 lifting body and Soviet BOR-4 spaceplane designs. Langley-funded developmental studies were undertaken by Rockwell International in October 1989 and Lockheed Advanced Development Projects in October 1991. The HL-20 was a lifting body with a desirable 1.5-G vehicle reentry profile and would have been launched by a Titan IV. Langley carried out extensive wind tunnel testing. It would have landed horizontally on a conventional runway. North Carolina State University and North Carolina A&T University built a full-scale mockup that was used to investigate the ergonomics of a medical evacuation. It is now on display in Denver, CO, United States. The projected cost of $2 billion led to early cancelation by 1993.

There were also studies in the ACRV Program involving less expensive ballistic vehicles. The most feasible one was the Station Crew Return Alternative Module (SCRAM), first

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proposed in 1986, which used a Mars Viking heat shield (**Fig. 2**). However, it had a 3.5–8-G_x reentry profile, making it a poor choice for medical evacuation. A full-scale prototype was used in a wave tank to develop procedures for extraction of injured crewmembers after an ocean landing. It is now in Corsicana, TX, United States (**Fig. 3**).

In 1993, Russia was invited to join the partnership and the redesigned station was renamed the International Space Station. The use of the Russian Soyuz as a medical evacuation or escape vehicle had been discussed with the Russians since 1991 and became more acceptable due to the low cost involved. The Soyuz had been used for three minor medical evacuations (actually these were early returns for medical reasons) during the Salyut/Mir Programs. The Soyuz was a very reliable spacecraft, but had several deficiencies as a medical evacuation vehicle. It was extremely cramped, requiring abnormal body positions for crewmembers, had a 3.8-G_x nominal reentry profile (9.0 G_x if ballistic), and terminated in a hard landing. Several injuries had been documented with nominal Soyuz landings. The health medical system used onboard the ISS was now oriented toward stabilization and transport, and NASA flight surgeons and biomedical engineers used the Soyuz simulator in Star City, Russia, to work out medical equipment deployment and medical procedures for a possible medical evacuation. The decision to use the Soyuz for medical evacuation was finalized in 1996 and was considered temporary until a more capable system was developed. Contingency recovery sites were designated in Utah and Australia in addition to the nominal recovery site in Kazakhstan to decrease the definitive medical care time for a medical evacuation to 6–24 h.

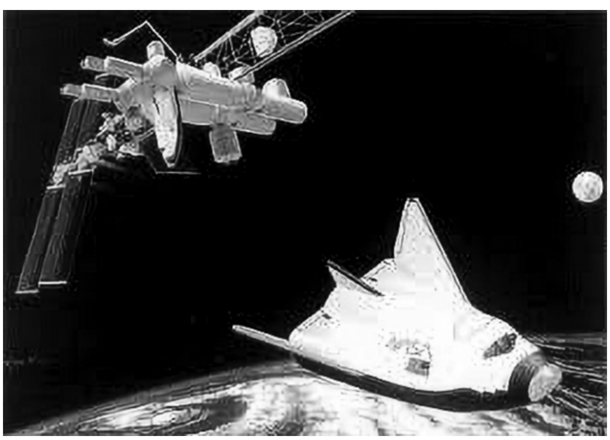

Fig. 1. Conception of the HL-20 ACRV in 1990 (courtesy of NASA).

The French and later European Space Agency (ESA) continued development of the ACRV and had proposals for both lifting bodies derived from the 1975–1992 Hermes project as well as three different ballistic vehicles. Dassault and Aerospatiale had submitted competing proposals for Hermes in 1987 and a full-scale mockup had been constructed. Hermes was canceled in 1992 due to a projected cost of $4.5 billion. Integrated engineering teams from 1993–1996 that involved ESA and NASA engineers and flight surgeons were meeting regularly to further design work on a lifting body, the ESA Crew Return Vehicle (CRV). Controversy ensued about the requirements for medical evacuation, which dictated supine positioning of crewmembers to experience reentry G forces in the G_x axis and insistence by ESA on vertical positioning of the crew (reentry forces in the less tolerable G_z axis) as they wanted

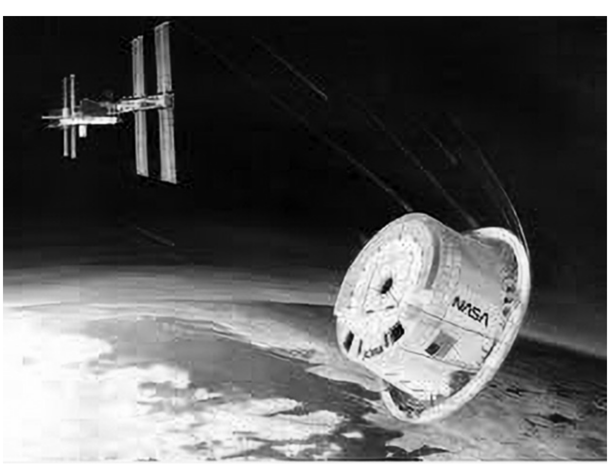

Fig. 2. SCRAM (ballistic ACRV) as envisioned by NASA in 1993 (courtesy of NASA).

Fig. 3. SCRAM prototype in Corsicana, TX (courtesy of the Corsicana Daily Sun).

Fig. 4. X-38 CRV in drop tests in 1998 (courtesy of NASA).

the ability to pilot the spacecraft. The $1.7 billion cost and eventual acceptance of the Soyuz as a rescue vehicle led to cancellation in 1996.

Following cancellation of the ESA CRV, the United States and ESA began development of the X-38 CRV. The design was dedicated to medical evacuation with supine positioning (reentry forces in the G_x axis), automated return (in fact it did not have any windows but did have a manual override), lifting body design with reentry forces on the vehicle of <2.0 G, and a parafoil landing. The landing was a nonprecision desert landing that did not require a pilot or a runway. This is important, as the longest Shuttle flight (and therefore the longest that a pilot has been in space before piloting a vehicle on return) was only 17.5 d. How a pilot would perform on longer missions was speculative. A full-scale mockup was used in parabolic flight to study ingress and egress of medical transport and to optimize medical equipment deployment. Two 80% scale test vehicles were used in drop tests from a B-52 at Dryden Flight Research Center in 1998–1999 to validate flying characteristics (**Fig. 4**). They are now on display in museums in Oregon and Nebraska. A full-scale prototype that was to be launched on the Shuttle to the International Space Station for unmanned testing/demonstration was being constructed in-house at Johnson Space Center. It was 90% complete when the program was canceled in 2002 as the cost was projected at $1.1 billion.

The SpaceX Crew Dragon (operational since 2019) can now be used for medical evacuation and, although ballistic, has far more interior space than the Soyuz. Currently in development, the Starliner (ballistic) and Dream Chaser (lifting body) spacecraft are also being studied for medical evacuation configurations. Sierra Space Corporation began development of the Dream Chaser, which was directly derived from the HL-20 and the X-38, in 2004. It will be launched vertically on a Vulcan Centaur, has manned and cargo versions, has only a 1.5-G vehicle reentry profile, and terminates with a horizontal runway landing that can be automated.

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