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LOX/Methane Main Engine Glow Plug Igniter Tests and Modeling

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Abstract

Ignition data for tests with a LOX/methane igniter that utilized a glow plug as the ignition source are presented. The tests were conducted in a vacuum can with thermally conditioned (cold) hardware. Data showing the effects of glow plug geometry, type, and igniter operating conditions are discussed. Comparisons between experimental results and multidimensional, transient computer models are also made.

Nomenclature

light	Ignition obtained
O/F	Oxidizer to fuel ratio
Plug voltage	Voltage supplied to the glow plug
P_{Finl}	Pressure measured at the inlet of the fuel valve
P_{Oinl}	Pressure measured at the inlet of the oxidizer valve
Tip temperature	The surface temperature at the tip of the glow plug
T_b	Igniter body temperature
T_{Finj}	Temperature measured downstream of the fuel valve
T_{Finl}	Temperature measured at the inlet of the fuel valve
T_{Oinj}	Temperature measured downstream of the oxidizer valve
T_{Oinl}	Temperature measured at the inlet of the oxidizer valve
W_{CH4}	Flow rate of methane
W_{O2}	Flow rate of oxygen
$_{head}$	Flow through the injection elements excluding the internal cooling flow
$_{main}$	The final flow rates during a test

Introduction

The LOX/methane propellant combination is being considered for the Lunar Surface Access Module ascent main engine propulsion system. The proposed switch from the hypergolic propellants used in the Apollo lunar ascent engine to LOX/methane propellants requires the development of igniters capable of highly reliable performance in a lunar surface environment. The most stringent requirement for reliability discussed would require a redundant ignition system with no common components or mechanisms with the primary ignition system. An ignition test program was conducted at the NASA Glenn Research Center (GRC) that used an in-house designed LOX/methane torch igniter and automotive glow plugs to evaluate their potential as a redundant ignition system. The tests were conducted in the vacuum facilities in Cell 21 of the Research Combustion Laboratory (RCL) at the GRC. Data from tests to evaluate the effects of operating conditions as wells as the igniter and glow plug geometry on ignition boundaries are presented. Tests were conducted with the glow plug just upstream of the igniter face, recessed behind the igniter face, and penetrating through the igniter sidewall to the centerline. Results from tests conducted with metal and ceramic sheathed glow plugs and platinum coated glow plugs are also discussed. The effects of varying the power supplied to the glow plug are presented. The National Combustor Code (NCC) was used to perform unsteady, Computational fluid dynamic (CFD) simulations of the ignition process inside the glow plug torch igniter. Comparisons are made between the simulations and experimental results.

Igniter Hardware

The igniter was a three piece modular design consisting of a head end, a chamber section, and a fuel coolant sleeve as shown in Figures 1, 2, and 3. At the top of the igniter head end, are the propellant inlets to which the valve offsets were attached. The valve offsets were small tubes attached to the valves at one end and threaded into the igniter head at the other end. The valve offsets were instrumented with a thermocouple inserted into the flow as well as pressure transducer located on a tube brazed into the offset. The oxygen propellant inlet (on the left in Figure 1) feeds a ring manifold with five petals. Four petals of this oxygen manifold each feed a canted impinging injection element that injects oxygen through the top face of the igniter. The methane propellant inlet (on the right in Figure 1) feeds a ring manifold running behind the chamber wall at the head end of the igniter. The methane manifold feeds four canted impinging injection elements as well as four tangential inlets (the tear shaped surfaces in Figure 1.) to swirl the interior coolant flow. The methane injection elements inject through the side of the chamber wall and are located between the oxygen elements on the face. The flow split between the methane injection elements and the swirled internal cooling flow is controlled by the relative flow areas of these passages and is fixed. Additional cooling was provided by a separately controlled methane flow that was directed down between the exterior of the igniter tube and the interior of the coolant sleeve. The results of testing this hardware with a spark plug as the sole ignition source are presented in Reference 1.

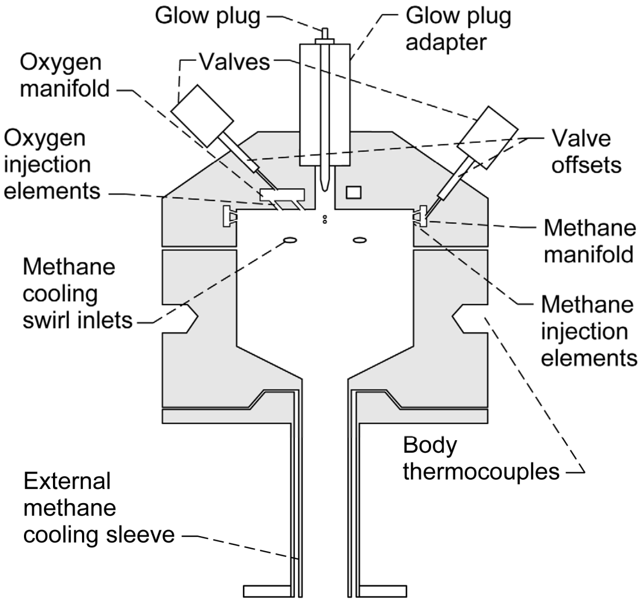


Figure 1.—Glow plug igniter schematic.

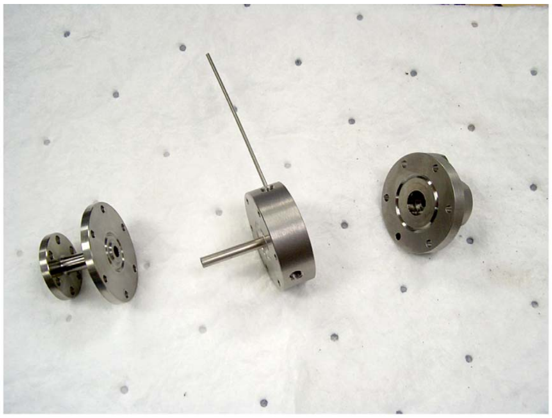


Figure 2.—From right, igniter head end, chamber with center flame tube and pressure port attached, and coolant sleeve.

Figure 3.—Assembled igniter stack, chamber with center flame tube and pressure port attached, and coolant sleeve.

Figure 4.—Metal sheathed glow plug.

Adapters were used to mount glow plugs in the head end port designed for a spark plug (Fig. 1). Various length adapters were used to position the tip of the glow plug in front of as well as recessed behind the igniter face. A port was also provided through the side wall of the igniter to allow for testing with a spark plug (at the head end) and a glow plug simultaneously. The glow plugs utilized in this testing were automotive glow plugs typically used in diesel engines (Fig. 4).

A facility power supply was used to power the glow plugs. The power supply was triggered during the test to supply a fixed voltage to the glow plug. No attempt was made to regulate the current to the glow plug with a glow plug controller. For those tests with both a glow plug and a spark plug, a low tension spark plug was mounted in the center head end of the igniter and the spark plug tip was flush with the top face of the igniter. The glow plug was mounted on the side of the igniter and its tip penetrated to the centerline. A variable spark energy (0.007 to 0.55 J) and spark rate (to 196 SPS) Unison exciter was used to fire the spark plug.

Igniter body temperatures were measured by two spring loaded thermocouples mounted in taps on the sides of the igniter. Small tubes were used to mount the valves to the igniter head. These tubes offset the valves from the igniter body to permit the installation of a pressure tap and thermocouple to measure propellant temperatures and pressures downstream of the valve. Propellant flow rates were measured by differential pressure measurements across a calibrated orifice as well as by a turbine flow meter.

Facility Description

The LOX/LCH$_4$ glow plug igniter was tested at the NASA GRC in RCL-21, which is an altitude test stand used for ignition testing and for testing low thrust propulsion devices. The igniter mounted on the test stand in RCL-21 with the ejector can pulled back is shown in Figure 5. The altitude simulation is maintained by an air driven ejector train capable of simulating 29,000 m (95,000 ft) (10 torr or 0.2 psia). A laboratory propellant feed system capable of supporting cryogenic propellants was used. This feed system condensed gaseous oxygen and gaseous methane in small propellant tanks using a liquid nitrogen cooling system. The liquid nitrogen lines also traced the propellant lines from the tank to the igniter inlet valves to help ensure the propellants remained in a liquid state up to the igniter manifold. Control relays cycled the liquid nitrogen on and off to each circuit based on the desired tank temperature (90 K for the liquid oxygen, 112 K for the liquid methane). Each bottle held about 2 liters of propellant. The liquid propellants were pressurized by the regulated gaseous propellant feed system with pressures up to 2760 kPa (400 psia). Tests were initiated by a Quantum Programmable Logic Controller which triggered the valves, glow plug power supply, and Unison Controller to time the spark. Figures 6 and 7 show successful ignition tests recorded on video by use of a window and mirror arrangement in the ejector can. For most of the cold body igniter tests the hardware was chilled by flowing ("burping") propellant through the igniter. For a few of the coldest test cases it was necessary to utilize a liquid nitrogen flow loop (Fig. 8) to further chill the hardware. The liquid nitrogen loop was also used for those tests in which the aim was to test with warm propellants and with cold hardware.

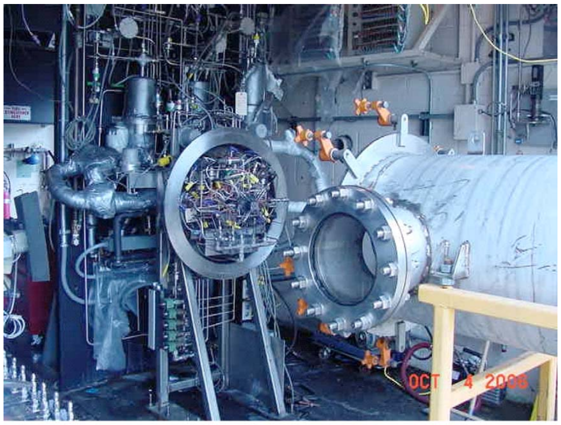


Figure 5.—Igniter mounted on the test stand in RCL Cell 21 with ejector can pulled back.

Figure 6.—Successful igniter test in ejector can.

Figure 7.—Ignition test with nozzle at reduced igniter body temperature.

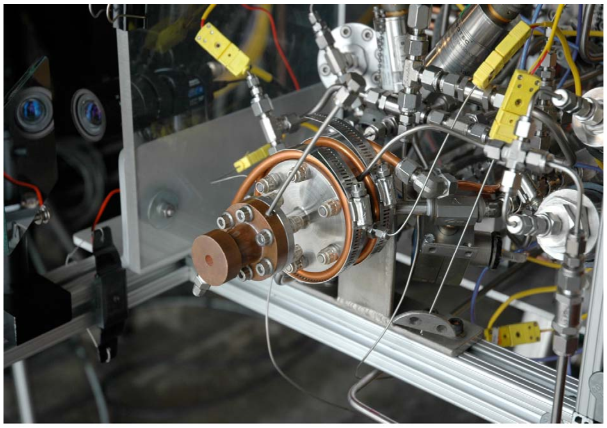


Figure 8.—Igniter with copper nitrogen cooling loop installed and nozzle attached.

Igniter Modeling

The National Combustor Code (NCC) (Ref. 2) was used to perform unsteady simulations of the ignition process in the GRC main engine igniter. The NCC is a state-of-the-art computational tool which is capable of solving the time-dependent, Navier-Stokes equations with chemical reactions. The NCC is being developed primarily at the NASA Glenn in order to support combustion simulations for a wide range of applications, and has been extensively validated and tested for low-speed chemically reacting flows.

Second-order accurate central-differences are used for the inviscid and viscous flux discretizations, and a Jameson operator (a blend of 2nd and 4th-order dissipation terms) is used to maintain numerical stability. In order to enhance convergence acceleration in pseudo-time, implicit residual smoothing is used to smooth the computed residuals. Dual time-stepping is used to obtain second-order time-accuracy for time-accurate simulations.

Turbulence closure is obtained by a low-Reynolds number two-equation k-e model. A finite-rate chemistry model is used to compute the species source-terms for methane/oxygen chemistry. The chemistry model incorporates 9 species and 7 chemical reaction steps and is detailed in Table 1. The model is based on the Sandia one-dimensional flame methane/air kinetics model (Ref. 3) with the reactions involving nitrogen as a species removed. The Peng-Robinson equation of state is used to calculate thermodynamic quantities.

TABLE 1.—O_2/CH_4 CHEMICAL KINETICS MODEL

No.	Reaction	A	n	E	
1	$CH_4 + 2O_2 <=> CO_2 + 2H_2O$	6.70E+11	0.0	48400.0	Where the rate constant, k, is given by
2	$H_2 + O_2 <=> H_2O + O$	5.00E+12	1.0	4.80E+4	
3	$H_2 + O <=> H + OH$	2.50E+14	0.00	6.00E+3	$k = A\,(T/T_{ref})^n e^{-E/RT}$
4	$H + O_2 <=> O + OH$	4.00E+14	0.00	1.80E+4	
5	$CO + OH <=> CO_2 + H$	1.51E+07	1.28	–7.58E+2	T_{ref} is a reference temperature
6	$O_2 + H_2O <=> 2O + H_2O$	5.00E+18	0.00	1.12E+5	and R is the ideal gas constant
7	$CO + H_2O <=> CO_2 + H_2$	5.50E+04	1.28	–1.00E+3	

A three-dimensional grid of the igniter flow path was developed (Fig. 9). The flow path modeled the igniter geometry downstream of the valves and included the drills to the fuel and oxidizer manifolds. The fuel manifold is the annular structure surrounding the top of the igniter. The oxidizer manifold is the annular ring with five petals on the top surface of the igniter. The fuel and oxidizer injection elements, the tangential fuel cooling inlets, the combustion chamber, and exhaust tube are modeled as well. The tip of the glow plug was modeled as a constant surface temperature boundary condition.

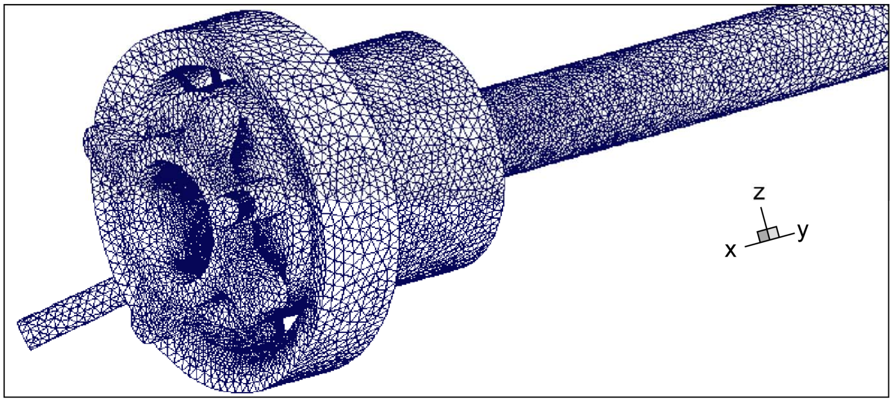


Figure 9.—Three-dimensional computational mesh of igniter geometry.

Experimental Test Results

Prior to conducting ignition tests, tests were conducted with the glow plugs to determine the length of time it took for the glow plugs to reach their maximum tip temperature as well as how maximum tip temperature varied with the voltage applied to the glow plug. The variation in tip temperature with applied voltage is shown in Figures 10 and 11 for a metal and ceramic sheathed glow plug, respectively. Due to the difficulty in bonding a thermocouple to the ceramic sheathed glow plug, the thermocouple was held in place manually during the tests which is responsible for some of the scatter in the data. A comparison of Figures 10 and 11 shows the significantly higher tip temperature achieved with the ceramic sheathed glow plug. The ceramic sheathed glow plug attains this higher tip temperature while operating with less power input than the metal sheathed glow plug. There was no controller used to limit the current to the glow plug for these tests. A typical voltage and current trace for the ceramic sheathed glow plug is shown in Figure 12.

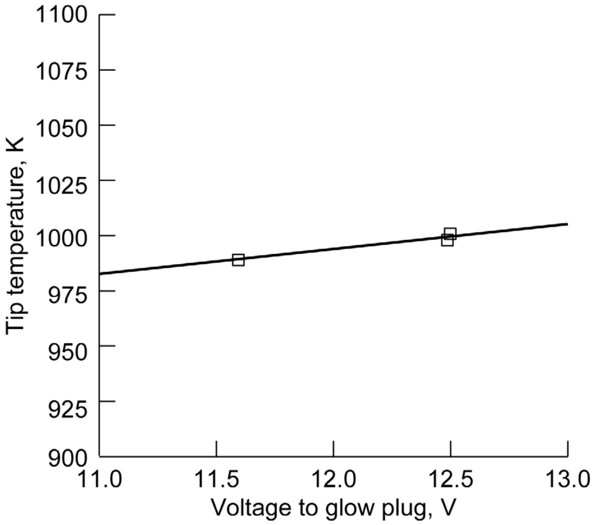


Figure 10.—The tip temperature obtained for the voltage applied to a metal sheathed glow plug.

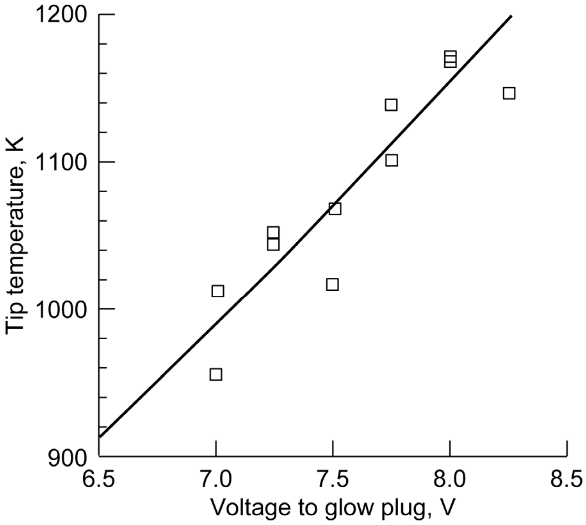


Figure 11.—The tip temperature obtained for the voltage applied to a ceramic sheathed glow plug.

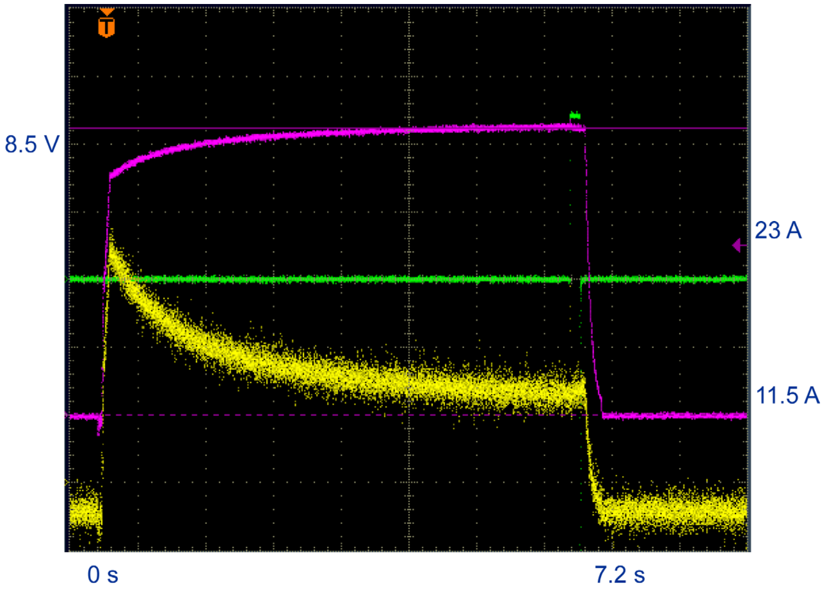


Figure 12.—A typical voltage and current trace for a ceramic sheathed glow plug during an ignition test.

Neglecting the current spike on startup, the ceramic sheathed glow plug required about 83 W and the metal sheathed glow plug required about 127 W. It took 7.2 s for the ceramic sheathed glow plug to attain its maximum temperature and 11 s for the metal sheathed glow plug to reach its maximum temperature.

The first igniter configuration tested was a metal sheathed glow plug with its tip extending approximately a 0.006 m downstream of the igniter face at the head end. This represented the most benign condition for the igniter hardware should ignition be obtained. Various propellant and glow plug timings, mixture ratios, and glow plug voltages were tried but no ignitions were obtained. It is surmised that with this tip forward position, convective effects limit the ability for a high temperature region to be sustained at the tip of the glow plug and thus for combustion to be initiated.

Table 2 presents the ignition test results for an igniter with a ceramic sheathed igniter that was recessed behind the igniter face head end (Fig. 1). The recess used for these tests ranged from 0.014 to 0.016 m. The ceramic sheathed igniter has a higher tip temperature capability than the metal sheathed glow plug. The tests were run with minimal propellant conditioning (warm propellants) and no attempt to lower the igniter body temperature. Between mixture ratios of 9 to 14 all the ignition tests were successful. Below a mixture ratio of 5.8, none of the ignition tests were successful. These tests utilized an oxygen lead in the valve sequencing in order to obtain an oxidizer rich region in the recess near the glow plug tip. The power to the glow plug was initiated typically 7.2 s before the propellant valves were commanded to open.

TABLE 2.—WARM IGNITER AND PROPELLANTS WITH CERAMIC SHEATHED GLOW PLUG WITHOUT NOZZLE

RUN no.	Plug voltage, V	Estimated tip temperature,	W_{O2}, kg/s	W_{CH4}, kg/s	O/F main	O/F head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5024	8	1174	0.068	0.02	3.41	5.66	116	227	0.83	150	245	0.72	N	242
5025	8.5	1231	0.092	0.017	5.44	9.02	99	210	1.12	140	229	0.71	N	230
5026	8.5	1231	0.099	0.016	6.22	10.3	97	232	1.11	140	242	0.72	Y	234
5027	8.5	1231	0.098	0.013	7.54	12.5	94	225	1.11	154	241	0.72	Y	234
5028	8.5	1231	0.102	0.014	7.32	12.1	92	241	1.11	155	251	0.73	Y	239
5029	8.5	1231	0.102	0.016	6.41	10.6	92	221	1.04	146	238	0.71	Y	237
5030	8.5	1231	0.109	0.013	8.44	14.0	95	233	1.19	155	246	0.72	Y	239
5031	8.5	1231	0.098	0.014	7.00	11.6	94	224	1.19	149	240	0.72	Y	242
5032	8.5	1231	0.098	0.015	6.54	10.9	95	231	1.26	144	244	0.72	Y	242
5033	8.5	1231	0.10	0.013	7.71	12.8	92	215	1.26	143	233	0.71	Y	237
5034	8.5	1231	0.103	0.016	6.43	10.7	92	220	1.33	141	235	0.71	Y	234
5035	8.5	1231	0.095	0.013	7.32	12.1	93	221	1.32	141	236	0.72	Y	234
5036	8.5	1231	0.098	0.014	7.01	11.6	93	218	1.40	140	234	0.72	Y	232
5037	8.5	1231	0.102	0.014	7.30	12.1	91	206	1.40	141	225	0.72	Y	226
5042	8.5	1231	0.062	0.010	6.23	10.3	97	225	1.27	158	232	0.73	Y	227
5043	8.5	1231	0.059	0.011	5.36	8.89	97	225	1.27	159	232	0.74	Y	227
5044	8.5	1231	0.059	0.016	3.75	6.22	94	231	1.24	142	241	0.76	N	238
5045	8.5	1231	0.063	0.011	5.77	9.57	95	232	1.24	142	241	0.77	Y	241
5046	8.5	1231	0.065	0.010	6.52	10.8	95	233	1.26	142	237	0.79	Y	224
5047	8.5	1231	0.060	0.013	4.62	7.66	96	211	1.24	143	223	0.85	N	224
5048	8.5	1231	0.068	0.017	4.07	6.75	96	237	1.26	144	243	0.85	N	234
5049	8.5	1231	0.068	0.016	4.34	7.20	93	227	1.24	144	236	0.85	N	235
5050	8.5	1231	0.064	0.013	4.93	8.18	93	209	1.25	151	232	0.71	N	237
5051	8.5	1231	0.061	0.015	4.07	6.75	96	224	1.26	152	234	0.71	N	240
5052	8.5	1231	0.063	0.015	4.21	6.98	92	227	1.27	142	235	0.71	N	241
5053	9.5	1372	0.067	0.017	3.97	6.58	92	223	1.27	152	232	0.73	N	238
5054	9.5	1372	0.059	0.018	3.28	5.44	94	224	1.26	141	232	0.73	N	236

Tests were conducted with a metal sheathed glow plug that had a proprietary platinum based catalytic coating on the tip of the glow plug. The tip of the plug was recessed behind the igniter face. Table 3 shows that there was only one successful ignition. The successful ignition occurred on the first test and it is possible that the coating was damaged on this test (subsequent tests did not ignite).

TABLE 3.—IGNITIONS WITH CATALYTIC COATED METAL SHEATHED GLOW PLUG WITHOUT NOZZLE ON THE BACK

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5071	11	978	0.052	0.009	5.77	9.57	101	235	1.24	142	245	0.71	Y	237
5072	11	978	0.055	0.012	4.58	7.6	100	232	1.25	158	243	0.71	N	239
5073	11	978	0.060	0.015	4.0	6.64	96	239	1.26	167	250	0.69	N	246
5074	11	978	0.056	0.012	4.67	7.75	93	211	1.27	161	234	0.72	N	244
5075	11	978	0.063	0.010	6.3	10.4	90	216	1.27	171	230	0.72	N	234
5076	11	978	0.063	0.008	7.88	13.1	90	216	1.27	171	229	0.71	N	234
5077	11	978	0.071	0.010	7.1	11.8	93	240	1.14	164	249	0.79	N	236
5080	11.5	984	0.056	0.015	3.73	6.19	94	231	1.19	162	242	0.72	N	245

In order to enhance the probability of ignition, a small copper nozzle was bolted onto the back of the igniter (Figs. 7 and 8). This reduced the minimum area of the igniter from 3.9×10^{-5} to 1.54×10^{-5} m^2 which increased cold flow igniter chamber pressure and the heat flux from the tip of the glow plug. The nozzle had a small expansion section downstream of the throat. The results of ignition tests with a recessed, metal sheathed glow plug with the nozzle attached to the back of the igniter are shown in Table 4. Four successful ignitions were obtained above a head end mixture ratio of 9.7 and there were four unsuccessful tests below this mixture ratio range. This was a significant improvement over ignition tests with this glow plug configuration without the nozzle on the back of the igniter. Similarly, tests with a catalytic coated metal sheathed glow plug and the nozzle on the back of the igniter (Table 5) were more successful. Four successful ignitions were obtained compared to one without the nozzle on the back. Run 5225 in Table 5 is labeled as a weak ignition. This indicates that a visible flame and some chamber pressure rise were detected but that the ignition may not have been of sufficient strength to ignite main combustor flows.

TABLE 4.—IGNITIONS WITH METAL SHEATHED GLOW PLUG WITH NOZZLE ON BACK OF IGNITER AND WARM PROPELLANTS

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5194	11.5	984	0.061	0.019	3.21	5.32	99	255	1.31	125	260	1.28	N	234
5195	11.5	984	0.069	0.016	4.31	7.15	93	267	1.59	133	269	1.08	N	236
5196	11.5	984	0.038	0.003	12.7	21.0	116	250	1.59	149	252	1.09	Y	233
5197	11.5	984	0.074	0.013	5.72	9.48	92	256	1.76	148	258	1.09	Y	235
5198	11.5	984	0.073	0.011	6.6	10.9	92	254	1.78	152	259	1.22	Y	235
5199	11.5	984	0.073	0.011	7.82	13.0	90	243	1.79	152	251	1.23	Y	233
5201	11.5	984	0.076	0.015	5.07	8.41	90	254	1.78	152	259	1.22	N	186
5202	12	989	0.078	0.013	5.85	9.70	91	241	1.79	152	247	1.23	N	229

TABLE 5.—IGNITIONS WITH CATALYTIC COATED METAL SHEATHED GLOW PLUG WITH NOZZLE ON BACK OF IGNITER

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5223	12.5	995	051	020	2.55	4.23	111	259	1.78	139	261	1.21	Y	236
5224	12.5	995	067	018	3.72	6.18	96	256	1.92	143	258	1.22	Y	238
5225	12.25	992	068	009	7.55	12.5	95	254	1.93	148	254	1.22	W	236
5226	12.25	992	068	020	3.35	6.03	93	254	1.92	135	256	1.42	N	238
5227	12.5	995	075	021	3.55	5.89	93	250	1.93	132	251	1.42	Y	235
5228	12.25	992	071	021	3.38	5.61	93	249	1.93	134	251	1.43	N	236

The most successful igniter configuration tested consisted of a recessed ceramic sheathed glow plug with the nozzle attached at the end of the igniter (Table 6 and Figure 13). There were 18 successful ignition tests with unconditioned (warm) propellants and cold igniter hardware. There were no unsuccessful tests in this series. Ignitions were obtained over a head end mixture ratio range of 6.3 to 37. Successful ignitions were obtained down to an igniter body temperature of 152 K. This configuration was also tested with conditioned (cold) propellants that were burped recycled and burped through the hardware in order to obtain liquid propellants at the valve inlets. There were 7 successful ignition tests with no failures to ignite (Table 7 and Figure 14). Ignitions were obtained over a head end mixture ratio of 3.8 to 7 and with igniter body temperatures down to 134 K. Additional tests were performed with this configuration to explore the ignition boundaries with regards to ignition. By changing the voltage supplied to the plug, the affects of plug tip temperature could be explored. Figure 15 shows that ignitions were obtained down to a tip temperature of approximately 1015 K. In Figure 16 ignitions are obtained down to a mixture ratio of 2 until they grow progressively weaker until no ignitions are obtained below a mixture ratio of 1.

TABLE 6.—IGNITIONS WITH COLD IGNITER AND WARM PROPELLANTS WITH CERAMIC SHEATHED GLOW PLUG

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5150	8.3	1199	0.063	0.009	7.0	11.7	94	269	1.78	152	266	1.22	Y	236
5151	8.3	1199	0.067	0.003	22.3	37.2	92	253	1.78	164	250	1.23	Y	225
5152	8.3	1199	0.074	0.007	10.6	17.5	90	247	1.78	153	247	1.28	Y	220
5153	8.3	1199	0.070	0.011	6.36	10.6	100	242	1.77	154	241	1.33	Y	213
5154	8.3	1199	0.075	0.015	5.02	8.4	91	236	1.78	153	236	1.33	Y	204
5155	8.3	1199	0.073	0.016	4.56	7.6	96	233	1.80	152	234	1.33	Y	203
5156	8.3	1199	0.064	0.017	3.76	6.3	96	231	1.80	152	230	1.33	Y	198
5157	8.3	1199	0.067	0.016	4.19	7.0	99	228	1.75	153	224	1.33	Y	190
5158	8.3	1199	0.070	0.018	3.89	6.5	91	226	1.80	154	221	1.33	Y	186
5159	8.3	1199	0.075	0.016	4.69	7.8	91	223	1.78	152	218	1.33	Y	176
5160	8.3	1199	0.071	0.015	4.73	7.9	95	214	1.78	153	210	1.33	Y	168
5161	8.3	1199	0.064	0.016	4.0	6.7	91	212	1.78	152	207	1.33	Y	166
5162	8.3	1199	0.068	0.011	6.18	10.3	93	245	1.78	151	241	1.21	Y	210
5163	8.3	1199	0.064	0.01	6.4	10.7	93	233	1.80	151	228	1.21	Y	192
5164	8.3	1199	0.076	0.014	5.42	9.1	103	225	1.76	152	224	1.21	Y	181
5165	8.3	1199	0.054	0.014	3.92	6.5	101	215	1.79	152	212	1.21	Y	165
5166	8.3	1199	0.071	0.014	5.07	8.5	92	210	1.80	152	209	1.22	Y	160
5167	8.3	1199	0.086	0.021	4.09	6.8	99	199	1.79	152	166	1.22	Y	152

TABLE 7.—IGNITIONS WITH COLD IGNITER AND COLD PROPELLANTS WITH CERAMIC SHEATHED GLOW PLUG

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5168	8.3	1199	0.095	0.025	3.78	6.3	88	172	1.77	138	163	1.23	Y	205
5169	8.3	1199	0.071	0.017	4.18	7.0	94	151	1.53	142	172	1.13	Y	190
5170	8.3	1199	0.042	0.018	2.30	3.8	90	125	1.46	137	160	1.12	Y	176
5171	8.3	1199	0.060	0.020	3.00	5.0	100	124	1.52	141	158	1.11	Y	164
5172	8.3	1199	0.051	0.020	2.53	4.2	96	111	1.51	126	149	1.11	Y	155
5173	8.3	1199	0.054	0.016	3.38	5.6	94	115	1.66	134	139	1.25	Y	143
5174	8.3	1199	0.052	0.019	2.73	4.6	90	103	1.66	134	139	1.25	Y	134

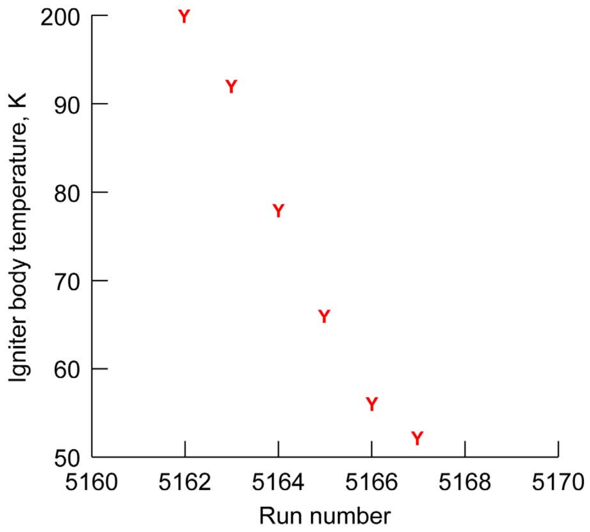


Figure 13.—Igniter body temperature ignition boundary for warm propellants with a recessed, ceramic sheathed glow plug.

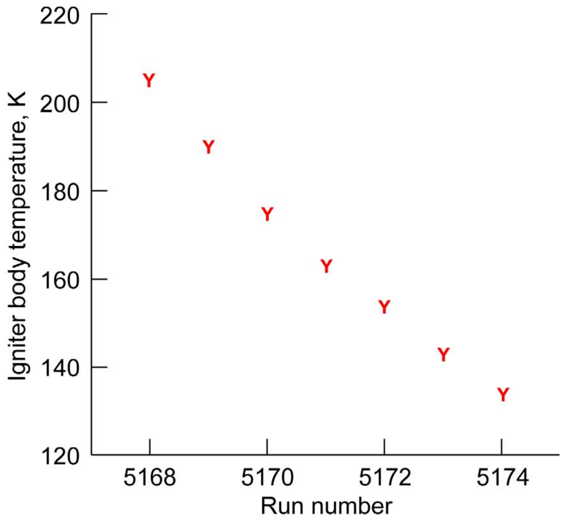


Figure 14.—Igniter body temperature ignition boundary for cold propellants with a recessed, ceramic sheathed glow plug.

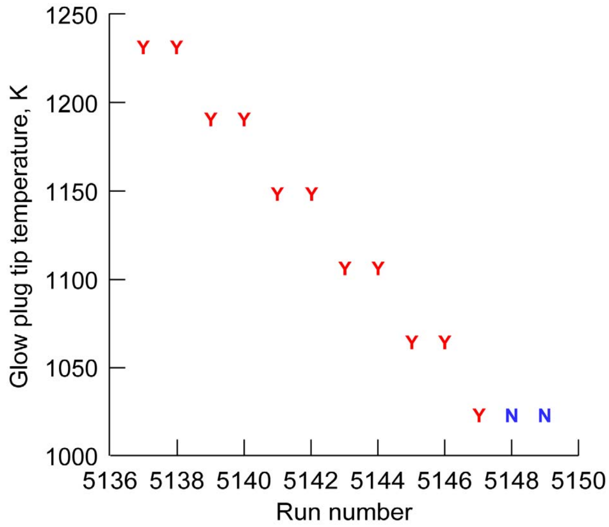


Figure 15.—Ignition boundaries with glow plug tip temperature for a ceramic sheathed glow plug igniter.

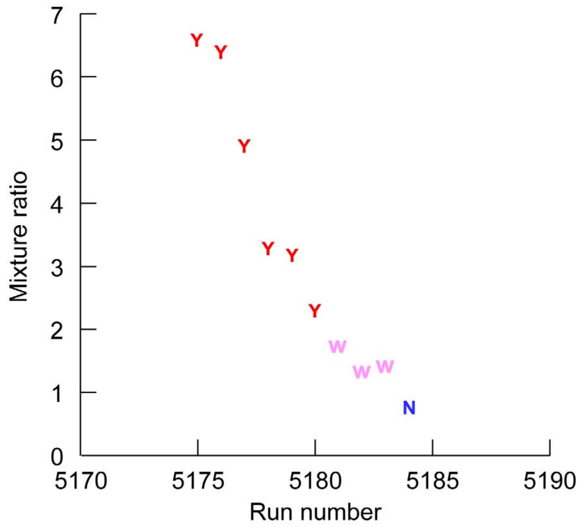


Figure 16.—Ignition boundaries with mixture ratio for a ceramic sheathed glow plug igniter.

Tests were conducted with the metal sheathed glow plug with the nozzle on the back of the igniter with both cold propellants and cold igniter hardware (Table 8). The lowest igniter body temperature at which a successful ignition occurred is much higher than for the ceramic sheathed plug, 194 versus 134 K, respectively. Similarly, the metal sheathed plug started encountering problems igniting around a mixture ratio of 4 compared to a mixture ratio below 1 for the ceramic sheathed glow plug.

TABLE 8.—IGNITIONS WITH METAL SHEATHED GLOW PLUG WITH NOZZLE ON BACK OF IGNITER AND COLD PROPELLANTS

RUN no.	Plug voltage, V	Estimated tip temperature, K	W_{O2}, kg/s	W_{CH4}, kg/s	O/F, main	O/F, head	T_{Oinl}, K	T_{Oinj}, K	P_{Oinl}, MPa	T_{Finl}, K	T_{Finj}, K	P_{Finl}, MPa	light	T_b, K
5203	12.5	995	0.078	0.014	5.57	9.24	91	243	1.78	149	249	1.23	Y	224
5204	12.5	995	0.052	0.010	5.20	8.62	103	268	1.79	149	266	1.22	Y	235
5205	12.5	995	0.063	0.012	5.25	8.71	100	160	1.80	147	183	1.26	Y	203
5206	12.5	995	0.064	0.019	3.37	5.58	96	147	1.79	138	170	1.26	Y	198
5207	12.5	995	0.059	0.017	3.47	5.76	97	145	1.79	140	176	1.25	Y	203
5208	12.5	995	0.048	0.016	3.0	4.98	146	142	1.79	129	156	1.26	Y	193
5209	12.5	995	0.075	0.020	3.75	6.22	93	140	1.96	151	158	1.28	N	187
5210	12.5	995	0.060	0.015	4.0	6.63	96	143	1.79	140	159	1.27	N	194
5211	12.5	995	0.069	0.018	3.83	6.35	93	137	1.80	135	159	1.27	W	201
5212	12.5	995	0.069	0.022	3.13	5.19	92	152	1.81	133	157	1.27	N	199
5213	12.5	995	0.067	0.023	2.91	4.83	93	171	1.80	135	107	1.27	N	204

Tests with both a glow plug and a spark plug mounted in the igniter were conducted. The spark plug tip was mounted flush with the face of the igniter head and the glow plug penetrated the sidewall of the igniter. The glow plug tip was approximately an inch downstream of the igniter face at the centerline of the igniter. When tests were run with this configuration using the glow plug only, no ignitions were obtained. This was most likely due to the severe convective environment at the tip of the plug. When the spark plug was fired, successful ignitions were obtained.

Several glow plugs were damaged during this testing. The ceramic sheathed glow plugs failed once when pushed well beyond their rated voltage and once when ignition was attempted during the heat up (and current transient) of the plug. The ceramic sheaths of these failed plugs sheared off near where the sheath entered the metal body of the plug. A metal sheathed plug failed once during cold body igniter testing. The plug opened up electrically but remained intact.

Computational Results

The two-dimensional grid used to perform computations with varying glow plug tip temperatures and chamber pressures is shown in Figure 17. For these computations, the surface temperature of the glow plug is fixed. In order to accurately capture the heat transfer from the surface of the glow plug tip a very fine grid must be used. The spacing at the tip for the two-dimensional mesh averaged 1.8×10^{-5} m and the spacing for the three-dimensional mesh averaged 2.5×10^{-5} m. These are average mesh spacing's as the mesh varies along the tip due to the nature of unstructured grid generation. The evolution of the flow field from a high thermal gradient at the plug tip to an ignition kernel is shown in Figure 18. The affects of glow plug tip temperature and chamber pressure are shown in Figure 19. As the chamber pressure is increased for a given glow plug tip temperature, ignition delay decreases. At a tip temperature of 1000 K, no ignition occurs. This is similar to what was observed experimentally by varying the voltage supplied to the glow plug (Fig. 15). Figure 20 shows the significant increase in heat flux from the tip as the igniter chamber pressure is increased.

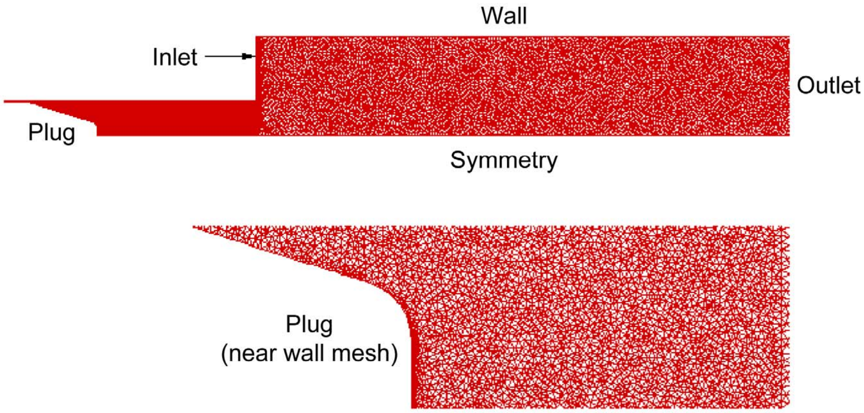


Figure 17.—Two-dimensional grid for CFD simulations of glow plug ignition.

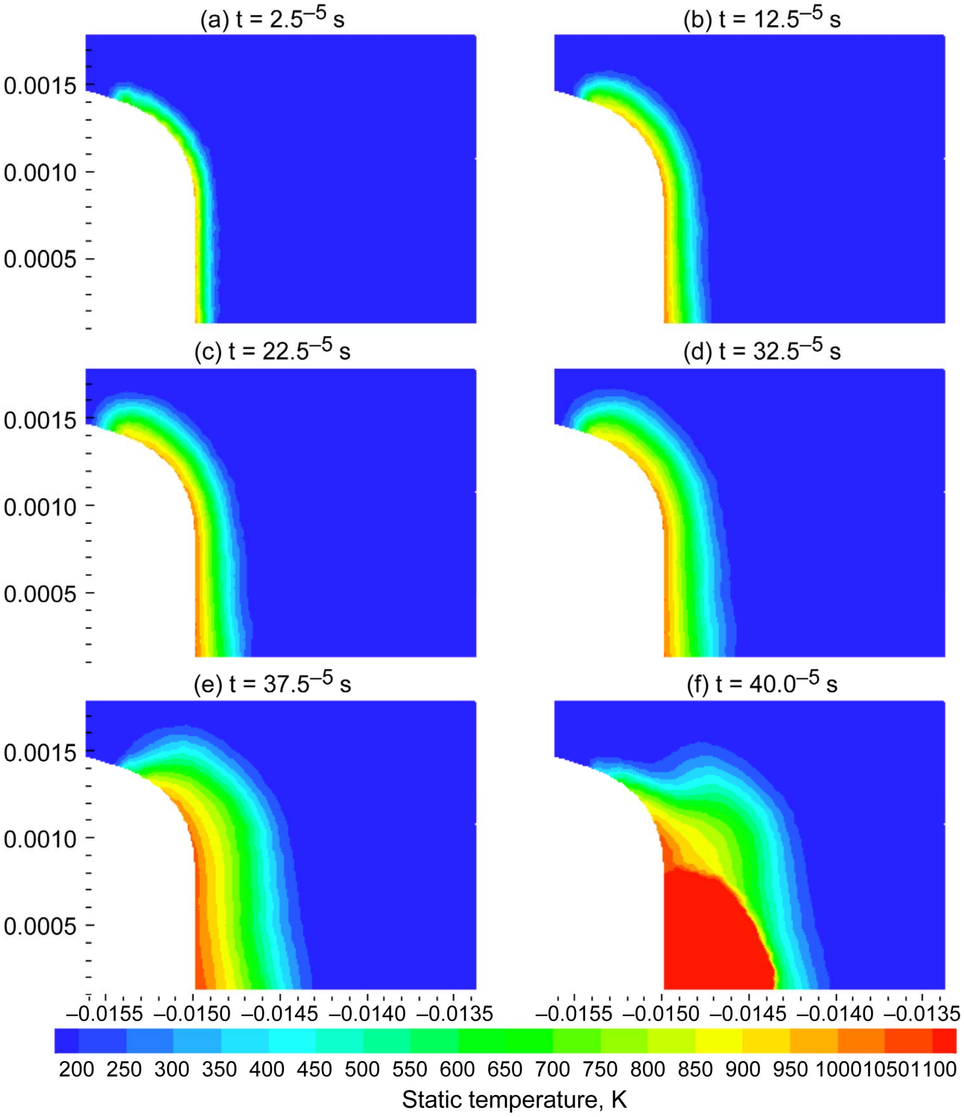


Figure 18.—Flow field development for the two-dimensional glow plug ignition simulation. (Note: negative axial values indicate recess).

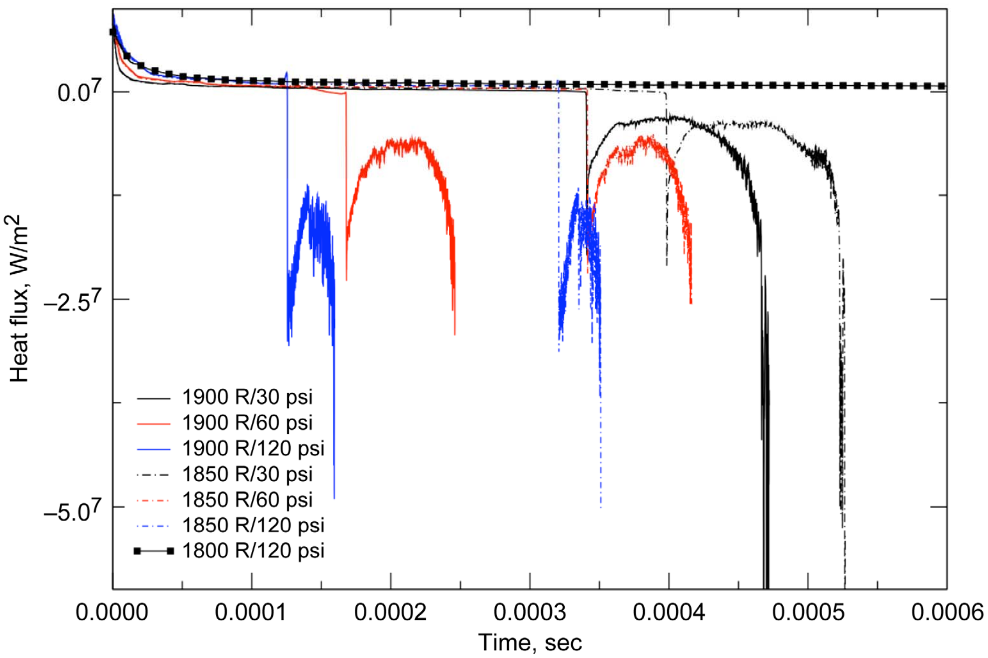


Figure 19.—The change in ignition delay with glow plug temperature and igniter pressure.

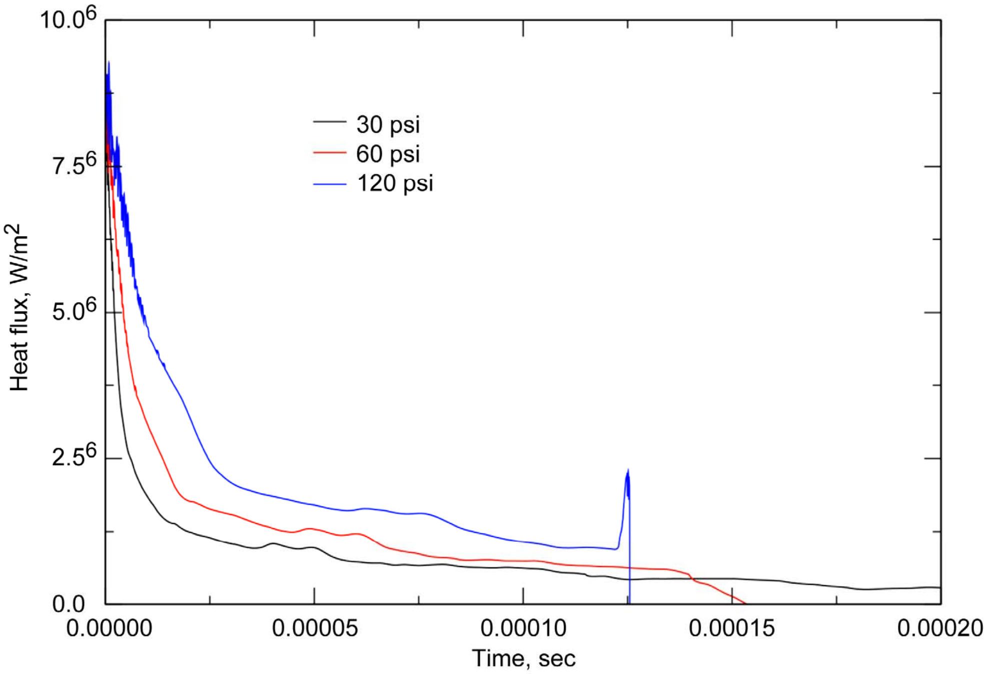
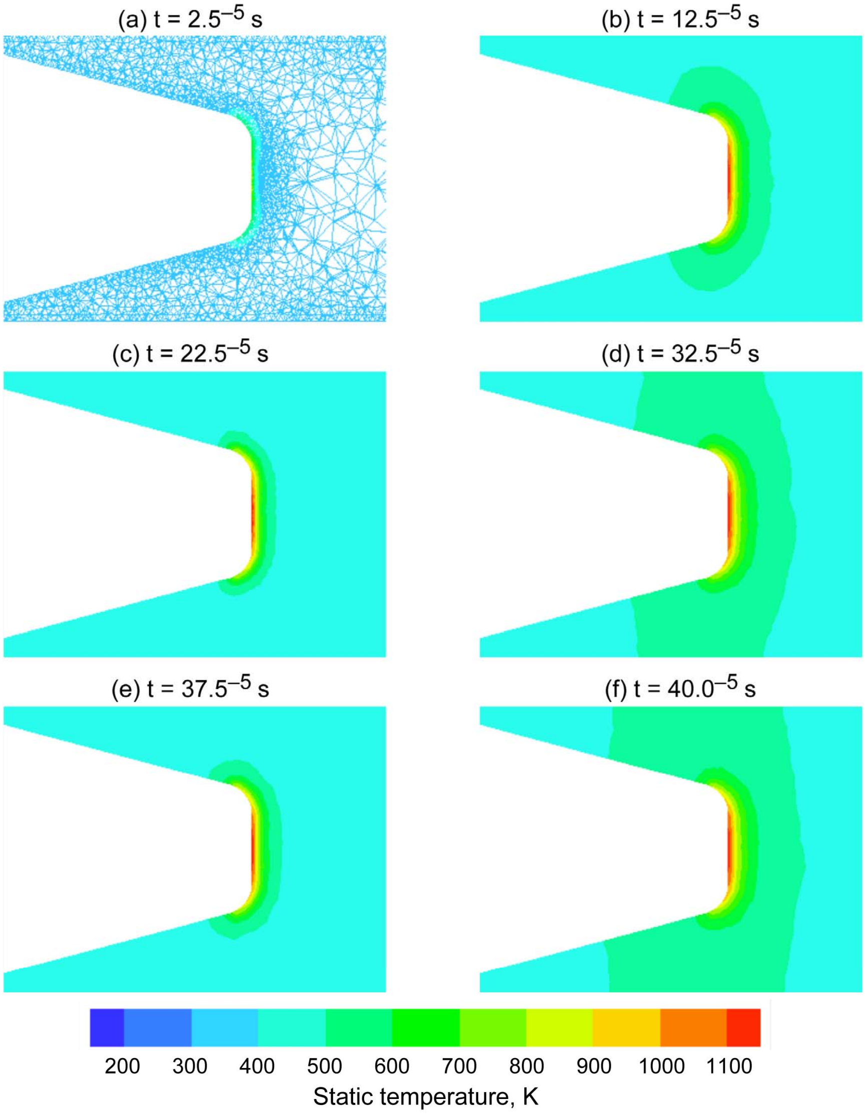


Figure 20.—The variation of glow plug heat flux with igniter pressure.

A three-dimensional computation was also performed after modifying the resolution in the near-wall mesh (shown in Figure 9) to match the near-wall resolution of the two-dimensional grid. The three-dimensional computation allows a more realistic flow field at the plug tip to be modeled than does the two-dimensional case. The three-dimensional computation provides this more realistic computation because it permits the modeling of the true geometries of the injection elements that is not possible to represent accurately in two-dimensions. Thus the three-dimensional computations provide a more realistic picture of the convective and mixture ratio environment at the tip of the plug. A cross-sectional slice of the three-dimensional results is shown in Figure 21. The glow-plug is modeled as a constant-temperature wall at 1100 K. The time-history of the near-wall temperature predicts a quasi-steady state temperature distribution around the glow-plug after 40 ms of flow-through time. In these computations, when the flows through the inlets to the oxidizer and fuel manifolds are started simultaneously, the mixture ratio in the recess near the tip becomes fuel rich rapidly (Fig. 22). This demonstrates why it was necessary to use an oxidizer lead experimentally to obtain successful ignitions.


(a) $t = 2.5^{-5}$ s

(b) $t = 12.5^{-5}$ s

(c) $t = 22.5^{-5}$ s

(d) $t = 32.5^{-5}$ s

(e) $t = 37.5^{-5}$ s

(f) $t = 40.0^{-5}$ s

Figure 21.—Evolution of glow plug tip temperature in the three-dimensional computation.

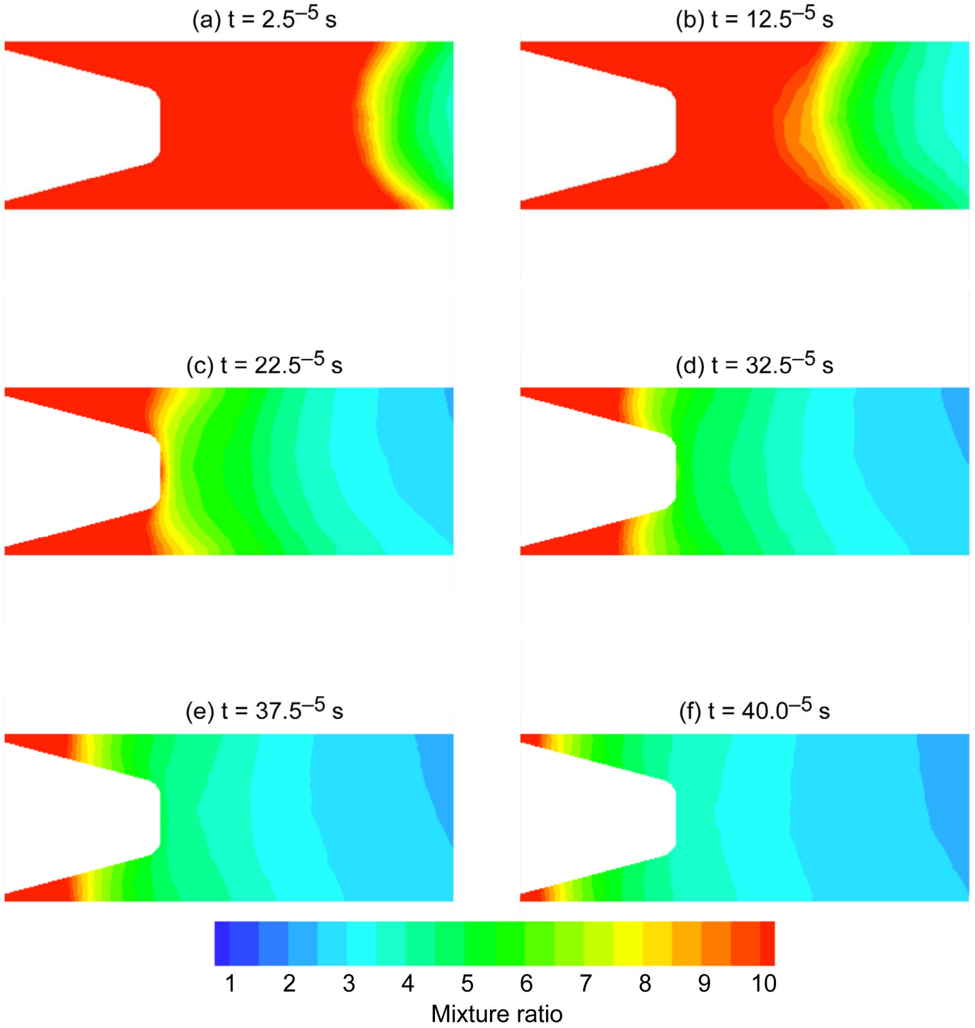


Figure 22.—Evolution of mixture ratio at the glow plug in the three-dimensional computation.

Summary and Discussion

The preliminary feasibility of using a glow plug as a potential secondary ignition source for a LOX/methane lunar ascent engine has been demonstrated. An igniter configuration utilizing a ceramic sheathed glow plug and a proper selection of cold flow igniter chamber pressure was capable of ignitions over a wide mixture ratio range with both warm and cold propellants down to an igniter body temperature of 134 K. The effects of glow plug tip temperature, igniter cold flow pressure, igniter body temperature, mixture ratio, and catalytic surface coatings on ignition boundaries have been evaluated. The CFD simulations of the glow plug igniter were able to capture the glow plug tip temperatures affect on ignition.

The automotive glow plugs used for this testing take a significant amount of time to reach their maximum temperatures (7 to11 s). This may be an issue with the time constraints placed on the engine system envisioned for abort scenarios for the Lunar Surface Access Module. One remedy may be to power up the plugs before any abort would be required. Of course, this would create a potential ignition source in the combustor before and in the event that no order was given to fire the ascent engine. Another potential remedy would be to power the glow plugs so that their tips were hot but not hot enough to be an effective ignition source. In the event of an abort, power could be quickly ramped to the plugs to fire the engine. This was attempted with the plugs during this testing by manually increasing the power supply and appeared to be effective. Of course, if the life constraints placed on automotive glow plugs (~100,000 starts) were relaxed, special purpose plugs could be designed that would shorten ramp time and decrease power consumption.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Ignition data for tests with a LOX/methane igniter that utilized a glow plug as the ignition source are presented. The tests were conducted in a vacuum can with thermally conditioned (cold) hardware. Data showing the effects of glow plug geometry, type, and igniter operating conditions are discussed. Comparisons between experimental results and multidimensional, transient computer models are also made.

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