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APOLLO 13 WHERE'S WALDO GAME[1]

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Warning: screens have black backgrounds, so printing this uses a lot of ink!

Apollo 13

On the night of April 13, 1970, several NASA engineers were following the flight of Apollo 13 from a rooftop observatory. Against a backdrop of distant galaxies, they saw a tiny flare of light and a glowing cloud that resembled an exploding star. An explosion occurred in the oxygen portion of the cryogenics system (oxygen tank 2). What was happening in Mission Control as flight controllers monitored spacecraft systems (cf., Murray and Cox, 1989)?

One mission controller (the electrical, environmental, and communication controller or EECOM) monitoring this system was examining a screen filled with digital values (see the display for 8 minutes before the explosion -- display CSM ECS CRYO TAB). Then he and most of the other mission controllers began seeing indications of trouble in the systems that they were responsible for. Among a host of anomalous indications, EECOM noticed that oxygen tank 2 was depressurized (about 19 p.s.i.). It took a precious 54 minutes as a variety of hypotheses were pursued before the team realized that the "command module was dying" and that an explosion in the oxygen portion of the cryogenics system was responsible.

You saw the movie, now you play the controller! Look at a sequence of the actual Mission Control screens and see if you can find the oxygen tank explosion that crippled the Apollo 13 spacecraft. The challenge is to locate the data values in a screen filled with numbers, like finding Waldo[2] in the popular children's book.

[1] Also available at http://www-iwse.eng.ohio-state.edu/homepages/nasaproject/0.html
[2] Hanford, Martin. (1987) Where's Waldo. Boston. Little, Brown.

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1. Eight minutes before the explosion
2. Moment of the explosion
3. Four seconds after the explosion
4. Four minutes after the explosion
5. The answer

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Eight minutes before the explosion

LM1839 CSM ECS-CRYO TAB 0613

CTE 055:46:51 ( ) GET 055:46:53 ( ) SITE GDS09

LIFE SUPPORT				PRIMARY COOLANT			
GF3571	LM CABIN P	PSIA		CF0019	ACCUM QTY	PCT	34.4
CF0001	CABIN P	PSIA	5.1	CF0016	PUMP P	PSID	45.0
CF0012	SUIT P	PSIA	4.3	SF0260	RAD IN T	°F	73.8
CF0003	SUIT ΔP	IN H2O	-1.68				
CF0015	COMP ΔP	P PSID	0.30	CF0020	RAD OUT T	°F	35
CF0006	SURGE P	P PSIA	891	CF1081	EVAP IN T	°F	45.6
	SURGE QTY	LB	3.67	CF0017	STEAM T	°F	64.9
O2	TK1 CAP ΔP	PSID	21	CF0034	STEAM P	PSIA	.161
O2	TK2 CAP ΔP	PSID	17	CF0018	EVAP OUT T	°F	44.2
CF0036	O2 MAN P	PSIA	105	SF0266	RAD VLV 1/2		ONE
CF0035	O2 FLOW	LB/HR	0.181	CF0175	GLY FLO	LB/HR	215.0
CF0008	SUIT T	°F	50.5				
CF0002	CABIN T	°F	65	SECONDARY COOLANT			
CF0005	CO2 PP	MMHG	1.5	CF0072	ACCUM QTY	PCT	36.8
H2O				CF0070	PUMP P	PSID	9.3
CF0009	WASTE	PCT	24.4	SF0262	RAD IN T	°F	76.5
	WASTE	LB	13.7	SF0263	RAD OUT T	°F	44.6
CF0010	POTABLE	PCT	104.5	CF0073	STEAM P	PSIA	.2460
	POTABLE	LB	37.6	CF0071	EVAP OUT T	°F	66.1
CF0460	URINE NOZ T	°F	70	CF0120	H2O-RES	PSIA	25.8
CF0461	H2O NOZ T	°F	72	TOTAL	FC CUR	AMPS	67.58

CRYO SUPPLY			O2-1	O2-2	H2-1	H2-2
SC0037-38-39-40	P	PSIA	913	908	225.7	235.1
SC0032-33-30-31	QTY	PCT	77.63	01.17	73.24	73.03
SC0041-42-43-44	T	°F	-189	-192	-417	-416
	QTY	LBS	251.1	260.0	20.61	20.83

Moment of the explosion

LM1839 CSM ECS-CRYO TAB 0613
CTE 055:54:52 (55.914) GET 055:54:54 (55.915) SITE GDS09

------------LIFE SUPPORT--------				--------PRIMARY COOLANT------			
GF3571	LM CABIN P	PSIA		CF0019	ACCUM QTY	PCT	34.4
CF0001	CABIN P	PSIA	5.1	CF0016	PUMP P	PSID	46.0
CF0012	SUIT P	PSIA	4.3	SF0260	RAD IN T	°F	73.8
CF0003	SUIT ΔP	IN H2O	-1.72				
CF0015	COMP ΔP	P PSID	0.30	CF0020	RAD OUT T	°F	35
CF0006	SURGE P	P PSIA	891	CF1081	EVAP IN T	°F	46.2
	SURGE QTY	LB	3.67	CF0017	STEAM T	°F	64.9
O2	TK 1 CAP ΔP	PSID	-12	CF0034	STEAM P	PSIA	.161
O2	TK 2 CAP ΔP	PSID	105	CF0018	EVAP OUT T	°F	44.2
CF0036	O2 MAN P	PSIA	103	SF0266	RAD VLV 1/2		ONE
CF0035	O2 FLOW	LB/HR	0.181	CF0175	GLY FLO	LB/HR	214.6
CF0008	SUIT T	°F	50.5				
CF0002	CABIN T	°F	65	-----SECONDARY COOLANT----			
CF0005	CO2 PP	MMHG	1.5	CF0072	ACCUM QTY	PCT	37.5
---------------H2O-----------------				CF0070	PUMP P	PSID	9.3
CF0009	WASTE	PCT	24.8	SF0262	RAD IN T	°F	76.5
	WASTE	LB	13.9	SF0263	RAD OUT T	°F	46.2
CF0010	POTABLE	PCT	104.1	CF0073	STEAM P	PSIA	.2460
	POTABLE	LB	37.5	CF0071	EVAP OUT T	°F	66.3
CF0460	URINE NOZ T	°F	72	CF0120	H2O-RES	PSIA	25.8
CF0461	H2O NOZ T	°F	72	TOTAL	FC CUR	AMPS	71.58

-------------CRYO SUPPLY-----------------			O2-1	O2-2	H2-1	H2-2
SC0037-38-39-40	P	PSIA	879	996	224.2	233.6
SC0032-33-30-31	QTY	PCT	76.83	47.04	73.24	74.03
SC0041-42-43-44	T	°F	-190	-329	-417	-416
	QTY	LBS	248.5	260.0	20.61	20.83

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Four seconds after the explosion

LM1839 CSM ECS-CRYO TAB 0613
CTE 055:54:56 (55.915) GET 055:54:58 (55.916) SITE GDS09

------------LIFE SUPPORT-------

GF3571	LM CABIN P	PSIA	
CF0001	CABIN P	PSIA	5.1
CF0012	SUIT P	PSIA	4.1
CF0003	SUIT ΔP	IN H2O	-1.64
CF0015	COMP ΔP	P PSID	0.30
CF0006	SURGE P	P PSIA	891
	SURGE QTY	LB	3.67
O2	TK 1 CAP ΔP	PSID	-109
O2	TK 2 CAP ΔP	PSID	-872
CF0036	O2 MAN P	PSIA	105
CF0035	O2 FLOW	LB/HR	0.181
CF0008	SUIT T	°F	50.8
CF0002	CABIN T	°F	65
CF0005	CO2 PP	MMHG	1.5

---------------H2O-----------------

CF0009	WASTE	PCT	24.8
	WASTE	LB	13.9
CF0010	POTABLE	PCT	104.1
	POTABLE	LB	37.5
CF0460	URINE NOZ T	°F	72
CF0461	H2O NOZ T	°F	72

--------PRIMARY COOLANT------

CF0019	ACCUM QTY	PCT	34.4
CF0016	PUMP P	PSID	46.7
SF0260	RAD IN T	°F	73.8
CF0020	RAD OUT T	°F	35
CF1081	EVAP IN T	°F	45.9
CF0017	STEAM T	°F	64.4
CF0034	STEAM P	PSIA	.161
CF0018	EVAP OUT T	°F	44.2
SF0266	RAD VLV 1/2		ONE
CF0175	GLY FLO	LB/HR	214.6

-----SECONDARY COOLANT----

CF0072	ACCUM QTY	PCT	36.8
CF0070	PUMP P	PSID	9.1
SF0262	RAD IN T	°F	76.5
SF0263	RAD OUT T	°F	46.2
CF0073	STEAM P	PSIA	.2460
CF0071	EVAP OUT T	°F	66.3
CF0120	H2O-RES	PSIA	25.8
TOTAL	FC CUR	AMPS	81.45

-------------CRYO SUPPLY		-----------------	O2-1	O2-2	H2-1	H2-2
SC0037-38-39-40	P	PSIA	782	19	224.2	233.6
SC0032-33-30-31	QTY	PCT	78.04	47.04	73.64	74.03
SC0041-42-43-44	T	°F	-190	84	-417	-416
	QTY	LBS	252.4	260.0	20.72	20.83

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Four minutes after the explosion

LM1839 CSM ECS-CRYO TAB 0613
CTE 055:58:24 (55.930) GET 055:58:26 (55.974) SITE GDS09

------------LIFE SUPPORT--------				--------PRIMARY COOLANT------			
GF3571	LM CABIN P	PSIA		CF0019	ACCUM QTY	PCT	35.6
CF0001	CABIN P	PSIA	5.1	CF0016	PUMP P	PSID	46.9
CF0012	SUIT P	PSIA	4.1	SF0260	RAD IN T	°F	56.4
CF0003	SUIT ΔP	IN H2O	-1.60				
CF0015	COMP ΔP	P PSID	0.30	CF0020	RAD OUT T	°F	34
CF0006	SURGE P	P PSIA	891	CF1081	EVAP IN T	°F	44.6
	SURGE QTY	LB	3.67	CF0017	STEAM T	°F	64.4
O2	TK 1 CAP ΔP	PSID	-514	CF0034	STEAM P	PSIA	.162
O2	TK 2 CAP ΔP	PSID	-872	CF0018	EVAP OUT T	°F	44.0
CF0036	O2 MAN P	PSIA	105	SF0266	RAD VLV 1/2		ONE
CF0035	O2 FLOW	LB/HR	0.181	CF0175	GLY FLO	LB/HR	211.9
CF0008	SUIT T	°F	50.5				
CF0002	CABIN T	°F	65	-----SECONDARY COOLANT----			
CF0005	CO2 PP	MMHG	1.5	CF0072	ACCUM QTY	PCT	36.8
---------------H2O-----------------				CF0070	PUMP P	PSID	9.3
CF0009	WASTE	PCT	25.6	SF0262	RAD IN T	°F	76.8
	WASTE	LB	14.3	SF0263	RAD OUT T	°F	47.4
CF0010	POTABLE	PCT	104.1	CF0073	STEAM P	PSIA	.2460
	POTABLE	LB	37.5	CF0071	EVAP OUT T	°F	65.7
CF0460	URINE NOZ T	°F	73	CF0120	H2O-RES	PSIA	25.8
CF0461	H2O NOZ T	°F	76	TOTAL	FC CUR	AMPS	61.29

-------------CRYO SUPPLY-----------------			O2-1	O2-2	H2-1	H2-2
SC0037-38-39-40	P	PSIA	377	19	228.7	236.6
SC0032-33-30-31	QTY	PCT	74.81	-103	74.05	-1.24
SC0041-42-43-44	T	°F	-195	-329	-417	-427
	QTY	LBS	241.9	260.0	20.84	-0.35

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What's wrong with this display?

The pressure value for oxygen tank number two is located on the fourth line from the bottom, third column from the right. It reads 906 psi (pounds per square inch) in the first screen, rising to 996 psi eight minutes later at the moment of the explosion. Four seconds later it has dropped to 19 psi, where it remains four minutes later.

The display -- a field of raw digital values -- had hidden the critical event (2 digital values, out of 54 changing digital numbers, had changed anomalously). One discussion of the accident described it this way, "So none of the three noticed the numbers for oxygen tank 2 during four particularly crucial seconds. At 55 hours, 54 minutes, and 44 seconds into the mission, the pressure stood at 996 p.s.i.--high but still within accepted limits. One second later, it peaked at 1,008 p.s.i. By 55:54:48, it had fallen to 19 p.s.i. ... If one of them had seen the pressure continue on through the outer limits, then plunge, he would have been able to deduce that oxygen tank 2 had exploded. It would have been a comparatively small leap ..." to have put the whole puzzle of multiple disturbances across normally unconnected systems together.[3]

It was reported that the relevant flight controller experienced a continuing nightmare following the incident. In the dream when the astronauts reported a problem, "he looked at the screen only to see a mass of meaningless numbers ..." Well, the screen is a meaningleess mass of numbers unless the observer has the knowledge in his or her head needed to extract what is significant about these changing values. It is not possible to easily check how values are changing or even whether a value is different from several seconds earlier. Interpreting the values requires intensive training -- for example, you need to know the normal pressure range during this part of the flight, and the maximum pressure the tank can withstand before bursting. But the flight controller still was deeply troubled because he knew it was his responsibility to be able to figure out quickly what was really going on in the space craft systems from these displays.

In other words, a poor representation can be compensated for through human adaptability and knowledge; as Don Norman (1988) likes to put it, knowledge-in-the-head can compensate for the absence of knowledge-in-the-world. However, what is the point of the computer as a medium for the display of data if it does not reduce practitioner memory loads. In fact, in computer system after computer system (e.g., Woods et al., 1991) we find that, despite the availability of new computational and graphic power, the end result is an increase in demands on practitioner memory. The contrast cannot be greater with studies of successful, but often technologically simple, cognitive artifacts such as Hutchins (1991) that reveal how effective cognitive tools offload memory demands, support attentional control and support the coordination of cognitive work across multiple agents.

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[3] Murray and Cox, 1989, p. 406.

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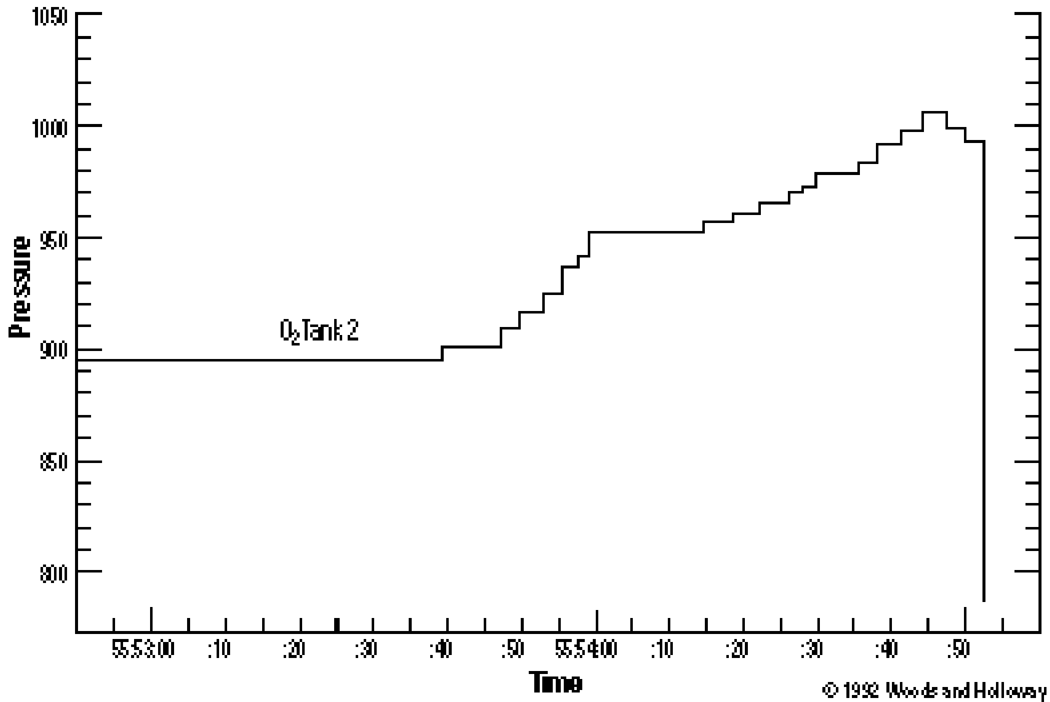
Finally, after two weeks a new version of the dream came to the flight controller -- he looked at the critical digitals "before the bang and saw the pressure rising. ... Then the tank blew, and he saw the pressure drop and told Flight exactly what had happened."[4] A second sequence of displays shows the event pattern that the controller wished he had been able to see.

Now that you've done it the hard way, look at these displays that capture the event patterns more directly. These displays illustrate the basic principles for representation design.

- Discover frames of reference that capture meaningful relationships.
- Put data into the context of related values;
- Highlight change and events.
- Highlight contrasts.

[4] Ibid, p. 407.

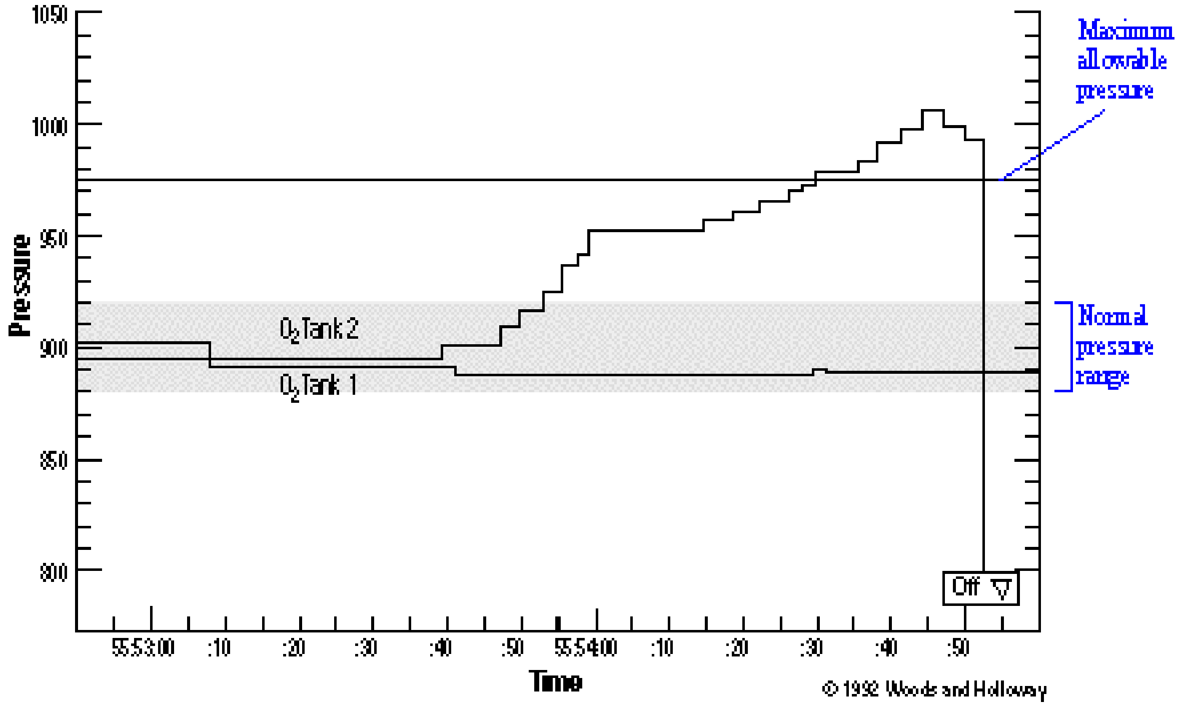
Depicting relationships in a frame of reference



The original display is presents instantaneous raw data values organized around subsystems. In order to go beyond mere data availability (one datum represented by one display element), the first step is to adopt a frame of reference that allows expression of meanigful relationships. One such frame of reference is the space defined by the value against time. This frame of reference expresses a set of relationships about temporal events in the cyrogenics systems and their associated functions.

Other frames of reference define different perspectives that can capture different kinds of relationships. It is up to the representation designer to discover what kinds of relationships are meaningful to practitioners, to discover what frames of reference define meaningful relationships, and to devise means to coordinate the views or perspectives defined by these different frames of reference.

Putting data into context



The current value (906, or 986, or 19) is just a piece of data. This datum is informative based on its relationship to other values and the expectations of the observer: What should be the value in this operating context? What are relevant limits or regions which should be avoided? What are critical values that trigger or deactivate automated systems?

In the original display, expectations of how the data should behave are contained entirely in the head of the controller. The data only becomes informative when it is known that:

- Both oxygen tanks should be reading approximately the same value.
- The pressure in this part of the flight should be approximately between 880 and 920 psi.
- A value of 19 psi is offscale low, meaning that the tank is depressurized, therefore holding no oxygen, and no longer supporting its functions.

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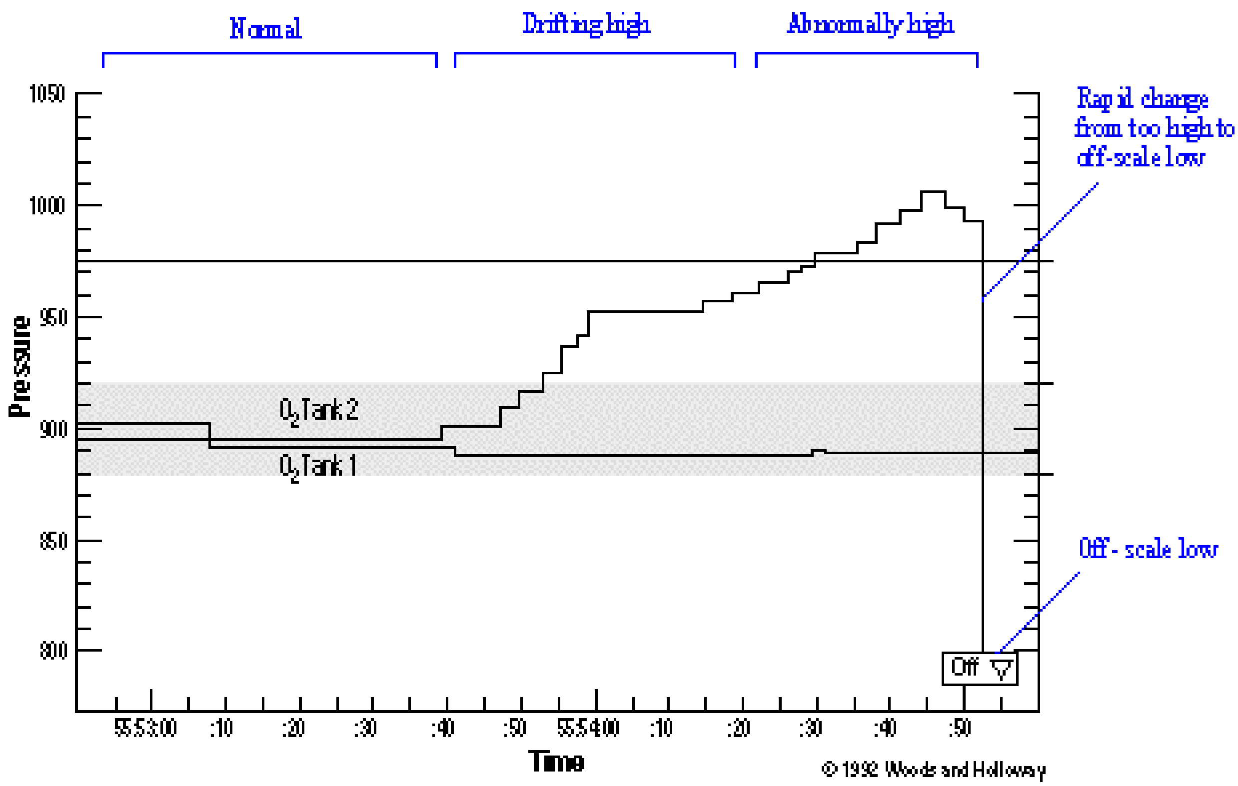
Highlighting events and contrasts



Ultimately in this accident it is the behavior of pressure that is informative, that is, temporally extended patterns of behavior or **events**. The events in this part of the incident are

- stable, normal
- drifting high
- abnormally high and increasing,
- and most critically
- rapid depressurization: offscale high followed immediately by offscale low
- depressurized (offscale low)

This frame of reference captures these different events in the relationship between current value and landmarks and past values . The event of rapidly changing from abnormally high to off-scale low is now directly visible in contrast to the expected behavior of these systems.

Because events are temporally extended patterns they can recede from view. As the flight controller monitored his systems he only saw the end result -- a depressurized system based on the displayed value (19), his domain knowledge, his knowledge of the

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context, and his expectations. Since events can recede, representations need mechanisms that can capture interesting events. For example, the temporal frame of reference provides a degree of event capture (though other mechanisms may be needed as well).

But there's not enough space!

The selected frame of reference should highlight events and contrasts. Notice how the frame of reference annotated with landmark references allows the story of the explosion to become a visible event, rather than a conclusion derived from a deliberative chain of reasoning.

One drawback of this representation is its demand on screen real estate. It is important to understand the tradeoffs involved in choosing to annotate data values vs. placing every value in context. At one extreme, annotating raw data values requires the user to keep the data history and expectations in the head. At the other extreme, displaying every value in a graphical format over time requires the user to navigate between many displays. Balancing tradeoffs like the annotation or navigate tradeoff is a difficult design challenge that is part of thinking about a display system at the workspace coordination level.