Infrared Imaging and Temperature Measurement under a Boeing 747 Center Wing Tank

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March 11, 1999

Explosion Dynamics Laboratory Report FM99-3

Prepared for and supported by the National Transportation Safety Board
Under Order NTSB12-97-SP-0127

1 Introduction

The tests which are reported here are part of the National Transportation Safety Board (NTSB) investigation on the crash of a commercial airplane Boeing 747 operated by TWA as Flight 800 [1]. These tests were performed on an aircraft operated on the ground. The purpose of the tests were to determine the thermal environment and the vapor conditions around the center wing tank (CWT) of a B747 with the air condition units in operation. The on-site part of this project was realized at Pinal Air Base (Marana, AZ). The staff of the Explosion Dynamics Laboratory (EDL) of CALTECH collaborated with teams of Boeing and of the Desert Research Institute (DRI) from University of Nevada (Reno, NV). The EDL team took infrared images (IR-images) of the machinery under the CWT and the DRI team worked on sampling vapors from the CWT while the Boeing team operated the systems of the aircraft. The present text is a brief factual report on EDL operations during those ground tests on May 29 through 31 1998. The vapor sample analyses by DRI are reported by J. Sagebiel[2].

The overall purposes of the tests were to map the ranges of heat generated underneath the CWT and to measure the vapor concentration above the fuel in this tank. EDL had two objectives at the testing site. The first was to assist in the installation and use of a heating system attachment to the pre-existing vapor sampling apparatus used by team DRI. The second objective was to take IR-images of the air conditionning machines (ACM) in order to measure the surface temperature of the three packs and their elements. The ACM bay is located right under the CWT. Images were taken both with and without the packs running.

2 Heating of the Vapor Sample Lines

Air samples of each bay of the CWT were collected in order to analyse their jet fuel composition. The points of collection were located near the center of each bay. In one bay (the middle one), two more samples were taken from a lower and a higher location. Only 50 gallons of fuel were in the CWT in order to simulate a nominally empty tank. Lines were connecting the inside of CWT to sampling bottles. Heating of the vapor sample lines was considered in order to preserve the nature of the samples. On site discussions with Boeing, though, determined that the heating was undesirable at this late a stage in test preparation, and at best was acceptable only outside the aircraft, due to safety concerns. Thus the heating was applied to the copper lines from the sampling bottles right up to the side of the aircraft where the lines penetrated the skin. This was considered an adequate compromise, as the dry bay heated up by midday (typical test start time was 1 pm and temperature in the shade was around 95°F during all three tests), and was expected to heat up even further, once the packs were started. This made the section of the vapor lines external to the aircraft, the coolest and therefore a likely place for condensation to occur.

The equipment for heating consisted of heating tape, a temperature controller, a relay, and two thermocouples. The first thermocouple was closest to the bottles , and the second thermocouple was in the dry bay where the vapor sampling lines fanned out before penetrating spanwise beam 3 (see Figure 1). Feedback to the temperature controller was provided by the first thermocouple, and the controller actuated the relay that, in turn, switched the heating tapes on and off. The controller consistently kept the temperature of the heated section between 140°F and 160°F. A handheld thermocouple probe was used to obtain additional measurements near the bottle furthest from the heater as well as near the point where the lines penetrated the aircraft skin. Aluminum foil was wrapped on the lines for uniformity of heating. Boeing allowed Raza Akbar to operate the temperature controller and take measurements, although Boeing personnel installed the equipment. Tables 1 and 2 show the temperature measurements taken at the first and third tests respectively (no vapor samples were collected during the second test).

[1] The aircraft was a Boeing 747-131, N93119. The accident occurred on July 17 1996, East of New York, NY.

[2] "Analysis of Vapor Samples Collected from the Center Wing Tank of a Boeing 747-100 Aircraft during Groung Tests", prepared by J.C. Sagebiel of Desert Research Institute, University of Nevada, for the National Transportation Safety Board (October 1998).

3 Imaging

An infrared (IR) camera was used for surface temperature measurements. It was a Prism DS IR camera rented from FLIR Systems (Portland, OR). This type of camera has a focal plane array system. The temperature it can read ranges from -10°C to 450°C (15°F to 840°F) and the user can set the emissivity between 0.05 and 1.0 with increments of 0.01. The camera has a video output, as well as a digital storage capability for single takes. The camera was not available for the first test. On the day of the second test, images of the ACM bay exterior were taken as a practice dry run. It was estimated that a few minutes would be required to image any given section. This is because, subsequent to the IR, a sweep of visible video was needed to assist in image identification during post-processing. An imaging time estimate of 60 min. with packs off, and about 30 min. with packs on was submitted to Boeing on the morning of the third test, along with a brief outline of procedure.

During the imaging, the video recorder ran continuously, with the line being attached alternately to the IR camera and the visible video camera. As a particular section was imaged, handheld thermocouple probes were used to get temperature readings for comparison with those obtained from the IR camera. Mark Ahler of Boeing also took temperature readings of the target objects. It was found that the response of the hand held probe was slow, and even the quicker one (Boeing's) was not stationary in output (indicated temperature was typically rising). The temperature data from IR camera and the handheld probes is given in Table 3 along with the description of the IR-images that were taken during this third test. Photos of typical assets of the ACM bay are shown on Figure ref-stillphotos and the layout maping the locations of the IR-images is at Figure 3. The IR-images themselves are in Figures 4, 5 and 6.

4 Post Processing

The settings on the IR camera were fixed during the testing, for ease of use. The most important of these is the emissivity, which directly affects the temperature readings. Although the value of emissivity used (0.95) is typical of painted surfaces, it is necessary to estimate of the change in temperature with variation in emissivity (representative of the surfaces imaged). This is to be done using post-processing software that operates on the digitized single takes from the IR camera. The software used for that purpose was the Irwin OLE Software (also rented at FLIR Systems). This was the way the temperatures were determined at precise locations on the IR images. Another set of temperature were also produced considering the hypothesis of an emissivity of 0.5. The two series of temperatures at each of the five points on the IR images are listed on Table 4 for the part of the tests when the packs were off and at Table 5 when they were on.

Table 1: Temperatures observed during the first test.

Time	T_1 [^{o}F]	T_2 [^{o}F]	T_{amb} [^{o}F]	$T_{bottle\ end}$ [^{o}F]	Notes
13:55	149	89.6	93	93	Time by observer watch
14:25	150	91.6	93	93.4	
14:41	158.5	93.4	94.8	95	Packs started
14:56	150	98.6	93.4	93.6	
15:11	154	104.8	96	97.6	T_{exit} (from aircraft) at about 105 ^{o}F
15:26	160	107	96	96	120 ^{o}F near bottles, from exhaust gusts
15:41	160	111	94	94	First Sample
15:56	146	112	95	95	
16:11	144	112	121	113	Exhaust gust in the vicinity of bottles
16:26	156	114	96	95	
16:41	160	114	96	95	Second Sample
16:56	148	114	110	104	T_{exit} (from aircraft) at about 108 ^{o}F
17:11	139	114.4	103	99	Exhaust gust in the vicinity of bottles
17:26	152	115	96	96	
17:41	142	115	96	96	ACM shutdown at 5:46 pm (17:46)

Table 2: Temperatures observed during the third test.

Time	T_1 [^{o} F]	T_2 [^{o} F]	T_{amb} [^{o} F]	$T_{bottle\ end}$ [^{o} F]	Notes
13:05	123	88	93	92.6	Heater on. Test started at 1 pm (13:00)
13:25	163	94	92	102	Exhaust gust near bottles
13:35	144	98	103	108	Bottle lines are hot!
13:50	147	103	92.4	93	
14:06	154	106	94	96	112 ^{o}F at T_{exit}
14:20	144	107	101	107	
14:35	142	108	104.4	105	
14:51	145	110	99	99	
15:05	156	111	93	94	
15:20	153	112	98	96	111 ^{o}F at T_{exit}
15:35	152	112	95	95	
15:51	151	113	95	94	
16:00	160	113	94	94	115 ^{o}F at T_{exit}

Table 3: IR-images indentification and temperatures at center of each one (test no.3).

Time	Shot #	Location in ACM bay	Emissivity	IR Temp [^{o} F]	Handheld (EDL) [^{o} F]	Handheld (Boeing) [^{o} F]
	d3im1	Pack 2 Flow control valve (silver surface)	0.95	255	180	-
	d3im2	Pack 2 Rear bleed duct (grey surface)	0.95	235	174-196	-
	d3im3	Pack 2 Compressor (inlet silver)	0.95	165	135	135
	d3im4	Pack 2 Turbine	0.95	145	131	127
	d3im5	Pack 2 Fan (non metal surface)	0.95	128	100	103
	d3im6	Pack 1 Flow control valve (grey)	0.95	140	121	136
	d3im7	Pack 1 Compressor (dirty grey)	0.95	124	110	123
16:35	d3im8	Pack 1 Turbine (silver)	0.95	126	110	117
	d3im9	Pack 1 Fan	0.95	111	96	101
	d3im10	Pack 3 Flow control valve (silver)	0.95	132	107	126
	d3im11	Pack 3 Bleed duct	0.95	115	101	105
	d3im12	Pack 3 Compressor	0.95	121	110	116
	d3im13	Pack 3 Turbine	0.95	116	105	114
	d3im14	Pack 3 Fan	0.95	110	98	104
	d3im15	Pack 3 Green tank bottom (beside louvres)	0.95	120	-	-
16:55	d3im16	Pack 1 Tank bottom near heat exchanger radiometer	0.95	188	-	-
	d3im17	Pack 1 Tank bottom beside compressor	0.95	114	-	-
	d3im18	Pack 3 Heat exchanger and tank bottom surface	0.95	113	-	-
	d3im19	Pack 3 Tank bottom (aft)	0.95	116	-	110
17:05		---------- Packs turned on ----------				
17:17	d4im1	Pack 2 Flow control valve	0.95	over-ranged	-	-
17:20	d4im2	Pack 1 Flow control valve	0.95	over-ranged	-	254
17:22	d4im3	Pack 3 Flow control valve	0.95	over-ranged	-	261
	d4im4	Tank bottom between Packs 1 and 2	0.95		-	-
	d4im5	Tank bottom between Packs 1 and 2	0.95	217	-	-
17:28		---------- Packs turned off ----------				
17:28	d4im6	Pack 3 Junction before flow control valve	0.95	201-190	-	196
	d4im7	Pack 3 Tank bottom (aft)	0.95	122	-	114

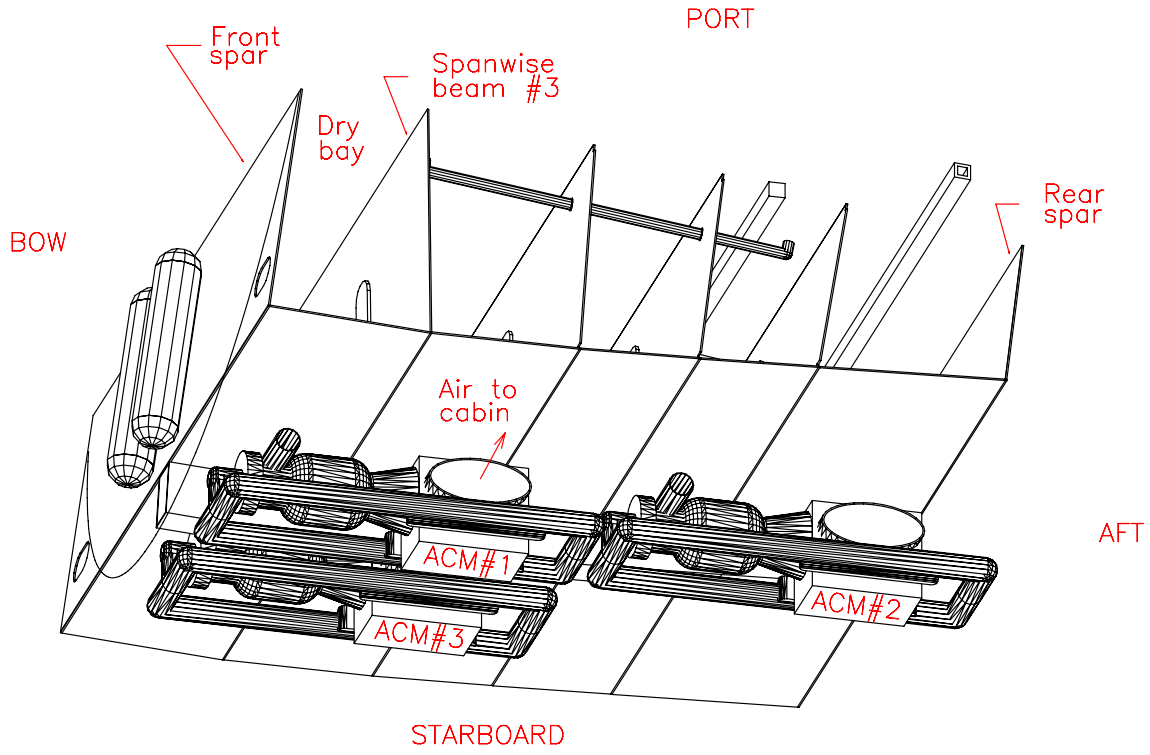


Figure 1: A 3-D schematic view of the tank along with the three ACM underneath it.

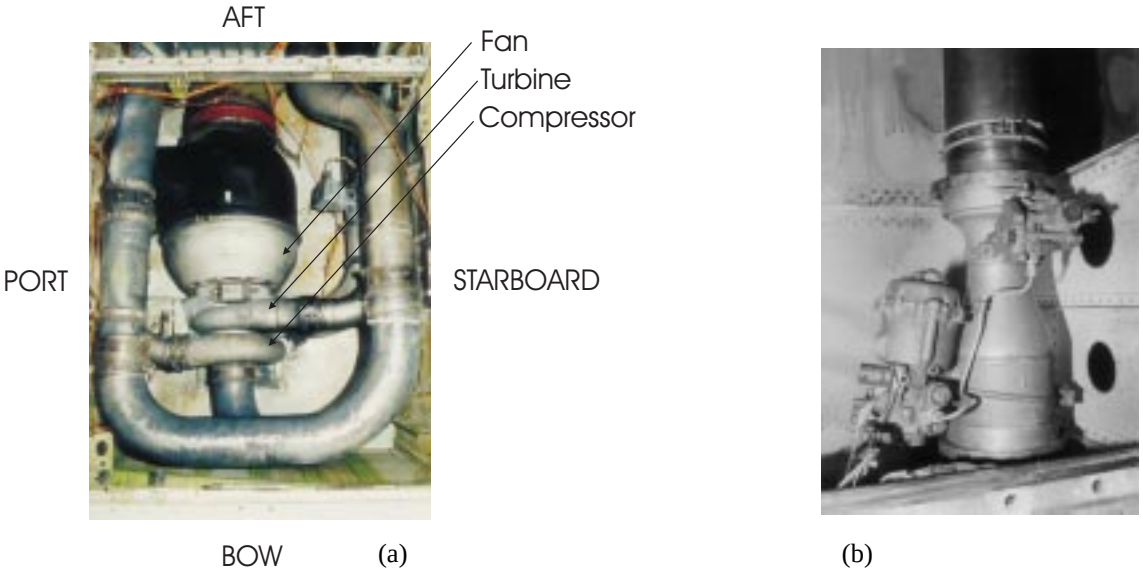


Figure 2: (a) Pack number 1 with parts identified; (b) Flow control valve number 3.

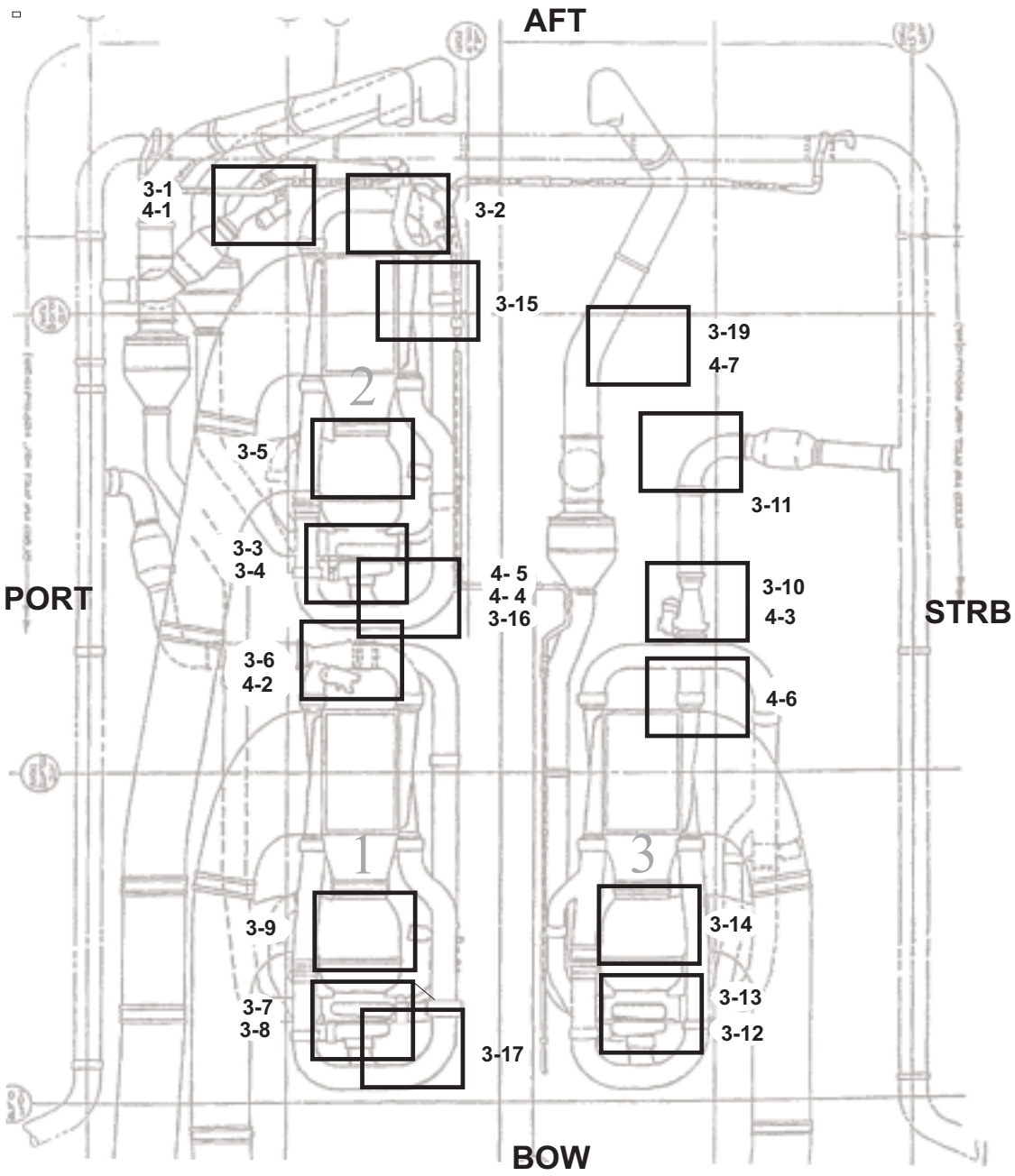
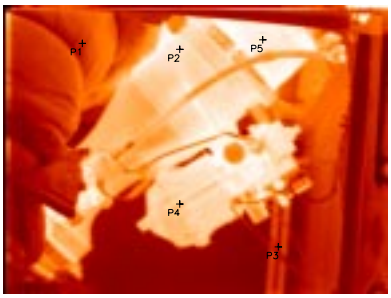
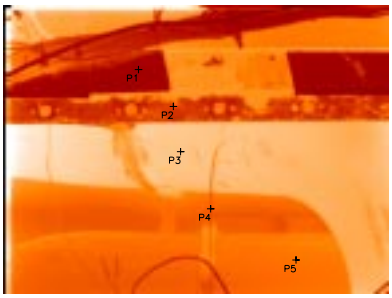


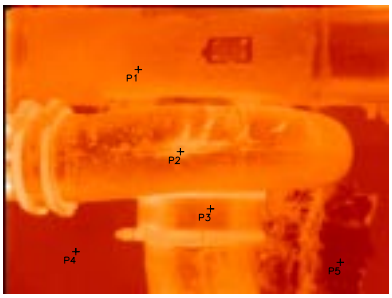
Figure 3: IR-images locations superimposed on schematic of ACM bay equipment (adapted from a Boeing technical drawing). The configuration of ACM bay is as seen from beneath the plane.



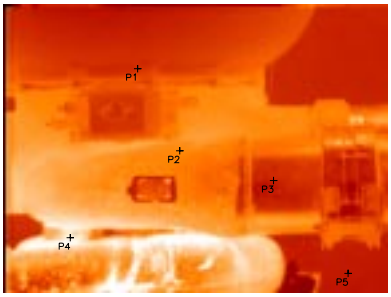
Flow control valve (silver surface)
Pack 2 (d3im1)



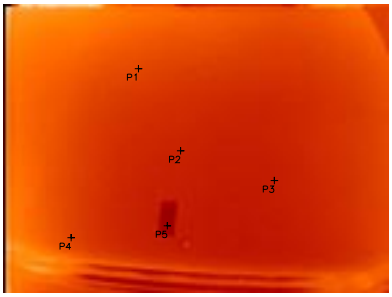
Rear bleed duct (grey surface)
Pack 2 (d3im2)



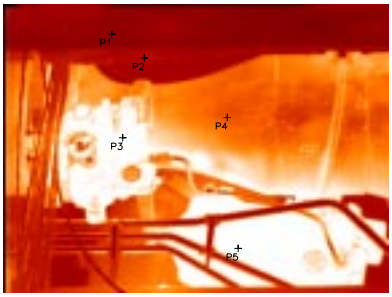
Compressor (inlet silver)
Pack 2 (d3im3)



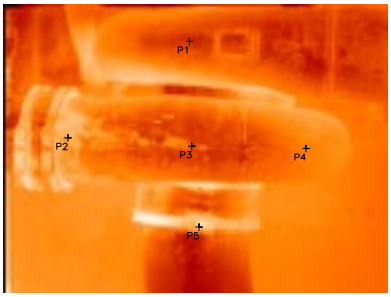
Turbine
Pack 2 (d3im4)



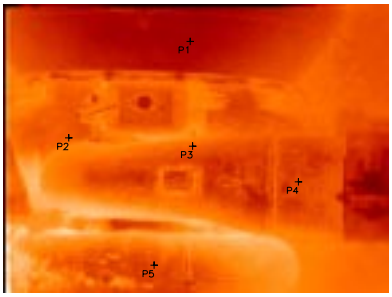
Fan (non metal surface)
Pack 2 (d3im5)



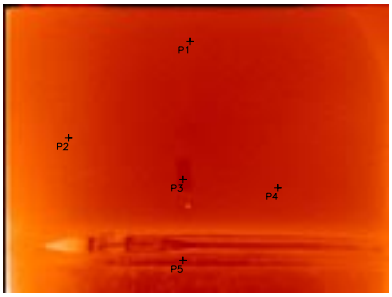
Flow control valve (grey)
Pack 1 (d3im6)



Compressor (dirty grey)
Pack 1 (d3im7)

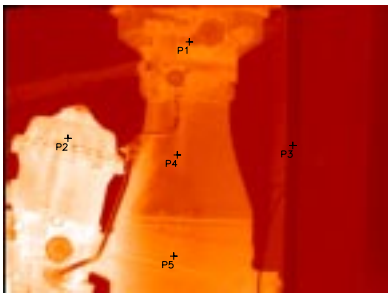


Turbine (silver)
Pack 1 (d3im8)

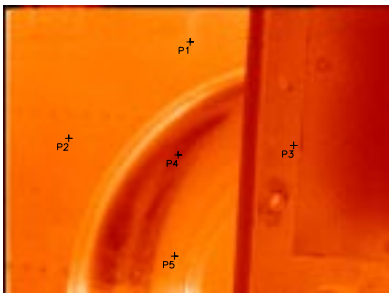


Fan
Pack 1 (d3im9)

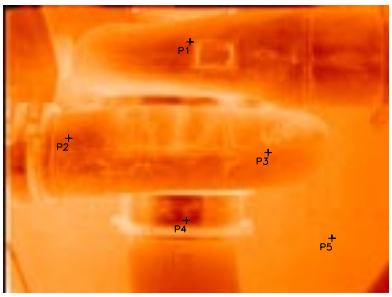
Figure 4: IR-images during cool-off phase (ACM packs off) of test no.3.



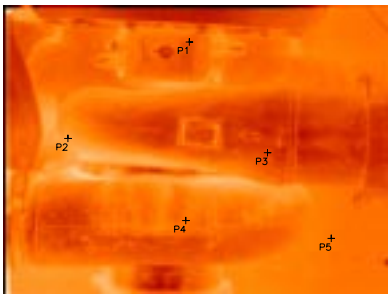
Flow control valve (silver)
Pack 3 (d3im10)



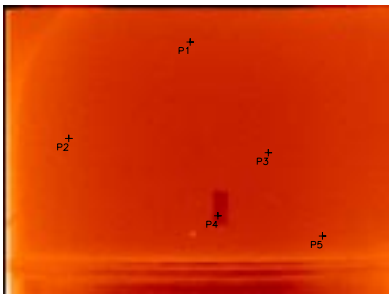
Bleed duct
Pack3 (d3im11)



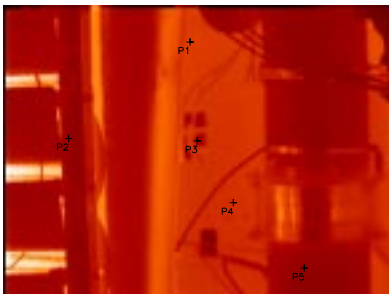
Compressor
Pack 3 (d3im12)



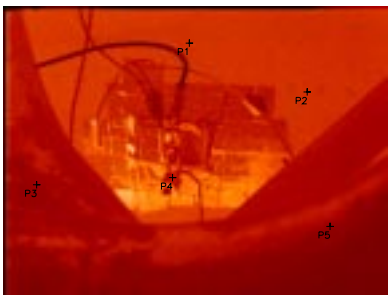
Turbine
Pack 3 (d3im13)



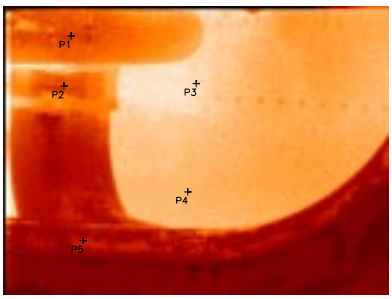
Fan
Pack 3 (d3im14)



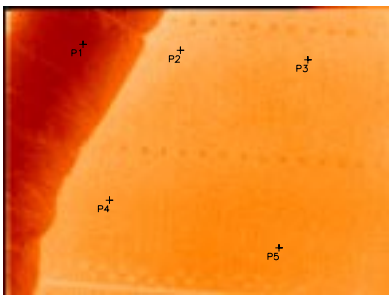
Green tank bonttom beside louvres
Pack 3 (d3im15)



Tank bottom near Pack 1 heat exch.
radiometer (d3im16)

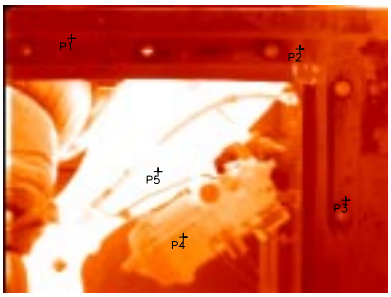


Tank bottom beside compressor
Pack 1 (d3im17)

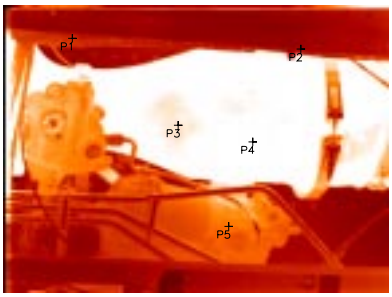


Tank bottom surface; aft
Pack 3 (d3im19)

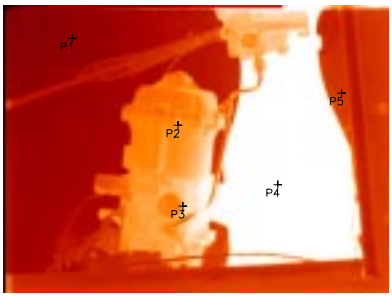
Figure 5: IR-images during cool-off phase (ACM packs off) of test no.3 ...continued.



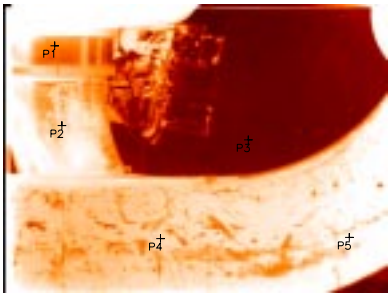
Flow control valve
Pack 2 (d4im1)



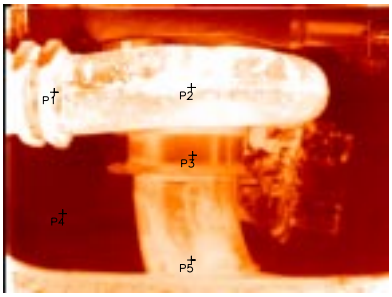
Flow control valve
Pack 1 (d4im2)



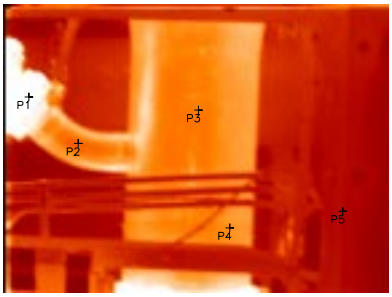
Flow control valve
Pack 3 (d4im3)



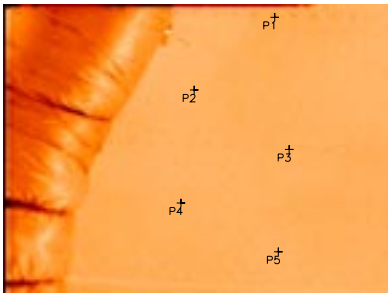
Tank bottom between
Packs 1 and 2 (d4im4)



Tank bottom between
Packs 1 and 2 (d4im5)



Junction before flow control valve
Pack 3 (d4im6)



Tank Bottom; aft
Pack 3 (d4im7)

Figure 6: IR images with ACM packs on during test no.3.

Table 4: Temperature readings at points identified on images; series with ACM packs off (during cool-off phase of test number 3)

Image #	P1 [F]	P2 [F]	P3 [F]	P4 [F]	P5 [F]	Emissivity set to
d3im1	191.06	259.67	185.94	238.01	262.42	0.95
	233.98	319.1	227.48	292.55	322.48	0.5
d3im2	160.05	179.37	236.74	187.03	197.5	0.95
	193.74	219.01	290.99	228.88	242.15	0.5
d3im3	157.55	168.94	156.61	145.02	137.32	0.95
	190.38	205.53	189.13	173.36	162.61	0.5
d3im4	135.1	146.17	133	157.39	132.16	0.95
	159.42	174.94	156.42	190.17	155.21	0.5
d3im5	132.09	128.7	127.67	132.56	123.01	0.95
	155.1	150.12	148.61	155.78	141.76	0.5
d3im6	123.1	129.82	159.16	137.97	160.17	0.95
	141.89	151.77	192.55	163.54	193.9	0.5
d3im7	124.64	134.41	126.7	132.38	137.95	0.95
	144.15	158.44	147.18	155.52	163.5	0.5
d3im8	120.28	128.79	128.23	125.95	126.43	0.95
	137.53	150.26	149.44	146.08	146.79	0.5
d3im9	113.03	115.81	110.67	112.99	111.51	0.95
	126.22	130.61	122.3	126.16	123.7	0.5
d3im10	135.06	151.35	118.16	133.76	138.94	0.95
	159.37	182.07	134.25	157.51	164.93	0.5
d3im11	118.05	117.76	115.78	113.47	118.08	0.95
	134.07	133.63	130.55	126.94	134.12	0.5
d3im12	120.77	121.41	121.78	116.72	124.59	0.95
	138.29	139.28	139.85	132	144.08	0.5
d3im13	118.39	123.79	117.77	120.26	120.51	0.95
	134.6	142.91	133.64	137.5	137.88	0.5
d3im14	112.01	113.66	111.94	109.14	113.6	0.95
	124.53	127.27	124.42	119.76	127.16	0.5
d3im15	123.12	115.29	116.15	121.83	114.4	0.95
	141.92	129.8	131.13	139.93	128.42	0.5
d3im16	109.34	110.02	105.99	108.46	105.55	0.95
	120.1	121.22	114.55	118.64	113.82	0.5
d3im17	108.5	109.71	115.03	113.79	107.31	0.95
	118.7	120.72	129.39	127.47	116.74	0.5
d3im18	119.77	115.45	118.89	115.8	114.73	0.95
	136.74	130.04	135.38	130.58	128.93	0.5
d3im19	111.06	117.63	117.78	117.16	115.88	0.95
	113.19	119.59	119.75	119.14	117.89	0.5

Table 5: Temperature readings at points identified on images; series with ACM packs on during test number 3.

Image #	**P1 [F]**	**P2 [F]**	**P3 [F]**	**P4 [F]**	**P5 [F]**	**Emissivity set to**
d4im1	175.06	188.02	181.1	221.49	306.15	0.95
	213.44	230.13	221.25	272.16	375.85	0.5
d4im2	196.09	187.42	262.03	306.15	219.7	0.95
	240.36	229.37	321.99	375.85	269.94	0.5
d4im3	164.76	222.04	232.22	306.15	185.6	0.95
	200	272.84	285.44	375.85	227.05	0.5
d4im4	208.77	234.23	174.98	231.11	242.81	0.95
	256.31	287.93	213.34	284.07	298.43	0.5
d4im5	306.15	306.15	213.93	183.07	255.57	0.95
	375.85	375.85	262.8	223.79	314.07	0.5
d4im6	306.15	194.07	203.19	211.53	172.39	0.95
	375.85	237.8	249.29	259.78	209.99	0.5
d4im7	124.9	125.67	124.64	125.19	125.85	0.95
	144.54	145.67	144.16	144.97	145.94	0.5

Appendix

List of times at which IR and visual images can be found on the video tape taken on May 31 1998 during the test number 3. The video recorder was alternately connected to the infrared and the visual range cameras. The initial time (0h00m00s) is set at the very beginning of the tape.

Image #	IR images Time	Visual images Time
d3im1	0:06:40	0:07:40
d3im2	0:11:00	0:11:50
d3im3	0:15:00	0:15:40
d3im4	0:17:00	0:18:00
d3im5	0:19:00	0:20:00
d3im6	0:21:40	0:22:40
d3im7	0:25:20	0:26:00
d3im8	0:27:10	0:27:50
d3im9	0:29:30	0:30:00
d3im10	0:31:10	0:32:00
d3im11	0:33:30	0:34:20
d3im12	0:36:10	0:36:50
d3im13	0:38:00	0:38:50
d3im14	0:40:00	0:40:50
d3im15	0:42:20	0:43:30
d3im16	0:44:50	0:45:40
d3im17	0:47:00	0:47:40
d3im18	0:50:00	—
d3im19	0:53:25	—
d4im1	0:55:50	—
d4im2	0:57:20	—
d4im3	1:00:00	—
d4im4	1:02:00	—
d4im5	1:02:30	—
d4im6	1:06:10	—
d4im7	1:10:30	—