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Incidence of an Astronaut Not Sealing the Pressure Garment Visor on Reentry

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Abstract

Audiovisual records of a Project Mercury pilot's activities during an orbital flight indicate that his visor was left open during reentry and descent to the sea surface, phases of flight during which cabin pressure loss was to be mitigated by suit pressurization; however, the suit could not have been pressurized with the visor open. Thus, for a presently unknown reason, a critical safety step—sealing the visor and making a pressure suit integrity test before reentry—was overlooked in this flight. Later, Space Shuttle flights were carried out with visors unsealed for much of the launch and landing phases, with the false assumption that they could be closed if the crew cabin were to lose cabin pressure rapidly. The lessons are clear: first, spaceflight crews should be trained to seal visors for the entire launch and landing phases; and second, procedure checklists will always be important to crewed flight, in both public and private spaceflight.

Keywords: flight safety, safety procedures, checklists, human factors, flight training, commercial space industry

1. Introduction

Checklists are used throughout the domains of aviation and astronautics and have played a large part in the superior safety record of modern flight. When flight systems are formalized, checklists are relatively straightforward to produce, but when technologies are being developed, checklists must change often to track varying system configurations and test objectives. In rapidly developing projects (such as our space suit development work), checklist adherence can be difficult as flight crews adjust to new sequences; other reasons for checklist failures include light crew fatigue, checklist illegibility, aircrew confusion of checklist sequences and meanings, and others (Turner & Huntley, 1991).

By reviewing Project Mercury video, audio and transcript records, the authors have identified a case of a Mercury astronaut not closing his pressure garment visor during reentry; this was a phase of flight in which ambient atmospheric pressure (exterior to pressure cabin) was lethally low (effectively vacuum), and the pressure garment was worn precisely as a backup in the event of pressure cabin pressure loss. This means that in this case, had a cabin pressure breach occurred, the pressure garment would not have been able to fulfill its essential function of keeping the astronaut's body at a physiologically perceived safe, low altitude, in terms of both gas pressure and composition. At some point, the checklist system here failed, as did the pilot's situational awareness and that of the ground team who monitored his voice transmissions closely; nobody noticed that sometime after about an hour into the roughly five-hour flight, the pilot opened his pressure suit visor, and left it open through the reentry phase. Evidence for this is given in Section 2, and the implications discussed in Section 3.

2. Video, Audio, and Transcript Evidence

We examined three main records of the Project Gemini *MA-6* mission, also known as the flight of *Mercury-Atlas 6*, the capsule being *Friendship 7* (not to be confused with the *Mercury-Redstone MR-3 Freedom 7* suborbital flight), flown on 20 February 1962 for three orbits. The records are summarized in Table 1 and described below. The records are the official NASA mission flight audio transcript taken from onboard tape recorders (NASA, 1962a), the digitized audio records of these tapes referenced to us by NASA archivists (NASA, 1962b), and the capsule footage from inside *MA-6* (NASA, 1962c). In Table 1, ten columns present the bulk of the evidence for our claim. Column 1 is a line number for referencing this document. Column 2 indicates mission elapsed time (MET) as recorded in the audio transcript, reported in NASA (1962a) as "elapsed time from the launch of the spacecraft in hours, minutes, and seconds that the communique was

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Table 1
Audiovisual and transcript evidence.

Line	MET	Altitude MSL	Ambient pressure (PSIA)	Transmission/notes	Video	Audio file	Audio	Visor	Figure
1	Countdown	0	14.7	–	0:26:27	691-AAE	0:17:35	Closed	–
2	0:00:03	>0	<14.7	–	N	691-AAE	0:17:49	Unknown (c)	–
3	0:00:23	>0	<14.7	P: "Roger, back up clock is started"	0:27:00	691-AAE	0:18:09	Closed	–
4	0:01:26	>0	<14.7	–	N	691-AAE	0:19:12	Unknown (c)	–
5	0:04:44	>15,000	<8.0	CC: "Roger 20 seconds to SECO"	0:28:48	691-AAE	0:22:18	Closed	2
6	0:16:35	Orbit *ca* 130 mi	<0.000	P: "…Cabin pressure holding steady at 5.7 [psi]…suit pressure is indicating 5.8"	N	691-AAE	0:35:00	Closed	–
7	0:21:59	Orbit *ca* 130 mi	<0.000	P: "…preferring to take xylose pill at present time…Unsealing the, going to unseal the faceplate. Over"	0:33:20	691-AAE	0:39:55	Opening, then closes	3, 4
8	0:52:00	Orbit *ca* 130 mi	<0.000	CC: "Roger. You do have your visor closed at this time [asking for confirmation]. Over"	N	691-AAE	1:10:16	Closed	–
9	0:52:03	Orbit *ca* 130 mi	<0.000	P: "That is affirmative. I had it open for a little while; its closed now. Cabin pressure is holding in good shape. Over"	N	691-AAE	1:10:19	Closed	–
10	0:55:33	Orbit *ca* 130 mi	<0.000	–	N	691-AAE	1:13:54	Unknown (c)	–
11	0:55:40	Orbit *ca* 130 mi	<0.000	Audio failure	N	691-AAE	1:14:00	Unknown (c)	–
12	0:59:44	Orbit *ca* 130 mi	<0.000	–	N	691-AAE	1:18:21	Unknown (c)	–
13	N		<0.000	Audio failure	N	691-AAE	1:18:50	Unknown (c)	–
14	1:00:45	Orbit *ca* 130 mi	<0.000	–	N	691-AAE	1:19:32	Unknown (c)	–
15	N		<0.000	Audio failure	N	691-AAE	1:20:15	Unknown (c)	–
16	1:02:31	Orbit *ca* 130 mi	<0.000	–	N	691-AAE	1:21:15	Unknown (c)	–
17	N		<0.000	Audio failure	N	691-AAE	1:21:30	Unknown (c)	–
18	1:13:09	Orbit *ca* 130 mi	<0.000	P: "This is Friendship Seven. Opening visor, going to eat, over"	N	691-AAE	N	Opening	–
19	1:14:30	Orbit *ca* 130 mi	<0.000	P: "This is Friendship Seven. Have eaten one tube of food, shutting the visor"	N	691-AAE	N	Closing	–
20	1:23:10	>360,000	<0.000	–	N	692-AAE	0:04:41	Unknown (o/c)	–
21	1:23:21	>360,000	<0.000	Change in video film	N	692-AAE	N	Unknown (o/c)	–
22	2:23:42	>360,000	<0.000	–	N	692-AAE	1:05:39	Unknown (o/c)	–
23	2:54:55	>360,000	<0.000	–	N	692-AAE	1:37:31	Unknown (o/c)	–
24	4:31:21	>360,000	<0.000	–	N	714-AAE	0:01:32	Unknown (o/c)	–
25	4:33:09	*ca* 360,000	<0.000	P: "Roger, retros are firing"	0:43:42	714-AAE	0:03:17	Open	5
26	4:34:39	>100,000	<0.016	P: "…suit temperature is 71 [degrees], suit pressure is 5.8…"	N	714-AAE	0:05:05	Says its closed	–
27	4:38:51	>100,000	<0.016	–	N	714-AAE	0:09:02	Unknown (o)	–
28	4:42:50	>100,000	<0.016	Audio failure	N	714-AAE	0:13:05	Unknown (o)	–
29	4:43:47	>100,000	<0.016	P: "This is Friendship Seven. A real fireball outside"	0:47:28	714-AAE	N	Open	6
30	4:47:55	*ca* 100,000	*ca* 0.016	P: "My condition is good but that was a real fireball, boy"	0:49:44	714-AAE	0:18:14	Open	7
31	4:48:07	80,000	0.40	P: "Altimeter off the peg indicating eight zero thousand [ft MSL]"	0:49:56	714-AAE	0:18:25	Open	8
32	4:49:20	*ca* 30,000	4.3	P: "…drogue [parachute] came out at 30,000…"	0:50:33	714-AAE	0:19:37	Open	9
33	4:50:10	10,800	>10.1	–	N	714-AAE	0:20:30	Unknown (o)	–
34	4:51:26	7,000	11.34	–	N	714-AAE	0:21:46	Unknown (o)	–
35	4:51:54	<7,000	>11	P: "This is Friendship Seven, going through checklist"	N	714-AAE	0:22:15	Unknown (o)	–
36	5:05:10	<300	<14.7	End transcript	N	714-AAE	N	Unknown (o)	–

Notes. MET = mission elapsed time (time from instant of liftoff); altitude MSL = flight plan altitude at given MET, in feet above mean sea level (MSL); ambient pressure = ambient atmospheric pressure; transmission = transmission from pilot to ground (P) or ground to pilot ("Capcom" or CC); visor = visor status, open (o) or closed (c); based on video frame at time of indicated transmission.

initiated" (p. 149). Column 3 is altitude in feet above mean sea level (MSL) as derived from the *MA-6* flight plan (NASA, 1962d) and corroborated by altitude reports from the pilot. Column 4 is the ambient pressure based on the 1976 U.S. Standard Atmosphere model for the reported altitude. Column 5 reports communications from the pilot or Capcom, evident in the video record, audio recording, and/or audio transcript. Column 6 reports time elapsed since beginning of the flight video (commencing roughly 30 seconds after the audio records). Column 7 indicates the audio file used to report a given transmission and column 8 the timeline for that particular audio file. Column 9 indicates the position (open or closed) of the pilot's helmet visor. Column 10 indicates the corresponding figure number in this report.

The internal capsule footage covers most of the *MA-6* flight, and certainly the reentry phase, during which the astronaut's visor position is nearly always visible and is certainly visible at times when ambient external pressure approximated vacuum. The audio transcript recorded all comprehensible transmissions from launch to landing, and was used to time-stamp the capsule footage, which does not have a visible clock or other time indicator. The audio records were used to corroborate the capsule footage and audio transcript. In sum, it was possible to accurately indicate that the astronaut's pressure suit visor was in the open position at phases of reentry when rapid capsule pressure loss would have been fatal.

Where the *MA-6* audio or visuals cut out—for example, audio failures at MET 0:55:40 or change in video film at MET 1:23:21—using the three media together allowed us to reasonably infer helmet visor status. The three independent records allowed unambiguous demonstration of the helmet visor status (open or closed) at the most relevant times, as discussed below, but some ambiguities of flight operations, also discussed below, remain.

For familiarization with the helmet in question, Figure 1 displays the fiberglass shell, polycarbonate visor built into the helmet of the modified Navy Mark V pressure garment. In Figure 1a, the helmet visor is up, leaving a distinctive black sealing ring or gasket visible around the perimeter of the face opening; this is seen again in Figure 1b. In Figure 2, the pilot is listening to the transmission from the ground (row two of Table 1 at 00:04:44), "Twenty seconds to SECO [supplementary engine cutoff]." At this time, the helmet visor is clearly down, with the black sealing strip noted in Figures 1a and 1b obscured by a metal cover visible in Figure 1a.

At MET 00:16:35 the pilot reports a cabin pressure of 5.7 psig and a suit pressure of 5.8 psig; these figures are correct for the flight plan, indicating a cabin pressure reduction from 14.7 psig at launch to *ca* 5 psig minimum (100% oxygen) during orbit. The additional 0.1 psi in the suit (yielding a suit pressure of 5.8 psi) at this point is expected, reflecting the experience of our test subjects that about 0.1 psi is a comfortable suit pressure (sometimes referred to as "ventilation pressure") which keeps the suit material slightly away from the body. This pressure in the suit cannot be maintained with the visor open, so although there is no video footage of this transmission, the numbers indicate that at this point the visor was closed.

In Figure 3a, the pilot is opening the visor to take a xylose (sugar) pill at MET 0:21:59. In Figure 3b, the pill is being consumed, and in Figure 4 the visor is closed again, just a few seconds after it was opened to take the sugar pill. At MET 00:52:00, Capcom asks the pilot to confirm that his visor is closed (line eight of Table 1); the pilot confirms this, indicating that he was closing the visor as it had been opened for some unreported time. At MET 01:13:09, the pilot reports opening the visor to eat; somewhat over a minute later, he reports having eaten (apple sauce from a tube) and that he is again closing the helmet visor. The next video footage pertinent to the subject of this brief is seen at MET 04:33:09, during the deorbit burn; here (see Figure 5) the visor is clearly open, with no metal band covering the black sealing strip identified in other figures.

Figures 6, 7, 8, and 9—all time-stamped to altitudes between orbit and 7,000 ft MSL—show an open visor. Viewing the continuous video footage through this period shows that the visor remained open though deorbit burn and landing (NASA, 1962a).

By referencing another Mercury flight, we see in Figure 10 that the *MR-3* pilot had the helmet visor down at 50,000 ft MSL. The helmet worn here did not differ from that worn by the *MA-6* pilot discussed in this report.

3. Discussion

Why was the helmet visor left open through the reentry phase of the *MA-6* mission? The reason might be simple oversight; the *MA-6* flight plan (NASA, 1962d) contains numerous checklists for the flight, reentry, and pickup phases of the mission. As described below, most do not carry explicit instructions to close the visor before reentry. Specifically, the flight plan checklists were:

1. BECO (booster engine cutoff; e.g. jettison emergency tower).

2. SECO (supplemental engine cutoff; e.g. periscope out, spot booster, report on tumbling sensations and zero-g sensations).

3. Orbit Checklist (various switch settings, none related to life support).

4. Control Systems Check (checking control performance against expected performance).

5. Yaw Maneuver Check (perform a yaw maneuver, and then stabilize all rates to zero).

6. Equipment Stowage (stowing away flashlight, cameras, and other loose items prior to reentry).

Life support systems and the helmet visor position are not mentioned in these lists. In the immediate pre-deorbit a

b

Figure 1. *MA-6* pilot wearing pressure helmet. (a) The helmet visor is open, revealing a distinctive black sealing strip around the perimeter of the face opening (derived from a NASA image at http://www.nasa.gov/content/astronaut-john-glenn-at-cape-canaveral); this is better seen in (b), which is derived from NASA (1962b). Images: NASA.

Figure 2. *MA-6* pilot at 20 seconds to SECO, visor closed. Sealant strip visible in Figures 1a and 1b not visible, here obscured by metal visor perimeter strip seen in Figure 1a. Image: NASA.

and reentry phase checklists there is also no mention of the helmet visor or other life support matters. In *Reference List 7*: *Preretrosequence Checklist* (NASA, 1962d, p. 80), the items are:

1. **Equipment**—STOWED.
2. **ControlSystem**—CHECK (thruster warmup).
3. **Emergency Retro** sequence fuse switch—no. 1.
4. **Transmit Switch**—UHF.
5. **Retro Man.** fuse switch—no. 1.
6. **Restraint Devices**—CHECK.
7. **Crosscheck Attitude**—window/instruments/scope.
8. **Time check** CET.

It is only in *Reference List 9, Post-Entry Checklist* (p. 82) that we see mention of the visor status: item 9 is "Astronaut preparation for landing" and item 9d is *disconnect visor seal hose* followed by 9e, *open visor*. These item 9 procedures are to be carried out after item 8, which is to check

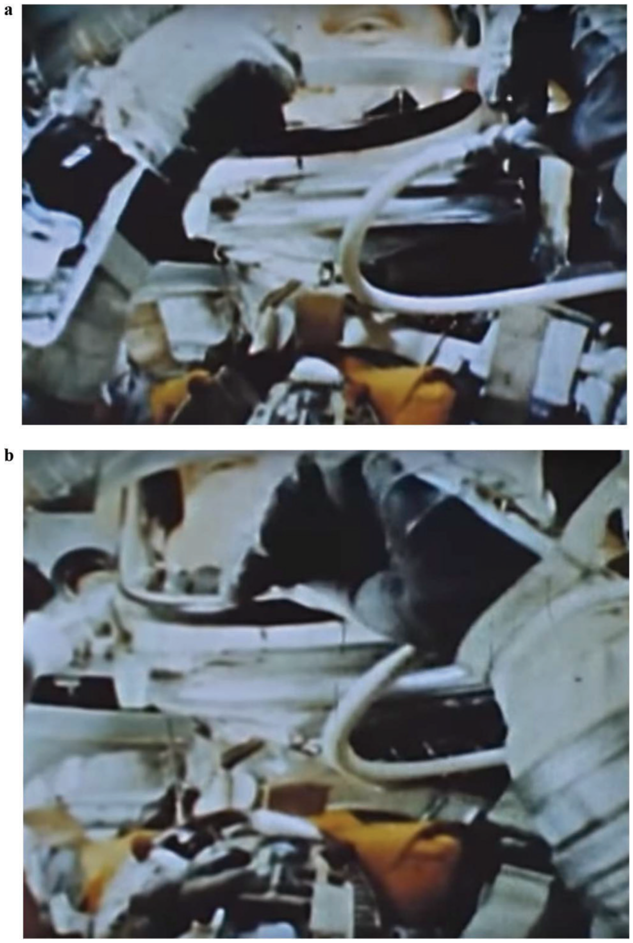

Figure 3. (a) *MA-6* pilot opening visor *ca* 20 minutes into flight. (b) Pilot consuming xylose (sugar) pill. Image: NASA.

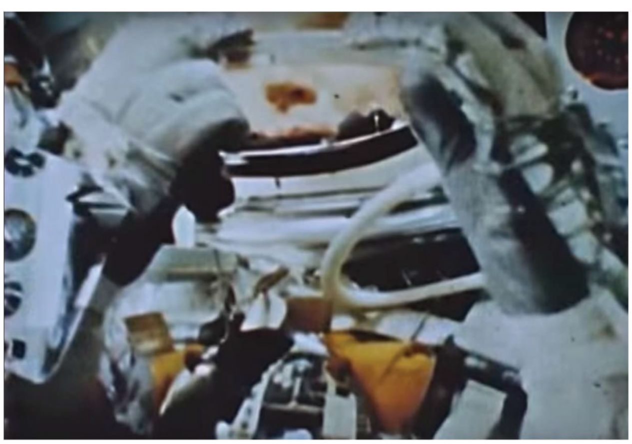

Figure 4. *MA-6* pilot closing visor after consuming xylose (sugar) pill while in orbit with hard vacuum beyond pressurized cabin hull. Image: NASA.

main parachute deployment visually, at an altitude of 10,000 ft MSL. Since the visor position was not listed in these checklists, its status might not have been checked; however, as Figure 10 indicates, other mission pilots did not leave the visor open through descent and landing.

Figure 5. *MA-6* pilot reporting "Roger, retros are firing" at entry interface (MET 04:33:09), with hard vacuum outside pressure cabin and helmet visor open, altitude *ca* 360,000 ft above MSL. Image: NASA.

Figure 6. *MA-6* pilot reporting "A real fireball outside" during reentry (MET 04:43:47), with hard vacuum outside pressure cabin and helmet visor open, altitude $>$100,000 ft above MSL. Image: NASA.

A possible contributing reason for this oversight might be imprecision in terminology; while most documents refer to the visor as a visor, the *MA-6* pilot once refers to the visor as the "faceplate" (at MET 00:21:59; see NASA, 1962c). Such discrepancies lead to uncertainties in our experience, but precisely how such would play out in this circumstance is unclear.

Quite a different reason for not sealing the visor is possible; the pilot of this flight was told to leave the retrorocket pack attached to his spacecraft during descent, for a number of technical reasons beyond the scope of this paper; the gist of the matter is that the pilot was aware of a

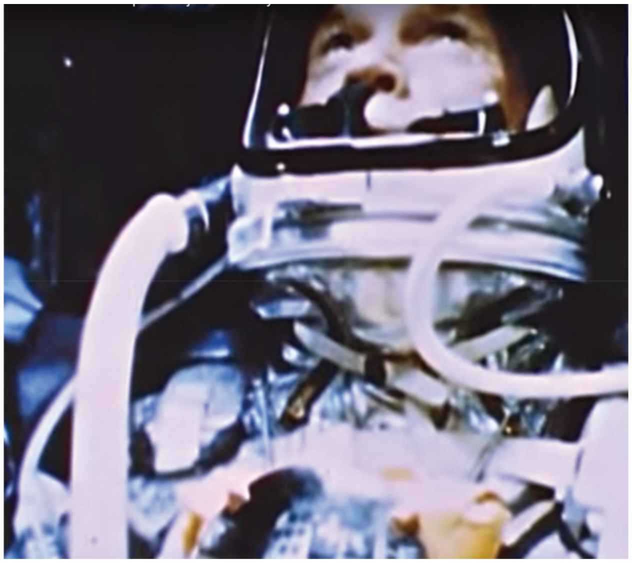

Figure 7. *MA-6* pilot reporting “My condition is good but that was a real fireball outside, boy!” during reentry (MET 04:47:55), with hard vacuum outside pressure cabin and helmet visor open, altitude *ca* 100,000 ft above MSL. Image: NASA.

Figure 8. *MA-6* pilot reporting “Altimeter off the peg indicating eight zero thousand” during reentry (MET 04:48:07), with <0.0 psia ambient pressure outside pressure cabin and helmet visor open, altitude 80,000 ft above MSL. Image: NASA.

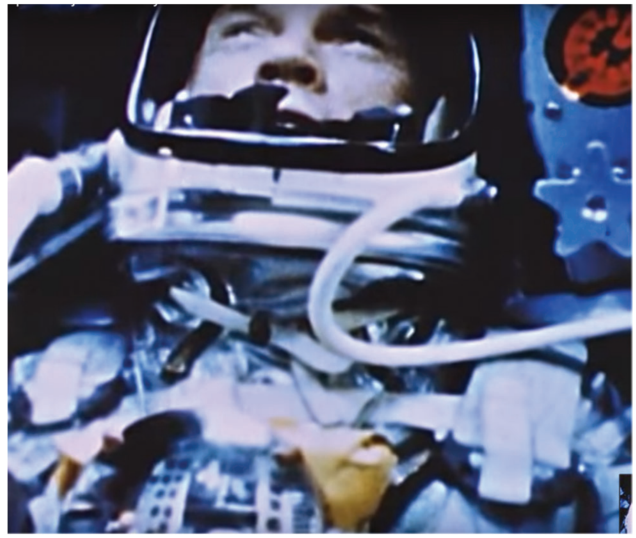

Figure 9. *MA-6* pilot reporting “…drogue [parachute] came out at 30,000…” during reentry (MET 04:49:20), with “only just physiologically safe” ambient pressure of 4.3 psia outside pressure cabin and helmet visor open, altitude *ca* 30,000 ft above MSL. Image: NASA.

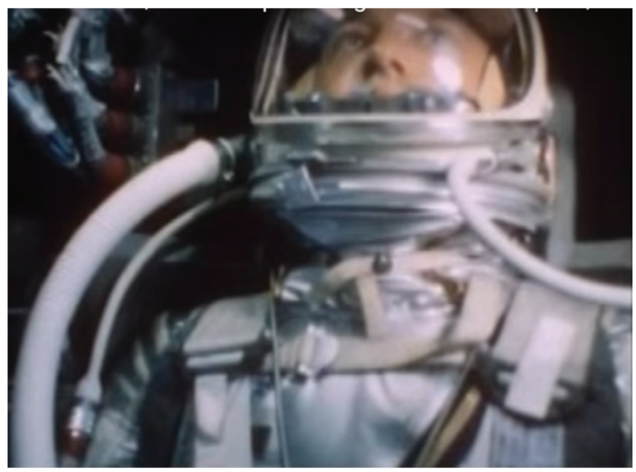

Figure 10. *MR-3* pilot reporting altitude of 50,000 ft above MSL during reentry with helmet visor closed, black sealing ring obscured by metal visor rim. Image: NASA.

major departure from the flight plan in this respect, and might have suspected that his heat shield was damaged, as was suspected by the ground team, but not communicated to the pilot. In this case, it might be that the pilot made a decision to leave the visor open in the event of a cabin pressure breach, suspecting that one would attend any destruction of the space capsule if the heat shield were indeed damaged. The pilot has not reported on this matter in public, and it is mentioned here only as a speculation.

Whatever the ambiguity here, it is clearly documented that somewhere between MET 01:14:30 and 04:33:09, the *MA-6* pilot opened the pressure garment visor, after which time he does not appear to close it again before reentry and into reentry, and in the last few minutes of reentry. Loss of cabin pressure—the contingency the pressure suit was worn to protect against—throughout this period would likely have been lethal with the visor open through the bulk of the descent, with a time of useful consciousness anywhere above 40,000 ft above MSL measured in less than 15 seconds (Federal Aviation Administration, n.d.). Space suit technician Jim LeBlanc was exposed to full vacuum in an accident in December 1966; when his pressure suit dropped instantaneously from a pressure of 3.8 psig to 2.5 psig he recalls having no time to react to what was happening before losing consciousness (Lewis, 2014).

4. Discussion and Conclusions

Three main conclusions derive from this investigation. First, vigilance with correct use of terms, development of unambiguous and thorough checklists, and adherence to these checklists are as critical to the successful operation of pressure garments as to the operation of aerospace vehicles. Until flight operations are entirely automated, checklists will be an important part of aerospace operations and will always require close attention.

Second, even with high-quality checklists, problems can occur in the *instructed* use of spaceflight protective garments. For example, while the crew of STS-107 (*Columbia*) could not have survived the high-altitude breakup of the shuttle in any conceivable scenario, it is notable that while they were wearing their ACES pressure suits during reentry, “per nominal procedures, the crew wearing helmets had visors up,” for various reasons including that “[wearing visors down on reentry] results in high oxygen concentrations in the cabin; gloves can inhibit the performance of nominal tasks; and the cabin stow/deorbit preparation timeframe is so busy that sometimes crew members do not have enough time to complete suit-related steps prior to atmospheric entry” (NASA, 2008, p. xxiv). In this case, astronauts used their suits *as instructed*, but due to a design that allowed high oxygen concentration in the crew cabin if the visor was down (sealed) on reentry, reentry was carried out with visors open (unsealed), presumably assuming that the crew could manually lower the visor if the cabin were perceived to lose pressure (we have heard incidentally that this problem is being addressed in the *Orion* capsule, but have not been able to verify this). However, this is a false assumption: at even modest altitudes for spaceflight, this is not guaranteed. In a stratospheric balloon flight separate from Project Mercury, there is record of a likely helmet pressure breach at >50,000 ft above MSL. The pilot in this case was heard to exhale briefly before losing consciousness; he was unable to make even the simple motion of resealing the visor with an arm and hand motion (Ryan, 2008) and, after landing in an unresponsive state he later perished after some months in a coma. On the other hand, in the case of STS-51L (*Challenger*) the crew did not have pressure suits but did have helmets fed by shipboard supplies of oxygen and, when the craft broke up and exposed the cabin to the ambient atmosphere of *ca* 48,000 ft above MSL, three crew were conscious long enough to activate supplemental breathing gas flow into the helmets (though they were not able to escape the tumbling crew cabin, and perished on impact with the ocean) (Committee on Science and Technology, 1986).

Table 2 places these cases in context and indicates that in some cases, high-altitude cabin loss of pressure is potentially survivable. In the case of an SR-71 high-altitude disintegration in 1966, the pilot survived exposure to >70,000 ft above MSL conditions of deep cold and effective vacuum because during aircraft breakup his pressure suit inflated to compensate for lowered ambient pressure; this was possible because he was flying with the visor closed. This has significance for this paper.

Table 2
Flight incidents of accidental crew exposure to high altitude and space-equivalent conditions (listed chronologically; see text for discussion).

Flight	**Approximate altitude of decompression (ft above MSL)**	**Protective garments**	**Protective garments worn/used as trained?**	**Survival of initial decompression?/visor status**	**Could initial decompression have been survived with correctly established use of suit?**
Dolgov balloon, 1962	*ca* 93,000	Full pressure garment with helmet	Yes	Unclear; visor sealed but breached by impact with aircraft on skydive exit (Shayler, 2009)	N/A (no cabin)
SR-71, 1966	*ca* 80,000	Full pressure garment with helmet	Yes	Yes; flying with suit on, visor down, suit partially pressurized and suit’s independent oxygen supply flowing after loss of cabin supply (Graham, 2008)	Yes
Piantanida balloon *StratoJump III*, 1966	*ca* 57,000	Full pressure garment with helmet	Possibly not; anecdotal evidence suggests pilot varied from proper suit use	Yes; pressure visor deliberately opened while suit pressurized at >50,000 ft above MSL, leading to immediate unconsciousness; survived in coma until death months later (Ryan, 2008)	N/A (no cabin)
Soyuz 11, 1971	>500,000	None	N/A	N/A	N/A (no pressure garment)
STS-51L (*Challenger*), 1986	*ca* 48,000	Unpressurized suit, helmet-supplied breathing gas from cabin	Yes	Likely; visors sealed shortly before launch; consciousness lost after some seconds due to loss of oxygen supply from cabin (Committee on Science and Technology, 1986)	Yes
STS-107 (*Columbia*), 2003	>150,000	Launch–entry full pressure suit with helmet	Yes	No; visors open; consciousness lost almost instantly (NASA, 2008)	Yes; decompression of cabin took *ca* 30 seconds
Virgin Galactic Spaceship Two (*VSS Enterprise*), 2014	*ca* 50,000	Unpressurized suit, oxygen mask	Pilot: yes; copilot: yes	Pilot: yes; copilot: unknown (no pressure visors); pilot survived, copilot suffered fatal “blunt force trauma” related to ship breakup (National Transportation Board, 2015)	Yes

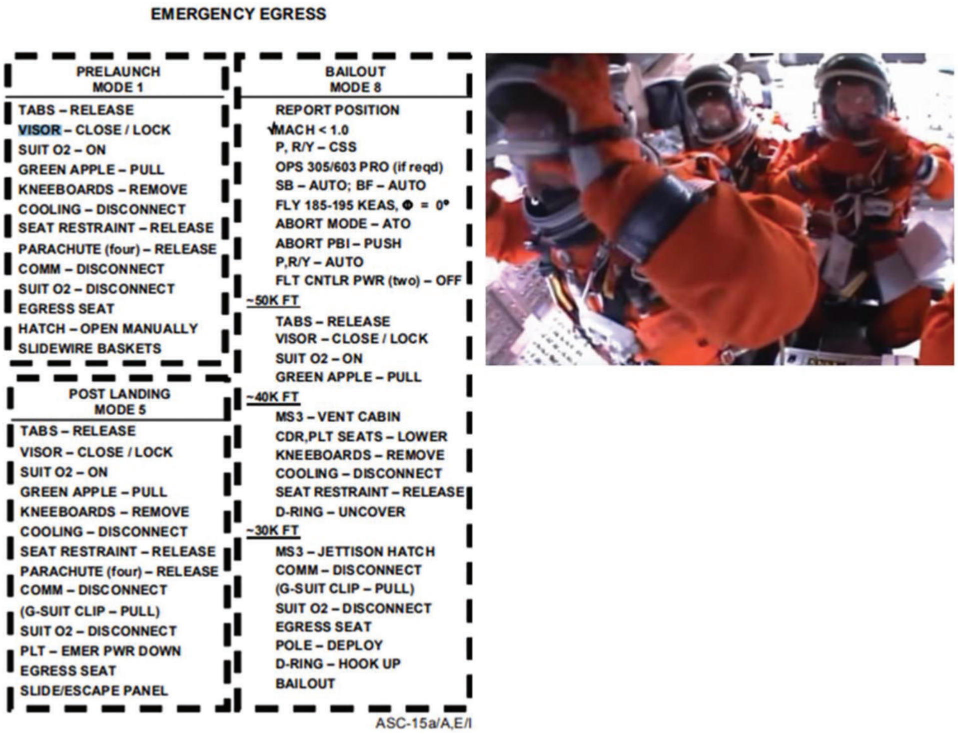

Figure 11. Space Shuttle bailout checklist and ascent image. Left: Note that if altitude is >50,000 ft above MSL, checklist indicates to CLOSE and LOCK visor and turn on suit's independent oxygen supply (via pulling the "Green Apple" handle on the oxygen supply actuator cord). ASC/134/FIN of *Ascent Checklist, STS-134*. Mission Operations Directorate, Lyndon B. Johnson Space Center, Houston, Texas. Right: Space Shuttle STS-135 crew opening visors 2 minutes and 11 seconds after launch, as instructed; just before launch they were instructed "Close and lock your visors and initiate O_2 flow," so that visors were locked (sealed) for only about two minutes of the launch phase. Altitude at this time is *ca* 158,000 ft above MSL with hard vacuum outside crew cabin, but visors are unsealed and the likelihood of closing them in case of rapid cabin pressure loss is highly variable. Images: NASA.

Current and past SR-71 flights are carried out with some aircraft cabin pressure (anecdotally reported as equivalent to 26,000 ft above MSL, which would be of the order of 5 psig; see Graham, 2008), but with the suit visor closed and the suit partially pressurized. This "ventilation pressure" of the suit makes it more comfortable to wear (which is not a triviality) and allows the pressure differential between suit and ambient conditions, in the case of rapid cabin decompression, to be less than if the cabin were flown at full pressure with the suit unpressurized. This lowered pressure differential should decrease the likelihood of barotrauma in the case of sudden cabin decompression. It also allows the pilot to remain conscious and healthy at the moment that a rapid decompression takes place, or when a slower decompression begins to have significant physiological effects.

Our third conclusion derives from the discussion above and our noting that currently Soyuz crews both ascend to orbit, and return to Earth, entirely with the suit pressurized and the visor closed (this tradition began after the *Soyuz 11* disaster) (Shayler, 2009) (see Figure 11). This is a simple way to ensure that the pressure suit can carry out its function of keeping the crew alive and conscious in case of cabin loss of pressure. Flying in these phases of a mission with the visor closed is simple enough; but as we have seen in this paper, it will always require an up-to-date checklist, and proper use of that checklist, to ensure flight safety. Figure 12 shows the shuttle bailout procedure checklist. In flight bailout (Mode 8) the crew are instructed to close and lock their helmet visors and then activate their suit oxygen supplies; this reiterates that shuttle ascents and descents were made with visors open, with the expectation that they could be closed in the event of cabin pressure loss, and that the suit/cabin interface problem of enriching the shuttle crew cabin with oxygen when the visor was down (sealed) became normalized: indeed it was institutionalized by inclusion in the checklist.

Figure 12. Soyuz capsule reentry, crewmember with helmet visor sealed. Image: European Space Agency.

In sum we recommend, both for the federal and rapidly growing private space industries:

- Continual vetting of flight checklists.
- Flight protective garment training to highlight checklist use.
- Pressure garment/spacecraft design integration such that garment may be used as designed for use and not in some other configuration.
- Standardization of flight procedures such that launch-to-orbit and reentry are always carried out with the helmet visor closed and the suit pressurized to a significant fraction of the 3.5 psig operating pressure of most launch–entry suits when breathing 100% oxygen.

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