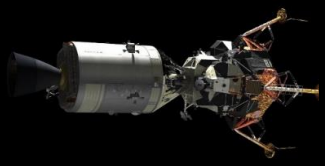
The Manuals that Saved Apollo 13

How two rare historic Apollo mission manuals played their part in the rescue of Apollo 13



by Dr Michael Warner

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On April 13th 1970, at 55 hours, 54 mins and 53 seconds ground elapsed time (GET), and 60,000 km from the moon, oxygen tank 2 on Apollo 13 exploded, forcing the crew to retreat from the command and services module Odyssey, to the relative safety of the docked lunar module Aquarius.

The world watched and listened as astronauts Jim Lovell, Jack Swigert and Fred Haise executed frantic contingency procedures to power and navigate the stricken spaceship and sustain the vessel's life support systems. Some of the emergency procedures were envisaged prior to the Apollo 13 mission. Others were adapted or devised anew by the hundreds of NASA scientists and engineers and thousands of private contractors who rushed to assist the plight of Apollo 13. The new procedures were tested in simulators at Kennedy Space Center, Cape Canaveral, and at the Johnson Space Center, Houston, then narrowed down to the most practicable option, and finally funnelled through to Mission Control be read up by the single point of voice communication between Earth and crew - the Capsule Communicator or 'CapCom'.

Role of the Apollo 13 LM Contingency Checklist

A sizable portion of the history of 'NASA's finest hour' is captured in a single rare document: the heavily-annotated Apollo 13 Lunar Module Contingency Checklist, used by CapCom Charlie Duke to read up to the crew rescue procedures during the crisis. The manual was part of Charlie Duke's collection of NASA artefacts until it's auction in 2010, and is signed with quotations by Apollo 13 astronauts Jim Lovell (Commander) and Fred Haise (Lunar Module Pilot), by Mission Control CapComs Jack Lousma, Vance Brand, Charlie Duke and Joe Kerwin, and by Jerry Bostic (Flight Dynamics Officer in charge of monitoring trajectories and spacecraft manoeuvres) (Fig 1).

Fifty years on from the launch of Apollo 13 on 11th April 1970 from the Kennedy Space Center, Charlie Duke's annotated Apollo 13 LM Contingency Checklist remains in its original form, it's 61 double-sided pages of typed and hand-written procedures intact and complete. The manual is now part of a declared private collection of space mission artefacts[1]. Charlie Duke takes up the story of the checklist, as described in its accompanying Letter of Provenance:

> *"Congratulations on acquiring the full copy of the Apollo 13 LM Contingency Checklist marked Qtrs. I was privileged to serve as the backup lunar module pilot for Apollo 13. Our crew was John Young, Jack Swigert and myself. Unfortunately, due to a case of the measles, Jack Swigert was substituted for TK Mattingly, who then became part of the backup crew. As you know, about 55 hours GET, one of the tanks exploded which caused a leak in the other oxygen tank. This resulted in a complete loss of oxygen and the fuel cells in the CSM. Mission Control instructed the crew to power up the LM and it would be used as a 'life-boat'. The backup crew was notified and within 30 minutes we were at MCC to assist.*
>
> *The immediate problem was to get Apollo 13 back via a free return trajectory, so we had to develop the procedures for the powerup and the PC+2 burn* [two hours after Apollo 13's closest approach to the moon, known as Pericynthion]. *John and I manned the simulator to devise and try out the*

[1] The full collection is viewable on-line at: www.apollomissionartefacts.com

procedures. During this time we were successful in devising the procedures for the PC+2 burn. At other times throughout the flight, we devised procedures for the MCC-5 burn which was a manual burn without the aid of a computer or mission timer. We also developed various power up and power down procedures to conserve our precious battery power…At the appropriate times, I acted as Capcom in MCC and read up the revised procedures to Fred Haise and the GET when to implement them"

The Apollo 13 LM Contingency Checklist was referenced at various times by Gene Kranz during the press conferences that filled the airways during the early days of the crisis. Asked by a journalist, "*what single factor if any is giving you the most concern at this time*", Kranz responded in his usual laconic style, "*the one thing, if anything, is the large amounts of checklist changes*"[2]. Kranz was referring to changes required to the lunar module contingency checklist, so that the spacecraft could function as a lifeboat for the afflicted crew. The pre-typed pages of the checklist had anticipated a variety of emergency situations in which the lunar module could be deployed in roles outside the mission's flight plan. The checklist offered fast-track and computer-override procedures, including rapid two hour, and thirty minute, lunar module power-up activations; computer and manual docked burns of the lunar module descent and ascent engines; and emergency lunar module power-down procedure. Shown below is the chronology of read up procedures (Fig 2).

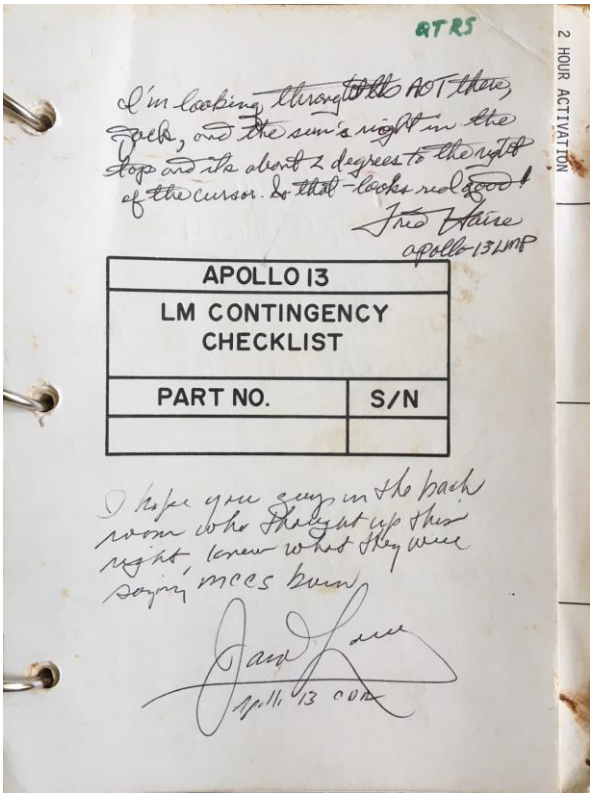


Fig 1
Apollo 13 LM Contingency Checklist

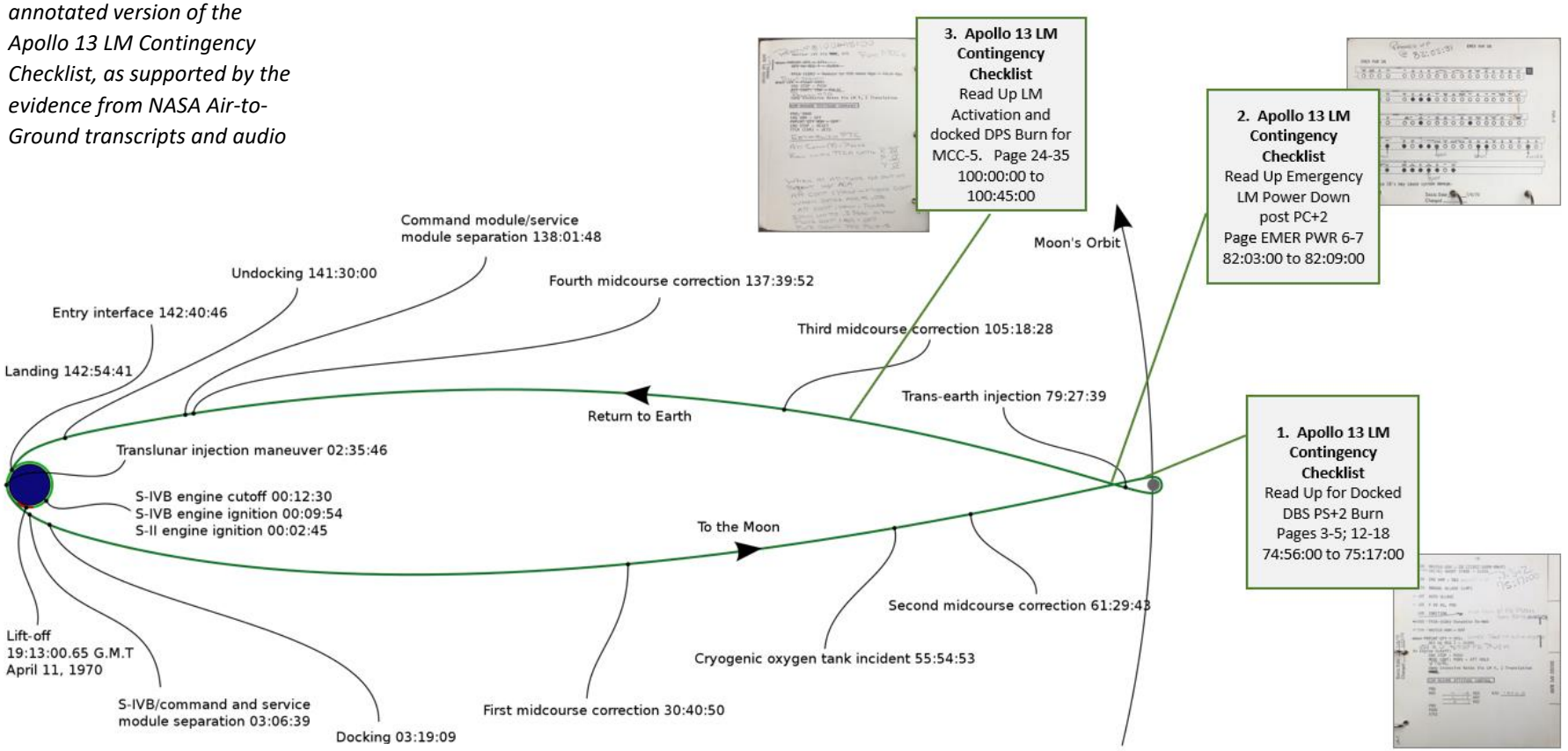
Front cover of *the Apollo 13 LM Contingency Checklist marked Qtrs, with procedures read up by Charlie Duke to the crew of Apollo 13 for the critical PC+2 and MCC-5*

[2] Full interview available online: https://www.youtube.com/watch?v=9CHah3e7e_8. Kranz's reference to "checklist changes" at 30:15.

Fig 2

Chronology of Read Up Improvised Procedures

Figure shows the chronology of the principal read ups matching Charlie Duke's annotated version of the Apollo 13 LM Contingency Checklist, as supported by the evidence from NASA Air-to-Ground transcripts and audio



Adapted from: https://commons.wikimedia.org/wiki/File:Apollo_13_timeline.svg

Role of Apollo 9 LM Systems Evaluation Checklist

The 1995 film 'Apollo 13', directed by Ron Howard and staring Tom Hanks, Kevin Bacon and Ed Harris, was praised on its release, not only for it's thrilling suspense, but also its technical detail. Althoughg reat entertainment the film indeed was, it could not tell the whole story of the rescue of Apollo 13 - a story that dates back to the mission of Apollo 9.

In the aforementioned private collection, accompanying Charlie Duke's Apollo 13 LM Contingency Checklist, is the original and complete Apollo 9 LM Systems Evaluation Checklist (Fig 3). The checklist flew on board Apollo 9 in lower Earth orbit. It contains 77 pages of pre-typed procedures, and handwritten notations made by the astronauts in real-time as they tested the spacecraft's systems in the weightlessness of space. Until its auction in February 2014, the Apollo 9 LM Evaluation Checklist was owned by the former commander of the mission, Jim McDivitt[3]. Described by McDivitt in the artefact's Letter of Provenance: "*most of the numbers were written by lunar module pilot Rusty Schweickart while I checked the systems, but some were written by me…. This checklist was used to evaluate the LM systems whilst docked with the Command/Service Module*".

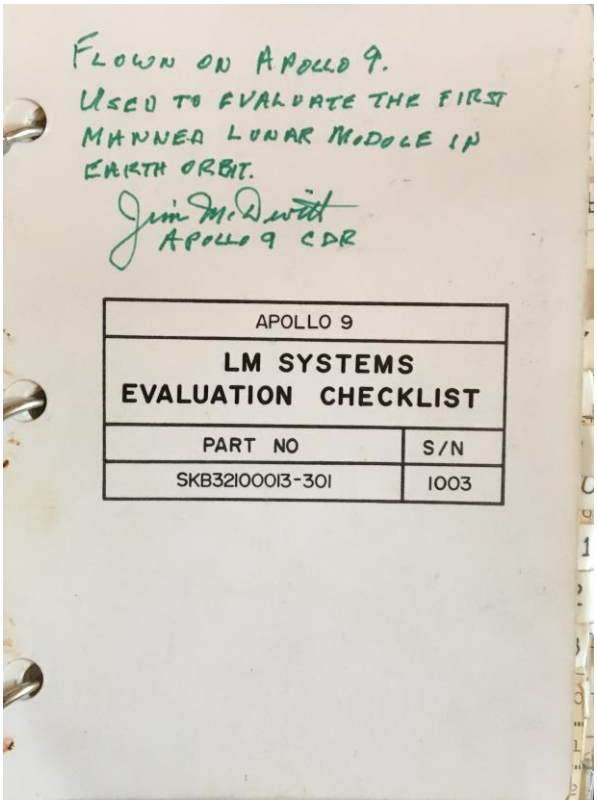


Fig 3
Apollo 9 LM Systems Evaluation Checklist

Front cover of *the Apollo 9 LM Systems Evaluation Checklist, used on board Apollo 9 to record the first manned throttling of an engine in space – a burn of the lunar module descent engine whilst docked with the command and service module.*

In late 1968, NASA authorised the Apollo 8 mission to be swapped with Apollo 9. The Grumman Corporation's lunar module construction was exhibiting faults and had fallen behind schedule. To compound NASA's frustration, the Soviet Union's Zond 5 mission had just flown terrestrial organisms (two tortoises) around the Moon and back to Earth, alive. In response, the Apollo 9 spacecraft configuration, their crew, and the flight plan, were re-assigned as Apollo 8. NASA succeeded in its audacious gamble, catapulting the United States ahead of the Soviet Union to become the first nation to send humans to the Moon.

[3] The 112th Congress passed Act H.R. 4158 in 2012. This law grants US astronauts who participated in the Gemini, Mercury or Apollo programs "*full ownership of and clear title to*" artefacts received during their missions.

Obscured by the media blitz that followed the success of Apollo 8, but undaunted, the military test flight pilots who crewed Apollo 9 - Jim McDivitt, Dave Scott and Rusty Schweickart – considered their mission the 'mother of all test flights'. The objective was to evaluate, in low Earth orbit, the first all-up test of the complete Apollo lunar landing mission system - Saturn V, CMS, LM and PLSS (Personnel Life Support System). The mission comprised the first manned free flight of the lunar module; first rendezvous and docking of lunar module with command module, and, of critical importance to the subsequent safe return of the Apollo 13 crew, the first burn of the lunar module lunar module DPS engine whilst the docked with the CSM (Fig 4).

Fig 4
Onboard Apollo 9 lunar module

'Rusty' Schweickart holding the Apollo 9 LM Systems Evaluation Checklist whilst inside the lunar module 'Spider', with McDivitt to his left and Scott in the command module 'Gumdrop'

Image credit: NASA/JSC: still from film "Apollo 9 - Three to Make Ready" https://www.youtube.com/watch?v=xytZh161E7o

As Gene Kranz attested a year later during an Apollo 13 press conference, "*we had made long DPS burns back in the Apollo 9 missions, we were pretty confident of those procedures".* Kranz was citing the test of a docked lunar module DBS burn during Apollo 9. It was this successful test, in particular, which then informed the pre-written procedure contained in the Apollo 13 LM Contingency Checklist for a computer-controlled docked DBS burn.

Bringing the two checklists together allows comparison of the LM DPS docked burn procedure and tracked evaluation notations in the Apollo 9 LM Evaluation Checklist, with the read up Apollo 13 LM Contingency Checklist procedures for a docked DPS burn (Insert Fig 5). To account for the unforeseen loss of electrical power in the Apollo 13 command module, the pre-written procedure in the Apollo 13 checklist was hurriedly amended in the early hours of the crisis, both for an initial DPS docked burn to place the ship back on a free-return trajectory, and for a subsequent PC+2 burn to speed the return of the crew to Earth. For the PC+2 burn, the improvised docked DPS burn procedure was read up by Charlie Duke to Fred Haise between GET 74:56:00 and 75:17:00[4].

Of note, inspection of pages 59-60 from the Apollo 9 manual, suggests the docked DBS test burn anticipated a computer-controlled ignition. In contrast, as the desperate realities of the Apollo 13 rescue unfolded, the equivalent PC+2 DPS burn procedure included back-up steps, should the

[4] It is noteworthy that Jim Lovell's book 'Apollo 13' cites Vance Brand as the CapCom who read up the PC+2 procedures, just before the spacecraft entered the shadow of the moon. However, NASA Air-to-Ground transcripts and the distinctive voice of Charlie Duke in the NASA audio archives, confirms that CapCom at this time was Charlie Duke. From the transcript: *"03 03 15 03 LMP Okay, I got you, Charlie. 17,"CB(16) INVERTER 2, CLOSE*". 03: 03: 15: 03 is 75:15:03 GET, and PC+2 Trans-Earth Injection burn took place 79:27:39 GET.

computer fail to activate ignition. As Lovell describes in his book 'Apollo 13': "*If the engine did not fire at precisely 79:27:40.07, he* [Lovell] *would take over that function too, using two bright red, silver-dollar-sized buttons – with the words 'Start' and 'Stop' stencilled beneath them*" (p246). Air-to-Ground transcripts of Duke reading up these ignition back-up procedures verifies Lovell's recollection: (*03 03 15 58)* "*OK, back to page 18. We'll continue on as is at 30 seconds, 10 seconds, 7 seconds, minus 5 seconds. At "ignition," no ignition and we'll add here, "if no ignition, START pushbutton – push; still no ignition, DESCENT ENGINE COMMAND OVERRIDE, ON".*

As illustrated, the role played by the Apollo 13 LM Contingency Checklist can be brought to life by matching to each checklist procedures the relevant Air-to-Ground transcript of the read ups and the associated NASA audio archive recording. With regards to the PC+2 docked DPS burn, the transcribed and audio record of the read ups includes not only the augmented procedures, but also instructions from Mission Control for the crew to re-position circuit breakers on the guidance and control panels (Fig 6 and Fig 7).

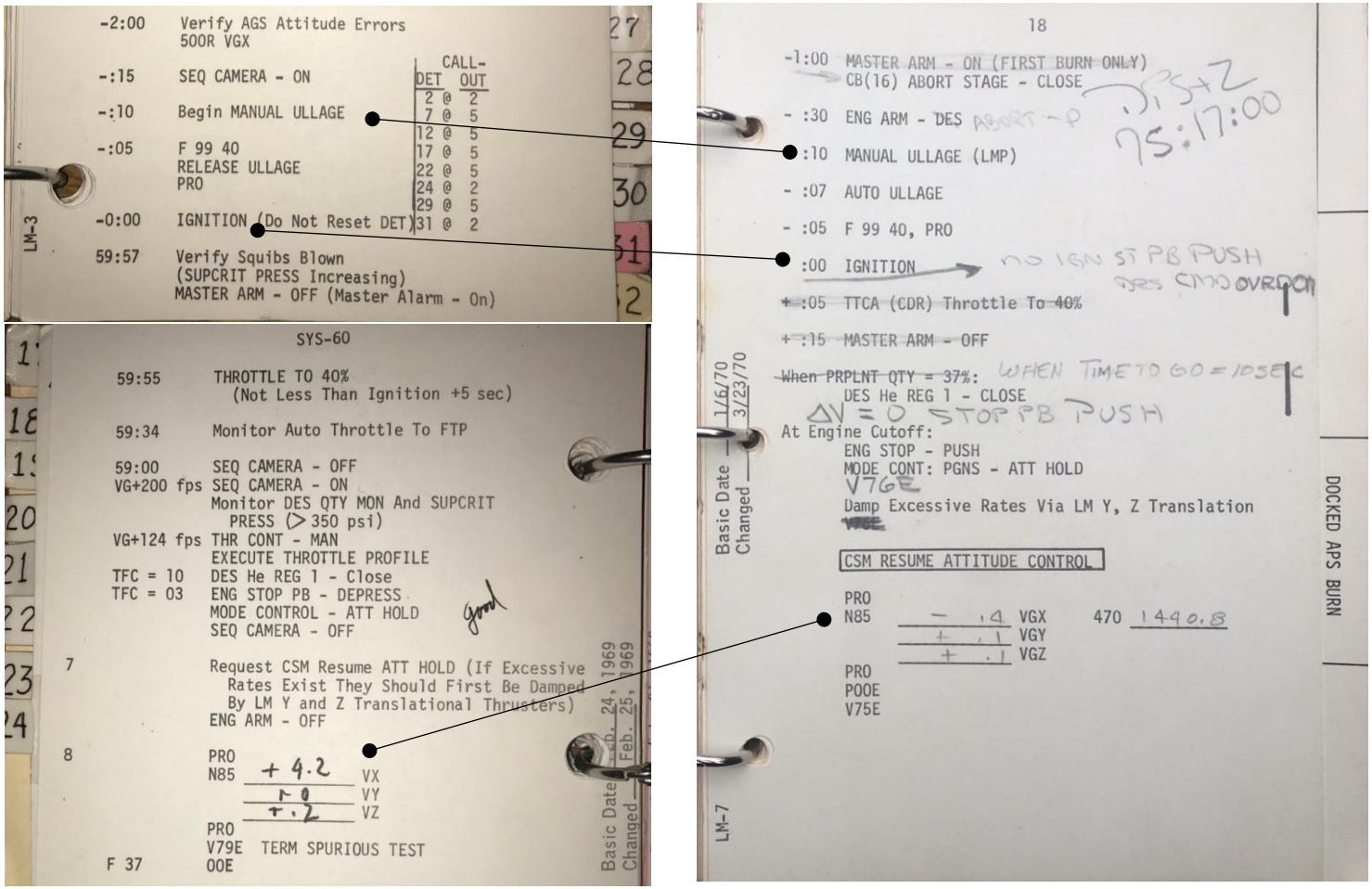


Fig 5

Comparison of Docked DPS Burn Procedures: Apollo 9 (left) vs Apollo 13 (right)

These pages compare the LM DPS docked burn procedure and evaluation notes written in the flown Apollo 9 LM Evaluation Systems Checklist, with the read up of augmented Apollo 13 LM Contingency Checklist procedures for the PC+2 docked DPS burn.

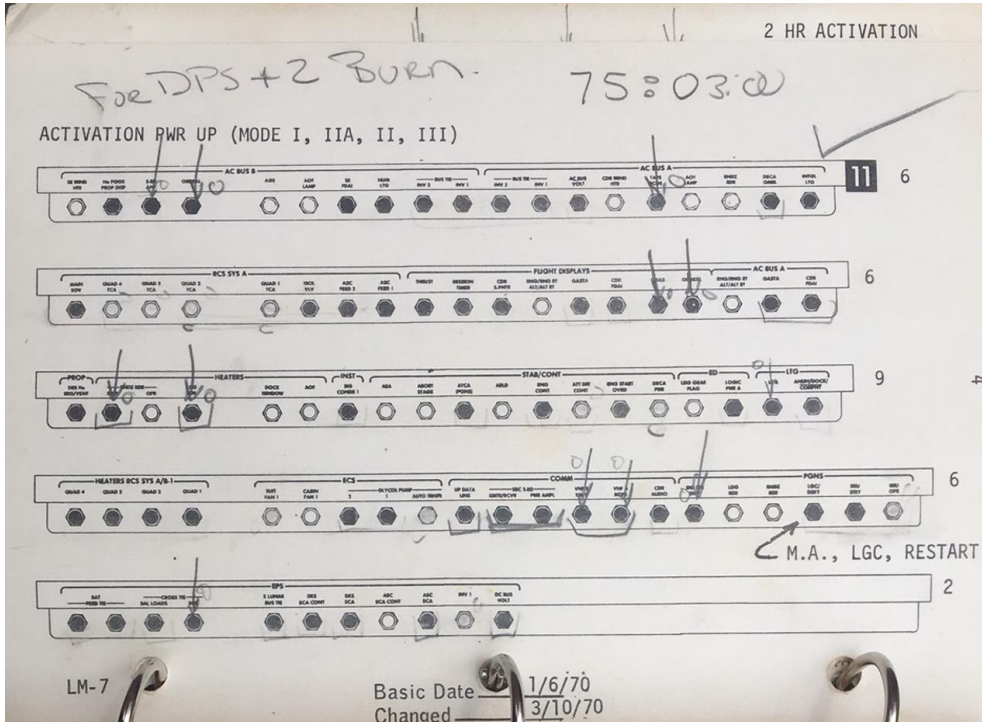
03 03 14 07	LMP	Okay, on page 18, and I've already done that at 1 minute; "MASTER ARM - ON," I'll scratch - -
03 03 14 14	CDR	- - Slipped that ... and I won't have anything to do - -
03 03 14 15	LMP	- - I've already scratched "CB(16) ABORT STAGE - CLOSE" for the previous burn.
03 03 14 20	CC	Okay. We want you to close the CB(16) ABORT STAGE. Over.
03 03 14 33	LMP	Okay. You got some special reason for that?
03 03 14 36	CC	Yes, sir. We like - In case we don't get a manual ON - I mean, an AUTO ON, we're going to back up using the abort stage in the descent-engine command override at ignition plus 1 second. Backing up to page 17, at minus 4 minutes, you read "CB(11) INVERTER 2," it should be "CB(16) INVERTER 2." Over.
03 03 15 03	LMP	Okay, I got you, Charlie. 17, "CB(16) INVERTER 2, CLOSE."
03 03 15 08	CC	Okay, back to page 18. We'll continue on as is at 30 seconds, 10 seconds, 7 seconds, minus 5 seconds. At "ignition," no ignition and we'll add here, "no ignition, START pushbutton - push; still no ignition, DESCENT ENGINE COMMAND OVERRIDE, ON." Over.
03 03 15 45	CDR	I got it out there, but I can't get to see it closer.
03 03 15 58	LMP	Okay, on channel - on page 18, right on down the line, everything holds until after "ignition"; "if no ignition, START pushbutton - push; still no ignition, DESCENT ENGINE COMMAND OVERRIDE switch ON."

Fig 6

Apollo 13 Air-to-Ground Transcript and Audio

Transcript: *Read up by Charlie Duke to Fred Haise of augmented ignition and timing procedures for PC+2 docked DPS burn*

Audio: *as above, minutes 23 to 26*



03 03 01 35	LMP	Okay, stand by just 1.
03 03 02 01	LMP	Okay, panel 11 configuration, top row: AC BUS B I want the S-BAND ANTENNA, OPEN, ORDEAL, OPEN; AC BUS A, TAPE RECORDER, OPEN. Second row, under RCS SYSTEM A, I want MAIN SOV through QUAD 1 TCA, all CLOSED. COMMANDER's X-POINTER under FLIGHT DISPLAYS, OPEN; COAS, OPEN; ORDEAL, OPEN. Third row: RENDEZVOUS RADAR STANDBY HEATER, OPEN; LANDING RADAR HEATER, OPEN. Under STAB/CONTROL: ATTITUDE DIRECT breaker, CLOSED; ED: LOGIC POWER A, OPEN; LIGHTING: UTILITY, OPEN. Under ECS: SUIT FAN CLOSED; AUTO TRANSFER, CLOSED. Under COMM: VHF TRANSMITTER, OPEN; VHF A RECEIVER, OPEN. Under PGNS: SIGNAL STRENGTH DISPLAY, OPEN; IMU OPERATE, CLOSED. Bottom row, EPS: CROSS TIE BUS, OPEN; INVERTER 1, CLOSED.

Fig 7

Apollo 13 Air-to-Ground Transcript and Audio

Transcript: *Read up by Charlie Duke to Fred Haise of augmented circuit breaker positions for guidance and control panel 11, in preparation for PC+2 docked DPS burn*

Audio: *as above, minutes 11 to 13*

“Hold the Earth in the Window”

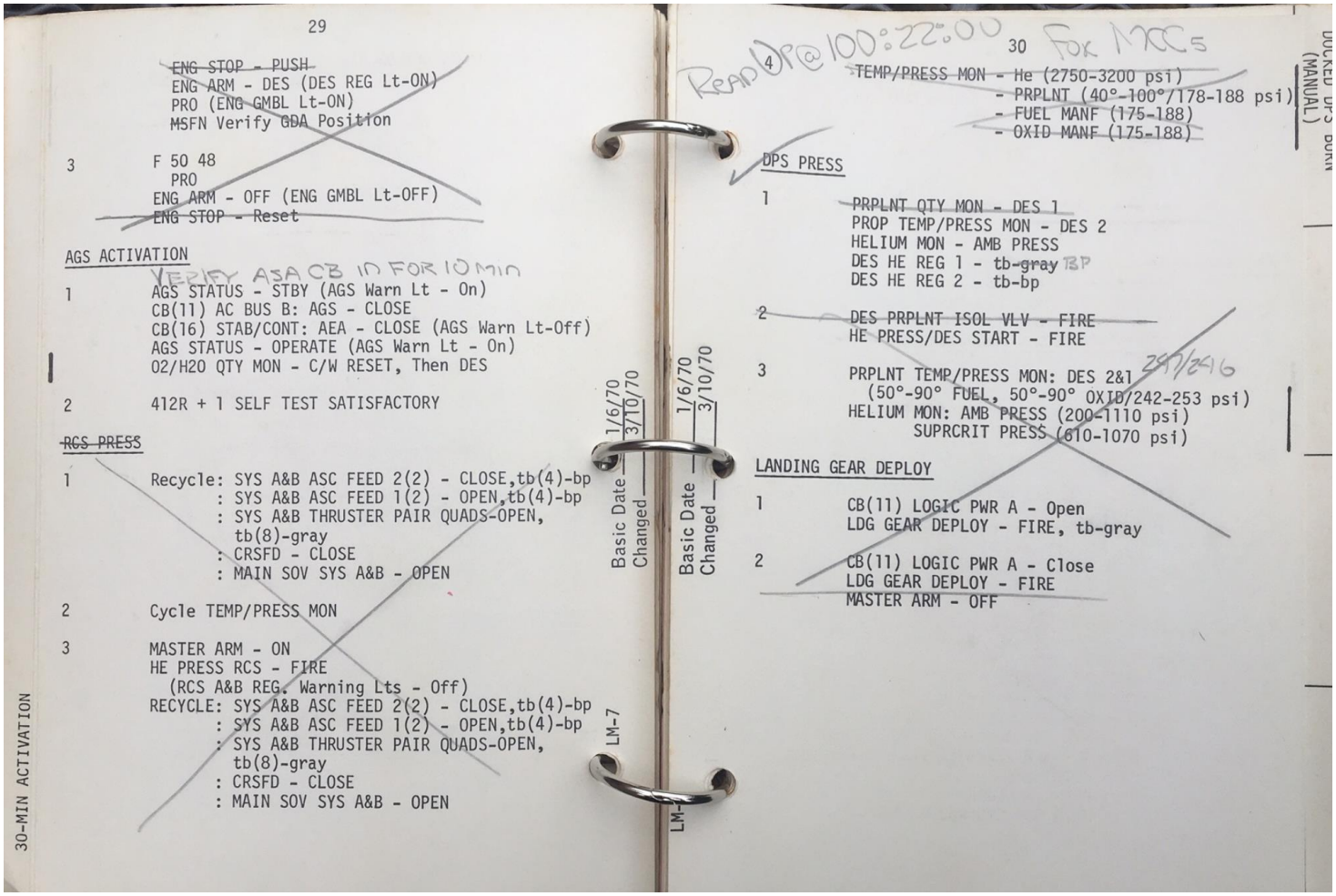
Halfway back to Earth, with the PC+2 DPS burn complete and concerns over running out of consumables forestalled - the latter by minimising usage of electrical power and deployment of Lithium Hydroxide canisters from the command module to scrub CO^2 build-up in the lunar module – attention at Mission Control turned to the accuracy of the Earth-bound trajectory. It was becoming clear that without a further course correction the spacecraft would risk skipping off the earth’s atmosphere into an endless orbit of sun. A mid-course correction (MCC-5) was deemed necessary. It was to be executed at 105:18:28 GET.

As now immortalised in the scene from the film ‘Apollo 13’, to save on critical electrical power an entirely new manual orientation procedure was devised to control the attitude of the craft during the correction burn (Fig 8). The procedure involved positioning the Earth’s terminator on the cross-hairs of the COAS (Crewman Optical Alignment Sight) in the lunar module front window, so as to control pitch and yaw, and maintaining the sun in the second detent position of the AOT (Alignment Optical Telescope), to control roll.

Movie artistic license aside, the annotations in the Apollo 13 LM Contingency Checklist and associated transcripts and audio archive informs us that it was NASA engineers, rather than Jim Lovell (or Tom Hanks!) who devised the innovative Earth-Sun manual reference procedure (Fig 9 and Fig 10).

Credit: still from film ‘Apollo 13: http://v3.danielmall.com/articles/how-to-make-a-performance-budget/

Fig 8
Still from film ‘Apollo 13’ of Earth in the Window
On-line movie clip of scene



29

~~ENG STOP - PUSH~~
ENG ARM - DES (DES REG Lt-ON)
PRO (ENG GMBL Lt-ON)
~~MSFN Verify GDA Position~~

3 F 50 48
PRO
ENG ARM - OFF (ENG GMBL Lt-OFF)
~~ENG STOP - Reset~~

AGS ACTIVATION

VERIFY ASA CB IN FOR 10 MIN

1 AGS STATUS - STBY (AGS Warn Lt - On)
CB(11) AC BUS B: AGS - CLOSE
CB(16) STAB/CONT: AEA - CLOSE (AGS Warn Lt-Off)
AGS STATUS - OPERATE (AGS Warn Lt - On)
O2/H2O QTY MON - C/W RESET, Then DES

2 412R + 1 SELF TEST SATISFACTORY

~~RCS PRESS~~

1 Recycle: SYS A&B ASC FEED 2(2) - CLOSE,tb(4)-bp
: SYS A&B ASC FEED 1(2) - OPEN,tb(4)-bp
: SYS A&B THRUSTER PAIR QUADS-OPEN,
tb(8)-gray
: CRSFD - CLOSE
: MAIN SOV SYS A&B - OPEN

2 Cycle TEMP/PRESS MON

3 MASTER ARM - ON
HE PRESS RCS - FIRE
(RCS A&B REG. Warning Lts - Off)
RECYCLE: SYS A&B ASC FEED 2(2) - CLOSE,tb(4)-bp
: SYS A&B ASC FEED 1(2) - OPEN,tb(4)-bp
: SYS A&B THRUSTER PAIR QUADS-OPEN,
tb(8)-gray
: CRSFD - CLOSE
: MAIN SOV SYS A&B - OPEN

30-MIN ACTIVATION

Basic Date 1/6/70
Changed 3/10/70

LM-7

Basic Date 1/6/70
Changed 3/10/70

LM-

30 For MCCs

Read DP@100:22:00

4 ~~TEMP/PRESS MON - He (2750-3200 psi)~~
~~- PRPLNT (40°-100°/178-188 psi)~~
~~- FUEL MANF (175-188)~~
~~- OXID MANF (175-188)~~

DPS PRESS

1 PRPLNT QTY MON - DES 1
PROP TEMP/PRESS MON - DES 2
HELIUM MON - AMB PRESS
DES HE REG 1 - tb-gray TBP
DES HE REG 2 - tb-bp

2 ~~DES PRPLNT ISOL VLV - FIRE~~
~~HE PRESS/DES START - FIRE~~

3 PRPLNT TEMP/PRESS MON: DES 2&1 29/246
(50°-90° FUEL, 50°-90° OXID/242-253 psi)
HELIUM MON: AMB PRESS (200-1110 psi)
SUPRCRIT PRESS (610-1070 psi)

LANDING GEAR DEPLOY

1 CB(11) LOGIC PWR A - Open
LDG GEAR DEPLOY - FIRE, tb-gray

2 CB(11) LOGIC PWR A - Close
LDG GEAR DEPLOY - FIRE
MASTER ARM - OFF

DOCKED DPS BURN (MANUAL)

Fig 9

Manual Procedure for mid-course correction (MCC-5)

Pages 29 and 30 of the Apollo 13 LM Contingency Checklist, with improvised Earth-in-the-Window manual procedure read up by Charlie Duke (CapCom) to Jim Lovell (Commander) 100:00 to 100:45 GET. The matching Air-to-Ground transcript and audio archive are also provided.

04 04 21 22	CC	What we're really trying to do is get you in a posture so that when you see the Earth come through the window, you can damp her out and hold - hold the Earth in the window. Proceeding on to the rest of page 29, under "RCS PRESS," scratch the entire three steps as printed. On page 30, scratch step 4 under the "RCS PRESS." Over.
04 04 21 55	CDR	Roger. Under "AGS Activation," well, I included that step on the ASA circuit breaker and we'll do step 1 and 2 under "AGS Activation." But then we'll scratch steps 1, 2, and 3 under "RCS PRESS" and, on page 30, we'll scratch step 4.
04 04 22 12	CC	Affirm. Under "DPS PRESS," step 1, line 1, scratch. Line 4, "DESCENT HELIUM REG 1, talkback barber pole." Under step 2, scratch; step 3, scratch; "LANDING GEAR DEPLOY," scratch. Over.
04 04 22 47	CDR	Okay. Under "DPS PRESS," we'll scratch the first line and we'll have the "DESCENT HELIUM REG, talkback to barber pole." We'll scratch steps 2 and 3, and we'll scratch the "LANDING GEAR DEPLOY."
04 04 23 03	CC	Roger. Now we got, on the back of page 30, Jim, you've got a blank page in your checklist, or should have, and we'd like to add a procedure to get you to burn attitude. Over.
04 04 23 20	CDR	Okay. A procedure to get the burn attitude.

Fig 10

Manual Procedure for mid-course correction (MCC-5)

***Transcript**: Read up by Charlie Duke to Jim Lovell of improvised Earth-in-the-Window manual procedure*

***Audio**: as above, minutes 37 to 40*

Restoring Barbeque Roll

In preparing for the manual MCC-5 docked DPS burn, the flight directors at Mission Control were challenged further with how to rectify the rotation of the two docked crafts following engine shutdown. Passive Thermal Control (PTC) was the term used to describe how the spaceship would be controlled in a steady 'barbeque roll' of 0.3° per second, thereby distributing the heating and cooling effects of the sun and space across the ship's full exterior. As Gene Kranz explained in a press conference at the time: "*Our primary concern in modifying these checklists was to use minimum power…At around 75 hours [GET] we got into a relatively long discussion about Passive Thermal Control [PTC]…. We came through with a relatively detailed Checklist update".*

The update referred to by Kranz was an improvised manual procedure for returning the craft to a steady longitudinal rotation. The procedure can be seen written out by hand in full on page 34 of the Apollo 13 LM Contingency Checklist. It was read up to the crew by Charlie Duke Control to Jim Lovell at 100:38:51 GET. The supporting Air-to-Ground transcript and audio archive are also provided (Fig 11 and Fig 12).

Note the annotations towards the top of page 34. These are the final set of procedures read up for the mid-course correction (MCC-5) manual burn, and, along with the associated transcript and audio archive, are the historic version of the more dramatic dialogue when, in the film Apollo 13, Tom Hanks smashes the 'Stop' button shouting "*shutdown*".

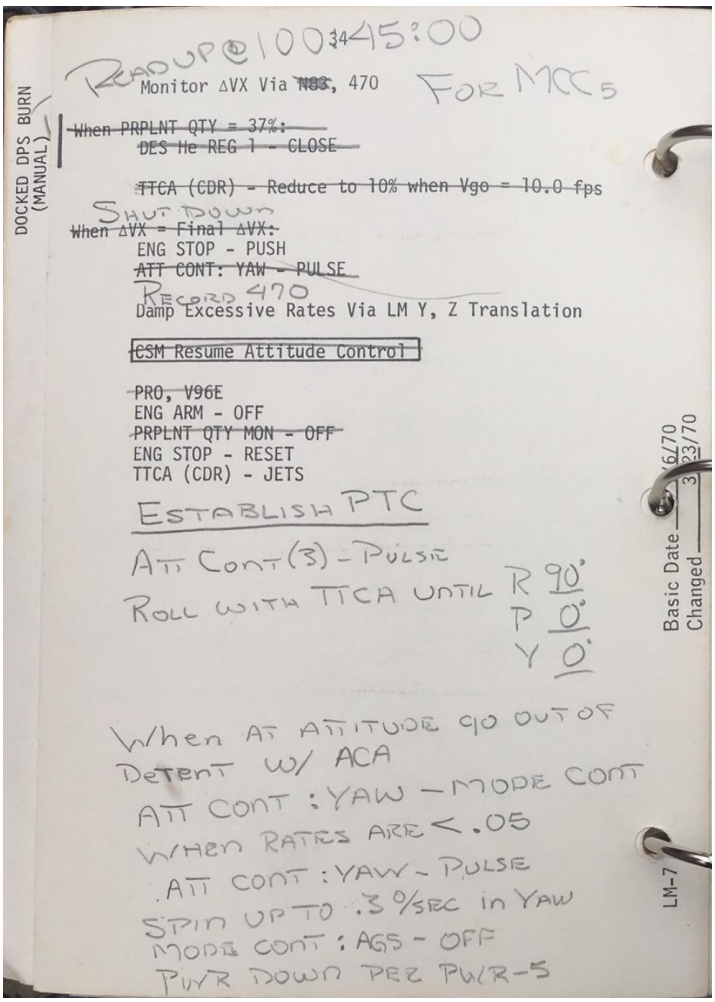


Fig 11
Manual Procedure for re-establishing PTC (MCC-5)

Page 34 of the Apollo 13 LM Contingency Checklist, with hand-written manual procedure to return the spacecraft to Passive Thermal Control ('Barbeque Roll) following the Earth-in-the-Window corse correction. Read up by Charlie Duke to Jim Lovell 100:45 GET.

04 04 38 51	CC	Roger. Now, at the bottom of that page, I have a procedure for you to reestablish PTC. Over.
04 04 39 30	CDR	To reestablish PTC. Go ahead.
04 04 39 33	CC	Okay. First line, "ATTITUDE CONTROL, three to PULSE"; line 2, "Roll with the TTCA until attitude is roll, plus or minus 90; pitch, 0; yaw, 0." Over.
04 04 40 39	CDR	Okay. Step 1, "ATTITUDE CONTROL, three to PULSE"; 2, "Roll with the TTCA ... pitch is 0 and yaw is 0," and I think that will be on the AGS ball.
04 04 40 56	CC	That's affirmative. You broke up there for a minute, Jim. We'll do that on the AGS ball from the burn attitude. We just want you to roll either way 90 degrees, keep pitch 0 and yaw 0. Now, step 3; "When at - when at attitude, ACA out of detent." Step 4; "ATTITUDE CONTROL: YAW, to MODE CONTROL. When rates are less than 0.05, ATTITUDE CONTROL: YAW, to PULSE."
04 04 41 52	CDR	Okay, Charlie. Can you hold up here a second? I lost you.
04 04 41 55	CC	Roger.
04 04 42 00	CDR	Start with step 3 again. "When attitude - When at attitude, ACA out of detent."
04 04 42 09	CC	That's Roger. Next step, step 4: "ATTITUDE CONTROL to YAW" - Correction, "ATTITUDE CONTROL: YAW, to MODE CONTROL." Over.
04 04 42 33	CDR	Okay. Step 4 is "ATTITUDE CONTROL: YAW, to MODE CONTROL."
04 04 42 37	CC	Roger. Step 5: "When rates are less than 0.05 degrees per second, ATTITUDE CONTROL: YAW, to PULSE."
04 04 43 08	CDR	Okay. "When rates are less than 0.05 degrees per second, ATTITUDE CONTROL: YAW, to PULSE."
04 04 43 16	CC	Roger. Step 6: "Spin up to 0.3 degree per second in yaw," and that takes about 21 pulses. Step 7 - Yes.
04 04 43 49	CDR	Okay. Go ahead.
04 04 43 51	CC	Okay. Step 7: "MODE CONTROL, AGS, OFF."
04 04 44 09	CDR	Okay. Step 6 was "Spin up to 0.3 degrees per second in yaw"; that's about 21 pulses. Step 7 was "MODE CONTROL, AGS, to OFF."
04 04 44 19	CC	That's affirm. Step 8: "Power down per power" - Correction, "Power down per contingency checklist page Power 5." Over.
04 04 44 46	CDR	Okay. And step 8 is Power down per contingency checklist Power 5," and I take it that's been revamped considering our situation. Okay.

Fig 12

Manual Procedure for re-establishing PTC (MCC-5)

***Transcript**: Read up by Charlie Duke to Jim Lovell of manual procedure to return the spacecraft to Passive Thermal Control*

***Audio**: as above, minutes 55 to 60*

Risk Assessment and Apollo 13

Much has been written of the approach to risk assessment that guided key decisions to rescue Apollo 13. The mission has been acclaimed as introducing a new approach to risk management, termed Failure Modes and Effects Analysis (FMEA). The improvised procedures annotated in Charlie Duke's Apollo 13 LM Contingency Checklist provides a record of this development in the field of risk management, and how it was applied during the crisis that was Apollo 13.

In summary, two core risk management principles were at work. First, risks were resolved only when the combination of probability and severity of a risk identified it as mission-critical (ie the risk, or combination of risks, were key limiting factors to the safe recovery of the crew); and secondly, the choice of risk mitigate measure was optimised to preserve, where possible, redundancy in the ship's systems to address other risks as these subsequently escalated to become mission-critical.

In Jim Lovell's book 'Apollo 13', the playing out of these principles is illustrated starkly in the unprecedented meeting between the operational flight teams and NASA senior administrators, hurriedly convened to select which procedural option to adopt for the mission-critical PC+2 DPS burn. Lovell describes the meeting, which took place in the glass-walled VIP meeting room at Mission Control, a few hours before the spacecraft disappeared behind the moon:

> "[Chris] *Kraft wasted little time getting things started. 'In about twelve hours' he began, we're going to need to execute our PC+2 burn'…..*[Gold Team Director, Gerald] *Griffen stepped forward….and began to describe the procedure* [options]… *Get back to Earth quickly enough, and the problems with all the other consumables will take care of themselves*. *The obvious answer, then, was to burn the LEM's decent engine at full throttle for as long as the fuel supply would allow, increasing the ship's velocity until it could be increased no more. But the obvious answer was not necessarily the best answer. Burning the engine until it ran dry would leave almost no fuel for subsequent mid-course correction*…[and] *this superfast…go-for-broke maneuver… would* [require] *jettison* [of] *the now useless service module*…[which was] *protecting the heatshield"….The* [third] *option was the slowest... fire Aquarius's descent engine for only four and a half minutes, and only part of the time at full throttle…aim[ing] the crew in the friendly Pacific…but [taking] a day longer than necessary. Kraft and his directors let the arguments play out and watched satisfied as the men in the room settled on the slowest alternative"* (p219).

In all, three docked DPS burns were executed in accordance with these risk management principles: (i) the MCC-2 burn to place the docked crafts back on a free-return trajectory; (ii) the Trans-earth injection PC+2 burn to accelerate the return to Earth by ten hours and shift the landing zone from the Indian to the Pacific ocean; and (iii) the manual MCC-5 burn to fine-tune re-entry into Earth's atmosphere, which, by using the Earth and Sun as reference points to control attitude and re-establish PTC, saved power critical for the subsequent rebooting of the command module electrical systems.

This redundancy approach to risk management proved effective. Command module Odyssey splashed down on April 17, 1970 in the Pacific Ocean. All three crew members had survived.

End Note

In addition to the flown Apollo 9 and mission control Apollo 13 checklists, the private collection includes other historic artefacts from the Apollo 13 mission, including internal NASA memos on the dangerous decline in adequacy of water, electricity and oxygen consumables following the oxygen tank explosion; part of the splashdown parachute; evidence of a mission by the US Atomic Energy Commission to determine the risk of radiation in the atmosphere south of the Fifi islands from the plutonium fuel capsule, which was attached to the lunar module as it disintegrated in the Earth's atmosphere; and part of the stowage assembly netting from the lunar module Aquarius aft bulkhead. The netting is referenced in a letter of provenance by Fred Haise, when describing the moments just before jettisoning the lunar module prior to Earth entry: "*I did the best I could in a short time to retrieve the items that were easily moveable. For example ....the hand controller arm rests (one removed while Jim was still using the hand controller)...and all the inner netting material. I don't think Jim liked the pinging noise as I pulled loose the metal snaps holding the material to the outer wall".*

The full collection is on-line at: www.apollomissionartefacts.com, or QR scan below. An exhibition of these Apollo 13 historic artefacts, accompanied by talks and personal reflections from those who witnessed the drama, will run from x to x at the xxx Art Gallery, Henley-on-Thames in April 2020.