Space Rescue

Space Rescue has been a topic of speculation for a wide community of people for decades. Astronauts, aerospace engineers, diplomats, medical and rescue professionals, inventors and science fiction writers have all speculated on this problem. Martin Caidin's 1964 novel "Marooned" dealt with the problems of rescuing a crew stranded in low earth orbit. Legend at the Johnson Space Center says that Caidin's portrayal of a Russian attempt to save the American crew played a pivotal role in convincing the Russians to join the real joint Apollo-Soyuz mission. Space Rescue has been a staple in science fiction television and movies portrayed in programs such as **Star Trek**, **Stargate-SG1** and **Space 1999** and movies such as **Mission To Mars** and **Red Planet**. As dramatic and as difficult as rescue appears in fictional accounts, in the real world it has even greater drama and greater difficulty.

Space rescue is still in its infancy as a discipline and the purpose of this chapter is to describe the issues associated with space rescue and the work done so far in this field. For the purposes of this chapter, the term space rescue will refer to any system which allows for rescue or escape of personnel from situations which endanger human life in a spaceflight operation. This will span the period from crew ingress prior to flight through crew egress postlanding. For the purposes of this chapter, the term "primary system" will refer to the spacecraft system that a crew is either attempting to escape from or from which an attempt is being made to rescue the crew.

Legal and Diplomatic Basis

Article V of the United Nations Treaty on the Peaceful Uses of Outer Space states

"States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas. When astronauts make such a landing, they shall be safely and promptly returned to the State of registry of their space vehicle.

In carrying on activities in outer space and on celestial bodies, the astronauts of one State Party shall render all possible assistance to the astronauts of other States Parties.

States Parties to the Treaty shall immediately inform the other States Parties to the Treaty or the Secretary-General of the United Nations of any phenomena they discover in outer space, including the moon or other celestial bodies, which could constitute a danger to the life or health of astronauts"

Space Rescue requires attention because spaceflight is currently significantly more dangerous than other types of flight

Development of all space rescue systems eventually turns into a risk versus cost discussion. Due to the nature of the technology, space rescue systems are usually

complex, expensive and difficult to test. When primary development programs get into cost, schedule or technical difficulty, the requirements for space rescue are often challenged as they involve significant investment in a system that is intended for use only when all of the other aspects of the primary design have failed. It is often argued that resources should be used to improve the reliability of the primary system being developed to eliminate the need for a rescue system rather than in implementing a difficult and costly rescue option. In discussing the necessity for space rescue systems, arguments often revolve around an argument utilizing commercial airliner flight. The argument is that at one time commercial airliners carried parachutes but that is no longer the practice and why should astronaut crews have an escape option that airline passengers do not have. Similar arguments have been made regarding the risks associated with flight in military transport aircraft and helicopters in a combat zone.

JSC Safety and Mission Assurance (SMA) recently compared the relative dangers of different types of flight. As a relative order of magnitude metric, JSC SMA estimated the following risks:

Risk of loss of life in a commercial airplane	1 in a 1,000,000 flights
Risk of loss of life in a military aircraft	1 in 100,000 flights
Risk of loss of life in combat in a military jet aircraft	1 in 10,000 flights
Risk of loss of life in human spaceflight	1 in 100 flights

At this time, human spaceflight is significantly higher risk than any other type of flight and these statistics represent the best counter to the “rescue systems aren’t required” argument. This very high risk of human spaceflight is driven by many factors. The maturity of the technology is a major contributor. Compared to commercial or military aviation, human spaceflight has accumulated relatively few hours of operation and has had very few generations to accomplish design evolution of a highly reliable system. Space systems also operate in a very demanding environment due to the speeds required to reach orbital velocity and the amount of fuel and oxidizer mass required at launch. This forces tremendous efficiency in structural design and propulsion efficiency. For example, the tank wall of shuttle external tank, if scaled down to handheld size would be significantly thinner than that of a soda can. The Space Shuttle Main Engine (SSME) is one of the most efficient powerplants ever produced by humans. Robert Ryan, the former director of Structures at Marshall Space Flight Center, has developed several interesting metrics to help people understand the design challenges associated with space launch. He compared the horsepower/weight ratio for several different types of engines and the comparisons are shown in the table below:

Engine	Weight (lbs)	Horsepower	Horsepower/weight
automobile	370	200	0.54
Indy 5600 Racing Engine	275	800	2.91

Small Jet Engine	2890	52900	18.3
Large Jet Engine	13065	1950300	149.3
Space Shuttle Main Engine (SSME)	7480	6786981	907.4

It is pretty amazing to realize that there are 3 orders of magnitude between a car engine and the SSME. There is even a factor of 6x between the SSME and the only comparable mass produced engine, a large jet engine ! Mr Ryan further went on to compare propulsion power/structural system weight ratio and propellant mass fraction

System	Propulsion Power/System Dry Weight	Propellant Mass Fraction
Automobile 1995 Mustang	40.5	<.1
Commercial Airliner (747 and 737)	326.8	.4
Apollo Saturn	76,700	.9

Mr Ryan points out that if an automobile was designed at the same propulsion power/structural weight ratio would only weigh 2.5 lbs ! Spaceflight systems clearly operate at the extreme end of human design capability for both propulsion and structures in a highly demanding environment.

The spaceflight environment contains many hazards that are not present in the terrestrial environment. The crew must be protected from the vacuum of space and many materials perform differently at vacuum than at sea level pressure. The crew must be protected from extremes of temperature present on orbit. It is not unusual to have a 400 degree Fahrenheit environmental gradient within a few inches when transitioning from full sunlight to full shadow. The aerodynamic loads on the vehicle during ascent can be large, between 700 and 800 pounds per square foot on the shuttle during ascent. The heating and aerodynamic loads during entry are equally severe with aerodynamic loads of nearing 500 pounds per square foot while temperatures can range near 2800 degrees F. These combined environment stresses are unique to the aerospace environment. On orbit there are unique environmental hazards due to the lack of atmospheric protection such as solar radiation and Micrometeoroid Orbital Debris (MMOD). Several space shuttle outer windows and thermal radiators have suffered impact damage from MMOD.

Perhaps one of the most difficult things about dealing with these extreme performance requirements and hazardous environments is the relatively few times engineers can take advantage of lessons learned by the opportunity to in building a new design. Most of the hardware in both the US and Russian programs represents a slow evolution of design. In the United States, opportunities to design and test new human space vehicles have been separated by large amounts of time.

Aerospace engineers also struggle with the fact that even on the rare occasion of development of a new system, it is very hard to ground test such systems in the laboratory because of the "combined environments" problem. It is almost impossible to test designs with all of the loading factors on a design simultaneously as they are applied inflight. Aerospace engineers are most often forced to observe the performance of their design in one loading environment at a time, whether temperature, inertial loads, aerodynamic loads or vibration and then combine the loads through computer modeling to ascertain the adequacy of their designs.

Unlike aviation, spaceflight provides very few opportunities for buildup testing. In an aircraft development program, an aircraft is first flown at lower dynamic pressures and Mach numbers and the aircraft is monitored for performance. The allowable flight envelope is slowly expanded as test data map to preflight predictions. This can occur over a sequence of perhaps 100 flights. This is very hard to do in space systems as most space systems operate in an "all or nothing" environment. Once a new space system is launched, it usually has to go through its entire flight envelope the first time. This, along with the combined environments test problem, explains why so many new rocket systems fail on their first flight attempt where this type of first flight failure is now almost unknown in the aircraft industry. It is worth pointing out that the first space shuttle went supersonic 60 seconds into its first flight. It went hypersonic 2 minutes after that. There was no opportunity to look at the data, decide that things weren't as expected and then return to base for a quiet examination of the flight performance.

Given the high costs of current spaceflight systems, there are also very few opportunities to perform dedicated test flights. Unlike an aircraft certification program, which cannot practically be performed in a new aircraft in under a hundred flights, space systems are routinely declared operational after one or two flights. As such, space systems have to perform the majority of their certification through model predictions of performance followed by validation of models by monitoring flight performance in a limited number of flights.

Due to the hostile environment that human spaceflight must operate in, the high performance required in space vehicles and the limited opportunities for new development and test of these vehicles, human spaceflight will remain the riskiest mode of human flight for many years to come. Given this is the case, it is important to understand and consider rescue in all phases of human spaceflight.

Rescue Modes and Probabilities

The probability of crew survival in a space system with a rescue capability can be computed from the equation

$$P_{crewsurvival} = 1.0 - (P_{primaryfailure})(P_{rescuefailure}))$$

Which is equivalent to

$$P_{crewsurvival} = 1.0 - (1.0 - P_{primarysuccess})(1.0 - P_{rescuesuccess})$$

From these equations it can be seen that the primary value of a rescue system from the perspective of crew survival is that it enables a higher probability of crew survival without having to drive higher levels of reliability into the primary system. Reliability is usually a major cost driver in systems development. A system with a .99 reliability is usually significantly more expensive than a system with .9 reliability. The cost increase associated with increasing system reliability from .99 to .999 is usually even higher in terms of percentage of system cost associated with increased reliability. It can be seen from these equations that the probability of crew survival with a system, for example, with a .9 reliability can be increased to .99 by employing a rescue system of .9 reliability.

This type of increase is particularly critical when trying to achieve high reliability rates for vehicles with long mission lifetime. In these types of vehicles it is very hard to engineer in high levels of reliability due to the effect of extended mission duration rate on probability of failure. If the failure rate of components is expressed in failures/unit time, then the failure probability is

$$1.0 - e^{-\lambda t}$$

Where λ = failure rate/unit time. Using this in an example, consider a system that has a part with a Mean Time Between Failures (MTBF) of 500 hours. The following table shows the expectation of failure after increasing numbers of hours of operation

Number of Hours of operation	Probability of failure if MTBF = 500 hrs	Probability of failure if MTBF=1000 hrs
250	0.394	0.221
500	0.632	0.394
1000	0.865	0.632
5000	0.99996	0.993
10000	1.0	0.99996

It can be seen from this equation that even high reliability components can have difficulty meeting high reliability levels when the mission duration is sufficiently long. In these cases the normal design strategy is for redundancy and inflight maintenance but this can be problematic when the logistics depot is on earth and the operational location is in earth orbit or deeper in space. In these cases a rescue system may provide an alternative to engineering increasingly higher reliability in the primary system. The addition of a rescue/escape system in these types of systems can have a large effect on the probability of crew survival.

It is interesting to note that the calculation of expectation of crew survival also can be used to determine the effectiveness of a crew escape system in increasing the probability of crew survival in a launch system that was not originally designed for high reliability. NASA has several times considered the possibility of launching crews on vehicles riding atop available expendable launch vehicles. As calculated by JSC Safety and Mission Assurance, as of early 2004, the raw reliability of these expendable launch systems ranges from .77 to .96. From these calculations it can be shown that a launch abort system with even a 90% probability of success can raise the expectation of crew survival into the range of .91 to .996 with these expendable launch vehicles.

At first blush, it may sound as though a launch escape system with a 90% reliability shouldn't be too difficult to develop. However there are many phases of flight where abort systems cannot function due to combinations of speed, altitude and dynamic pressure. These are called "black zones" and they significantly limit abort/escape systems. These are especially limiting when ejection systems are used as crew escape/rescue systems. In Gemini and early Space Shuttle, ejection seats were provided for crew escape. These had significant limits as to the phase of flight in which they were effective. During early shuttle flights during ascent, Mission Control would radio up a call to the crew with the words "Negative Seats". This indicated that speed and altitude had reached limits where ejection was no longer possible. It is worth noting that even in military jet aircraft, ejection seats only achieve crew survivalin 90% of all ejections and in only 95% of cases where ejection occurs within the certified ejection envelope of speed and altitude.

Space flight is a very risky form of flight and rescue/escape systems of reasonable reliability can have a major effect on expectation of crew survival but even reasonable reliability numbers may be difficult to achieve in the space launch environment.

Hazards in the different phases of flight

We will consider the seven primary phases of human spaceflight and the hazards that are present there in order to determine the types of rescue and escape systems that might be required.

The seven primary phases of human spaceflight are

Phase	**Definition**
Prelaunch	Crew Ingress to liftoff
Ascent	Liftoff to achieving orbit
Orbit	The phase from achieving orbit to initiating an orbital change that results in entry back into the atmosphere. This phase could actually include periods of time in a transfer from earth orbit to orbit about another body such as the moon, an asteroid or another planet
Rendezvous/docking/departure	The phase from the start of maneuvers to bring two

to/from another spacecraft	spacecraft together, through docking/undocking and departure from the other spacecraft
Descent and ascent from a non-terrestrial surface	This is the time from initiating an orbital change that results in a non-terrestrial landing to the time back in a stable orbit above a non-terrestrial location. The non-terrestrial location could be the moon, an asteroid or another planet
Extra Vehicular Activity (EVA)	the period of time spent outside the spacecraft
Entry	the period of time from initiating an orbital change that results in atmospheric entry until landing on earth

The primary, but not inclusive, list of primary hazards during these phases are:

Phase	**Primary Hazards**
Prelaunch	Fire or explosion due to systems failure, loss of structural integrity, natural environment or propulsion related failure
Ascent	Systems malfunction, loss of control, loss of structural integrity, natural environment induced failure, propulsion related failure
Orbit	systems failure (explosion, loss of attitude control, loss of critical function, toxic material release), natural environmental hazard (solar radiation, Micro-Meteoroid orbital debris (MMOD)), health issue for the crew
Rendezvous/docking/departure to/from another spacecraft	Collision with another spacecraft, systems failure (explosion, loss of attitude control, loss of critical function, toxic material release), natural environmental hazard (solar radiation, MMOD), health issue for the crew, improper targeting or trajectory (off-course)
Descent and ascent from a non-terrestrial surface	Takeoff or landing related accident due to systems malfunction, propulsion malfunction or natural environment, improper targeting or trajectory (off-course) or surface impact
Extra Vehicular Activity	Suit systems malfunction, hole in suit, crew health issue, loss of crew connection to spacecraft (crewmember adrift - tether protocol lost)
Entry	Systems or structural failure, natural environment induced failure, loss of control

Many of the entries in this table are the same for all flight phases. For example malfunction in life-critical or mission critical systems can occur in any phase and can be catastrophic. Aerospace systems engineers have developed techniques, such as systems redundancy, to avoid this type of predicament. Similarly structural failure occurs in all

phases. Again aerospace structural engineers have developed techniques, such as defining a design limit load and ensuring a factor of safety against that load, which prevent failures under anticipated design conditions. In many ways it is the job of a rescue system designer to consider design solutions for those scenarios which cannot be anticipated by these design techniques. In many cases in order to achieve a practical design solution in terms of weight and performance, the design engineer of the primary system must "play the odds". For example, it is often impossible to design a structure capable of withstanding the worst case meteoroid impact, or protecting the crew and life critical systems in the worst case solar flare. In most cases it is even impossible to develop an in-space crew medical facility capable of handling all of the ailments which can arise inflight in an otherwise healthy human even with thorough preflight medical screening. For these risks which are very hard to evaluate and control, a space rescue system often provides the degree of assurance necessary to proceed to flight.

Historical Distributions of Failures

David Shaylor's book, Disasters and Accidents in Manned Spaceflight, has an excellent chronology of spacecraft accidents and near-accidents. In reviewing that chronology we can separate major events into the 7 phases. *Italics indicate fatal accident*

Phase	**Major Historical Incidents**
Prelaunch	*Apollo 1 fire*, Soyuz T-10 Abort, Gemini 6 Prelaunch Abort, Prelaunch aborts following engine start on multiple shuttle flights
Ascent	Apollo 12 lightning strike, Soyuz 18-1 Loss of control during ascent, *Challenger explosion, Columbia debris damage*, STS-51F engine shutdown and abort to orbit, STS-93 electrical short
Orbit	Gemini 8 thruster fails on and loses control, Apollo 13 oxygen tank explodes en route to the moon, Fuel Cell failures on STS-2 and Fire onboard Mir, medical conditions on multiple Mir flights
Rendezvous/docking/departure to/from another spacecraft	Collision between Mir and Progress resupply vehicle
Descent and ascent from a non-terrestrial surface	Apollo 10 ascent loss of control during practice landing mission
Extra Vehicular Activity	Crew helmets fogging (Gemini, Mir), Crew exhaustion (Apollo lunar surface)
Entry	*Soyuz 1 parachute failure, Soyuz 11 decompression, Columbia*, Soyuz 23 landing in a frozen lake

.

In reviewing Shayler's chronology, the incidents count can be characterized by phase as

Phase	Major Historical Incidents
Prelaunch/Ascent	12/2 fatal
Orbit/EVA/Rendezvous	13/0 fatal
Entry	10/3 fatal

This leads to the conclusion that although the risk of incident is pretty much uniform through flight, that the risk of fatal accident is largest during the dynamic phases of flight of ascent and entry. This maps into the conventionally held wisdom in the aerospace industry that the dynamic phases of flight represent the greatest hazard. This is sometimes summarized by the adage "the farther the hardware is away from the launch site, the safer it is". This adage summarizes the industry experience that once space hardware is in a quiescent state for which it was designed, e.g. the space environment, generally the less likely it is to succumb to critical failure. It is interesting to note that even very dramatic failures in the space environment (Gemini 8 thruster failed on, Apollo 13 explosion, Mir fire and Mir Collision) all represented situations where the crew and ground control were able to stabilize a precarious situation and bring the crew home alive. Dynamic flight phase incidents generally do not afford the luxury of time and rescue/escape mechanisms must be designed in and prepared to go at a moment's notice as there is usually no time to improvise when an incident occurs during these flight phases.

Historical Rescue Systems

Given the conventional wisdom and the reality of historical incidents, the development of rescue and escape systems reflects an approach to control risk during the dynamic phase of flight. Most of the rescue systems for more quiescent phases of flight in the space environment are more conceptual and few have proceeded into any hardware development stage.

Phase	Historical Controls
Prelaunch	Rapid pad egress systems (slidewires), launch abort rocket systems, ejection seats
Ascent	Launch abort rocket systems, ejection seats, intact abort modes such as Return To Launch Site, abort to orbit modes, bailout systems
Orbit	Return vehicle for Skylab, Salyut, Mir, ISS. A variety of concepts.
Rendezvous/docking/departure to/from another spacecraft	None other than orbit rescue concepts
Descent/ascent from a non-terrestrial surface	None – some ability for spacecraft in orbit above the nonterrestrial surface to maneuver to rescue the lander vehicle if it is in a low orbit
Extra Vehicular Activity	Self rescue (secondary oxygen pack), SAFER for emergency return of a astronaut adrift
Entry	Ejection seat or bailout

Prelaunch and Ascent Escape

Prelaunch and ascent escape concepts have been dominated by escape rockets which lift the entire crew module away from the launch vehicle stack. The requirements for these systems are driven by two estimates. First what is the warning time of imminent explosion and second what is the blast danger radius. The large blast danger area associated with most launch vehicles combined with the short to nonexistent warning times forces launch escape rockets to be very high thrust with a rapid buildup. Thee characteristics along with the desire for storability and low complexity tend to force the selection of solid rocket motors for these tasks.

The Space Shuttle does not have a crew escape rocket system but the addition of a winged vehicle added new options for self rescue that were not possible in previous launch systems,. This type of self-rescue is called intact aborts. Intact aborts are those missions which do not achieve the planned orbital mission yet result in a landing of the Space Shuttle Orbiter and crew on a runway. Several classes of intact orbits have been defined. The first type of intact abort is an Abort To Orbit (ATO). In an ATO case a propulsion malfunction results in reduced engine performance or an engine shutdown. Both of these occurred on shuttle mission 51-F on two separate engines. Depending on the nature of the malfunction, it may no longer be possible to reach orbit with the available propellant so the vehicle is steered to the best orbit achievable. Once this orbit is achieved, a plan can be generated to use Orbiter onboard propellant to achieve the mission and then deorbit and land or to simply directly deorbit and land. Another intact abort is the Abort Once Around (AOA). AOA is a demanding maneuver used for system malfunctions which severely limit the ability of the crew to survive. In cases such as loss of all cooling or atmospheric pressurization onboard the orbiter during ascent, the crew will press to orbit and then immediately deorbit to land at a west coast landing site such as Edwards Air Force Base or White Sands Space Harbor in New Mexico.

Two other dramatic intact abort scenarios exist in which a landing is attempted within minutes of launch. The first is nominally designed for a case where a Space Shuttle Main Engine shuts down just as the shuttle leaves the pad. In this case it is no longer possible to make it to orbit, however it is impossible to really do anything until the two Solid Rocket Boosters (SRB) have burned out. So the crew flies past nominal SRB separation and then flies a powered trajectory back to the launch site. As the propellant runs down, the main engines are shutdown and the External tank is jettisoned in the Atlantic. At that point he orbiter glides back to the launch site runway. This intact abort mode, called Return to Launch Site (RTLS) is the highest stress case for the shuttle for many of the shuttle components and it has never been attempted in actual flight.

The second intact abort with a rapid landing is a Transatlantic Abort Landing (TAL) or East Coast Abort Landing (ECAL). These intact aborts are designed for a propulsion malfunction later in flight which does not provide sufficient energy to make orbit but which have moved the vehicle far enough downrange that a RTLS is no longer possible. In a TAL< the crew flies to a landing in Europe or Africa. In an ECAL, they attempt to land at a runway on the east coast of the United States.

In the event of a propulsion malfunction such that it is impossible to reach a runway, the crew can perform a Contingency Abort. In this mode, the crew flies the best trajectory possible to get close to land. Then the engines are shutdown and the External tank is jettisoned. The Orbiter is then flown as a glider as close as possible to land. At a specified altitude the crew engages an automated routine which flies the orbiter in a straight path and the crew bails out. A escape pole is deployed from the side hatch and the crew is attached to the pole via a slide. The crew bails out attached to the pole. Sliding along the pole allows the crew to reach a position so that when they slide off the end of the pole they can avoid re-contact with the shuttle. This capability was added after the Challenger accident and is mainly intended to deal with cases where the only alternative is an ocean ditching. Although the orbiter shape has been studied and has good ditching characteristics, the payload attachments in the payload bay cannot withstand the deceleration and the vehicle would be rapidly be torn apart by a loose cargo after water impact. The bailout option allows the crew to leave the orbiter before it reaches the ocean. The orange Launch Escape Suits (LES) worn by shuttle crews provide them physiological support for the high altitude bailout as well as ocean survival capability to enable them to survive until they are rescued by recovery forces.

Orbit Rescue

The subject of rescue from a stranded vehicle on-orbit has received a lot of concept attention over the last 5 decades. This subject is treated in some detail on Mark Wade's www.astronautix.com website. On this site Wade provides the details of 35 different concepts for rescue from earth orbit. These concepts generally arise out of two paradigms. Orbit rescue concepts based on the "lifeboat" paradigm generally are based on a small spacecraft that can act a as a lifeboat to bring the crew home. These vehicles struggle with packing crewmembers and spacecraft systems into a small functional spacecraft. Another set of rescue concepts are based on the "parachute" paradigm. These systems are generally intended for a single crewmember at a time and involve deployable systems usually made from inflatable or foam structures and usually involve a parachute as the final stage of crew recovery. These systems struggle with implementing structures with enough structure to handle re-entry aerodynamic loads (400 pounds per square foot) and heating/temperatures (1000-2800 degF) and with sufficient systems to perform the deorbit maneuver and maintain life during the entry.

One exception to this concept work has been the implementation of the Simplified Aid For EVA Rescue or SAFER. This is a small compressed nitrogen system that can be worn on the bottom of an astronauts life support backpack. This system has thrusters and controls which enable the crew member to propel themselves back to the Space Station or Space Shuttle if their tether connecting them to the spacecraft is severed. Often referred to as an "EVA parachute" it mitigates one of the major risks of EVA operations, that of becoming separated from the spacecraft.

Space Rescue is currently primarily "self-rescue"

There are many factors which make rescue of one spacecraft by another very difficult, given the current state of human spaceflight technology. This forces space rescue to primarily be a "self-rescue" type of operation although rescue by other vehicles is possible in certain circumstances.

This problem of rescuing one spacecraft by another is determined by the characteristics of the spacecraft in distress and the rescue spacecraft. The rescue task is made increasingly easier if the spacecraft in distress can maintain human life for a longer period of time. The rescue task is also made easier the more rapidly a rescue craft can be prepared for launch. Finally the rescue task is made easier the fewer the limitations on launch of the rescue vehicle (weather, systems, orbital mechanics).

Given these characteristics, rescue scenarios are optimized when a spacecraft in distress can dock with another vehicle that can provide life support while waiting for a rescue vehicle and where the rescue vehicle can be rapidly prepared and launch into the same orbit as the spacecraft in distress.

The successful response to the famous Apollo 13 explosion was made possible by the fact that the Apollo Command Service Module, which suffered the explosion, was docked to the Lunar Module (another spacecraft) which supported life long enough until the crew could use the limited capabilities of the Command Module to return to earth. Even though two vehicles were involved, this can clearly be seen as a case of "self-rescue".

In current Low Earth Orbit (LEO) operations, survival in a contingency can be extended by docking to the International Space Station (ISS). This is only possible when the spacecraft in distress can maneuver to rendezvous and dock to the ISS. Orbital mechanics may limit the ability of the spacecraft in distress to perform this maneuver. If the spacecraft in distress is not already in an orbit planned for rendezvous with the ISS, then this is unlikely to be possible.

One of the questions asked after the loss of the shuttle orbiter Columbia has been whether or not the Columbia's crew could have sought safe haven aboard the ISS. Reviewing this case is instructional regarding the difficulties of space rescue. Columbia did not carry a docking port for the ISS, nor did it carry full spacesuits for each crewmember. Solutions could have been developed for each of these problems by stationkeeeping the orbiter near the ISS and transferring the crewmembers using the station and shuttle robotic arms. The Launch Escape Suits (LES) (the orange suits worn by shuttle crews for launch and return) do have a limited capability in vacuum and crewmembers in these suits could have been carried between the orbiter and the space station by astronauts in regular spacesuits.

As problematic as these solutions are, they are simple to solve in comparison to the problems of Columbia actually reaching the ISS on its last flight. In order to maximize scientific payload, Columbia's last flight was launched into an orbit at a 39 degree inclination to the equator. The ISS orbits in an orbit inclined 51.6 degrees to the equator.

To shift the orbit 2 degrees in inclination would take almost all of the orbital maneuvering fuel onboard the orbiter. So even if practical solutions existed for the transfer of crew between vehicles, there was no way for Columbia to have even maneuvered anywhere near the orbit of the ISS.

An optimal rescue vehicle is one that can be rapidly prepared for launch and has few limitations on the conditions for launch. The Soyuz vehicle is by this metric, a very good rescue vehicle because the vehicles and their launchers are in a production line and the launchers are capable of launching in a wide range of weather conditions. The Space Shuttle is less optimal by this metric because the turn-around time vary based on discoveries in post-launch inspections and the weather limits on launch are more restrictive than Soyuz. There are other metrics to consider however. Where Soyuz must be launched with at least one crewmember and is capable of returning three, the shuttle can be launched with three-four crewmembers and return 7 nominally and a larger crew in a contingency. It would require 3 Soyuz flights to return to earth the numbers of crewmembers that can be carried in a single shuttle in a contingency.

Current launch rates and the ability to launch on time make it difficult to implement a rescue launch capability to spacecraft with a short mission life except where measures are taken to prepare a rescue mission prior to the launch of the first or primary mission.

For example the United States has gone to significant measures following the Columbia accident to maintain a rescue flight capability in case an orbiter is stranded in orbit. This essentially makes it necessary to prepare two missions whenever one is launched, the primary mission as well as the rescue mission. As a practical matter, the rescue mission is not usually completely prepared before the launch of the primary mission. Techniques have been developed to allow the rescue mission to only be partially assembled before the launch of the primary mission.

In particular, the shuttle rescue mission capability is based on the preparation of the next regularly scheduled shuttle mission. A rescue mission is considered “ready” when the number of days to complete launch preparations of the rescue mission on a highly expedited schedule is less than the maximum number of days that the space station could support life for the normal space station crew and the space shuttle crew who would be seeking a safe haven aboard the space station. In this way the space station serves as a place for the crew of a damaged shuttle to dwell while waiting for a rescue launch. Although there are two ports on the space station capable of shuttle docking, mechanical interference prevents two orbiters from being docked to the space station simultaneously. Therefore if a shuttle crew is seeking a safe haven in the international space station, the orbiter in which they arrived must be jettisoned while it still has enough electrical power and fuel to successfully undock and maneuver out of the way of the space station. This automated departure procedure required technique development to allow the orbiter to be disconnected with the entire crew onboard the ISS.

The Russian Soyuz vehicle is more suitable as a rescue vehicle for a space station based crew than the Space Shuttle for several reasons. First once a Soyuz crew is on the station,

they can dwell there for some time. The basic Soyuz vehicle has an on-orbit lifetime of 6 months versus the 14-19 days of the Space Shuttle so it is possible to keep a Soyuz at the space station continuously by launching a new Soyuz every 6 months and using the older Soyuz on the station to rotate a crew to earth. While the Soyuz is at the station, it is available for rapid (45 minutes) activation and emergency return of the crew. The Soyuz launch vehicle is capable of launching under a much wider range of weather conditions than the shuttle increasing the availability for a rescue launch. The major limitation on the Soyuz as a rescue vehicle is crew size. As a crew return vehicle for a 3 person ISS crew, the Soyuz is very near an optimal solution. However if a shuttle were stranded at the ISS, with seven crewmembers onboard, it would take 4 Soyuz flights (Launched with only one crewmember) to return all seven crewmembers to earth. This would be a tremendous amount of hardware to be readied and launched to accomplish this rescue mission.

It is worthwhile to note that when multiple vehicles are required to rescue the entire crew that the Probability of the entire crew survival is defined by

$$P_{entirecrewsurvival} = 1.0 - (1.0 - P_{primarysuccess})(1.0 - (P_{rescuesuccess})^{flightsrequired})$$

So as the number of rescue flights to bring the entire crew home rises, so must rise the reliability of each individual rescue flight in order to meet the same probability of entire crew surviving. This can really cause a complexity increase in the rescue vehicle and is the reason that for the proposed United States Crew Return Vehicle (CRV) for the ISS that a single vehicle was equipped to return the entire seven person crew of the ISS.

Limitations of Ground Based Rescue

The fundamental issue with a ground based rescue is the limitations on its use. First, the rescue mission must be able to be launched within the available life support capability of the stranded spacecraft. The time required to prepare a mission as well as the possibility of a mission scrub due to systems failure or weather significantly reduces the effectiveness of this type of rescue option. These limitations may be major, as in the case of the shuttle, or minor as in the case of the Soyuz.

Launch sites for the rescue mission must be able to reach the orbits of the stranded vehicle. The minimum inclination that can be reached by a launch site is determined by the launch site's latitude. This is due to the limitation of basic orbital mechanics that requires the center of the earth to be at the center of an orbit. Because of this, a launcher can never launch into an orbit at lower inclination than the latitude of the launch site. This significantly limits rescue options. For example, when NASA launches a Hubble Space Telescope maintenance mission to a 28.5 degree inclination orbit, it is impossible for Russian launch vehicles to be of assistance because the latitude of the Russian launch sites are so much farther north that they can never achieve a 28.5 degree inclination orbit.

Orbital mechanics also significantly limits the number of launch opportunities to perform a rescue. Normally for rendezvous with objects in low earth orbit, the number of launch opportunities a day is limited to two relatively short windows from a single launch site.

The tougher question is whether or not a failure that strands one spacecraft on-orbit is also likely present in an identical rescue spacecraft. If the hazard that caused the first crew to be stranded on-orbit is present in an identical rescue vehicle, then launching the rescue flight may result in additional crewmembers stranded on-orbit if the hazard also disables the rescue spacecraft. This has been a major question when considering the use of shuttle vehicles to rescue another shuttle stranded at the ISS due to ascent debris damage. If ascent debris has disabled the first vehicle at the ISS, then the possibility exists that a rescue flight could be disabled by a similar debris strike.

This is not just an issue for the spacecraft systems but also for the launcher. It is interesting to note that the Soyuz launcher is used for both human launches and cargo launches. There have been cases where a malfunction in a cargo launch has caused a temporary grounding of the Soyuz launcher for human as well as cargo flights.

This question is especially problematic for the space shuttle. Given the short time that he space shuttle can dwell at the space station, it places the space shuttle managers in a difficult posture. In the 14-19 day on-orbit life of the orbiter at the station, if there is serious damage to the orbiter they must evaluate the risk of the debris on the rescue flight and decide whether to commit to returning the crew in the damaged/repaired orbiter or decide to jettison the damaged orbiter while it still has power/propulsion in order to clear the way for a rescue flight.

Another major problem with ground based rescue is the problem of docking with a spacecraft that is tumbling. The United States demonstrated the ability to rendezvous and capture spacecraft spinning about a single axis on a number of occasions (Solar Maximum satellite, the Westar and Palapa rescues, the Intelsat Syncom Rescue) however docking with a tumbling spacecraft is a much more difficult task.

Simulations conducted during the X-38/Crew Return Veicle (CRV) project showed that it is much easier to escape from a tumbling spacecraft with a crew escape type of vehicle rather than to approach and dock with it. In particular large appendages, such as solar arrays, radiators and antennae) sweep out a large volume when a spacecraft is tumbling. This volume becomes a ”keep-out” zone for any rescuing spacecraft attempting to fly to and dock to the tumbling spacecraft. As the rescuing spacecraft approaches a tumbling spacecraft with complex geometries it becomes very difficult to determine if the rescuing spacecraft is even in a location where a safe approach path exists to the tumbling spacecraft.

In contrast escaping from tumbling spacecraft in a rescue craft that is initially docked with the rescue spacecraft is a much easier problem. The geometry is fixed. The rescue spacecraft is at a known orientation with regard to the body coordinates of the tumbling spacecraft. Given the appendages that are part of the tumbling spacecraft, it is possible to

compute a trajectory that leads to clearance from the appendages with usually three propulsive maneuvers of achievable magnitude. In a large number of simulations with a mix of pilot and non-pilot astronauts it was demonstrated repeatedly that escaping from a docking port on the bottom of the ISS was relatively easy to do with a CRV even with the ISS tumbling at up to 5 degrees/second. The 5 degrees a second was established as a reasonable loss of control limit because it was determined that this was the amount of rotation that would occur if a single propellant tank on the ISS lost all of its contents in a single propulsive impulse.

Because the difficulties of ground based rescue explained in this chapter, the ISS Program Office chose to implement a space based self-rescue system, the CRV. This was initially planned to be first provided by the Russian Soyuz and then implemented with a US developed CRV. As history has developed, the CRV has been canceleld and the Russian Soyuz has filled this role for the ISS.

The Crew Return Vehicle as a Study in Space Rescue

Because the CRV was the first custom built space rescue vehicle it is worthwhile to examine its development and its driving requirements in order to understand the desirable characteristics and rationale for any future space rescue system.

Following the Challenger accident in 1986, the Space Station Freedom Program (as it was known at the time) baselined an Assured Crew Return Vehicle (ACRV). This vehicle was to meet three basic missions

The first mission was to return the crew if a crewmember(s) became ill or injured while the space shuttle orbiter was not at the station.

The second mission was to return the crew in the event that a catastrophic failure of the station made it unable to support life and the space shuttle orbiter was not at the station or was unable to reach the station in the required time.

The third mission was to return the crew in the event that a problem with the space shuttle made it unavailable to resupply the station or changeout crew in a required timeframe.

Prior to the baselining of an ACRV, the Space Station Freedom had baselined an onboard health facility to deal with astronaut health emergencies ad a “safe haven” capability to deal with failures aboard the station. Significant architectural modifications were incorporated in the Space Station Freedom design to make safe haven a possibility. For example, the modules of the Space Station were arranged in an elliptical “racetrack” pattern. This precluded the possibility of a failure in one module making other modules inaccessible as well as ensured that there were two exits from every module. The subsystems of the Space Station Freedom design were also distributed that loss of any of the racetrack modules did not disrupt any critical services.

The baselining of the ACRV occurred with significant trepidation. The concern was that a adding another full spacecraft to the Space Station Freedom would significantly increase the development and cost risk to the program. It is important to note that the requirement was baselined without any increase in the expected cost to complete of the Space Station program. When the Space Station Freedom evolved into the International Space Station (ISS), the United States committed in an international Memorandum of Understanding to produce the ACRV while Russia committed to providing CRV capability with its Soyuz vehicle during the initial ISS operations. Once again, no resources were committed to the ACRV development but rather the ACRV was viewed as a threat to the ISS budget.

From 1986 to 1995 there were 12 different attempts to define an ACRV configuration. While significant work was done to refine the requirements for the vehicle, limited progress was made in actually starting a full development. Without an agreed to budget for the project, each attempt foundered over concerns over development cost. A wide range of options were studied during this time ranging from Apollo type capsules to biconic vehicles to lifting bodies to a mini-shuttle orbiter and consideration was even given to building an entire additional shuttle orbiter so that one could be continuously located at the station. In all of these concepts, test verification was a major cost driver in the program.

In 1995 the final and most long lived of the CRV projects was started. The X-38/CRV project would run from 1995-2002. It was based on using a lifting body with a detachable propulsion unit. The propulsion unit would maneuver the craft away from the ISS and provide a deorbit maneuver. The propulsion unit would then be jettisoned and the lifting body would fly back to earth much in the same manner as an orbiter. At the end of the flight a large parafoil would be deployed to allow landing at low velocities (35 knots) and at slow descent rates (25 fps) on a wide variety of desert type terrain.

This X-38 project conducted over 40 development tests of the large parafoil with conventional airdop techniques. The project also conducted 8 free flight tests of the lifting body/parafoil combination by dropping the lifting body from the wing of NASA's B-52 bomber. On the final flight of the X-38 project, the lifting body intercepted the trajectory of a CRV returning from space at approximately 50,000 feet and flew the trajectory successfully to large parafoil deployment at 15,000 ft. The world's largest parafoil (7500 square feet) then deployed and flew the vehicle to a precision touchdown within 150 ft of the planned target. This accuracy was obtained while dropping from the B-52 close to 10 miles from the intended launch point. Steering winches on the lifting body allowed it to manipulate the parafoil for precision approach and landing.

A space test vehicle which was to be carried aloft by the Space Shuttle was over 75% complete at the time of project cancellation. Structural and systems tests conducted after the project cancellation showed that the design would have passed NASA requirements to fly in the shuttle bay and that its systems were capable of completing a vehicle return mission,

At the time of cancellation of the X-38 project it was projected that a fleet of 3 vehicles could be built and fully qualified for approx $1.5 billion. This would have resulted in a dramatic decrease in the cost to produce a CRV which according to previous NASA cost models would have cost over $3 billion to develop alone. They key to the reduced cost to develop this vehicle was in its verification approach which used a build-up method similar to modern aircraft testing for the atmospheric flight phases. The basic lifting body shape was a modified version of the X-23/X-24 shape that the United States Air Force had flown to space and in the atmosphere in the 1970s. This served as the basis for the design and this part of the design, although modified for the CRV role, was in many ways "pre-tested" before the start of the program. Parafoil only flight were conducted to qualify the parafoil system. (For reference, the parafoil system was the largest square parachute in the world with a deployed wing area 50% bigger than that of a Boeing 747.). Then flights utilizing the lifting body/parafoil combination in the earth's atmosphere were conducted. Components of the X-38/CRV were tested onboard the Space Shuttle (inertial-Global positioning system navigation system) and NASA's F-15 (electromechanical flap actuator) in order to qualify them for flight. Then a full set of ground tests and a space flight test were to be conducted. This build-up approach was a significant factor in reducing the number and costs of testing the CRV.

There were several technology firsts in the X-38 CRV. In addition to the world's largest parafoil and the first new lifting body shape (modified X-23/X-24) flown in 20 years, the X-38 incorporated the following new technologies:

- Flush air data system for angle of attack and sideslip tied directly into the flight control system
- Neural Network for computing angle of attack and sideslip from flush air data system
- Laser initiated pyrotechnics
- Electromechanical actuators for full authority flight control surfaces
- Hot structures for nosecap and body flaps
- Dynamic Inversion flight control laws
- Electromagnetic International berthing Docking Mechanism
- Large space qualified Lithium-Ion batteries

The X-38/CRV represented the first attempt in space technology to build a complete spacecraft dedicated to the rescue/escape role. Future space rescue vehicles may or may not incorporate the technologies pioneered in this project. The requirements developed by the project to drive this design are more instructive than the actual technologies involved because they represent the first clear statement for what a rescue spacecraft designed from a "clean sheet" of paper would need to be.

There were thirteen major requirements identified for the crew return vehicle. As further definition occurred the medical community did an extensive review of what would be required for a "space ambulance" and identified additional requirements. The thirteen major requirements are identified in the following table

Requirement	Rationale
Operate in a shirtsleeve environment	Crew might not have the time nor the physical ability to get into a spacesuit
Dual fault tolerant in critical systems	Necessary for human rating
Landing within a 5 NM radius	Minimize search and rescue time
Dry land touchdown	Deconditioned crewmembers may have trouble in ocean survival situation, Avoid the need for ocean recovery forces.
Supports medical mission	To be an ambulance an injured crewmember must be able to ingress/egress, must contain medical equipment, get injured crewmember to care in 24 hours.
Less than 4g sustained load inflight	Support deconditioned injured crewmember
7 crewmembers of 95% American male	Bring the entire crew down in a single flight
All attitude separation	Able to perform function even if ISS has lost attitude control
Separation in less than 3 minutes	Able to perform function rapidly in case of a growing catastrophe onboard the ISS
Two way communications with the ground	Ability coordinate rescue
Autonomous capability – pilot not required	Surviving crewmembers might not bepilot trained
Operation in English	US provided system
3 year life with 95% availability	Minimize costs associated with launch of replacement units

Deconditioning occurs in crewmembers after they have been in nmicrogravity condition on-orbit. Deconditioning starts to happen almost immediately on-orbit although significant symptoms only occur as the mission increases duration. Current constraints place a maximum duration shuttle flight at 19 days due to effects of deconditioning.

It is interesting to examine how the medical community expanded the requirements to turn the CRV into the world's first "space ambulance". They identified a specific set of equipment to be carried onboard and a set of vehicle capabilities that were unique to the rescue ambulance role.

In terms of medical equipment, the medical community identified the following capabilities and equipment:

"The CRV shall accommodate medical life support for one ill or injured crew member including, but not limited to: ventilation, physiological monitoring with defibrillation, intravenous fluid therapy, and pharmacotherapy services.

CRV Emergency Medical Kit (16 in x 15 in x 10 in or 2400 cubic inches at 30 lbs)
- Bandages, Equipment, and Meds (1080 cubic inches at 20 lbs)
- Pulse Oximeter (50 cubic inches at 1.2 lbs)
- Intravenous Fluids Pump (200 cubic inches at 3.0 lbs)
- Suction Device (14 cubic inches at 0.5 lbs)
- 2 liters IV fluids (200 cubic inches at 4.4 lbs)
- Ambubag (250 cubic inches at 0.9 lbs)

CRV hard mounted medical equipment (1200 cubic inches at 24 lbs)
- AED defib/monitor (768 cubic inches at 17 lbs)
- Autovent Ventilator/Respiratory Support Pack (432 cubic inches at 7 lbs)

Totals 3600 cubic inches at 54 lbs "

Most interesting to the vehicle designer was the implications of these capabilities on vehicle design. The X-38/CRV team spent a considerable amount of time assuring themselves that defibrillating someone in a metal spacecraft cabin would not result in hazardous currents to any other crewmember. Physiological monitoring, ventilation and intravenous fluids all required special accommodations in the vehicle design.

The medical community also identified a minimum survival kit for inflight and postlanding survival. This included the following requirement:

"The CRV System shall provide a minimum of 24 hours of crew survival equipment and consumables including, but not limited to:

Survival kits for 7 crewmembers
- Clothing, shelter, hygiene, and rations

Potable Water
- 10.5 liters (7 x 1.5 liters fluid loading)
- 7.0 liters (7 x 1.0 liters for 24 hrs survival)

(17.5 liters = 17.5 kgs = 38.5 lbs)"

Fluid loading refers to the procedure of having crewmembers drink significant amounts of water prior to entry to prevent blood pressure drops when they are back in an earth gravity environment.

The medical also placed requirements on the design which required the crew to be in a prone position at landing.

The medical also put some challenging requirements on the life support system designer. First in order to accomplish the ambulance function, the medical community required the ability to place an injured crewmember on 100% oxygen (4 lbs/hr) during the entire CRV flight. This was a problem for the life support designer because when a human is breathing 100% oxygen, their exhalation contains significant oxygen. In a small vehicle this can rapidly lead to an environment of increased flammability. The CRV was

designed to be equipped with nitrogen tanks and computer controlled valves to dump part of the atmosphere overboard and repressurize with nitrogen to keep the inside of the cabin within flammability limits. Given the small volume of the CRV this limit could be quickly reached with a crewmember on 100% oxygen.

The second challenging requirement from the medical community for the life support designers was the requirement to purge the CRV atmosphere. The medical community pointed out that one of the main scenarios for a CRV use would be a fire aboard the ISS. In this case the CRV atmosphere could be contaminated with smoke and combustion products before the hatch was closed. The life support system was provided with the ability to changeout the atmosphere as well as activated carbon filters to scrub the atmosphere.

.

Safe Haven

The final subject to be covered in space rescue is that of safe haven. When a crew in space is in trouble, the longer they can survive provides a longer time to prepare a rescue mission, significantly increasing the probability of success. On long duration missions to the Moon and Mars, safe haven technology may be the only rescue capability available to the crew.

Following the Columbia accident, NASA decided a Contingency Shuttle Crew Support (CSCS) capability onboard the ISS. Prior to every shuttle launch a computation is made of how long the ISS could support its nominal crew along with the shuttle crew. In order to have a rescue capability, the rescue shuttle would have to be able to be readied for flight on an expedited basis in less days than the maximum capability of the ISS to support the lives of the station and the shuttle crew.

NASA's experience on this is instructive. Although it may seem like a simple task to compute the maximum life support capacity of the ISS, several questions immediately come up as bounding assumptions. These include:

- What assumptions should be made on equipment failure rate ?
- What assumptions should be made on equipment lifetime ?
- Should hardware that is installed on the ISS but not yet exercised be counted as part of the capability ?
- Should nominal food, water and exercise (oxygen) consumption be planned or should a reduced consumption rate be assumed ?
- Should resupply of the ISS on normal schedules with non-shuttle assets (Russian Progress/Soyuz) be assumed ?
- Should it be assumed that 3 crewmembers would be immediately evacuated from the station using the Soyuz to decrease the overall life support requirement ?

In the end, NASA made the decision to compute three separate estimates. One estimate is based on the entire ISS and shuttle crew remaining aboard the station, being resupplied at nominal rates and consuming at nominal rates. When examining this number it is recognized that this assumes perfect hardware and resupply performance but that there is also some reduction in requirement that can be made by reduced food, water and oxygen (exercise) consumption. A second estimate, called the engineering estimate, assumes a failure rate of hardware consistent with recent experience. For example when the water electrolysis device on ISS, which generates oxygen, had a high failure rate, then engineering estimates included it as an already failed component. . A third estimate called worst case failure case assumed the worst possible failures to generate the minimum life support capability of the ISS. All three of these estimates are briefed at the flight readiness review and the engineering estimate is compared to the number of days required to prepare a rescue shuttle before the launch of a primary shuttle mission begins.

Conclusions

Space rescue is in its infancy as a technical capability. Given that it is likely that human spaceflight will remain the riskiest of human flight endeavors for the foreseeable future, it is likely that much more work will need to be done in this field. In this chapter we have reviewed the attempts to put together space rescue capabilities from operational capabilities as well as attempts to design a custom space rescue system.