Development and Evaluation of Space Shuttle Cockpit Displays

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Human Factors Symposium at NASA Ames Research Center

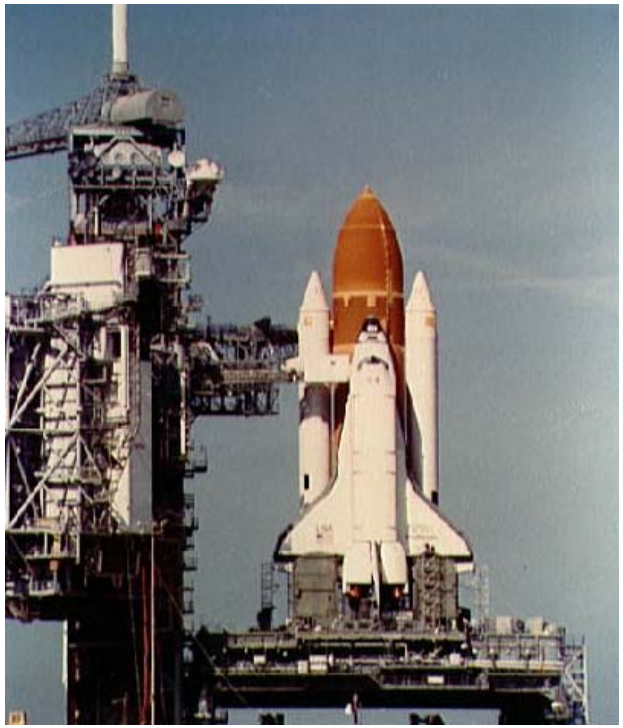
October 20, 2004

The Space Shuttle Cockpit Avionics Upgrade (CAU) Project is based at NASA Johnson Space Center with support from other organizations such as NASA Ames Research Center.

Space Shuttle images are credited to NASA.

Background

Overview

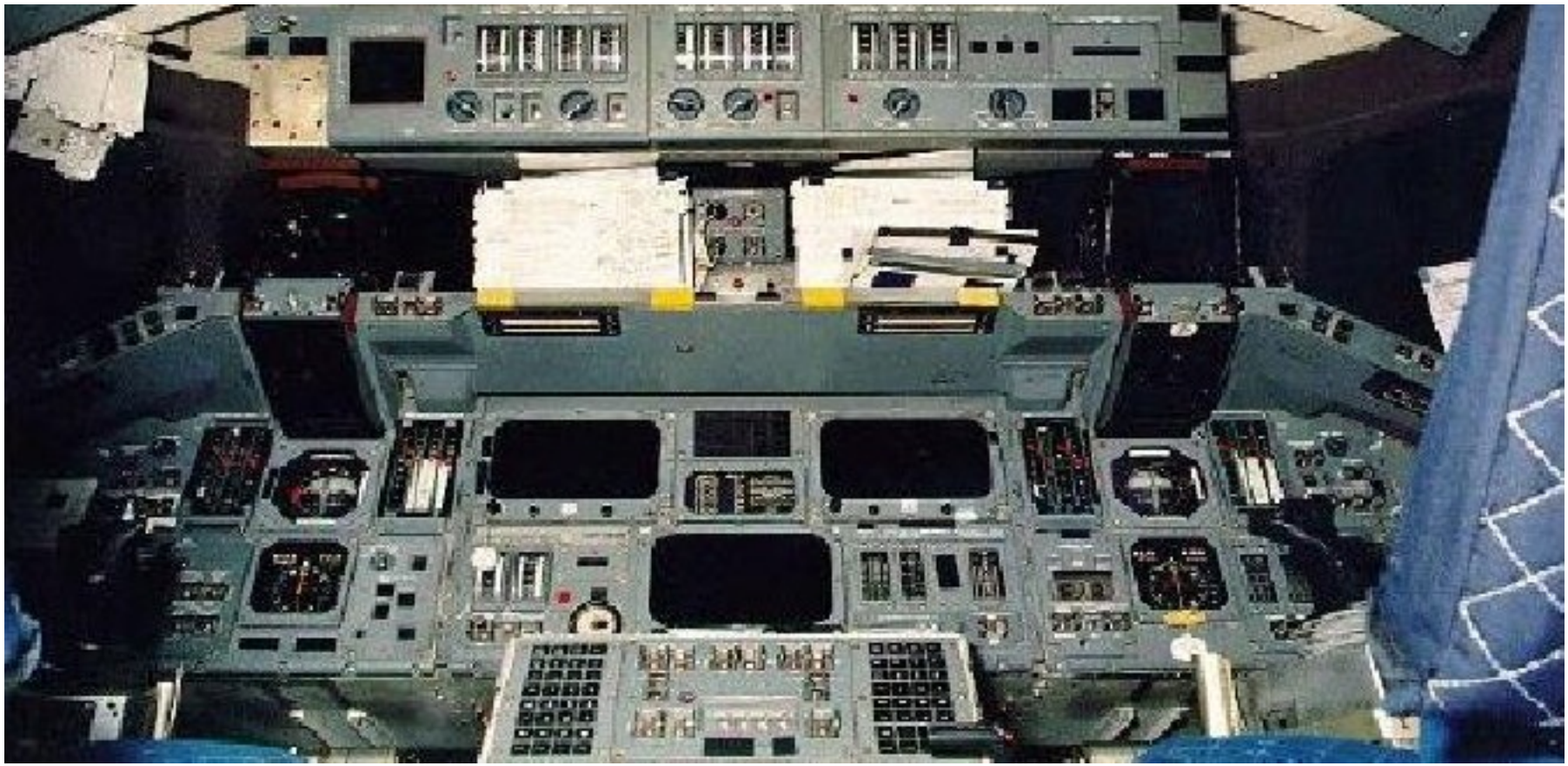


Arguably the most complex flying machine ever

- Launch rocket for 8½ minutes
- Orbital spacecraft for approximately 2 weeks
- Hypersonic plane for an hour
- Subsonic glider for about 5 minutes

Original Shuttle Cockpit (1981)

Multifunction CRT Display System (MCDS)



Original Shuttle Cockpit (1981)

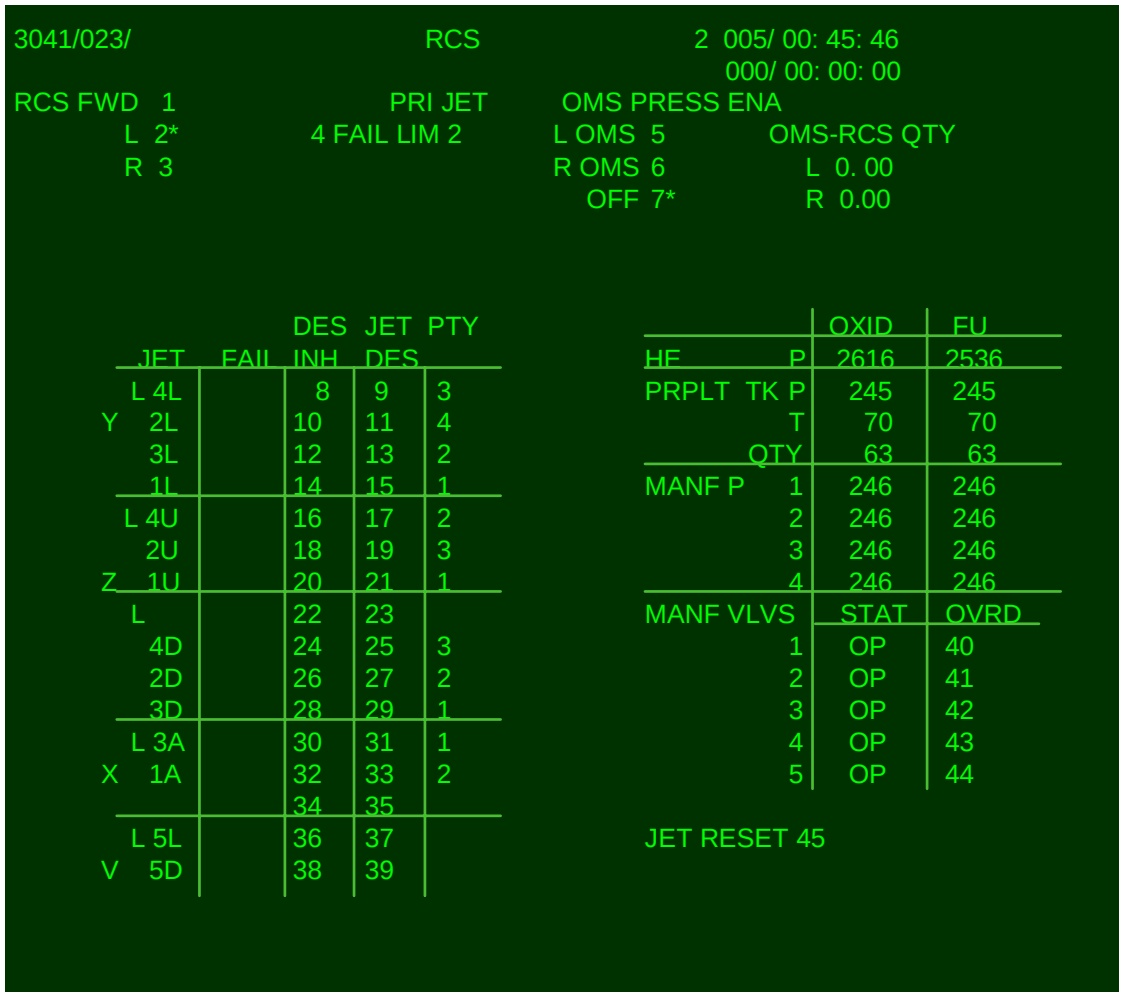
Multifunction CRT Display System (MCDS)

Drawbacks:

- Some gauges are needed only for a brief portion of the mission.
- Only three CRTs are available in the forward section to show display formats.

Original Shuttle Cockpit (1981)

Multifunction CRT Display System (MCDS)

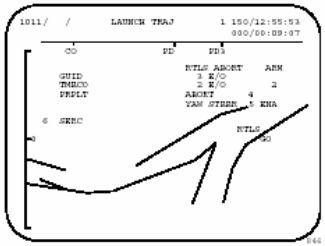


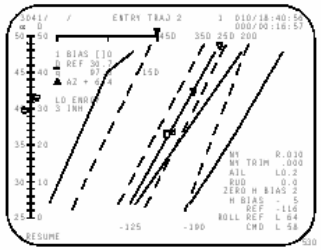
Drawbacks:

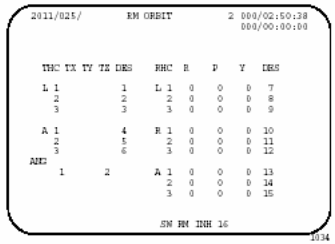
- Information is monochrome text.
- Information is not well consolidated.
- Each display title must be memorized according to its number. (Example: This is a SPEC 23.)

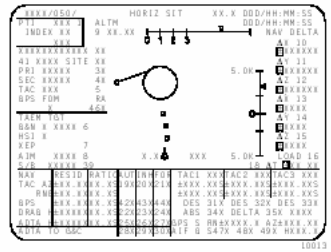
Original Shuttle Cockpit (1981)

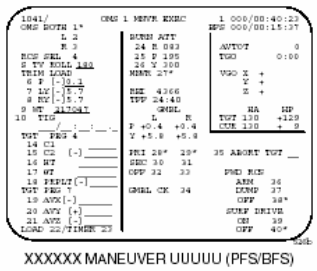
Multifunction CRT Display System (MCDS)

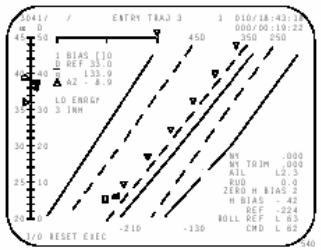

xxxxxx TRAJECTORY

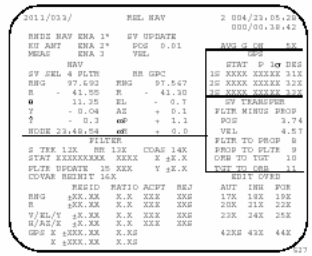

ENTRY TRAJECTORY 2

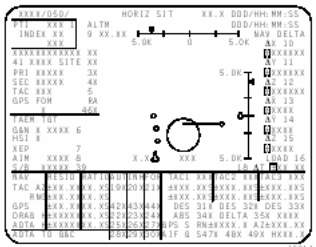

REDUNDANCY MGMT ORBIT

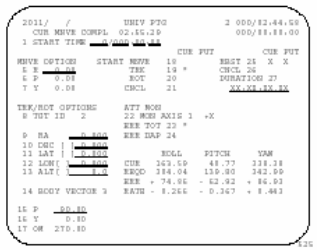

HORIZONTAL SITUATION (IN-LEFT)

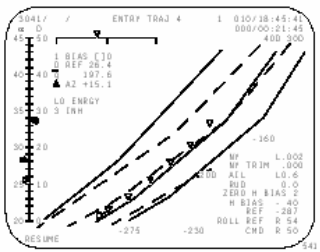

XXXXXX MANEUVER UUUUU (PFS/BFS)

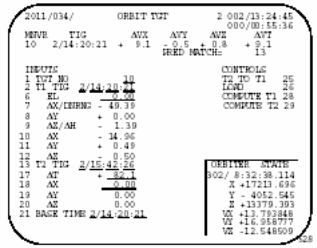

ENTRY TRAJECTORY 3

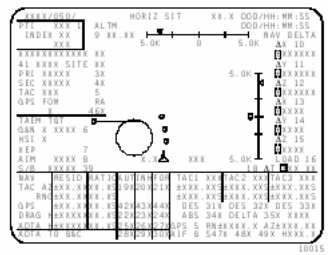

RELATIVE NAVIGATION

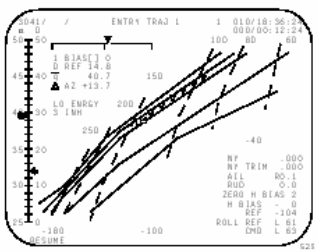

HORIZONTAL SITUATION (OUT-RIGHT)

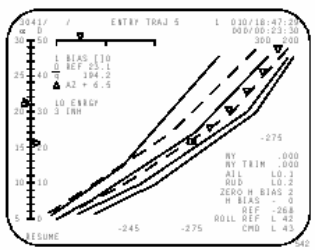

UNIVERSAL POINTING

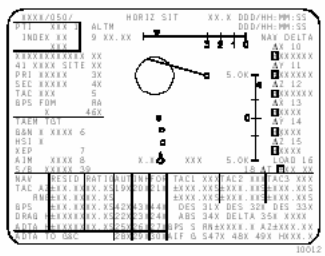

ENTRY TRAJECTORY 4

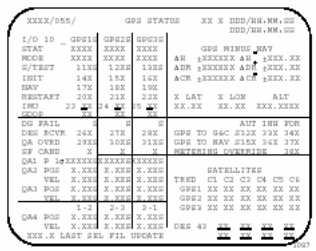

ORBIT TARGETING


HORIZONTAL SITUATION (OUT-LEFT)


ENTRY TRAJECTORY 1


ENTRY TRAJECTORY 5


HORIZONTAL SITUATION (IN-RIGHT)


GPS STATUS

In 1981 ...

The five onboard computers had 128K of RAM.

IBM PC had 64K RAM.

Windows

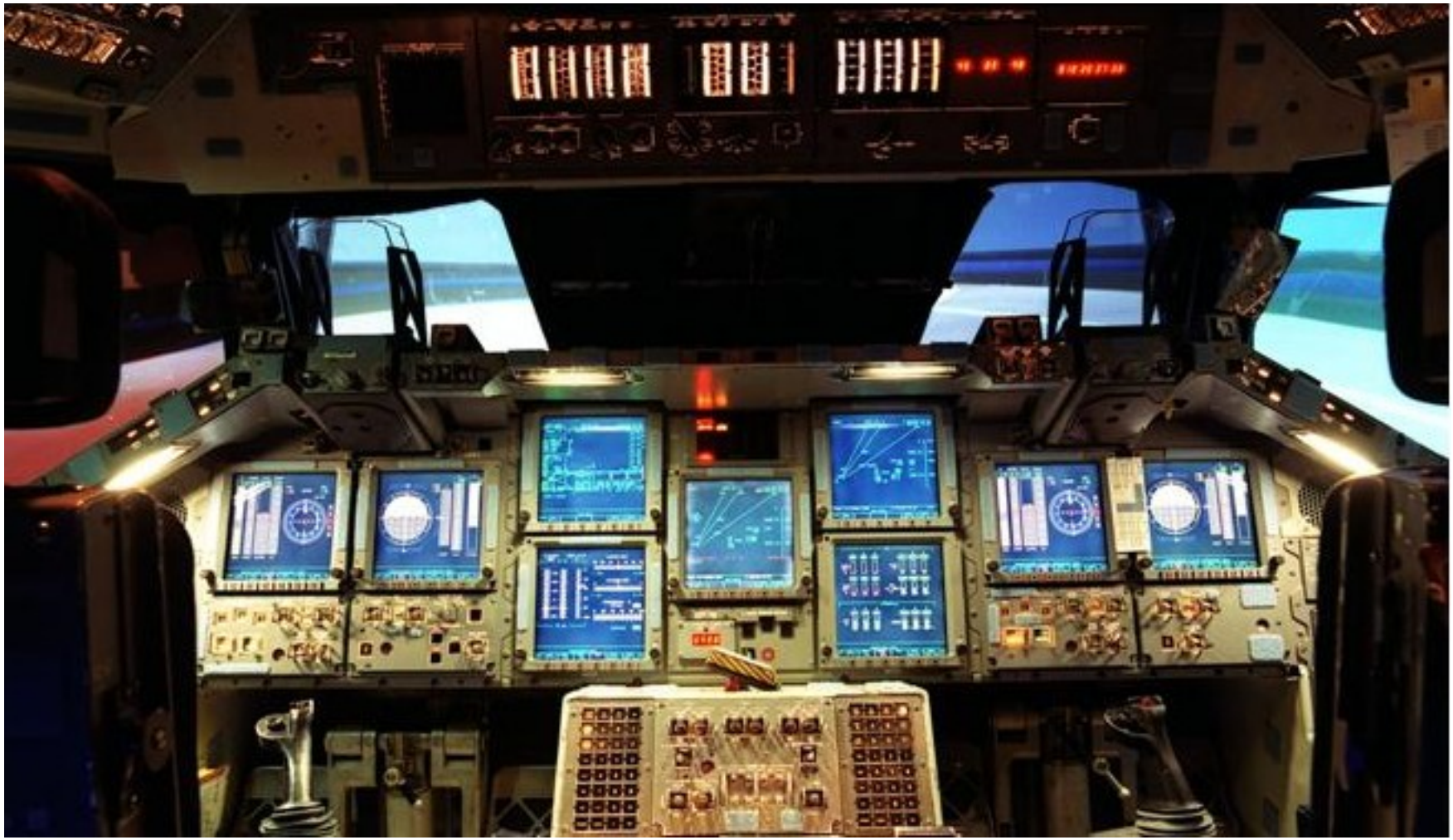
An exception 06 has occured at 0028:C11B3ADC in VxD DiskTSD(03) + 00001660. This was called from 0028:C11B40C8 in VxD voltrack(04) + 00000000. It may be possible to continue normally.

* Press any key to attempt to continue.
* Press CTRL+ALT+RESET to restart your computer. You will lose any unsaved information in all applications.

Press any key to continue

Current Shuttle Cockpit (2000)

Multifunction Electronic Display System (MEDS)



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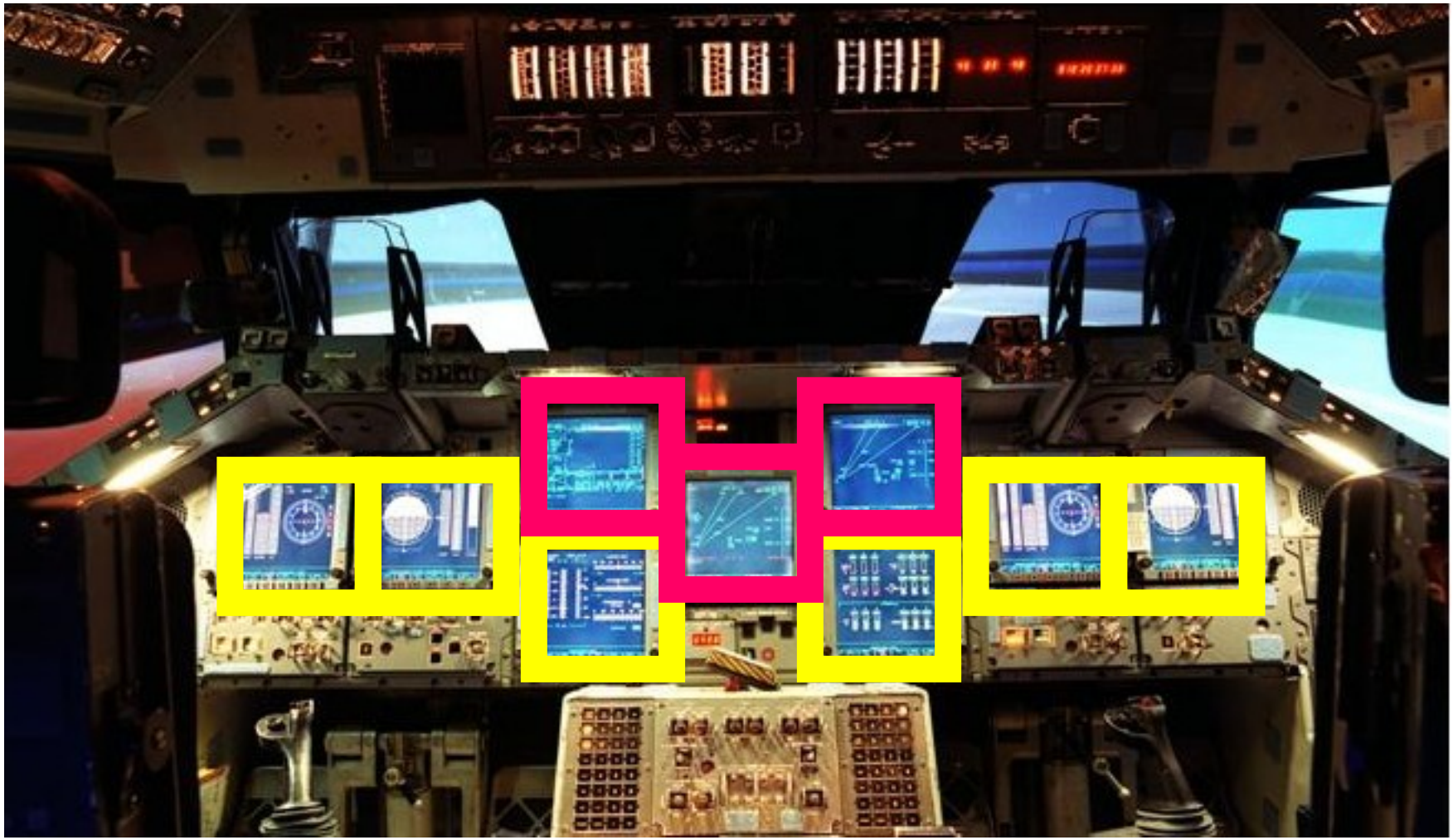

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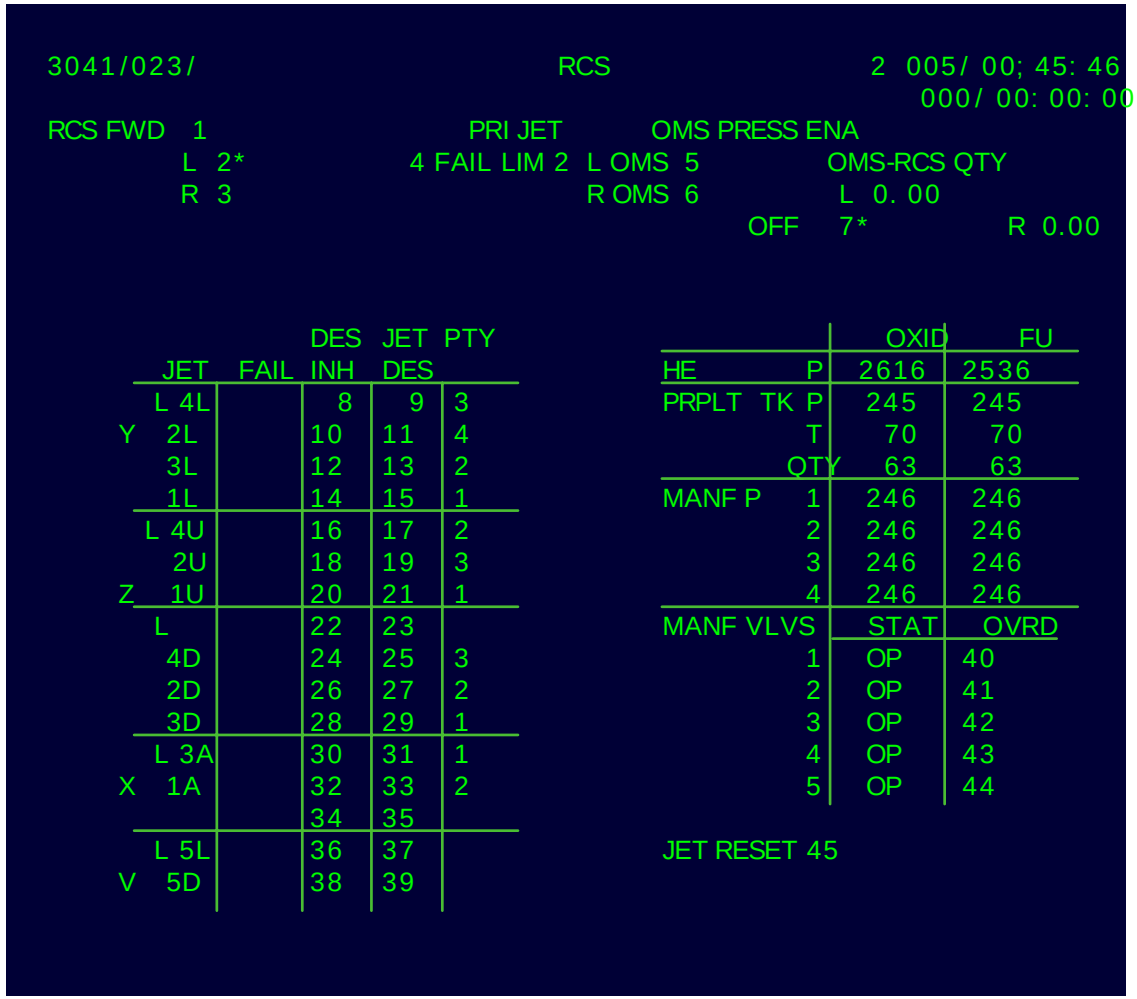

Resolving Malfunctions in the Current Cockpit

Example: Electrical Sub-Bus Failure

```
1021/     /099        FAULT                    5  000/00:01:55
                                              BFS  000/00:00:00
 CRT        FAULT                C/W    GPC        TIME
 ID
      MPS  LH2/LO2  ULL          *      5      000/00:01:50
 SM2  APU  SPD  LO  2            *      5      000/00:01:50
 SM0  THRM APU                         5      000/00:01:50
```

Resolving Malfunctions in the Current Cockpit

Example: Electrical Sub-Bus Failure

```
1021/   /018    GNC SYS SUMM 1        5 000/00:02:00
                                    BFS 000/00:00:00

    SURF       POS   MDM          DPS    1 2 3 4
    L OB                          MDM FF
      IB                              FA
    R IB                              PL
      OB
     AIL
     RUD                          FCS CH 1 2 3 4
     SPD BRK
     BDY FLP
MPS                L      C      R   NAV  1 2 3 4
HE TK P          3280   3230   3240   IMU
  REG P A         784    768    768   TAC
        B         776    766    770   ADTA
  dP/dT            10     10     10    MPS PNEU HE P
ULL P LH2        31.5   31.7   12.0↓        TK   4250
     LO2         21.1   21.0    0.0         REG   748
                                            ACUM  740
GH2 OUT P        3400   3358   3425   MANF P LH2   30
GO2 OUT T         420    418    427          LO2   60
```

Resolving Malfunctions in the Current Cockpit

Example: Electrical Sub-Bus Failure

```
 0001/   /079      SM SYS SUMM 2      5 000/00:02:30
                                   BFS 000/00:00:00
  CRYO TK    1      2      3      4      5   MANF1 MANF2
H2 PRESS   208    208    206    206    206    208   207
O2 PRESS   816    815    814    814    814    815   815
HTR T1    -248   -248   -248   -248   -248
    T2    -248   -248   -248   -248   -248
```

```
  APU       1      2      3     HYD     1      2      3
TEMP EGT  942    942    942   PRESS  3064   3064   3064
 B/U EGT  942    942    942   ACUM P 3080   3080   3080
 OIL  IN  250    250    250   RSVR T  116    153    142
     OUT  264    264    264
 GG BED   511H   511H     0L    QTY    72     74     71
 INJ     1271   1271   1271
SPEED  %   99      0L   101    W/B
FUEL QTY   59     60     62   H2O QTY  78     73     78
 PMP LK P  14     14     14   BYP VLV BYP    BYP    BYP
OIL OUT P  42     42     41
FU TK VLV
      A T  63     65     62    THERM CNTL    1     28
      B T  63     65     62   H2O PUMP P     23     63
  AV BAY   1      2      3   FREON FLOW   2384   2384
TEMP       97     97     83   EVAP OUT T     38     38
FAN ΔP   3.45   3.46   3.39
```

It is far better to adapt the technology to the user than to force the user to adapt to the technology.

- Larry Marine

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- Larry Marine

The Cockpit Avionics Upgrade

NASA Johnson Space Center

Proposed Shuttle Cockpit (2006)

Command and Data Processor System (CDPS)

Goal: Develop new display formats with:

- Consolidated information
- A better use of graphics
- A better use color

The anticipated benefits are:

- An increase in the crew's situational awareness
- A reduction in the crew's workload
- An improvement in the crew's performance

Solution: Team Effort in Designing Display Formats

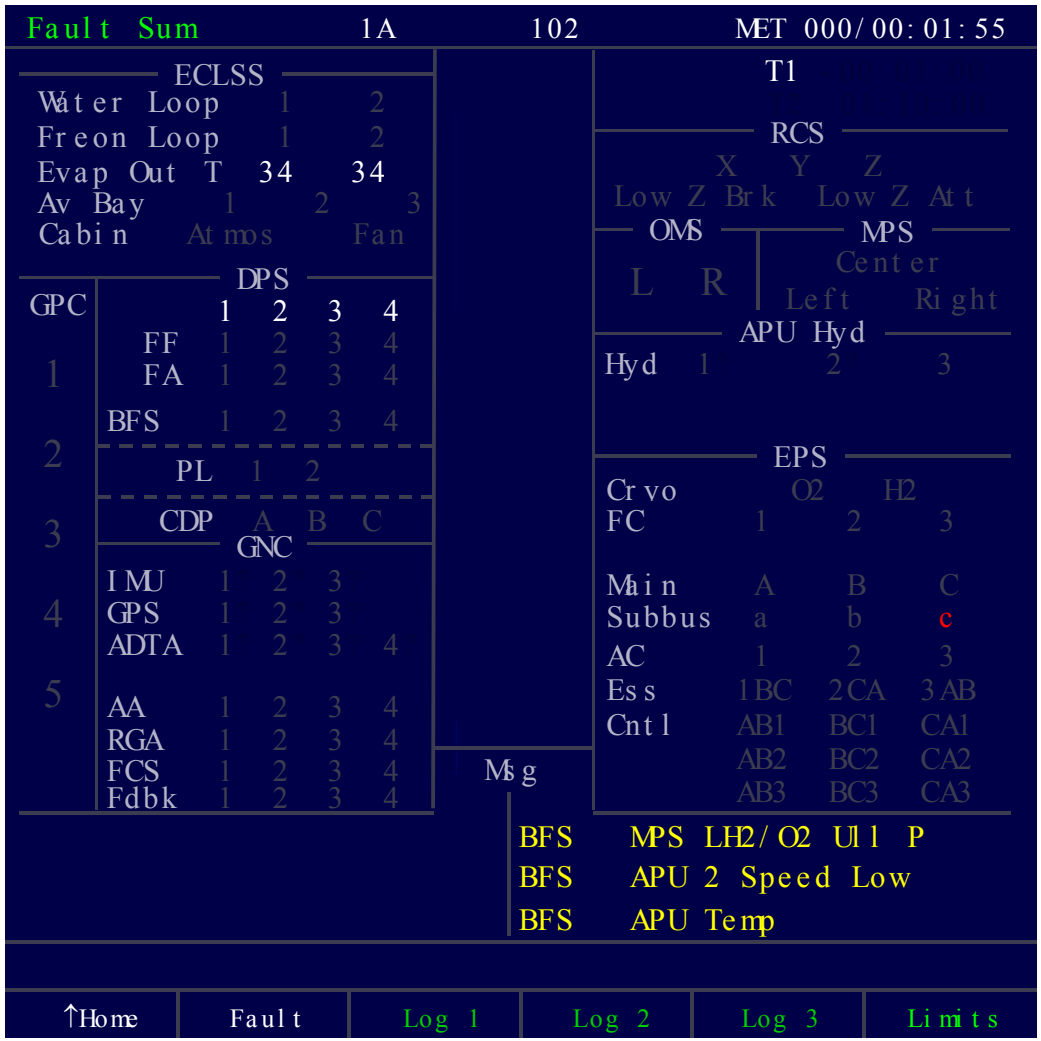
- Teams are assigned to each of the ~70 display formats.
- Each team typically has 5-10 people:
  - 1-2 astronauts
  - 1-2 engineers
  - 1-2 astronaut trainers
  - 1-2 Mission Control representatives
  - 1-2 human factors scientists
- Teams generally met 1-2 times per month for several months from 1999-2003.

You can use an eraser at the drafting table or a sledge hammer at the construction site.

- Frank Lloyd Wright

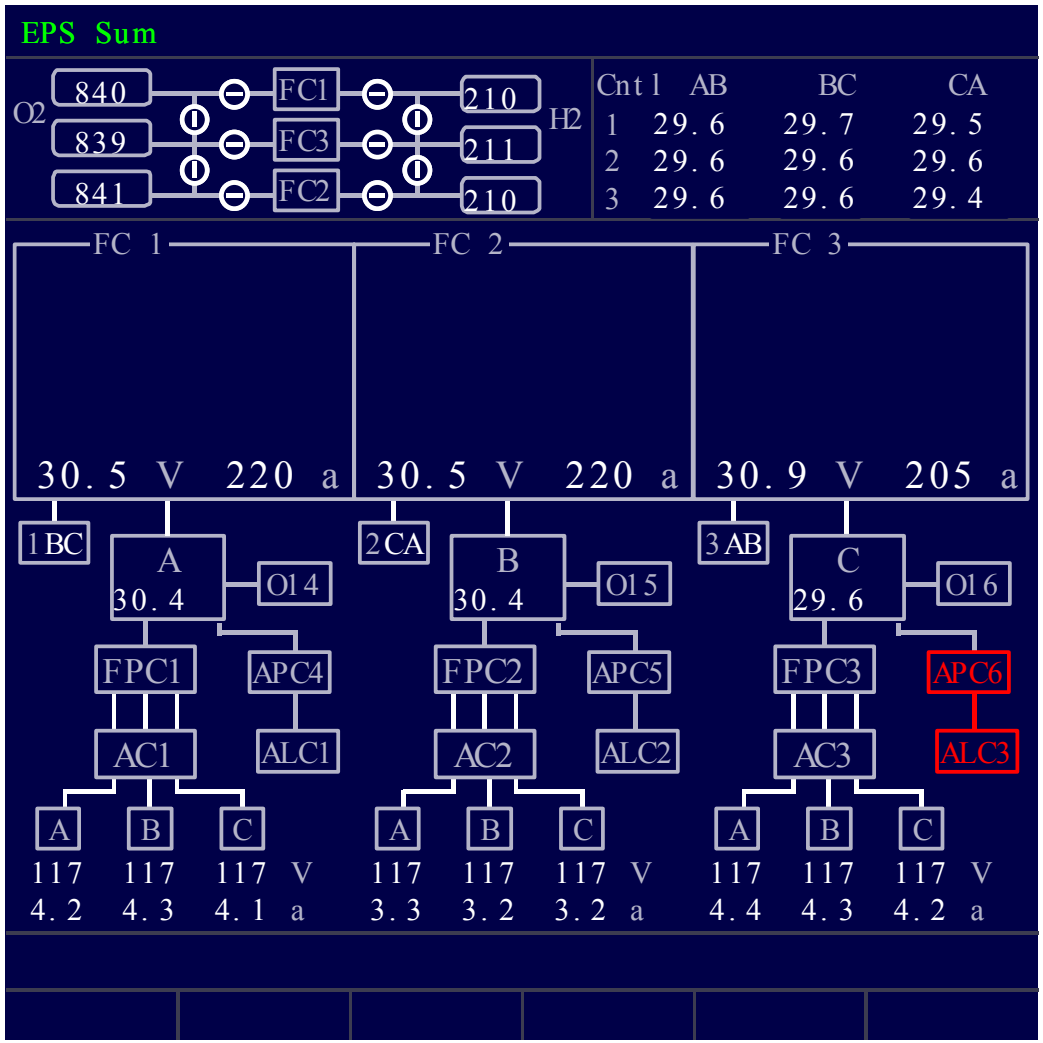
Resolving Malfunctions in the Proposed Upgraded Cockpit

Example: Electrical Sub-Bus Failure



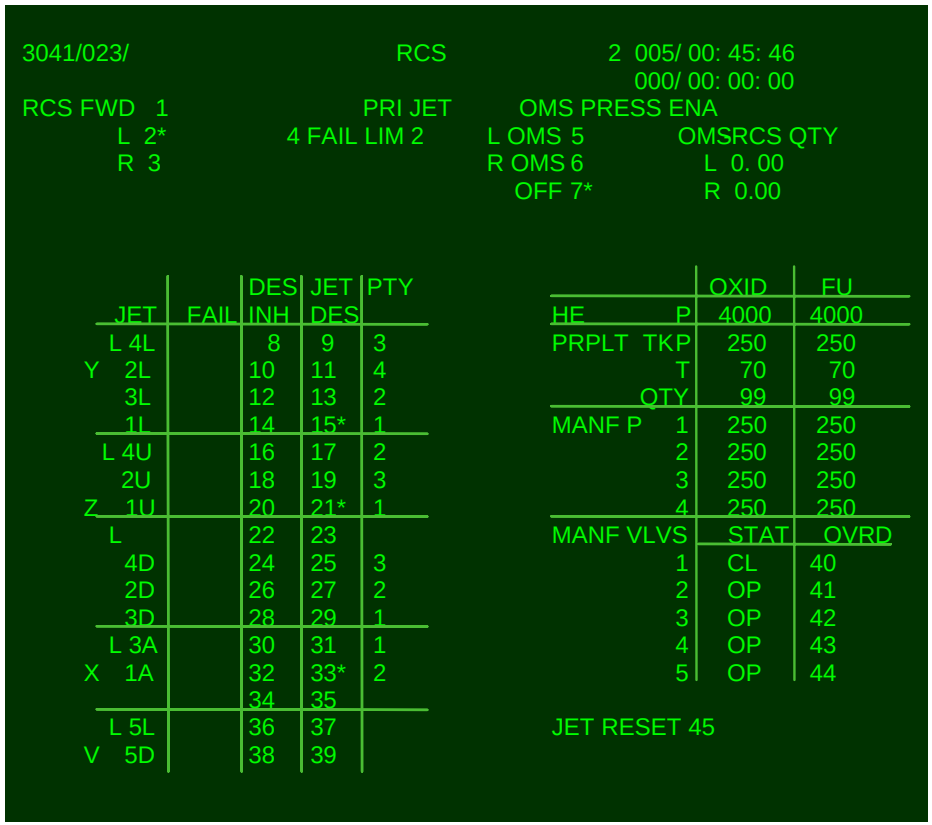
Resolving Malfunctions in the Proposed Upgraded Cockpit

Example: Electrical Sub-Bus Failure

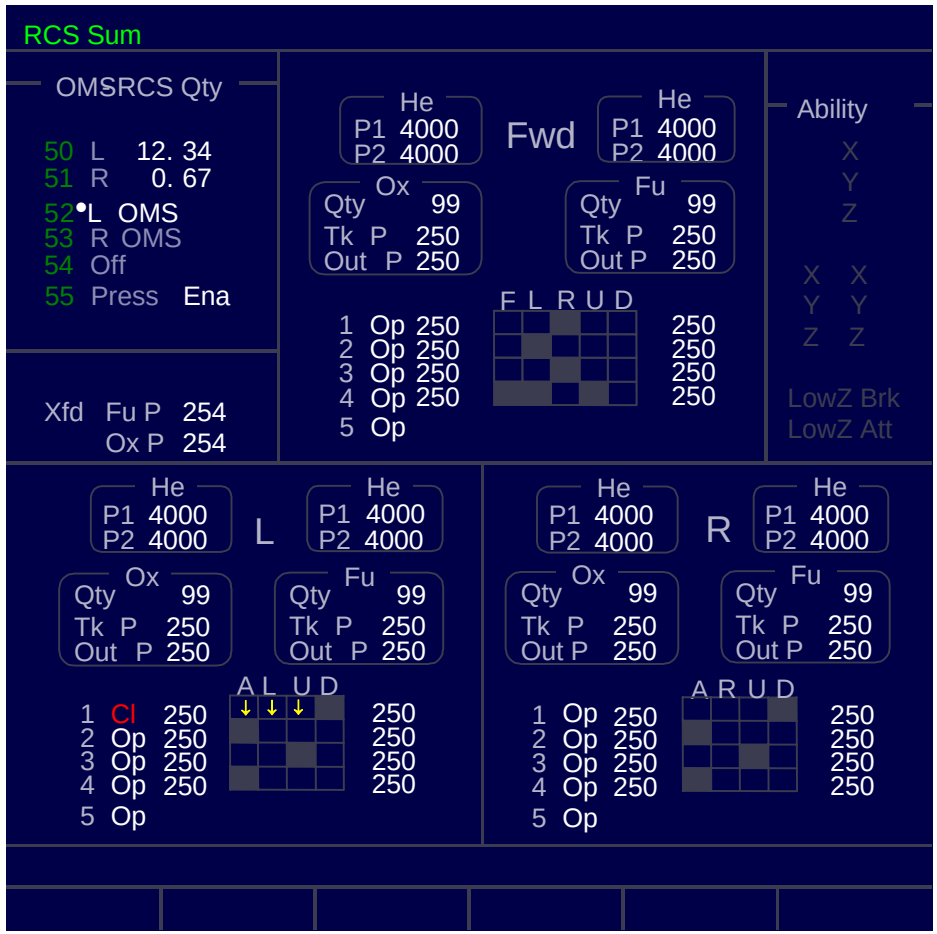


Comparison of Reaction Control System (RCS) Display Formats

Current RCS Display



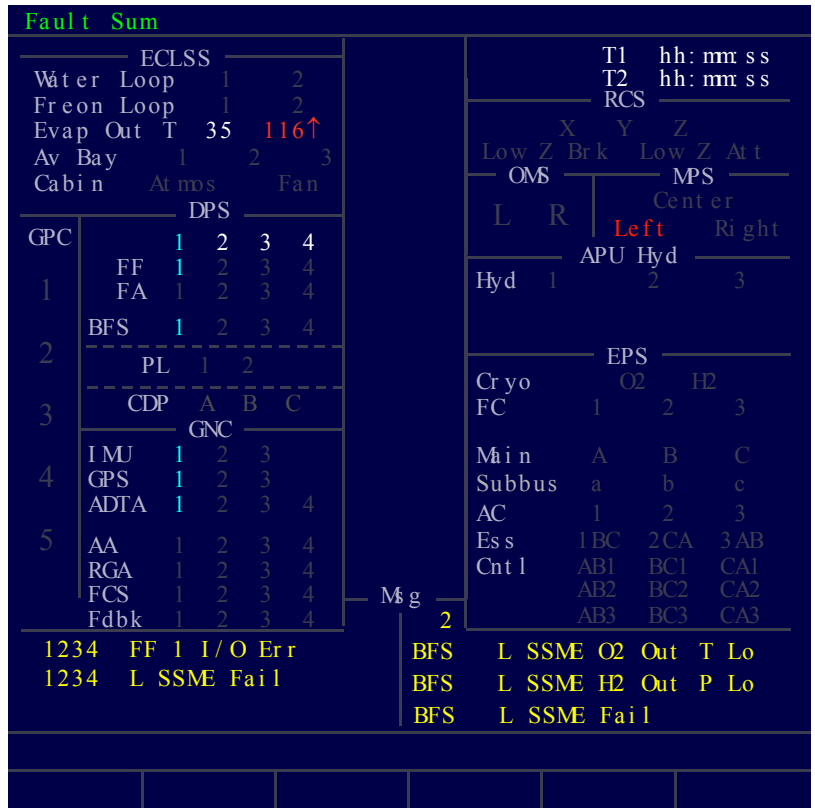
Proposed RCS Display



Comparison of Fault Summary Display Formats

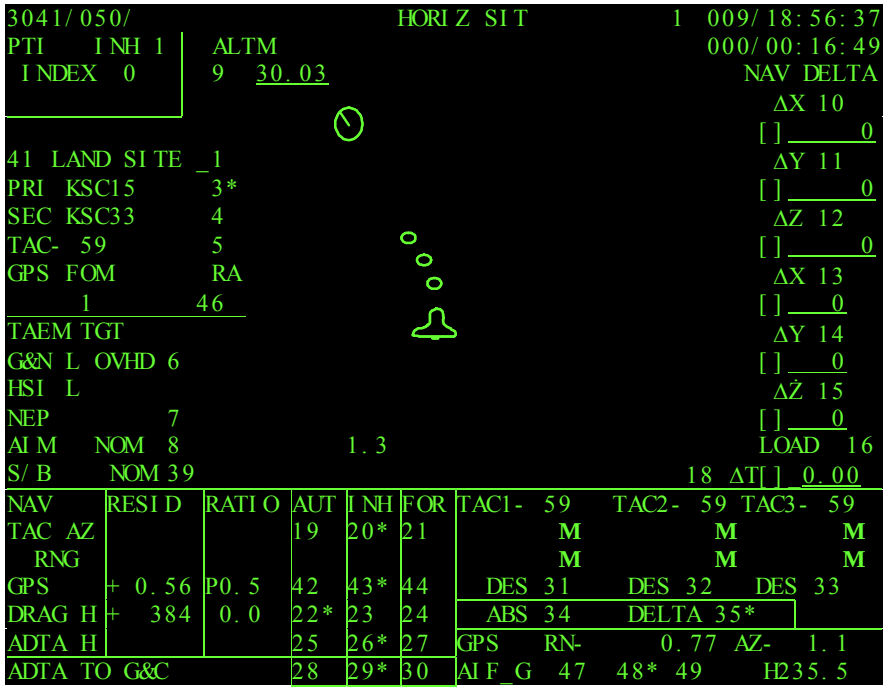
Current Fault Sum Display

Proposed Fault Sum Display

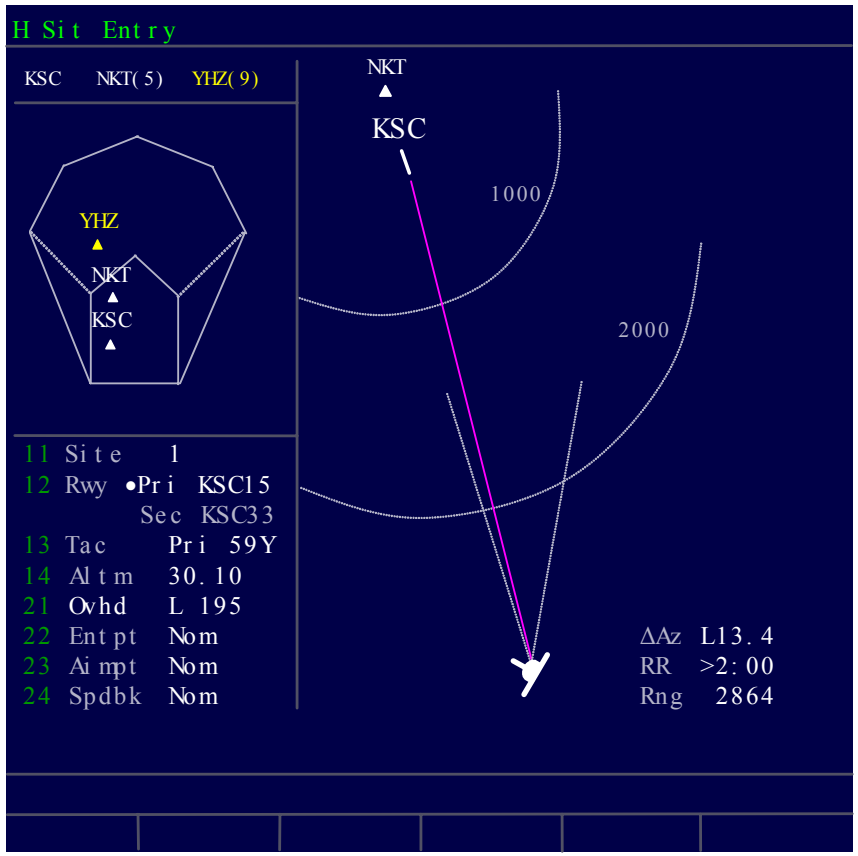


Comparison of Entry Trajectory Display Formats

Current Horiz Sit Display



Proposed Horiz Sit Display



Display Evaluation

Evaluation Methodology

Crews

- 6 crews of 3 members each.

Location

- Motion-based Shuttle Mission Simulator (SMS)

Timeframe

- Baseline evaluation was conducted over October-December, 2003.
- CAU evaluation was conducted over August-September, 2004.

Training

- Baseline display training occurred over the past 4-9 years (depending on each crew-member).
- CAU training lasted only several weeks.
    - Classroom training was 20 hours.
    - DST (Dynamic Skills Trainer) was 5 hours.
    - CAU display familiarization in the SMS was 10 hours.

Location

Shuttle Mission Simulator at NASA Johnson Space Center

Data

Two classes of data were obtained:

Objective data are externally-verifiable with a definitive correct or incorrect answer. An example is whether a crewmember knew which fuel cell had failed.

Subjective data are based on opinion with no correct or incorrect answer. An example is the crew rating (on a 1-10 scale) of his/her awareness of the fuel cell malfunction.

Minimum Success Criteria Overview

1) Increased situation awareness
    a) 100% improvement in trajectory monitoring.
    b) 50% improvement in monitoring DPS, EPS, MPS, OMS
    c) 20% improvement in monitoring APU/Hyd, Control, ECLSS, RCS, Nav systems
2) Reduced workload
3) Improved performance
    a) Reduced failure recognition time
    b) Reduced error rate (increased response accuracy)
    c) Reduced keystrokes

Minimum Success Criterion #1a: Monitoring trajectory

Goal: 100% improvement
Actual: 240% improvement (objectively) and 160% (subjectively)

		Baseline	**CAU**	**Improvement**
Objective results	Percentage answered correctly (out of 87 questions asked)	22%	76%	240% (76-22)/22
Subjective results	Subjective rating (1-10 SA scale) of trajectory-related issues such as aileron trim	3.2	8.3	160% (8.3-3.2)/3.2

Minimum success criterion is met with more than 99% confidence (based on a statistical two-sample test for means).

Minimum Success Criterion #1b: Monitoring DPS, EPS, MPS, OMS

Goal: 50% improvement
Actual: 75% improvement (objectively) and 132% (subjectively)

		Baseline	**CAU**	**Improvement**
Objective results	Percentage answered correctly (out of 300 questions asked)	42%	72%	75% (72-42)/42
Subjective results	Subjective rating (1-10 SA scale) of critical systems such as MPS	3.6	8.3	132% (8.3-3.6)/3.6

Minimum success criterion is met with more than 98% confidence (based on a statistical two-sample test for means).

Minimum Success Criterion #1c: Monitoring APU/Hyd, Control, ECLSS, RCS, Nav

Goal: 20% improvement
Actual: 235% improvement (objectively) and 119% (subjectively)

		Baseline	**CAU**	**Improvement**
Objective results	Percentage answered correctly (out of 183 questions asked)	21%	69%	235% (69-21)/21
Subjective results	Subjective rating (1-10 SA scale) of non-critical systems such as RCS	3.7	8.1	119% (8.1-3.7)/3.7

Minimum success criterion is met with more than 99% confidence (based on a statistical two-sample test for means).

Minimum Success Criterion #2: Workload (Bedford Scale)

Goal: Reduction in workload
Actual results: 46% reduction

		Baseline	**CAU**	**Reduction**
Subjective results	Subjective rating (1-10 Bedford scale)	6.6	3.6	46% (6.6-3.6)/6.6

Minimum success criterion is met with more than 99% confidence (based on a Student's paired two-sample test for means).

Minimum Success Criterion #2: Workload (NASA Task Load Index)

	Baseline	CAU	Reduction
Mental demand	7.4	3.9	47%
Physical demand	3.3	1.7	48%
Temporal demand	7.2	3.5	51%
Effort	7.1	3.6	49%
Frustration	7.0	2.8	60%
Weighted average	**6.7**	**3.3**	**51%**

Minimum Success Criterion #3a: Unidentified malfunctions

Goal: Reduction in unidentified malfunctions
Actual results: 67% reduction in the percentage of unidentified malfunctions

		Baseline	**CAU**	**Reduction**
Objective results	Percentage of unidentified malfunctions (out of 517 total)	30%	10%	67% (30-10)/30

All six crews produced a reduction in unidentified malfunctions.

Minimum Success Criterion #3a (continued): Recognition time

Goal: Reduction in recognition time
Actual results: 12 second reduction in recognition time

Quartile	**Description**	**Baseline Mean Recognition Time**	**CAU Mean Recognition Time**	**Diff**
Top quartile (fastest recognition times)	88 baseline recognitions occurred between 3 to 15 seconds after malfunction	11 seconds	14 seconds	+3 sec
Second quartile	87 baseline recognitions occurred between 15 to 27 seconds after malfunction	21 seconds	18 seconds	-3 sec
Third quartile	88 baseline recognitions occurred between 27 to 48 seconds after malfunction	36 seconds	29 seconds	-7 sec
Fourth quartile (slowest recognition times)	87 baseline recognitions occurred between 49 to 417 seconds after malfunction	116 seconds	76 seconds	-40 sec
Overall	**Overall**	**45 seconds**	**33 seconds**	**-12 sec**

Minimum Success Criterion #3b: Procedural errors

Goal: Reduction in procedural errors

	Baseline	**CAU**	**Reduction**
Percentage of malfunctions in which the crew failed to initiate the correct procedure	19%	10%	49% (19-10)/19
Percentage of procedures containing at least one error	22%	14%	38% (22-14)/22
Percentage of malfunctions in which the crew failed to complete the correct procedure	41%	25%	39% (41-25)/41

Minimum Success Criterion #3c: Key presses and switch throws

Goal: Reduction in key presses and switch throws

	Baseline	**CAU**	**Reduction**
Total number of navigation key presses and switch throws (examples: SYS SUMM key, FAULT SUMM key, IDP/CRT switch, DU key, edge keys)	9383	3000	68% (9383-3000)/9383
Total number of non-navigation key presses and switch throws (examples: ITEM key, ACK key)	4316	3325	23% (4316-3325)/4316

The End Result

Will the upgraded displays be implemented?

Arguments against:

- The funding is not available.
- Crews can be adequately trained on the original displays.
- The displays will only be flown a handful of times before the shuttle is retired.

Arguments in favor:

- In the tested environment, the new displays meet the minimum success criteria.
- The new displays will provide pragmatic lessons for the Crew Exploration Vehicle.

Bottom Line

Regardless of whether the Cockpit Avionics Upgrade (CAU) is implemented,

1) Display development in shuttle is applicable and relevant for aviation displays.

2) CAU displays provide guidelines for the next-generation spacecraft.