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NASA's New Millenium program will fly a xenon ion propulsion system on the Deep Space 1 Mission. Tests were conducted under NASA's Solar Electric Propulsion Technology Applications Readiness (NSTAR) Program with 3 different engineering model ion thrusters to determine thruster thermal characteristics over the NSTAR operating range in a variety of thermal environments. A liquid nitrogen-cooled shroud was used to cold-soak the thruster to -120 °C. Initial tests were performed prior to a mature spacecraft design. Those results and the final, severe, requirements mandated by the spacecraft led to several changes to the basic thermal design. These changes were incorporated into a final design and tested over a wide range of environmental conditions.

Introduction

NASA's Solar Electric Propulsion Technology Applications Readiness Program (NSTAR) will provide a primary propulsion system to NASA's New Millenium Deep Space 1 (DS1) Mission[1]. DS1, with a planned 1998 launch, will fly past a comet in 1999 and an asteroid in 2000. The primary propulsion system consists of a single ion thruster, a power processor, a digital control and interface unit, and a xenon propellant feed system. An extensive set of development tests has been completed including performance, life validation, and environmental testing. Of particular interest was the thermal behavior of the operating and non-operating thruster in various thermal environments. It was expected that the results of these tests would: 1) define the environmental qualification test capabilities for flight hardware, 2) quantify temperature margins for critical thruster components, such as the temperature-sensitive, rare-earth magnets used in the discharge chamber, 3) identify the thermal impact, if any, of the thruster on the spacecraft, 4) identify thruster thermal design modifications required for flight, and 5) evaluate thruster thermal behavior without ion beam extraction. The data were also required for the development and validation of thermal models of the thruster and its integration onto future near-Earth and planetary spacecraft, including DS1. Planetary mission environmental extremes range from a cold soak of the non-operating thruster radiating to deep space at several AU, to operation at full-power in a thermally isolated condition on an inbound mission with up to two-suns of incident solar flux. To examine the first extreme, a liquid-nitrogen cooled enclosure was fabricated for cold soak tests to assess the effects of low temperature storage and the subsequent thruster behavior both at startup and during full power operation. Operation at full power under thermally isolated conditions covered the warm environment demands. Use of a solar simulator was beyond the scope of this effort.

This paper presents only the results of tests conducted on three Engineering Model Thrusters (EMT) in a variety of thermal environments. Thermal models of the thruster and its environment have been generated but are not presented here.

Apparatus

This section describes the hardware used to conduct the series of NSTAR thermal tests known as Engineering Development Test 2. Table 1 lists the test segment, the thruster used, the environmental configuration, and primary objectives of each of the 4 test segments.

Thrusters

Four Engineering Model Thrusters (EMTs) have been fabricated for the NSTAR ground test program[2]. Figure 1 is a schematic of a typical EMT which has been described in References 2-4. Table 2 lists the evolution of the EMT design, which is discussed in detail in Reference 5, and the major use of each thruster. EMTs 1 and 2 were used for life validation tests[3,4,6]. The third thruster (EMT3) was fabricated to be identical to EMT2 and was used for thermal-vacuum tests including cold soaks, cold starts, and preliminary steady-state operation over the power throttling range. EMT3 was modified from earlier models both by grit-blasting the interior and exterior discharge chamber surfaces to increase component emissivity and by perforating the magnet retainers to enhance radiation heat transfer from the hotter magnet regions. This thruster was designated EMT3b.

All EMT magnets were temperature stabilized at 250 °C. Irreversible losses for these magnets, when "bench tested" at 295 °C, were found to be less than 2 percent. However, when tested at 350 °C these magnets showed irreversible losses up to 8 percent after only 56 hours and up to 12 percent after 2200 hours[7]. Magnets that will be used in flight thrusters were stabilized at 350 °C to reduce these irreversible field losses during operation. To provide margin from the uncertainties of flight conditions, a ground test maximum allowable magnet temperature of 310 °C was selected.

As the spacecraft and propulsion system designs matured, a fourth thruster (EMT4) was fabricated. In addition to the improvements listed above for EMT3b, this design employed most of the important features of the flight thruster including an all-titanium discharge chamber to minimize differential thermal expansion between components and wire mesh throughout the discharge chamber to contain sputter-deposited material. The wire mesh, which was diffusion bonded to a stainless steel substrate, also distributed localized heat due to electron collection at the magnetic field cusps.

Thermal Environments

Four different geometric configurations were used to provide different thermal environments for the EMTs and simulate an undefined DS 1 spacecraft geometry. All four configurations utilized a cylindrical shroud 1.2 m in diameter by 1.0 m long which was closed on the upstream end (shown in Figure 2). These outer surfaces of the shroud were enclosed in a coil of 1.9 cm diameter copper tubing which could carry either liquid nitrogen (LN_2) for cold soak tests (tests 2a and 2b) or water from a circulating bath to simulate temperatures in the DS1 spacecraft thruster cavity. The downstream-end opening in the shroud was reduced to a 0.66 m diameter with a passive, annular gimbal plate simulator. The inner surfaces of the shroud and gimbal plate simulator were painted with a high-temperature, high-emissivity (about 0.9) black paint while the outer surfaces were covered with 10 layers of aluminized mylar.

In the configurations used for cold soak tests, EMT3 was mounted on a thermally isolated table inside the shroud. For the first configuration, the downstream end of the shroud was open (test 2a, Table 1). For the second configuration, a sliding door, painted black on the inside and insulated with 10 layers of aluminized mylar on the outside, was used to lower the cold soak temperatures. For the last two configurations, the thrusters were mounted to another annulus (0.58 m ID) which was attached close to the downstream end of the shroud to the 0.66 m ID annulus described above. This configuration simulated the DS1 spacecraft thruster-gimbal-assembly inner ring. For the third configuration, an 8.9 cm gap existed between the thruster plasma screen and the gimbal ring simulator to approximate the spacecraft design as anticipated at the time of this test.

Also for the third configuration, EMT3b radiated to the warm shroud. However, on-going thermal analyses of the spacecraft indicated that significant heater-power savings could be realized by thermally isolating the thruster from the rest of the spacecraft and closing the gap. Thus, the fourth configuration surrounded the upstream portion of EMT4 with an "adiabatic" enclosure. This was done for test 2d as shown in Figure 2. This scheme sealed the spacecraft cavity and prevented heat loss with a non-operating thruster and also thermally isolated the spacecraft from the operating thruster. The can was painted black on the surface facing the thruster and wrapped on the outside with 10 layers of aluminized mylar with alternating layers of a fibrous dacron separator.

Facility

The tests were conducted in a large space simulation chamber at Lewis Research Center (4.16 m diameter by 18.3 m long[8,9]). Facility pressures at full-power thruster operation ranged from 6.7×10^{-4} Pa to 1.3×10^{-4} Pa depending on use of 20 - 0.81 m diameter oil diffusion pumps only or the addition of liquid helium cryopanels.

Instrumentation

Thruster and environment temperatures were measured with up to 33 thermocouples as detailed in Tables 3, 4, and 5. Thermocouple designations are nodes from an initial thermal model. Wherever two thermocouples are shown for the same axial location, they are, in actuality, 180° apart.

Procedure

The first two tests (2a and 2b with EMT3) each consisted of thruster performance tests, thruster cold soaks, and thruster starts. In each sequence, the thruster was turned on from cold conditions and then from warmer thruster conditions after it had been heated by different methods. Operational steady-state thruster temperatures were obtained over the full power throttle range of 0.5 kW to 2.3 kW. The impact of precluding heat conduction along the thruster mounting struts was also evaluated. Steady-state conditions were defined as when all temperature rates-of-change were less than 3 °C per hour.

For test 2c with EMT3b, the shroud was heated to approximate the temperatures expected in the actual spacecraft configuration. Shroud wall temperatures of 20 °C and 50 °C were maintained for the non-operating thruster and also for the thruster operating at full power to evaluate magnet temperature margins. To avoid unnecessary thruster shutdowns during unattended overnight operation, the high-voltage power supplies were typically turned off. The high voltage was also turned off to examine thruster thermal behavior for future environmental qualification testing in which flight hardware might be damaged by deposits of material eroded by the energetic ion beam. In these cases, the main discharge propellant flow was reduced to maintain the same discharge power and allow thruster steady-state temperatures to be reached. Steady-state high-voltage-off temperatures were recorded after extended periods and compared with high-voltage-on values.

As mentioned earlier, test 2d with EMT4 was conducted with the thruster thermally isolated from the shroud or spacecraft simulator. The shroud was heated to approximately 50 °C, the maximum spacecraft cavity temperature expected. The thruster was then operated at full and reduced power levels, again to evaluate magnet temperature margins.

Results and Discussion

This section discusses the results of the four thermal tests listed in Table 1.

Engineering Development Test 2a

The thermal environment for test 2a was configuration #1 in which the thruster was mounted inside the cylindrical shroud. EMT3 was tested and the beginning-of-life performance data were found to be similar to those of EMT2 (the thruster currently in operation in the Life Demonstration Test[6]). Following these initial performance tests, EMT3 was then turned off and allowed to cool. The hollow cathode discharges were then initiated repeatedly to obtain average warm-shroud ignition times. Those times were found to be 8.8 and 12.5 seconds, respectively for the neutralizer and discharge cathodes, after heating the cathodes normally and commanding the respective discharge supplies to turn on. For 14 ignition attempts of test 2a, the impact of two cold soak cycles appeared to be negligible.

The thruster was then operated at the lowest power level of about 0.53 kW to obtain steady-state values, shown in Table 3, after 4 hours of operation. At this time, the gimbal support heaters were energized to prevent heat conduction along the struts. The impact on thruster temperatures after 3 more hours is shown in Table 3. Magnet temperatures increased about 10 °C while the temperature of the accelerator grid stiffening ring increased 14 °C. The thruster and gimbal support heaters were then turned off and allowed to cool. The thruster was then operated at a medium power of 1.44 kW and the steady-state thruster temperatures, shown in Table 3, were obtained.

Steady-state temperatures at full thruster power could not be reached due to a high voltage short that appeared only after two hours of full-power operation. Therefore, the high-voltage power supplies were turned off and the main plenum flow reduced from 23.2 to 3.6 sccm to give the same discharge power as with beam extraction. All temperatures, with the exception of those of the ion optics, are representative of values expected with beam extraction. Steady-state temperatures for this case are shown in Table 3. Excluding the cathode keepers, the maximum temperature observed, 282 °C, was for the middle and forward (optics-end) magnets. To evaluate the impact, if any, of operation at magnet temperatures at the 310 °C limit, the discharge power was increased to 336 W to raise the magnet temperature to 310 °C where it was held for 24 hours. Later, it was found that operation at a beam current of 1.1 amp required about 8 percent more discharge current, at the same discharge voltage than it had earlier. This increase in discharge power is not unlike that observed early in the 2000 hour test of EMT1[3] and in the Life Demonstration Test of EMT2[6]. As mentioned earlier, the magnets in all EMTs were temperature stabilized by the manufacturer at 250 °C. Perhaps small irreversible changes occurred during operation of EMT3 at 310 °C. Sovey has shown that elevating individual EMT magnets to temperatures greater than the stabilized value leads to measurable magnetic field strength degradation[7]. Magnetic field strength measurements, at discharge chamber surfaces, typically have variations greater than 10 percent which can dominate the subtler performance changes observed here.

Engineering Development Test 2b

Test configuration #2, with the shroud sliding door, was used for test 2b. EMT3 was briefly tested over the power throttle range and overall thruster performance was essentially unchanged. The discharge current required at full power was about 10 percent greater than it was for test 2a and it is postulated that this may be due to magnet degradation from prior testing. The thruster was then turned off and allowed to cool to room temperature. The shroud sliding door was closed and LN_2 was applied to the shroud cooling lines. Figure 3 shows that the warmest (forward magnets) and coldest (neutralizer keeper) thruster temperatures reached steady-state (less than 3 °C/hour) after about 10 hours. After 24 hours, all thruster temperatures were between -109 and -129° C as shown in Table 4. These cold soak temperatures were achieved on 5 occasions for this test segment.

Three attempts were made to preheat the engine after cold soaks to identify the thermal requirements, if any, for successful hollow cathode ignition and thruster power throttling from 0.5 to 2.3 kW. These thruster heating options will not be required for the DS 1 mission, but, were examined for future applications. When 10 or 20 watts (total) of heat were driven through the mounting struts toward the thruster, the engine body temperatures increased as shown in Table 4. A less complex, spacecraft configuration independent, method of warming the thruster was to use the discharge cathode heater. Starting from cold-soak conditions, 50 watts of discharge cathode heater power was applied for 24 hours which resulted in the thruster temperature increases shown in Table 4. Several neutralizer cathode ignitions were attempted and, as expected, a trend of increasingly longer neutralizer ignition times (up to 86 seconds longer than nominal, as determined in test 2a) was observed as the initial neutralizer hardware temperature was reduced to the cold-soak values.

Thruster startup from cold-soak to ignition to beam extraction at the minimum power level of 0.53 kW was uneventful. Steady-state temperatures were reached after 4 hours. Initial and final (after about 24 hours) temperatures are shown in Table 4. Thruster starts from cold-soak conditions were repeated several times to evaluate the ability of the thruster to quickly throttle to full power. The thruster power could be increased from 0.5 kW to full power over three minutes with no adverse consequences.

Because the magnet temperatures, which are of major concern, are to first order only a function of the discharge power, additional operation without beam extraction was investigated. Table 4 gives the steady-state temperatures for the thruster when operating at 1.30 kW. Without beam extraction the xenon neutral density increases and the discharge voltage drops. To counter this drop and maintain a constant discharge power, the main flow was reduced from 12.5 to 3.0 sccm. The resulting temperatures are shown in Table 4. The thruster parameters were then increased to give full-power discharge chamber conditions without beam extraction. The main flow required was only 3.2 sccm compared to 23.2 sccm with beam extraction. The resulting temperatures are given in Table 4. The maximum temperature, excluding the keepers, was 309 °C at the forward (downstream) magnets. This temperature was higher than that for the corresponding data of test 2a because the discharge power here was 320 watts, 14% greater than the 280 watts of test 2a. About half of this increase was due to the required increase in discharge current (1.1A) discussed at the end of the previous section and the rest because the test 2b data were taken 14 hours (rather than 4 hours) after conditions were established. Thus, the last column of temperatures shown in Table 4 were closer to equilibrium in test 2b than in test 2a.

To evaluate the impact of a configuration in which heat conduction from a thruster, operating at full power, to the shroud was not allowed, a test was performed in which the heaters on the mounting struts were powered. After 5 hours of strut heater power adjustments, the thruster was at thermal equilibrium (less than 0.5 °C per hour change) at the temperatures shown in Table 4. The difference in magnet temperatures for this case with and without beam extraction was no more than 3 °C. Note that the forward magnet temperature increased to 312° C, slightly exceeding the upper-limit criterion.

On-going thruster thermal analyses suggested ways of removing heat from the thruster magnets. These included holes in the magnet covers and grit-blasted surfaces to increase emissivity and enhance radiation heat transfer. These improvements were incorporated into EMT3b and EMT4 and evaluated in subsequent tests.

Engineering Development Test 2c

At the time of this test, the DS1 Project was planning to mount the thruster (which has a 41 cm OD) to a 58 cm diameter (ID) double-ring gimbal assembly. The thruster was to be recessed in the conic-section of the spacecraft structure and radiate to the spacecraft and out through the approximately 9 cm wide gap. The spacecraft would maintain a cavity temperature range of 20 to 50 °C. To simulate the DS 1 configuration, a warm water supply replaced the LN_2 to the shroud for test 2c. Table 5 gives the steady-state non-operating thruster temperatures when the shroud temperature was slightly above the worst case DS 1 temperature (56 °C). Also shown are the steady-state full-power thruster temperatures with a 56 °C shroud. Note that the maximum magnet temperature (forward magnet) for EMT3b and the warm shroud was only 300 °C even though the required discharge power at this condition was 340 watts. The lower magnet temperatures, for a warm shroud and greater discharge power, are believed due to the thermal design changes built into EMT3b.

Engineering Development Test 2d

EMT4 was fabricated to incorporate most of the important features found in the flight thruster design[5]. Test 2d was undertaken with insulating surroundings enclosing the thruster and gimbal ring simulator annular opening to simulate the latest DS 1 thermal interface which thermally isolates the thruster from the spacecraft. This configuration, shown in Figure 2, was based on the needs to minimize spacecraft heat loss through the annular opening between the non-operating thruster and the gimbal ring and to also limit the maximum spacecraft thruster cavity temperature to 50 °C when the thruster was at full power. The objectives of these final tests were to thermally evaluate EMT4 in the isolated enclosure, validate the thruster thermal models, and quantify temperature margins for thermally sensitive rare-earth magnets in the discharge chamber.

Table 5 shows the temperatures of the non-operating thruster in the 53 °C shroud and resultant 37 °C adiabatic can. The thruster was throttled from 0.5 kW to 2.3 kW, allowed to reach steady-state with the high-voltage off, and then with the high-voltage on. These full-power thruster temperatures are shown in Table 5. The maximum magnet temperatures for this thermally isolated thruster are 288 °C for the aft magnets and 289 °C for the downstream or forward magnets, well below the 310° C limit set for a 40° C margin from the 350 °C magnet-stabilization temperature. For the DS 1 mission, operation of the NSTAR thruster over the power throttle range of 0.5 to 2.3 kW will lead to very conservative magnet temperatures.

Based on Mirtich's results of tests with a 2.6 kW mercury ion thruster[10], thruster temperature increases of 20 °C and 40 °C at the downstream end of the anode might be expected for either 2-sun illumination of the thruster or if the thruster were completly surrounded by other equal temperature thrusters, respectively. In these cases, the NSTAR design may be marginal for very extreme conditions in severe inbound missions. To further investigate this condition, tests with a solar simulator are required and some additional minor thermal modifications may be necessary.

Conclusions

The thermal behavior of three NSTAR Engineering Model Thrusters (EMTs) was evaluated in four different thermal environments. Each thruster was instrumented with up to 21 thermocouples. EMT3 was placed in a LN_2-cooled shroud which was either opened or closed at one end. The resulting thruster temperatures at the end of a typical cold-soak period ranged from -30 to -84 °C for the open-end case and from -109 to -129 °C for the closed-end case. All thruster startups from cold-soak conditions were successful with neutralizer hollow cathode ignition times up to 86 seconds longer than startups from room temperature. No other adverse effects of thruster cold-soak and startup to full power were noted. Thruster performance was unaffected by cold soaks.

Another concern was the temperature sensitivity of the rare-earth magnets used to enhance the discharge chamber ionization efficiency. Flight thruster magnets were stabilized at 350 °C. A 40 °C margin from this upper limit was desired. This goal, coupled with severe spacecraft thermal requirements, necessitated several changes to the thruster thermal design. These changes included grit-blasting the interior and exterior discharge chamber surfaces to increase component emissivity, perforating the magnet retainers to enhance radiation heat transfer from the hotter magnet regions, and using wire mesh throughout the discharge chamber to distribute localized heat at the magnetic field cusps. These modifications were incorporated into EMT4 which was subsequently tested over the throttle range in a thermally isolated environment simulating the DS1 spacecraft configuration. Operating at full power in the adiabatic enclosure, the warmest magnet temperature observed was only 289 °C. This is well below the maximum allowable temperature of 310 °C (including margin).

During testing it was observed that magnet temperatures were primarily a function of the discharge power and that if the discharge voltage and current, experienced with beam extraction, were maintained with the high voltage power supplies turned off by reducing only the main propellant flow, nearly all of the thruster steady-state temperatures were unchanged. This mode of operation could be useful for integration testing of ion thrusters on spacecraft with sputter-deposit-sensitive surfaces or lenses.

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Table 1. Engineering Development Test 2 Descriptions

Test	Thruster, EMT	LN2 cooling of Shroud ?	Heated Struts ?	End Door ?	Gimbal Ring Simulator ?	Adiabatic Can ?	Primary Test Objectives(1)
2a	3	Yes	Yes	No	No	No	Cold soaks, starts
2b	3	Yes	Yes	Yes	No	No	Cold soaks, starts
2c	3b	No	No	No	Yes	No	Warm cavity
2d	4	No	No	No	Yes	Yes	Thermally isolated

(1) In addition to steady-state operating temperatures

Table 2. Evolution of the EMT design (from ref. 5).

Major Features	EMT1a	EMT1b	EMT1c	EMT2	EMT3	EMT3b	EMT4	Flight
Major test	2030 h[3]	1000 h[4]	Random vibration	8000 h[6]	**Thermal vacuum**	**Thermal vacuum**	**Thermal vacuum**	Flight
Main cathode keeper electrode?	No	Yes	Mass model	Yes	Yes	Yes	Yes	Yes
Discharge chamber material	Al/Ti	Al/Ti	Al/Ti	Al/Ti	Al/Ti	Al/Ti	Ti	Ti
Wire mesh throughout ?	No	Partial	Partial	Partial	Partial	Partial	Yes	Yes
Gimbal bracket material	Stainless steel	Stainless steel	Al	Stainless steel	Stainless steel	Stainless steel	Stainless steel	Ti
Grit-blast for emissivity control?	No	No	No	No	No	Yes	Yes	Yes
Lightening holes ?	No	No	Yes	No	No	Yes	Yes	Yes

Table 3. Steady-state Temperatures for Engineering Development Test 2a (EMT3), °C

		Case:	cold soak	0.53 kW	0.53 kW adiabatic	1.44 kW	2.30 kW conditions
Thermocouple designation	Thermocouple location	Thruster on?	No	No	Yes	Yes	Yes HV off
207	middle magnet		-38	191	199	241	268
211	disch cham cyl		-34	193	203	248	281
223	forward magnet		-32	188	198	242	282
1	cathode cover		-39	195	203	237	262
203	aft magnet		-39	198	206	245	274
215	cham stiff aft		-36	187	197	236	263
501	cathode keeper		-	439	444	523	564
307	accelerator ring		-30	126	140	162	212
104	plasma screen middle		-84	61	89	83	99
400	neutralizer base		-49	166	173	194	197
101	p.s. upst. end		-76	64	83	86	101
102	p.s. middle		-82	63	94	84	101
112	p.s. mask opp neutralizer		-31	84	101	113	140
404	neut keeper		-54	575	576	539	603
GP	gimbal pads		-96	43	111	88	108
S	shroud		-139	30	47	25	29

Table 4. Steady-state Temperatures for Engineering Development Test 2b (EMT3), °C

		Case:	cold soak	10 W struts	20 W struts	50 W cath heat	0.53 kW	1.30 kW	1.30 kW	2.30 kW adiabatic	2.30 kW adiabatic
Thermocouple designation	Thermocouple location	Thruster on?	No	No	No	No	Yes	Yes HV off	Yes	Yes HV off	Yes
207	middle magnet		-109	-53	-10	62	187	207	-	271	-
211	disch cham cyl		-108	-52	-11	68	189	224	231	297	294
223	forward magnet		-108	-52	-11	71	206	242	247	309	312
1	cathode cover		-109	-56	-17	154	187	214	219	268	266
203	aft magnet		-109	-54	-14	127	189	222	229	286	289
215	cham stiff aft		-109	-51	-9	74	181	212	218	277	277
219	cham stiff fwd		-109	-51	-9	-	169	-	-	-	-
303	optics support		-109	-53	-10	-	141	-	-	-	-
501	cathode keeper		-	-	-	-	440	494	511	579	598
307	accelerator ring		-108	-57	-19	23	118	167	150	221	202
305	accelerator ring		-108	-57	-21	22	119	166	149	217	201
104	plasma screen middle		-126	-8	+51	-60	2	25	27	102	104
400	neutralizer base		-129	-88	-65	-58	152	140	147	147	157
101	p.s. upstream		-123	-91	-61	-37	6	26	29	68	71
102	p.s. middle		-117	-4	+51	-52	9	30	32	106	108
112	p.s. mask oppose neut		-126	-62	-27	-23	68	98	94	143	137
106	p.s. dnstrm near neut		-118	-73	-46	-33	87	103	104	136	136
108	p.s. dnstrm oppose neut		-118	-60	-25	-25	59	85	83	123	120
404	neut keeper		-117	-90	-71	-68	590	552	561	559	562
GP	gimbal pads		-122	+73	+98	-22	70	106	106	204	202
S	shroud		-187	-188	-187	-187	-180	-174	-175	-171	-171

Table 5. Steady-State Temperatures for Engineering Development Tests 2c and 2d,°C

			Test 2c (EMT3b)		Test 2d (EMT4)				
		Case:	warm soak	2.30 kW	warm cavity	2.30 kW conditions	2.30 kW	1.81 kW conditions	1.81 kW
Thermocouple designation	Thermocouple location	Thruster on?	No	Yes	No	Yes HV off	Yes	Yes HV off	Yes
205	middle magnet		38	254	34	242	249	217	219
207	middle magnet		38	256	33	246	252	219	222
221	forward magnet		33	300	33	286	289	256	256
223	forward magnet		33	299	32	284	285	254	252
203	aft magnet		39	263	33	282	288	256	261
303	optics support		41	218	-	213	213	189	188
307	accelerator ring		36	202	-	189	177	167	154
110	plasma screen mask, neut		23	137	31	130	128	116	113
112	p.s. mask opp. neut		31	141	-	124	121	108	106
GP	gimbal pads		48	111	38	122	124	107	108
S	shroud		56	56	53	49	48	46	46
AC	adiabatic can		---	---	37	120	123	105	107

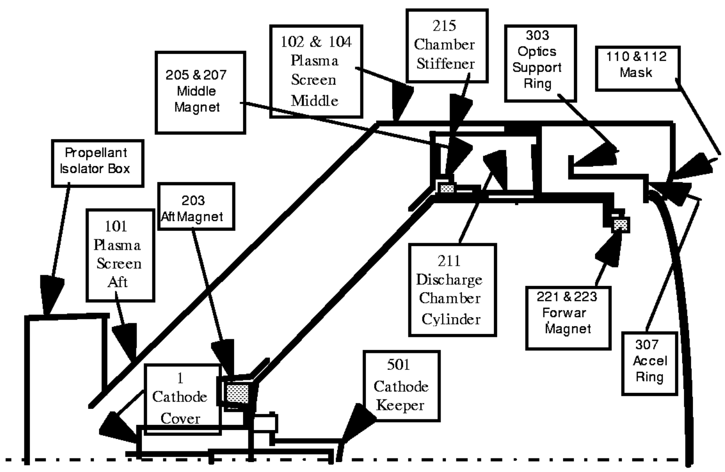

Figure 1. Thruster thermocouple locations

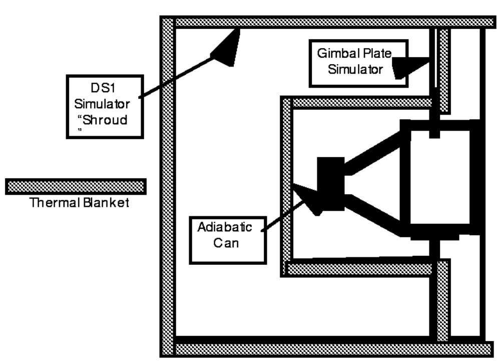

Figure 2. Test fixture

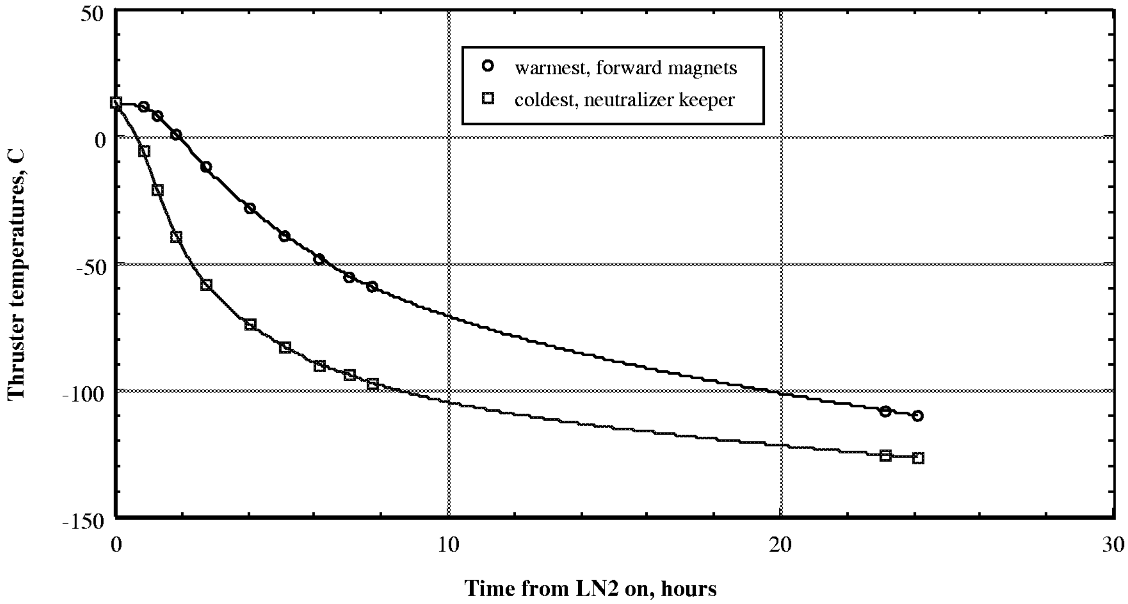

Figure 3. Cool-down temperatures vs time after LN2 on for test segment 2b.

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NASA's New Millenium program will fly a xenon ion propulsion system on the Deep Space 1 Mission. Tests were conducted under NASA's Solar Electric Propulsion Technology Applications Readiness (NSTAR) Program with 3 different engineering model ion thrusters to determine thruster thermal characteristics over the NSTAR operating range in a variety of thermal environments. A liquid nitrogen-cooled shroud was used to cold-soak the thruster to –120 °C. Initial tests were performed prior to a mature spacecraft design. Those results and the final, severe, requirements mandated by the spacecraft led to several changes to the basic thermal design. These changes were incorporated into a final design and tested over a wide range of environmental conditions.

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