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QUALITY SYSTEM REGISTERED TO ISO 9001:2000

November 29, 2006

Dr. R. Rhoads Stephenson
Motor Vehicle Fire Research Institute
1334 Pendleton Court
Charlottesville, VA 22901

Subject: SwRI® Project No. 01.06939.01.004

Dear Dr. Stephenson:

Enclosed please find two copies of the above-referenced final report, along with photographic and video documentation. If you should have any questions or comments or if I can be of further assistance, please feel free to contact me at 210-522-5483 or by fax at 210-522-3377.

Sincerely,

Nathan Weyandt
Senior Research Engineer
Engineering and Research Section

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Enclosures:
1) 2 Final Reports
2) 1 Photo CD
3) 1 Video (DVD)

cc: Dr. Kennerly Digges
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IGNITED HYDROGEN RELEASES FROM A SIMULATED AUTOMOTIVE FUEL LINE LEAK

FINAL REPORT
Consisting of 121 Pages

SwRI® Project No. 01.06939.01.004
Final Test Date: September 11, 2006
Report Date: December 1, 2006

Prepared for:

Motor Vehicle Fire Research Institute
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ABSTRACT

Southwest Research Institute's (SwRI) Fire Technology Department, located in San Antonio, Texas, performed a hydrogen release and ignition research program on October 27 and 28, 2005, February 17 and 28, 2006, and September 11, 2006, for the Motor Vehicle Fire Research Institute, located in Charlottesville, VA. The objective of this program was to investigate the hazards associated with ignited hydrogen releases from an automotive fuel system. The hydrogen releases were performed under a sport utility vehicle. Two types of releases were performed: one whereby a known amount of hydrogen was released then ignited, and another whereby a known flow rate of hydrogen was released as a jet-fire for a specified duration.

Two locations of release were used in the test series. One location was on the underside of the vehicle along the driver-side frame rail, near the center of the vehicle, consistent with the vehicle's original gasoline fuel line location. The other location was where the original fuel line bent upwards into the engine compartment; the nozzle pointed towards the underside of the hood.

Releases were controlled manually from within the control room, starting at a nominal 1-sec duration, and doubling up in each subsequent run to a final 256-sec duration release. Release rates were controlled to either a nominal 24 g/min or 48 g/min. The higher flow rate was chosen to provide credible leak rates suggested by a recent study conducted by Parsons Brinkerhoff.[1] The ignition source was an electric match-style pyrotechnic igniter, also activated manually from within the control room.

Measured data included temperature and heat flux on the bottom side of the vehicle, temperature on the interior of the passenger compartment, and four temperatures on the interior of the engine compartment. During the post-release (delayed) ignition tests, pressures were also measured in pursuant tests; one measurement was made on the interior of the engine compartment, and another on each side of the vehicle's perimeter.

Damage to the vehicle was minimal for the majority of tests and consisted mainly of burnt plastic components. Temperatures for short-duration delayed-ignition tests were higher in the location of the release, whether on the underside of the vehicle or in the engine compartment. Temperatures for longer duration delayed-ignition tests, however, were consistently higher in the engine compartment, where more hydrogen could accumulate. Heat flux data followed the same trend as temperature data.

Overpressures were less than 0.25 psig for the underbody releases, and less than 0.1 psig for the 24-g/min releases in the engine compartment. Pressures exceeded 3 psig for the 48-g/min releases in the engine compartment. This pressure, measured during ignition of the 64-sec duration release,

caused significant physical damage to the hood of the vehicle. Even the highest pressure obtained would be expected to dissipate to harmless levels at short distances from the vehicle, as evidenced by the lower pressures (less than 0.5 psig) observed at the rear of the vehicle (furthest sensor). Limited flames vented through the spaces around the vehicle would also present a limited hazard to people in the vicinity.

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1.0 INTRODUCTION

The objective of this program was to investigate the hazards associated with ignited hydrogen releases from an automotive fuel system. The objective was achieved by releasing various amounts of hydrogen on the underside of the vehicle and into the vehicle's engine compartment. The scenarios included tests in which hydrogen was released and then ignited as a flammable cloud producing a flash fire, and tests in which the hydrogen was ignited and released in a jet-fire scenario. Measurements included temperature and heat flux at various locations, as well as the blast wave pressures.

The results presented in this report apply only to the materials tested, in the manner tested, and not to any similar materials or material combinations. The results presented in this report apply specifically to the specimens tested, in the manner tested, and not to the entire production of these or similar materials, nor to the performance when used in combination with other materials.

2.0 TEST SETUP

All setup and testing was performed at Southwest Research Institute's (SwRI's) Fire Technology Department in San Antonio, TX. The Fire Technology Department's large-scale test laboratory consists of a 40 × 60-ft steel-lined building. Tests are controlled and viewed from an attached control room with video and data monitors.

A sport utility vehicle was chosen as the test vehicle, due to its popularity and ease of instrumentation and modification for testing. The vehicle was approximately 178-in. long and 70-in. wide with 11 in. of ground clearance. The vehicle was comprised mainly of plastic panels and components, increasing the chances of ignition.

The gasoline fuel tank and filters were removed from the underside of the vehicle, and the fuel lines were drained of residual gasoline. A hollow steel cylinder was put in place of the gasoline fuel tank to simulate the shape of a compressed hydrogen cylinder. The inside of the open-ended cylinder was used to house portions of the hydrogen release control system.

2.1 Hydrogen Supply System

Hydrogen was supplied from compressed gas cylinders located inside the control room. Each cylinder was placed on a load cell to monitor mass loss during tests. Hydrogen was regulated at the cylinder to give the appropriate line pressure for the desired flow rate. Hydrogen flowed out of the compressed cylinder and to the release control system located in the hollow cylinder mounted on the vehicle.

The release control system consisted of a $^1/_4$-in. pneumatic valve that was opened by pressurization from a control air source. The control air was supplied from a separate compressed gas cylinder and turned on and off by means of an electric solenoid. The solenoid was energized by the test operator from within the control room. This valve system had a response time of approximately 0.5 sec.

When actuated, hydrogen flowed from the pneumatic valve to the nozzle in the desired test location. The nozzle consisted of a brass cap with a $^{1}/_{16}$-in. (1.6-mm) orifice. Two locations on the vehicle were chosen for nozzle mounting, intended to represent possible leak locations for an actual fuel line running from the storage container to the engine. One location was on the undercarriage of the vehicle, just inside the driver-side frame at its nominal midpoint (fore to aft), directed toward the front of the vehicle. The other location was inside the engine compartment, 5-$^{1}/_{2}$ in. from the passenger firewall and 16 in. below the hood, directed towards the hood's nominal center. This location was where the normal gasoline fuel line bent up into the engine compartment.

2.2 Instrumentation

A 200-psig strain-gauge static pressure transducer was placed in-line near the nozzle to monitor the hydrogen release time and pressure. The accuracy of the sensor was within ± 1 psig, and a response time was 3 ms. Structural components on the underside of the vehicle were instrumented with eight combination thermocouple (TC)/heat flux sensors. These sensors were Kapton thin-film sensors with dual Type "K" thermopiles to measure a temperature gradient. The sensors were capable of measuring up to 30,000 Btu/ft^{2}hr (95 kW/m^2), and had a response time of 0.7 sec. Four 24-ga, exposed-bead, Type-"K" TCs measured the temperature near the top of the engine compartment at the hood's nominal quadrants. These TCs had a response time of less than 1 sec.

The hydrogen concentration inside the engine compartment was measured in two tests with a portable 10 ppm – 100-percent thin-film solid-state sensor calibrated specifically for hydrogen, located at the nominal center of the hood. The accuracy of this sensor was reported as ± 2 percent hydrogen, and the response time was approximately 8 sec.

For post-release (delayed) ignition tests, in which a mass of hydrogen was expected to accumulate in cavities underneath the vehicle, blast pressure probes were placed around the vehicle. One probe was located 6 in. off the ground on each side of the vehicle, with its sensor aligned with the vehicle's perimeter; another probe was located in a cavity at the front of the engine compartment with its sensor located 6 in. below the hood. In one test, another sensor was located 11 ft in front of the vehicle to measure pressures in the far field.

The blast pressure probes consisted of 35-psig piezoelectric transducers enclosed in an aerodynamic pencil-shaped housing. The sensors have a rise time of less than 4 μs and an accuracy of 0.2 psig. This type of sensor shows a negative pressure value when exposed to high temperatures; the stated temperature coefficient of sensitivity is ≤ 0.03 %/°F. Data from the sensors was continually logged in a buffer at a rate of 10 to 15 kHz, and data was saved on an automatic trigger (1 psig) or on a manual trigger by the test operator.

A thermal imaging camera with a wavelength response of 8 to 14 microns was used to view and record the size and shape of the hydrogen deflagration and jet-fires. Documentation also included two standard video views and digital photographs. Relevant digital photographs are included in Appendix F. Figure 1 below, depicts the instrumentation layout along with the locations of the release nozzle.

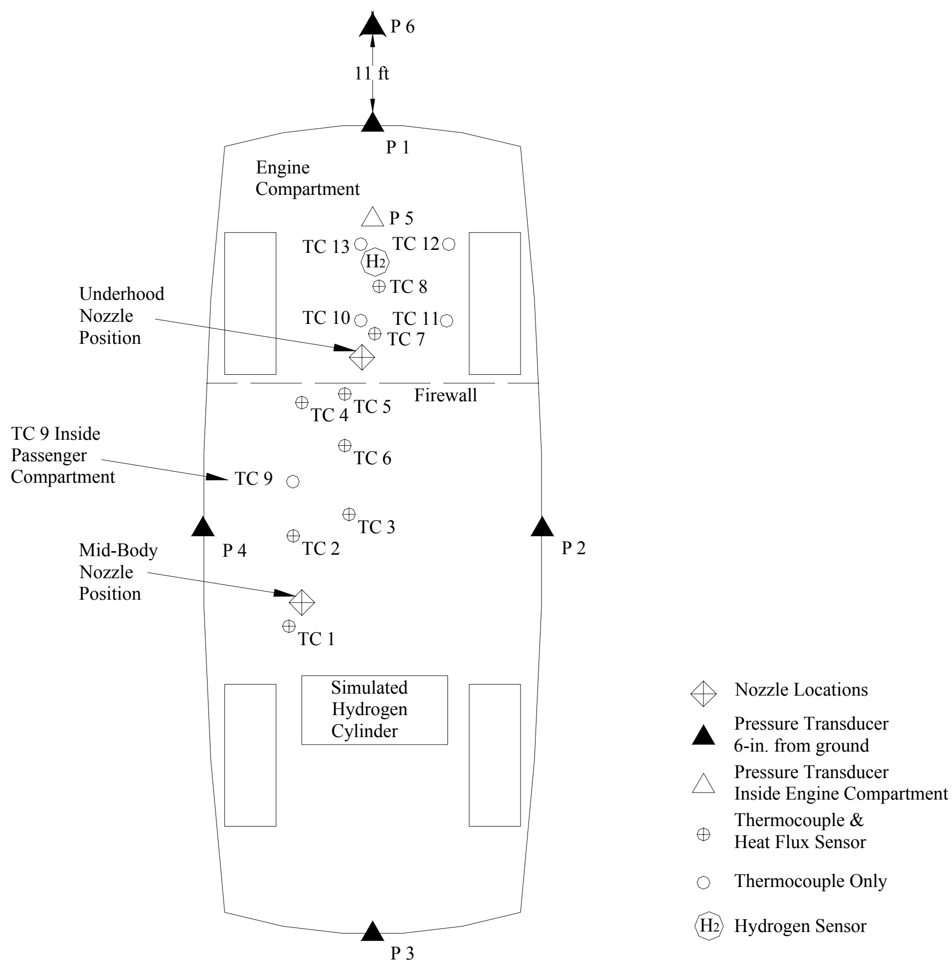


Figure 1. Instrumentation Layout and Nozzle Locations (Not to Scale).

2.3 Ignition System

The ignition source was an electric match-style pyrotechnic igniter. Each igniter consisted of 0.16-g of lead mononitroresorcinate. The igniter was placed between 6 and 12 in. in front of the nozzle and connected to a switched 6 V source in the control room via coaxial cable. The test operator manually activated the igniter from inside the control room by engaging the voltage source.

2.4 Nozzle Release System Calibration

Prior to testing, the nozzle system was set up with the pressure transducer to release hydrogen in an open building. The nozzle pressure was monitored as the weight loss from the hydrogen cylinder was recorded on a precision balance. The nozzle was found to release 53 g/min at 107 psig and 62 g/min at 120 psig. This two-point calibration was used to extrapolate flows from the nozzle at pressure near these points (above 90 psig). For lower nozzle pressures (nominal 50 psig), the intercept was forced to zero (0 psig, 0-g/min) to obtain more accurate values.

3.0 TEST PROCEDURES

Tests were performed on October 27 and 28, 2005, February 16 and 28, 2006, and September 11, 2006. Two similar test procedures were used for the post-release ignitions and ignited jet fires. In both procedures, the objective was to determine the effects of an ignited release, not to determine the likelihood of ignition. Two nominal flow rates were used, 48 g/min and 24 g/min.

A flow of 48 g/min was chosen to provide results comparable to a recent study conducted by Parsons Brinkerhoff [1] for the California Fuel Cell Partnership. This study used a maximum of 20-cfm (47-g/min) flow rate, because they assumed this magnitude of flow would be easily detectible such that the fuel system could be automatically shut down. This flow rate was provided as the expected hydrogen consumption by a vehicle operating at its maximum power.[1] The value of 24 g/min was chosen to observe the effect of leak rate, as opposed to total flow, on the experimental results. Release durations started at a nominal 1-sec release and doubled up to a nominal 256-sec release. The actual release rates and durations were calculated from pressure transducer data.

3.1 Post-Release Ignition Tests

In the post-release (delayed) ignition tests, hydrogen was released for increasing durations through the nozzle. The test controller initiated ignition while closing the hydrogen release valve. Observations of the test vehicle were made and the electric igniter was replaced after each test.

Three initial series of post-release ignition tests were performed. Series 1 was performed with the nozzle located on the underside of the vehicle along the driver-side frame rail. The nozzle pressure resulted in an average flow rate of 45 g/min throughout this series of tests. The nominal duration of the releases varied from 1 sec to 128 sec.

Series 2 and 3 were performed with the nozzle located inside the vehicle's engine compartment. The nozzle pressure resulted in an average flow of 47-g/min throughout Series 2, and 24 g/min in Series 3. The nominal duration of the releases varied from 2 sec to 128 sec for Series 2, and from 1 sec to 256 sec for Series 3.

Follow-up tests were performed to the Series 1, 2 and 3 test parameters. Instrumentation was reduced with the intent of gathering pressure data only. Prior to performing the follow-up tests, the rise of hydrogen concentration to a steady-state value was measured inside the engine compartment under the conditions of Series 1, 2 and 3. Hydrogen release was begun and continued until data indicated that a steady-state value had been reached. At that point, the hydrogen flow was stopped without attempting ignition. Figure 2 shows the rise in hydrogen concentration over time under Series 1, 2 and 3 conditions.

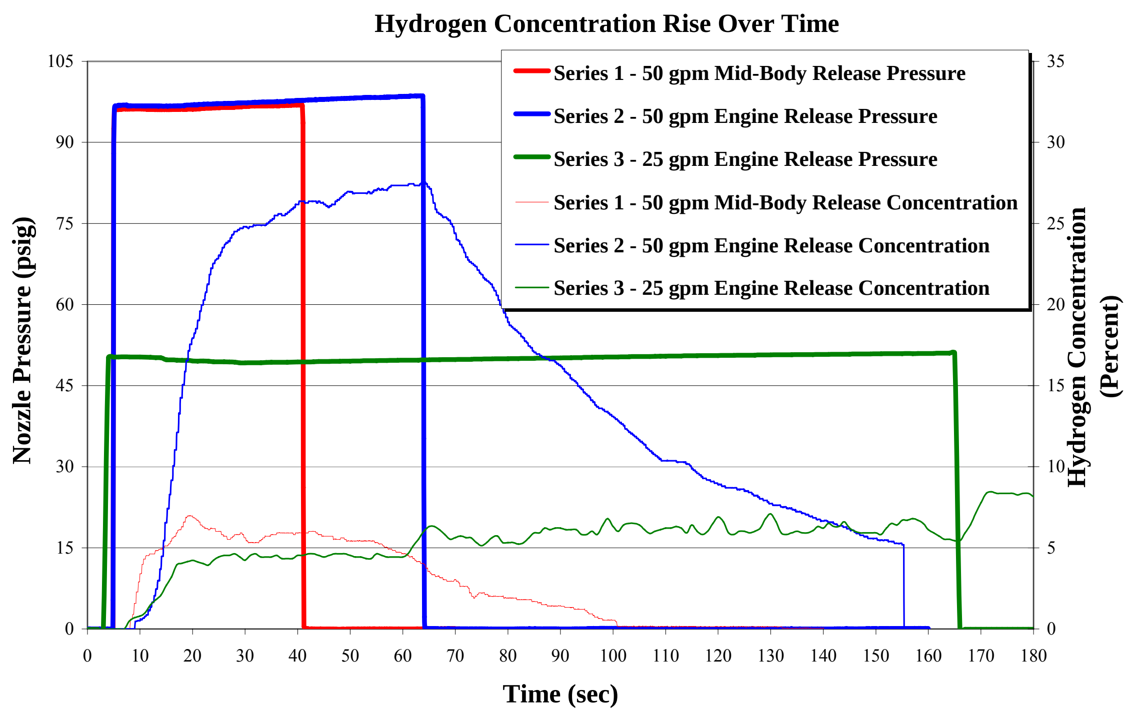


Figure 2. Engine Compartment Hydrogen Concentration Rise to Steady-State Values.

3.2 Jet-Fire Release Tests

In the jet-fire release tests, hydrogen was released for increasing durations through the nozzle. The test controller initiated ignition as soon as hydrogen began flowing from the nozzle. After each test, observations of the test vehicle were made, and the electric igniter was replaced for the following test.

Two series (Series 4 and 5) of jet-fire release tests were performed. In Series 4, the nozzle was located inside the engine compartment pointing upwards into the hood. The nozzle pressure resulted in an average flow of 48 g/min throughout the series. For Test No. 1, the hood was left open so that observations of the uninhibited flame could be made. For Test No. 2 through 4, the hood was closed, and the nominal duration of releases varied from 4 sec to 16 sec.

For Series 5, the nozzle was located on the underside of the vehicle along the driver-side frame rail. The nozzle pressure resulted in an average flow rate of 47 g/min throughout this series. The nominal release duration varied from 4 sec to 32 sec.

4.0 RESULTS

Results are discussed in terms of the nominal release times outlined in the Test Procedures section. A tabular summary of results is presented in Tables 1 through 4. It should be noted that response time of the TCs was not sufficient to accurately measure the deflagration temperatures in Test Series 1, 2 and 3, and only provide an indication of relative fireball size and duration.

4.1 Series 1: Mid-Body Post-Release (Delayed) Ignition Tests

At a release rate of 48 g/min, hydrogen concentration briefly peaked at approximately 7.0 percent before returning to its steady-state value of 5.9 percent in approximately 9 sec. Graphical data for Series 1 is included in Appendix A. Lower duration tests (less than 8 sec) during Series 1 showed the highest temperature spikes in the immediate vicinity of the release. A transition was evident in the data for the 8-sec duration test, and tests with a duration greater than 8 sec showed the highest temperature spikes in the engine compartment. This is probably due to the larger volume of hydrogen that accumulated in the engine compartment.

Blast wave pressures were not measured due to false triggers during the original Series 1 tests. The lack of automatic triggering of the transducers suggests that a pressure of greater than 1 psig was not achieved at any of the locations. A follow-up series was performed in order to obtain actual pressure data. The data acquisition system was manually triggered upon initiation of the igniter. All pressures measured were below the 1-psig threshold required for automatic triggering of the system.

With one exception, the highest pressures were consistently obtained at the driver-side and passenger-side locations. These pressures were typically on the order of 0.1 psig. Pressure in the interior of the engine compartment measured below 0.05 psig up to the 32-sec duration release, 0.09 psig for the 64-sec duration release, and 0.19 psig for the 128-sec release (when it exceeded the two side locations). The front and rear location pressures consistently measured below 0.05 psig with the exception of the last test in which they measured 0.07 psig and 0.08 psig, respectively. Figure 3 shows the maximum pressures obtained at each location during the Series 1 tests.

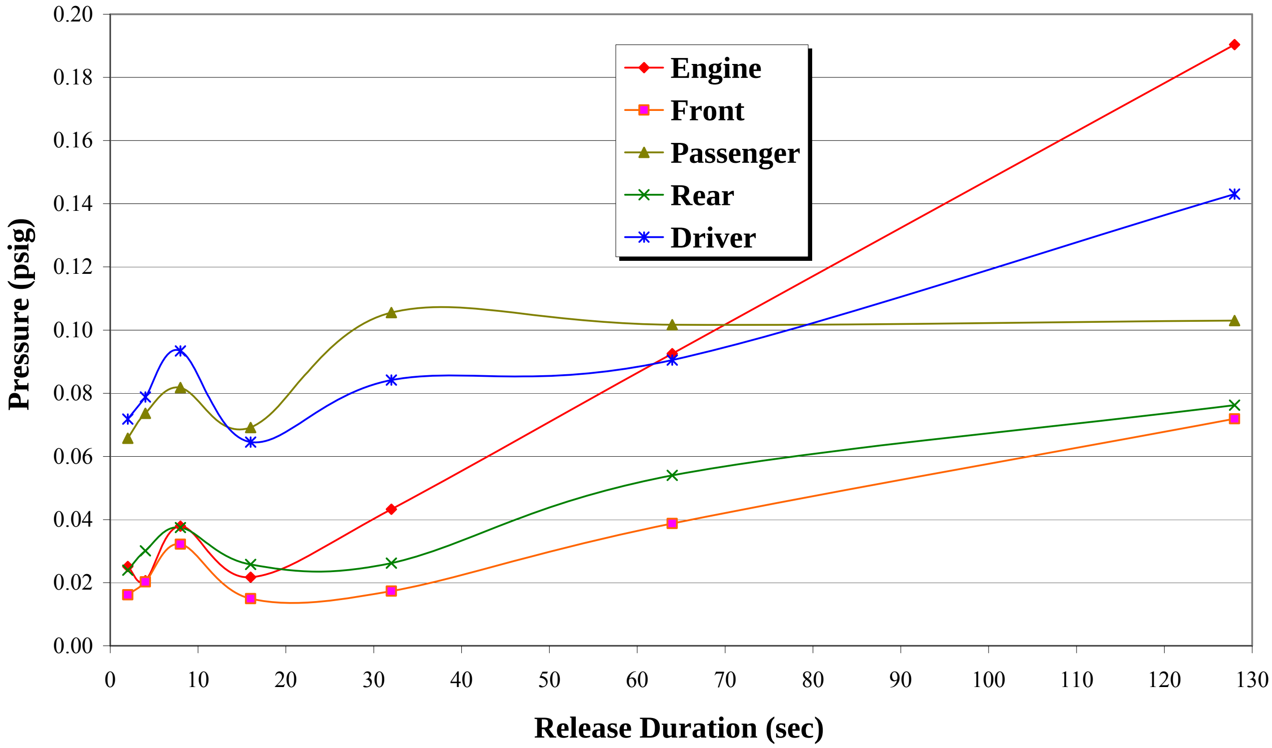


Figure 3. Maximum Blast Pressures Obtained During Series 1 Tests.

4.2 Series 2: Engine Compartment Post-Release (Delayed) Ignition Tests

At a nominal release rate of 48 g/min, hydrogen concentration appeared to reach its peak value of 27 percent after approximately 50 sec of hydrogen flow, as seen in Figure 2. Graphical data for Series 2 is included in Appendix B. Each test during Series 2 showed the highest measured temperature spikes in the engine compartment of the vehicle, averaging on the order of 400°F, well below actual flame temperatures. Most TCs on the underside of the vehicle showed insignificant temperature rises. TC 8, located just underneath the engine compartment, showed slight increases in 2-sec duration and longer releases, but reached a temperature of only 100°F at its maximum.

The pressure transducers were only triggered and recorded during one of the original Series 2 tests (16-sec duration). Figure 4 shows the pressure measured during this test. Note that this is also the only test for which the blast wave was measured 11 ft away.

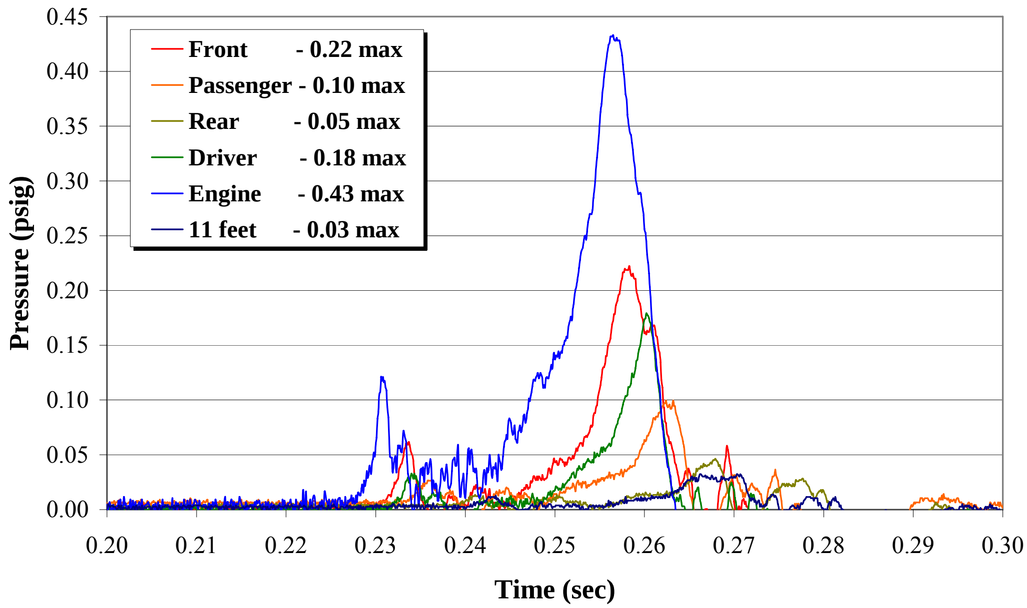


Figure 4. Initial Series 2 Tests – 16-Sec Hydrogen Release Ignition Pressure Data.

The lack of automatic triggering of the transducers during the remainder of the tests suggests that a blast pressure up to 1 psig was not achieved at any of the locations. A follow-up series was performed in order to obtain actual pressure data. The data acquisition system was set up to trigger upon initiation of the igniter.

Blast wave pressures were significantly higher in Series 2 than in Series 1. The highest pressures were consistently obtained inside the engine compartment. Engine compartment over-pressures ranged from 0.14-psig (2-sec duration) to 3.2-psig (64-sec duration) at this location. The next highest pressures were obtained at the front of the vehicle (up to 2.08 psig) followed by the passenger and driver sides, and finally the rear of the vehicle. Most tests resulted in little to no damage to the vehicle. The pressure rise time in the 64-sec duration test was about 10 ms. Pressure rise times between 15 and 20 ms were recorded in the tests with lower peak pressures. The overpressure during the 64-sec duration leak caused severe deformation of the hood and loosening of the passenger side fender. This is contrary to the results of the 64-sec duration leak from the original Series 2 tests in which no significant damage occurred. Furthermore, several pressures in excess of 1 psig were recorded for releases of 8 sec or greater duration during the follow-up tests.

Figure 5 shows the blast wave pressures measured with respect to hydrogen-release duration for the Series 2 tests. Figure 6 depicts the damage that occurred to the hood during the 64-sec release test.

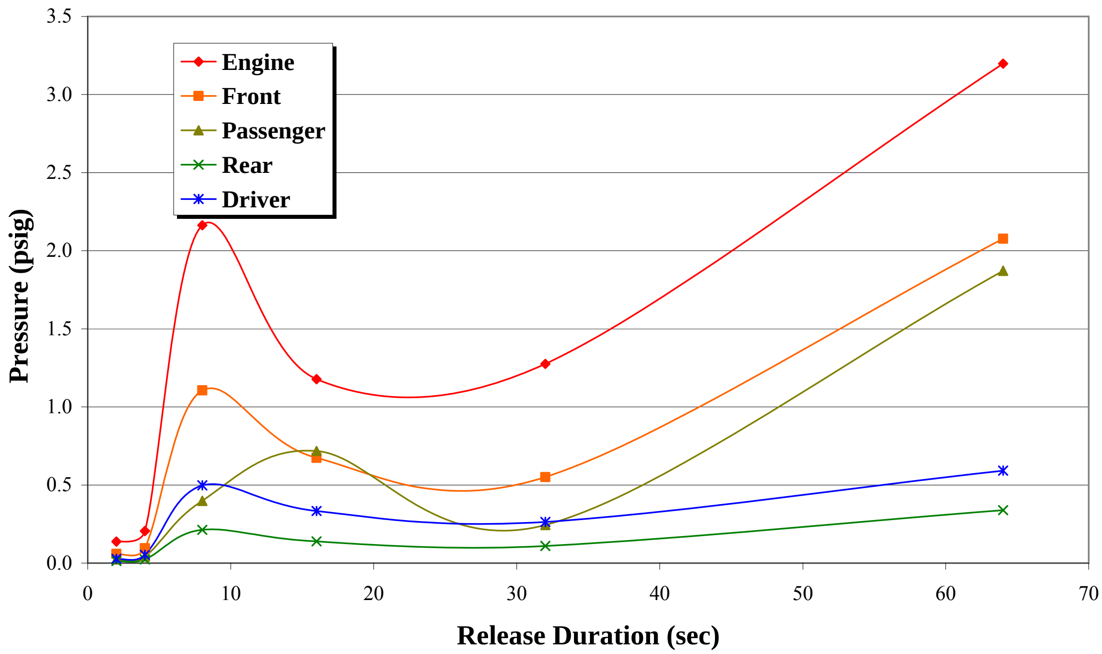


Figure 5. Maximum Pressures Obtained During Series 2 Tests.

Figure 6. 64-Sec Duration Test – Damage to Hood Following Series 2 Tests.

4.3 Series 3: Engine Compartment Post-Release (Delayed) Ignition Tests - Half Flow Rate

At a release rate of 24 g/min, hydrogen concentration appeared to reach its steady-state value of 6.2 percent in approximately 65 sec, as indicated in Figure 2. Graphical data for Series 3 is included in Appendix C. Temperature trends during Series 3 were similar to those in Series 2, although the maximum measured temperature in the engine compartment averaged only about 250°F. The highest measured underside temperature (TC 8) reached 95°F at its maximum.

Over pressures were not measured due to false triggers during the original Series 3 tests. The lack of actual triggering of the transducers suggests that a blast pressure up to 1 psig was not achieved at any of the locations. A follow-up series was performed in order to obtain actual pressure data. The data acquisition system was setup to trigger upon initiation of the igniter.

Pressures measured in Series 3 were rather insignificant. The highest pressures were consistently obtained within the engine compartment, but none of the pressures exceeded 0.05 psig.

4.4 Series 4: Engine Compartment Jet Fire Tests

Graphical data for Series 4 is included in Appendix D. The 48-g/min hydrogen jet-fires in Series 4 impinged directly on the underside of the hood of the engine compartment in all but the first test. The TC in the direct path of the jet-fire recorded a temperature above 2200°F in each test. Temperatures on the underside of the vehicle did not increase appreciably.

In Test No. 1, the visible jet fire appeared to reach 16 in. outside of the engine compartment, for a total length of approximately 32 in. from the nozzle. After a jet fire of 5.2 sec, the liner on the underside of the hood ignited. After the 9.8-sec duration jet fire, a plastic harness showed obvious deterioration, there was a hole in the hood liner, and the exterior of the hood showed slight warping and paint bubbling. After a 17.8-sec duration, the plastic harness was completely consumed, copper wires were severed, and the exterior of the hood was discolored with more warping and paint bubbling.

The peak engine compartment heat flux measured in the 8-sec duration engine jet fire test was about 3400 Btu/ft^{2}hr (11 kW/m^2). Measured heat fluxes were substantially lower in the other Series 4 tests.

4.5 Series 5: Mid-Body Jet-Fire Tests

Graphical data for Series 5 is included in Appendix E. The 48-g/min jet-fires in Series 5 impinged along the frame, fuel lines, and into plastic support components. Minimal damage occurred to the vehicle in this series. The jet-fire quickly destroyed the delicate combination TC/heat flux sensor in its direct path (TC 3), and only intermittently measured the jet-fire temperature of about 2200°F.

Even in the shortest duration test, the fuel lines were red hot and the plastic support brackets continued to burn following the test. For longer jet-fire durations, the fuel lines remained red hot for a longer period. After the final duration of 33 sec, the plastic bracket had been mostly consumed, but no other damage around the vehicle was evident. Peak heat fluxes measured in Series 5 tests were about 3600 Btu/ft^{2}hr (11 kW/m^2) as indicated in Table 1.

Table 1. Series 1-5 Test Temperature and Heat Flux Results Summary.

Series 1 - 48-g/min Mid-Body Post-Ignited Releases

Duration (s)	H2 Press (psig)	Flow (g/min)	Mass (g)	Max Temp °F	Max Flux Btu/ft^{2}hr
1.5	94.8	44.6	1.1	116	2923
2.6	94.7	44.5	1.9	92	3237
4.6	94.8	44.5	3.4	147	3425
8.4	94.8	44.6	6.2	165	3393
16.5	95.2	44.8	12.3	175	2852
32.5	95.9	45.3	24.5	183	3245
62.6	97.4	46.3	48.3	216	3374
64.5	100.6	48.6	52.2	210	3157
128.3	99.8	48.0	103	221	3060

Series 2 - 48-g/min Engine Compartment Post-Ignited Releases

Duration (s)	H2 Press (psig)	Flow (g/min)	Mass (g)	Max Temp °F	Max Flux Btu/ft^{2}hr
2.1	97.8	46.6	1.6	407	21
4.5	98.3	47.0	3.5	440	1306
8.9	98.0	46.7	6.9	521	3082
16.8	97.6	46.5	13.0	387	3163
32.9	96.0	45.4	24.9	395	3259
64.6	96.1	45.5	48.9	376	2775
64.6	102.0	49.5	53.3	323	3010
128.5	99.6	47.9	103	287	2451
131.8	105.9	52.3	115	614	2817

Series 3 - 24-g/min Engine Compartment Post-Ignited Releases

Duration (s)	H2 Press (psig)	Flow Rate (g/min)	Mass (g)	Max Temp °F	Max Flux Btu/ft^{2}hr
1.8	46.9	23.2	0.70	125	14
2.8	47.5	23.5	1.1	155	17
4.7	47.8	23.7	1.9	236	51
8.5	48.4	24.0	3.4	249	1068
16.7	48.3	23.9	6.66	302	3251
32.8	48.6	24.1	13.2	289	3001
64.6	49.4	24.4	26.3	295	2217
128.6	50.7	25.1	53.8	327	2791
256.6	50.2	24.9	106	288	2993

Series 4 - 48-g/min Engine Compartment Jet-Fire Releases

Duration (s)	H2 Press (psig)	Flow Rate (g/min)	Mass (g)	Underhood Max Temp (°F)	Max Flux Btu/ft^{2}hr
6.9	99.2	47.6	5.47	2263	49
5.2	99.9	48.1	4.17	2372	102
9.8	99.2	47.6	7.77	2370	3365
17.8	99.9	48.1	14.3	2235	361

Series 5 - 48-g/min Mid-Body Jet-Fire Releases

Duration (s)	H2 Press (psig)	Flow Rate (g/min)	Mass (g)	Underbody Max Temp (°F)	Max Flux Btu/ft^{2}hr
4.9	98.5	47.1	3.85	1320	3594
9.9	97.6	46.5	7.68	1944	3614
17.6	98.0	46.8	13.72	2257	3464
33.4	97.7	46.6	25.9	2239	3618

Table 2. Series 1 – Follow-Up Test Blast Pressures.

Duration	**48-g/min Underbody Release Blast Pressures (psig)**				
(sec)	Engine	Front	Passenger	Rear	Driver
2	0.03	0.02	0.07	0.02	0.07
4	0.02	0.02	0.07	0.03	0.08
8	0.04	0.03	0.08	0.04	0.09
16	0.02	0.01	0.07	0.03	0.06
32	0.04	0.02	0.11	0.03	0.08
64	0.09	0.04	0.10	0.05	0.09
128	0.19	0.07	0.10	0.08	0.14

Table 3. Series 2 – Follow-Up Test Blast Pressures.

Duration	**48-g/min Engine Compartment Release Blast Pressures (psig)**				
(sec)	Engine	Front	Passenger	Rear	Driver
2	0.14	0.06	0.02	0.01	0.03
4	0.21	0.10	0.04	0.02	0.05
8	2.16	1.11	0.40	0.21	0.50
16	1.18	0.67	0.72	0.14	0.33
32	1.28	0.55	0.24	0.11	0.26
64*	3.20*	2.08	1.87	0.34	0.59

***Hood Damaged**

Table 4. Series 3 – Follow-Up Test Blast Pressures.

Duration	24-g/min Underbody Release Blast Pressures (psig)				
(sec)	Engine	Front	Passenger	Rear	Driver
2	0.04	0.015	*	*	*
4	0.02	*	*	*	*
8	0.04	0.015	*	*	*
16	0.02	0.015	0.01	*	0.01
32	0.04	0.015	*	*	0.01
64	0.05	0.025	0.015	*	0.01
128	0.02	0.015	*	*	*

*** Insignificant pressure data obtained (< 0.01 psig).**

5.0 CONCLUSIONS

Several generalizations could be made about the tests performed. Only minor overpressures (less than 0.20 psig) were measured from releases on the underbody of the vehicle, and for the low flow rate (24-g/min) releases in the engine compartment. These pressures are not typically considered high enough to cause bodily harm or window breakage. Overpressures nearest the underbody release remained relatively constant with increased duration due to the lack of confinement areas for hydrogen accumulation. At longer durations, the overpressure on the interior of the engine compartment did increase for the underbody releases, although not enough to cause any apparent damage to the vehicle.

Higher overpressures were measured at all locations with high-flow (48-g/min) releases of hydrogen in the interior of the engine compartment. This is due to the fact that the peak concentration obtained during this type of release (27% hydrogen) is only slightly less than the stoichiometric mixture (30% hydrogen).[2] Pressures in excess of 3 psig were experienced in the engine compartment, and pressures on the order of 2 psig were experienced on the perimeter of the vehicle near the ground. The SFPE Handbook of Fire Protection Engineering estimates threshold pressures for glass breakage at approximately 1 psig, and for eardrum rupture at approximately 2 psig.[3] However, even the highest overpressures measured at the base of the car would be expected to dissipate to levels of only minor discomfort after several car lengths.

Significant physical damage only occurred to the vehicle during the 64-sec duration 48-g/min engine-compartment hydrogen release during the follow-up tests. It appeared as though the majority of pressures measured in the follow-up Test Series 2 were higher than the initial Test Series 2, as they were above the threshold trigger value. This was in spite of the fact that the tests were performed to identical parameters. Possible explanations include different hydrogen accumulations due to ignition timing discrepancies or slight differences in nozzle placement or orientation.

High temperatures were evident in the areas of the hydrogen release, and in areas such as the engine compartment, in which the hydrogen could collect. However, these temperatures were brief in the delayed ignition tests, insufficient to ignite surrounding exterior components. In the jet-fire tests, temperatures and heat fluxes were obviously of a magnitude and duration that could cause severe burns or ignite most plastic components. The extent of a jet-fire hazard would ultimately depend on the size, location, and direction of leak. At no time, however, was there a significant rise of temperature in the passenger compartment of the automobile.

6.0 REFERENCES

[1] Parsons Brinkerhoff, California Fuel Cell Partnership Commissioned Technical Report, *Support Facilities for Hydrogen-Fueled Vehicles.* July, 2004. p. ES-2.

[2] Underwriters Laboratories, UL 60079-1, *Electrical Apparatus for Explosive Gas Atmospheres – Part 1: Flameproof Enclosures "d."*

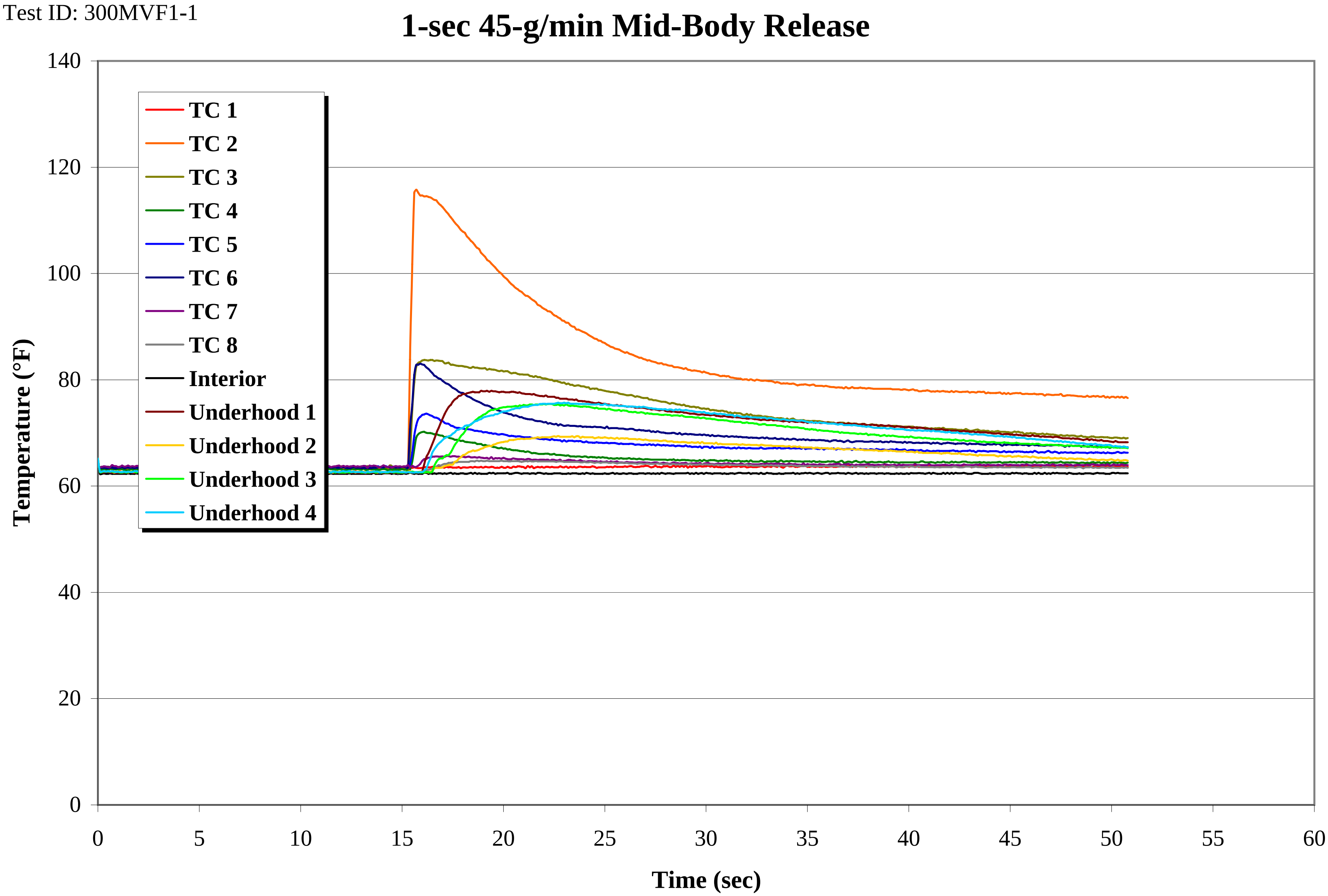
[3] Society of Fire Protection Engineers, *The SFPE Handbook of Fire Protection Engineering*, 2nd ed. National Fire Protection Association, 1995. pp. 3-326 - 3-327.

APPENDIX A

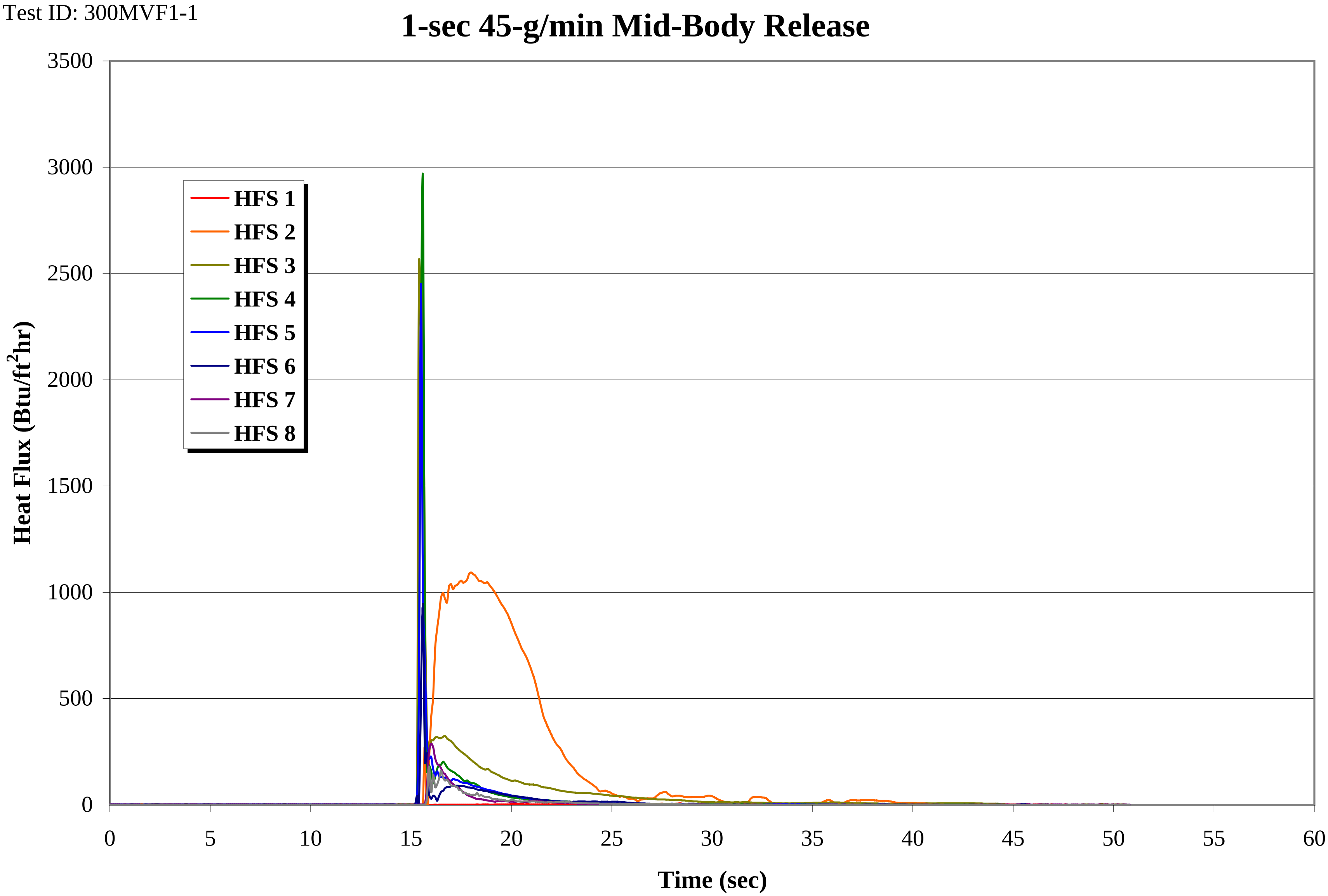
SERIES 1 GRAPHICAL TEST DATA

(CONSISTING OF 25 PAGES)

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF1-1



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF1-1



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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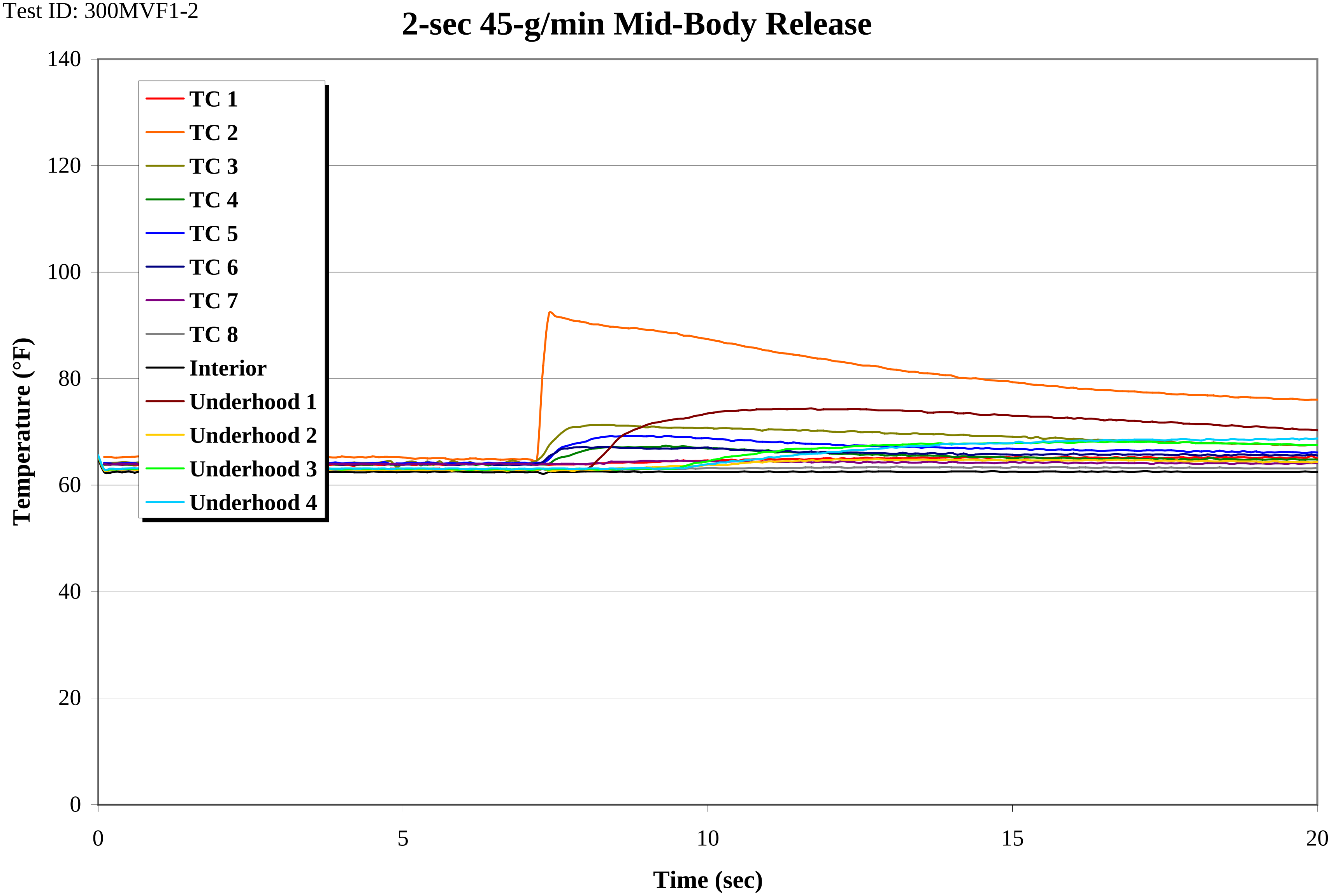

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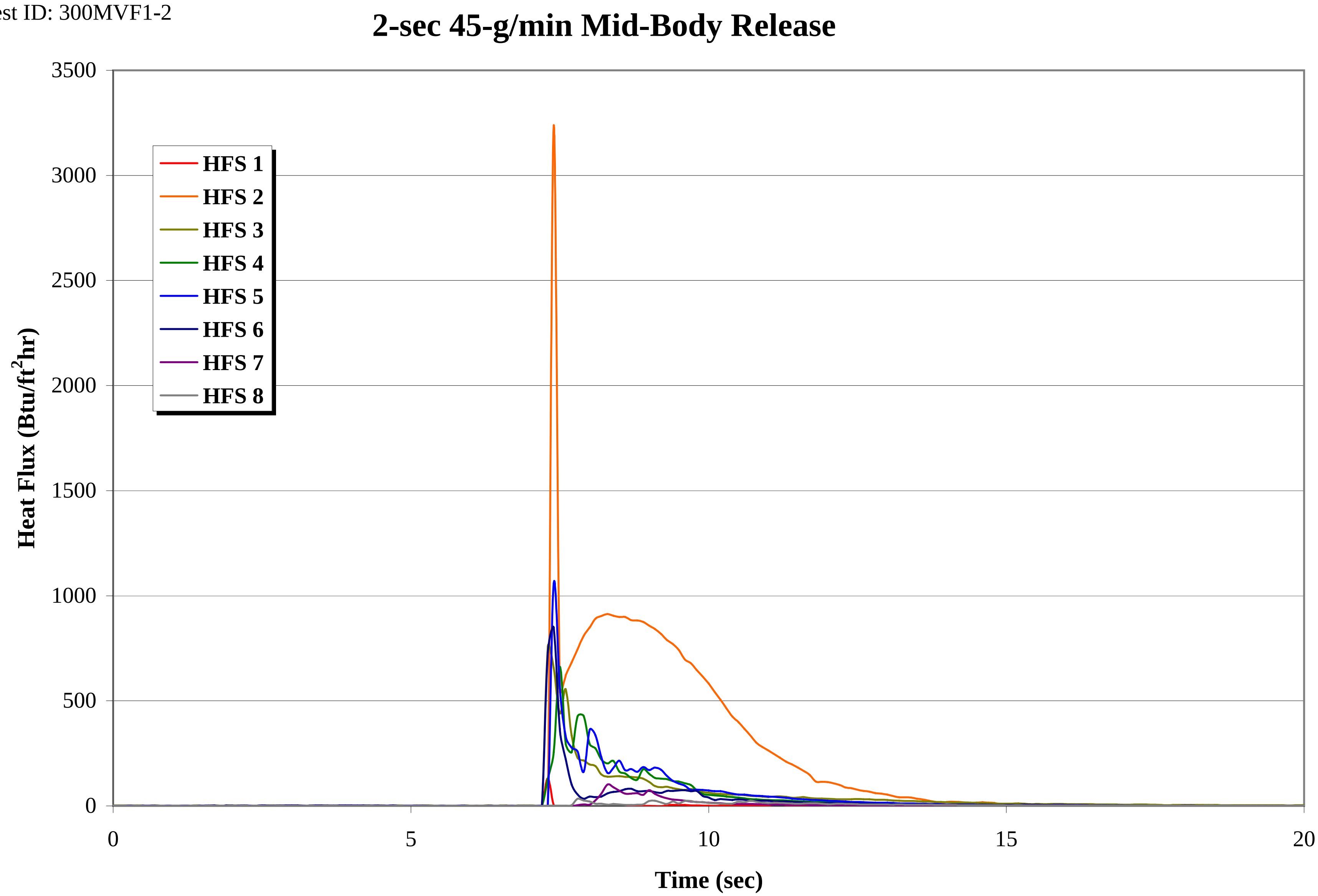

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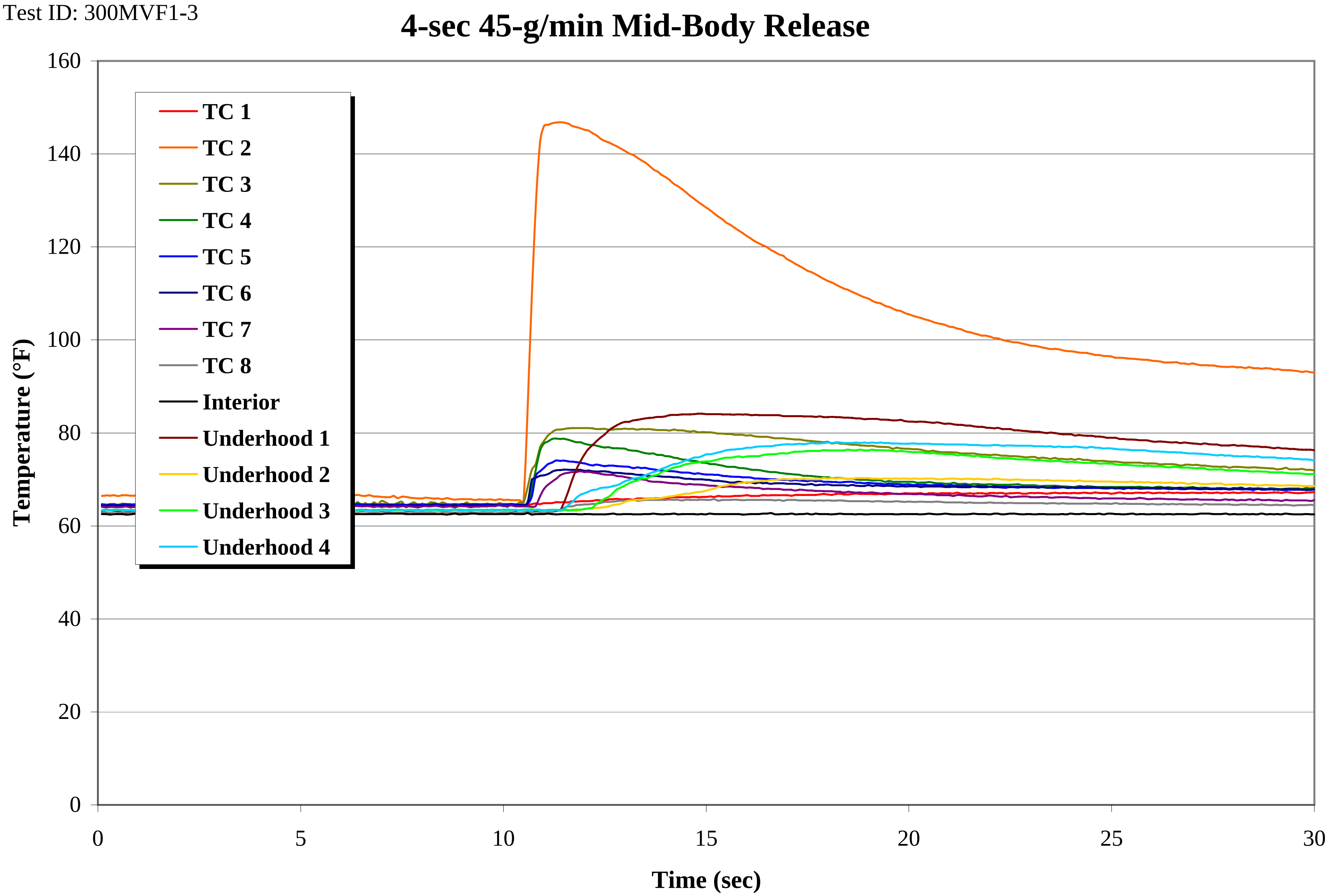
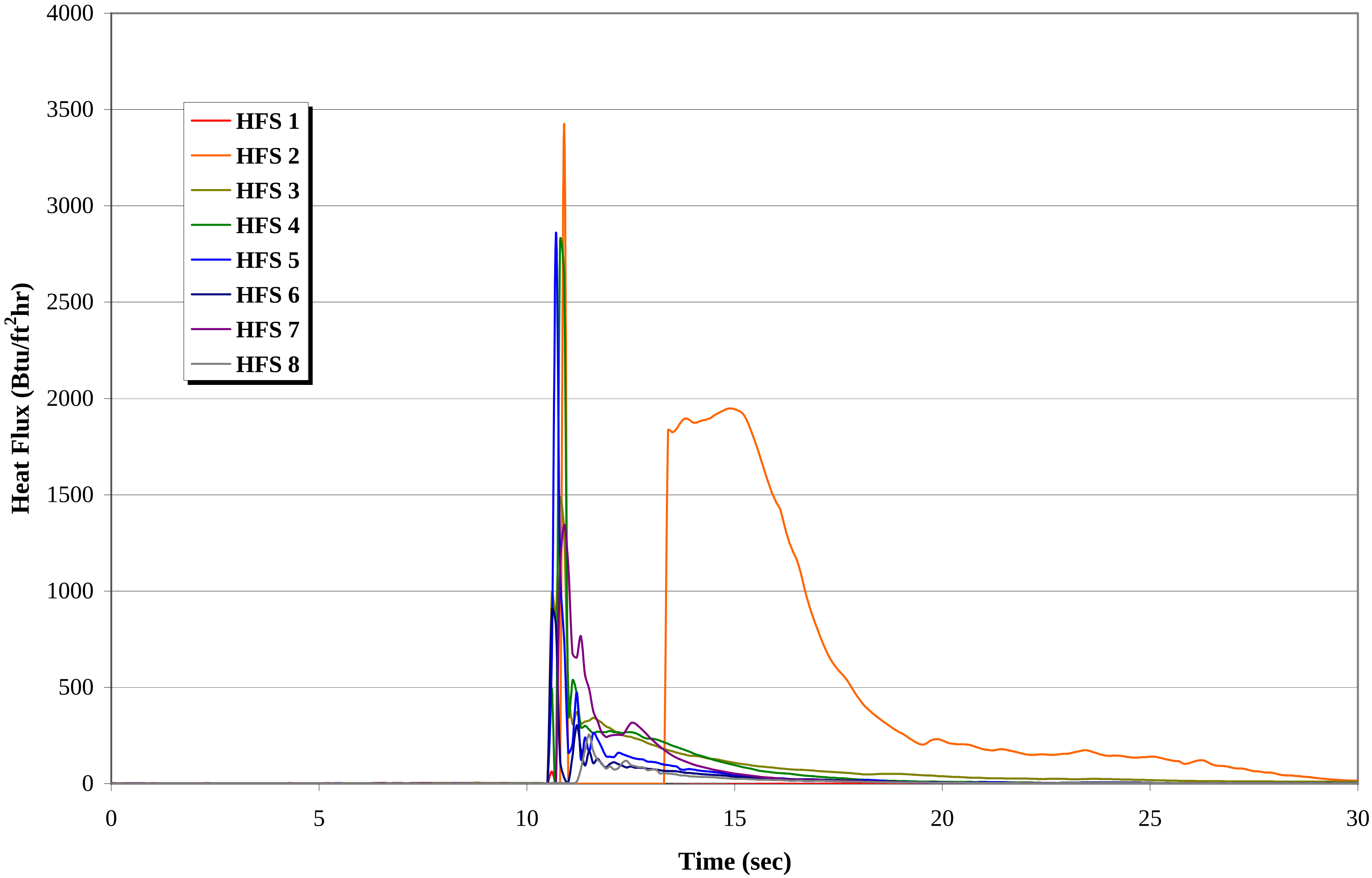


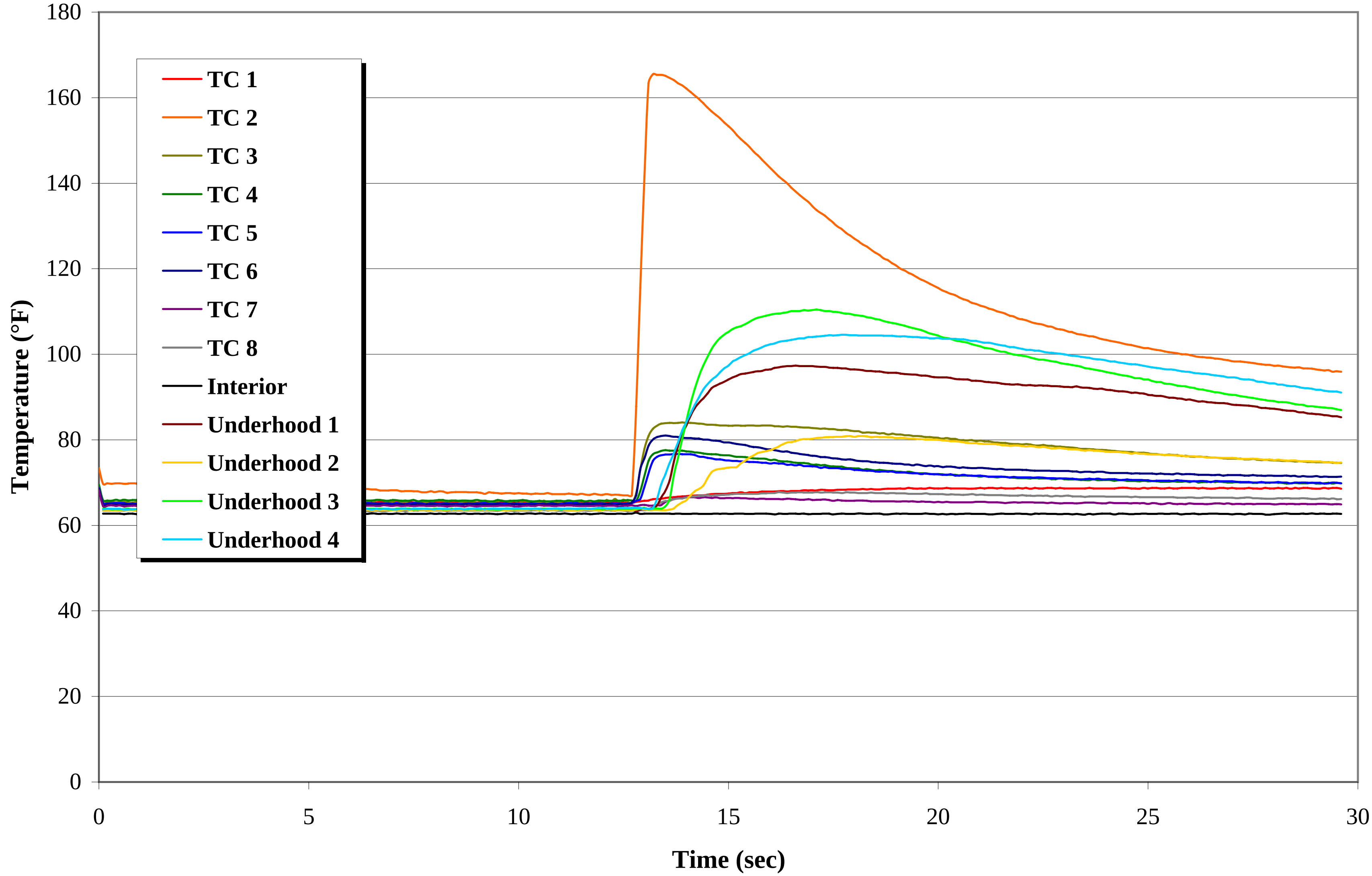
Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF1-3

4-sec 45-g/min Mid-Body Release



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF1-4

8-sec 45-g/min Mid-Body Release



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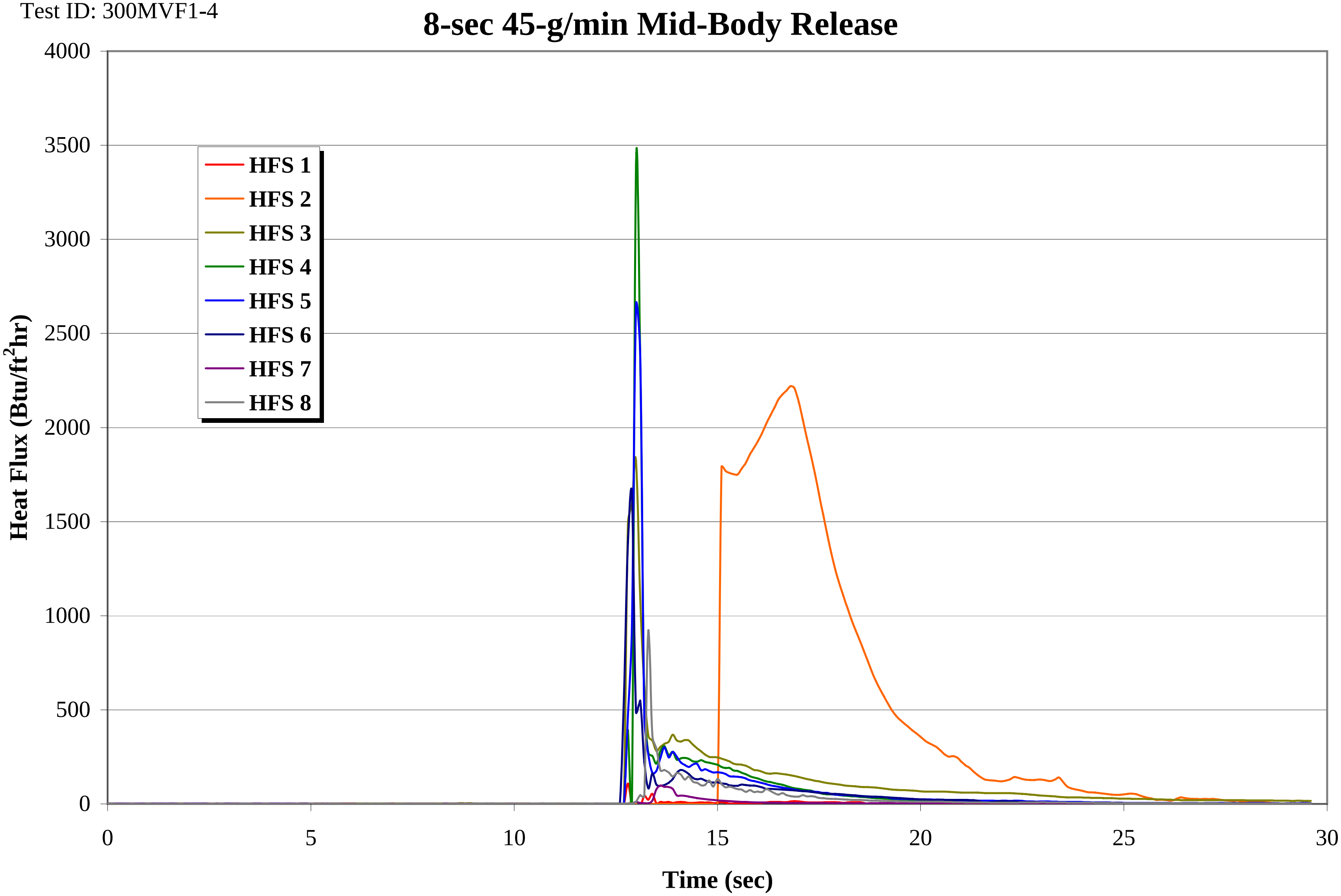

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SwRI Project No. 01.06939.01.004
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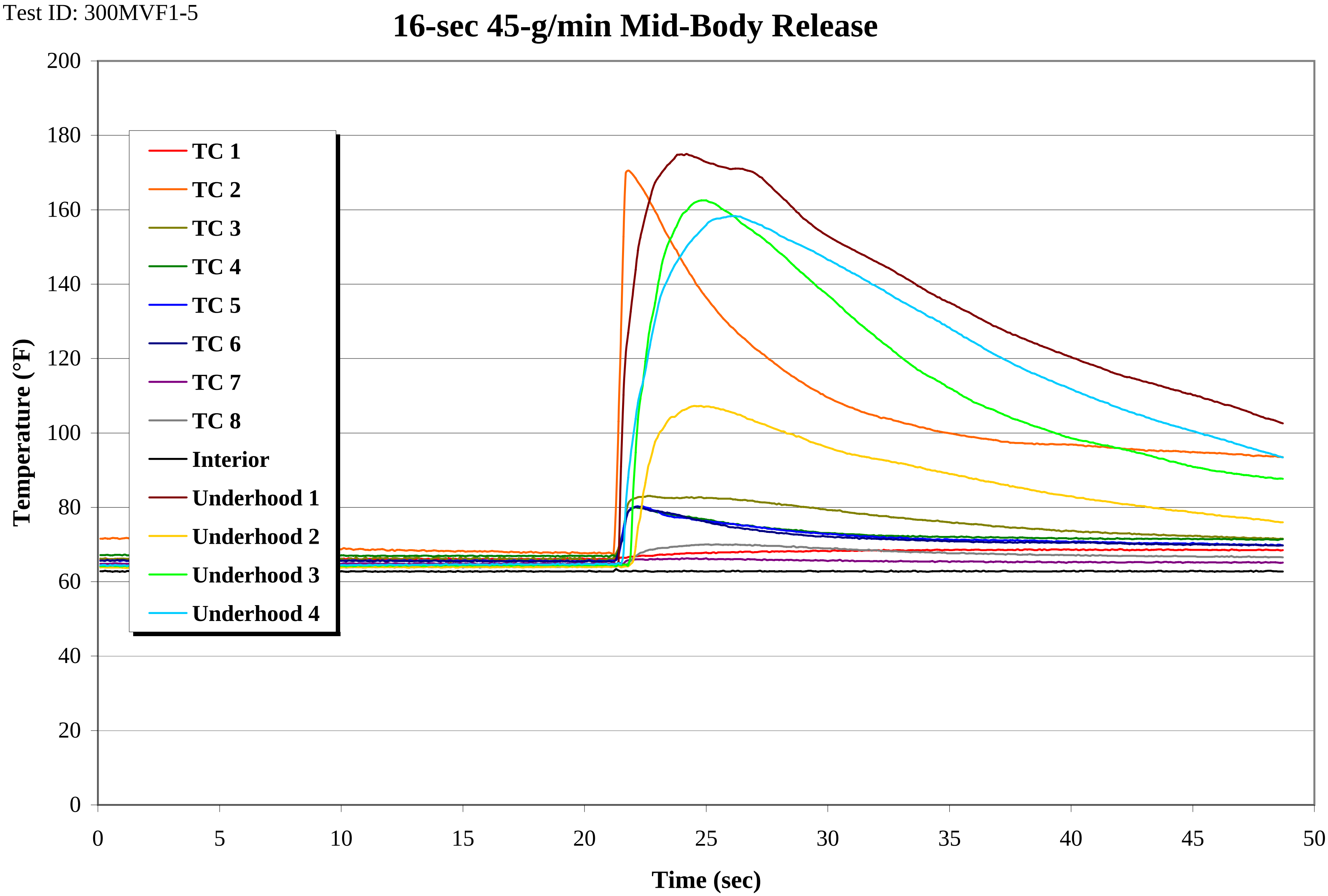

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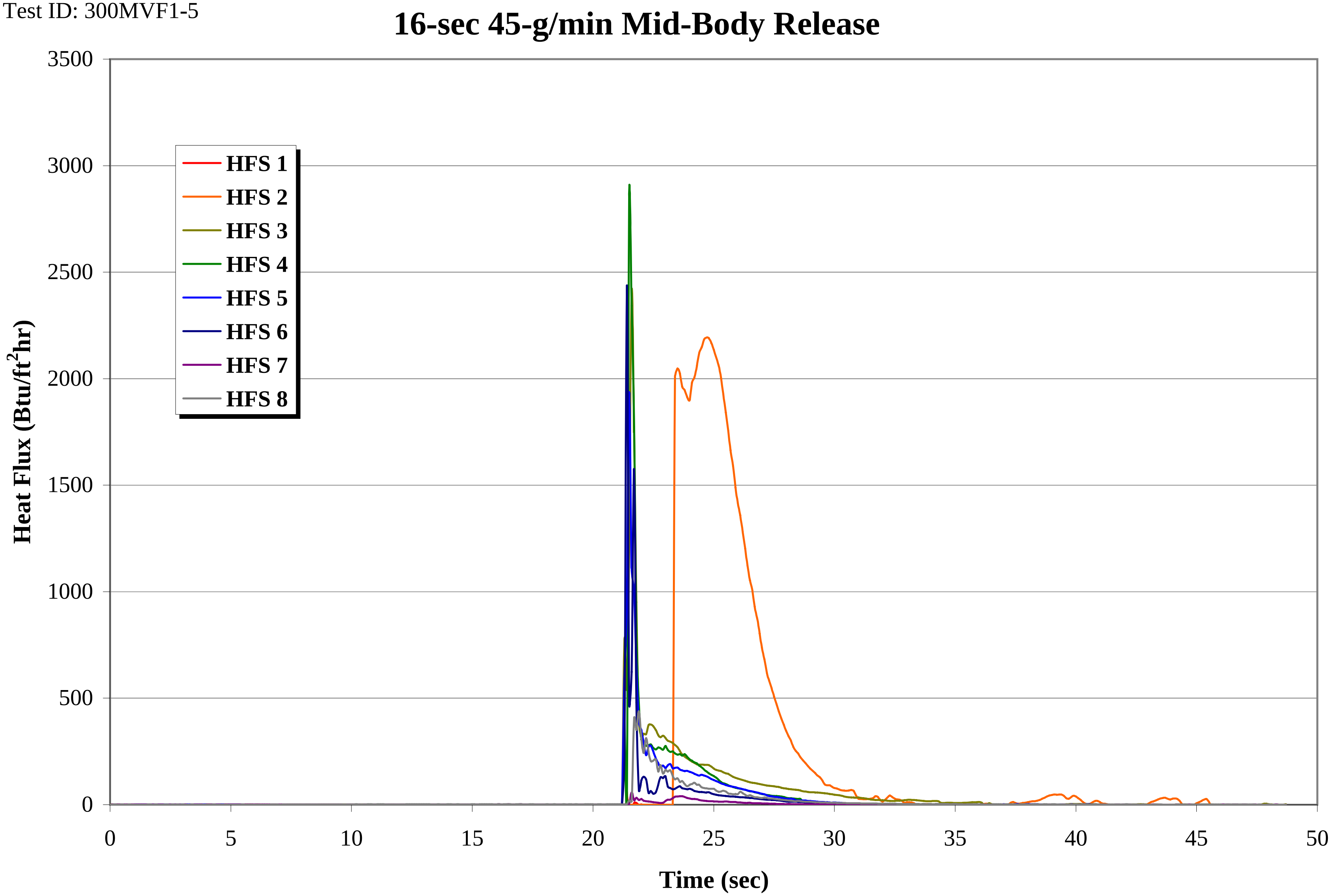

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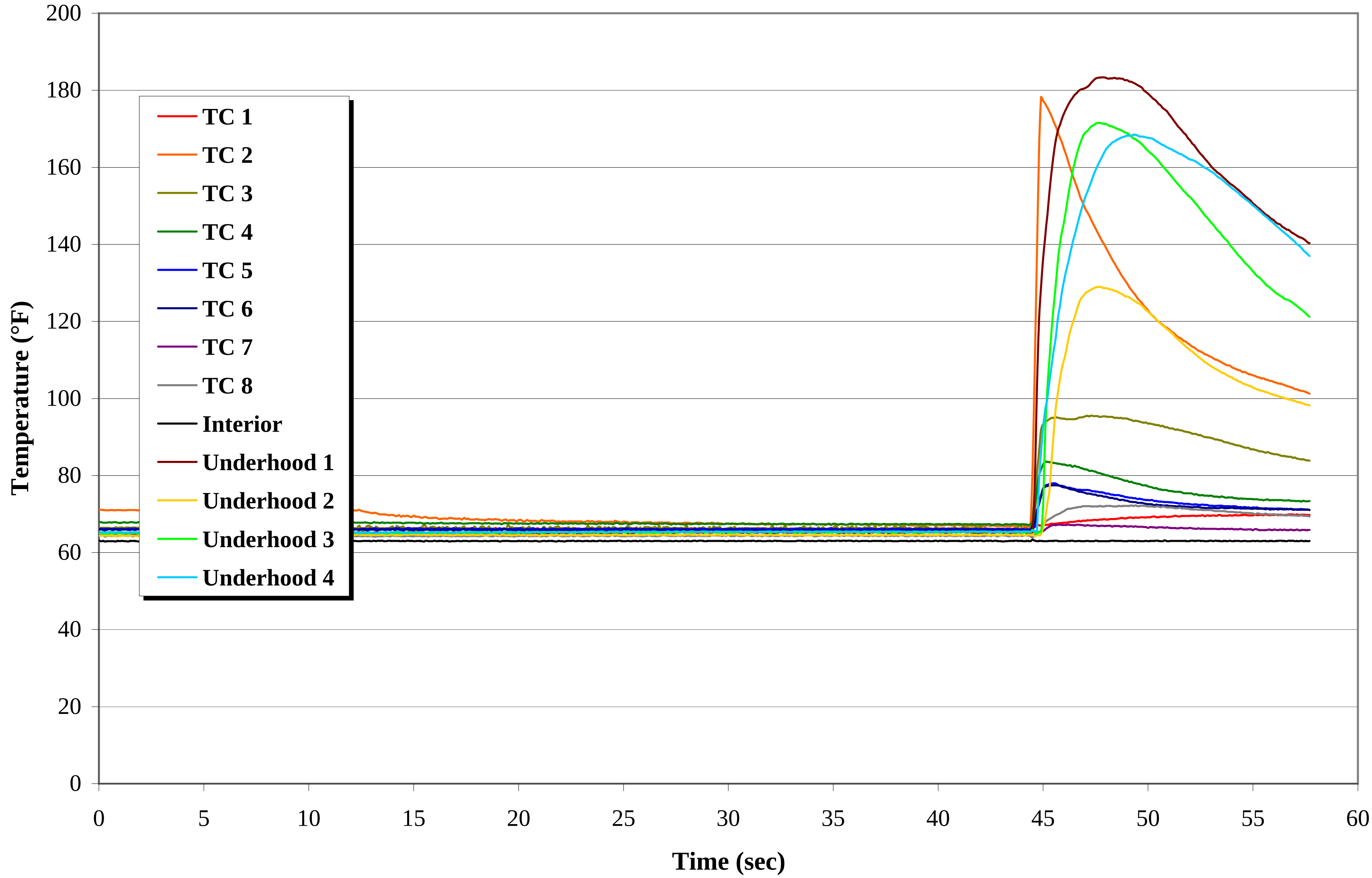
32-sec 45-g/min Mid-Body Release



Motor Vehicle Fire Research Institute
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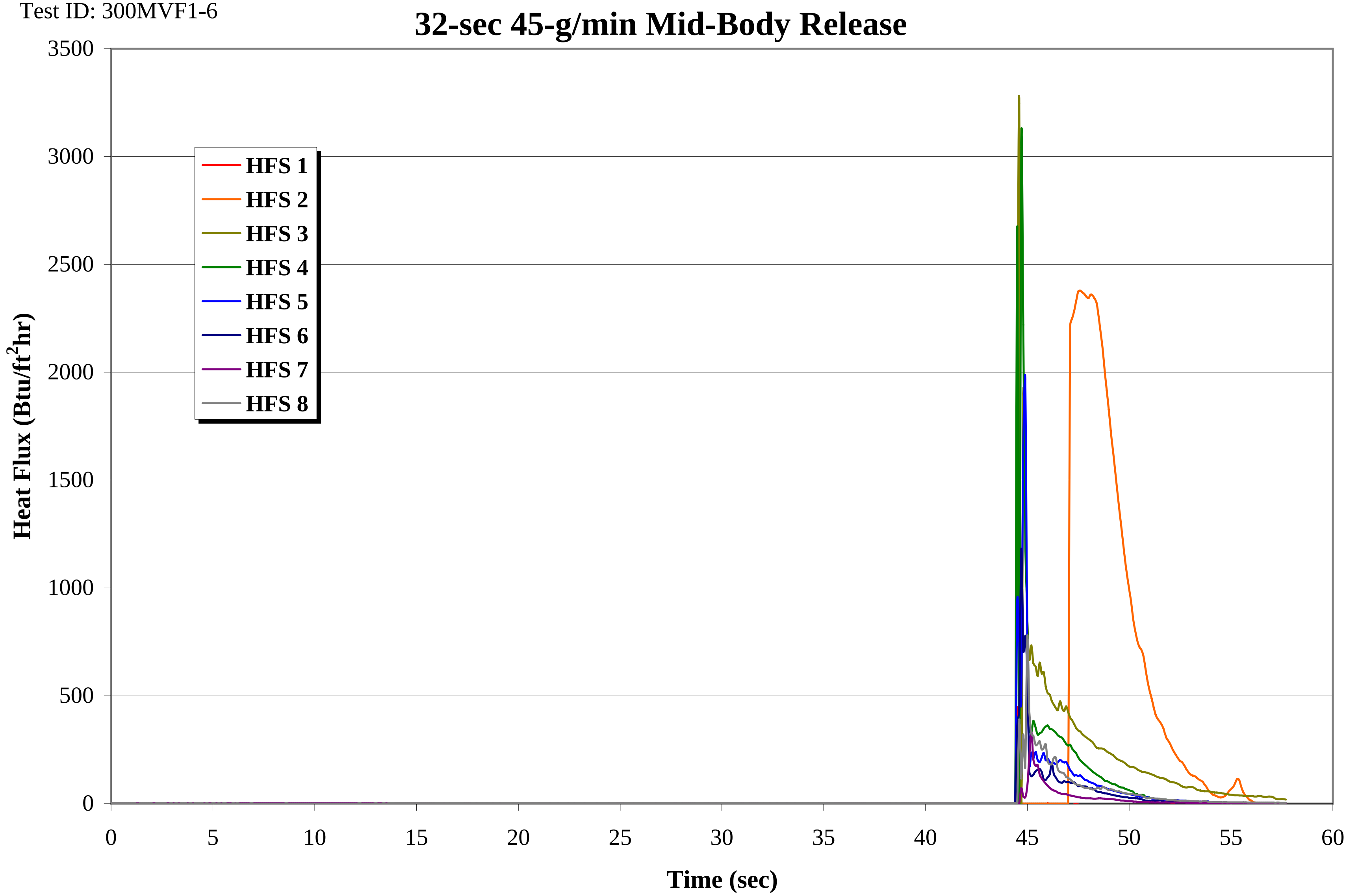

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SwRI Project No. 01.06939.01.004
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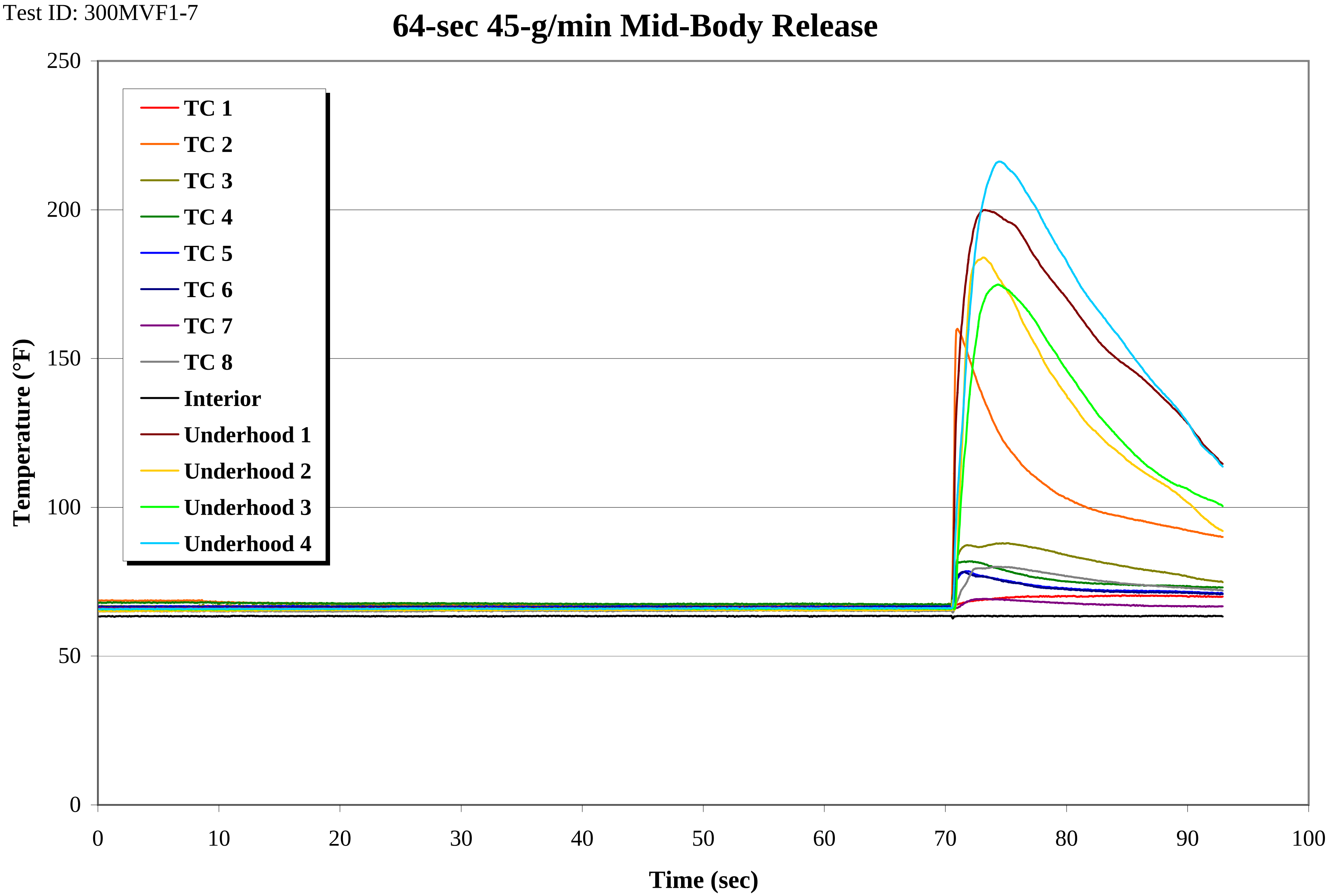

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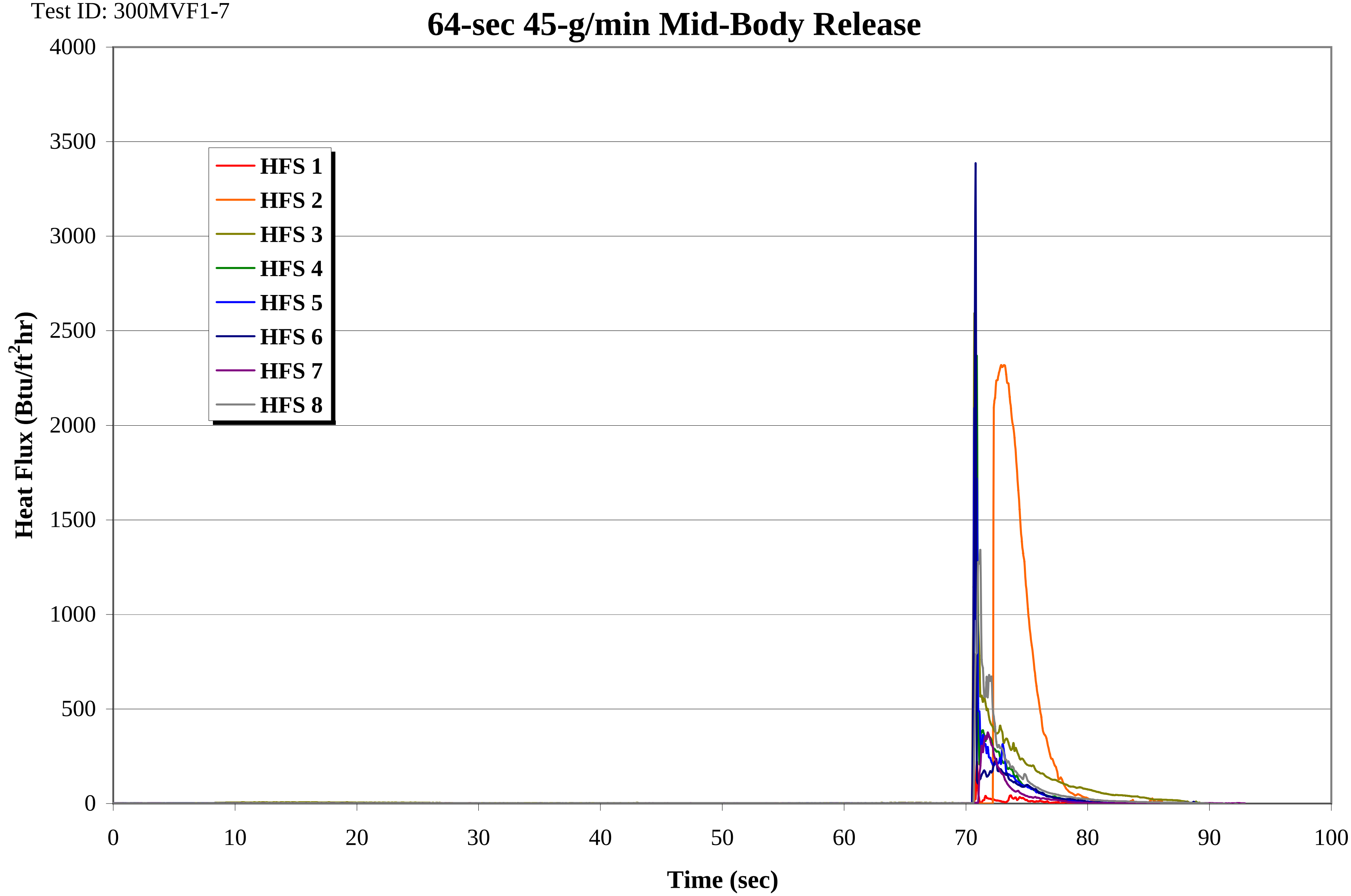

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date October 27, 2005
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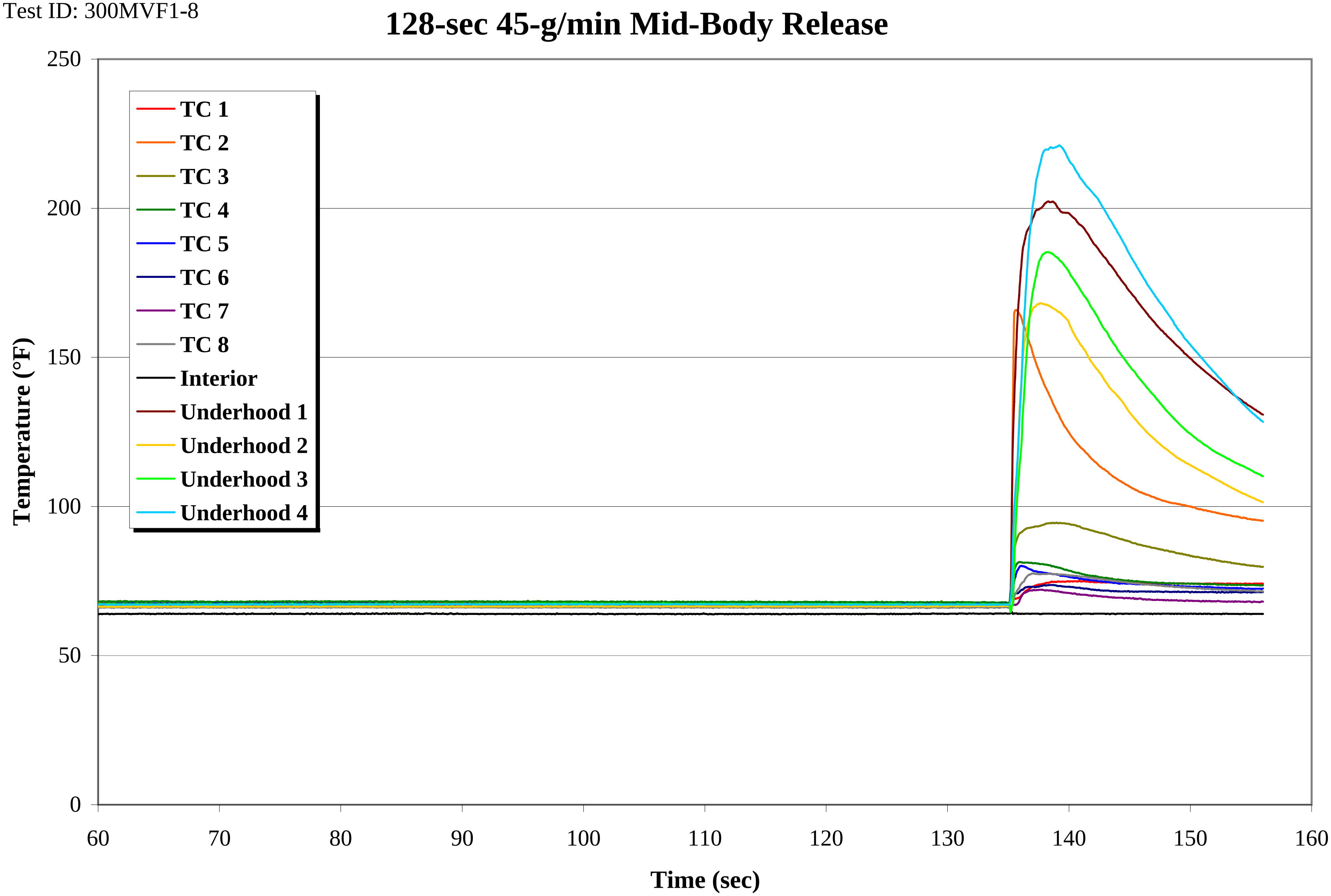

Motor Vehicle Fire Research Institute
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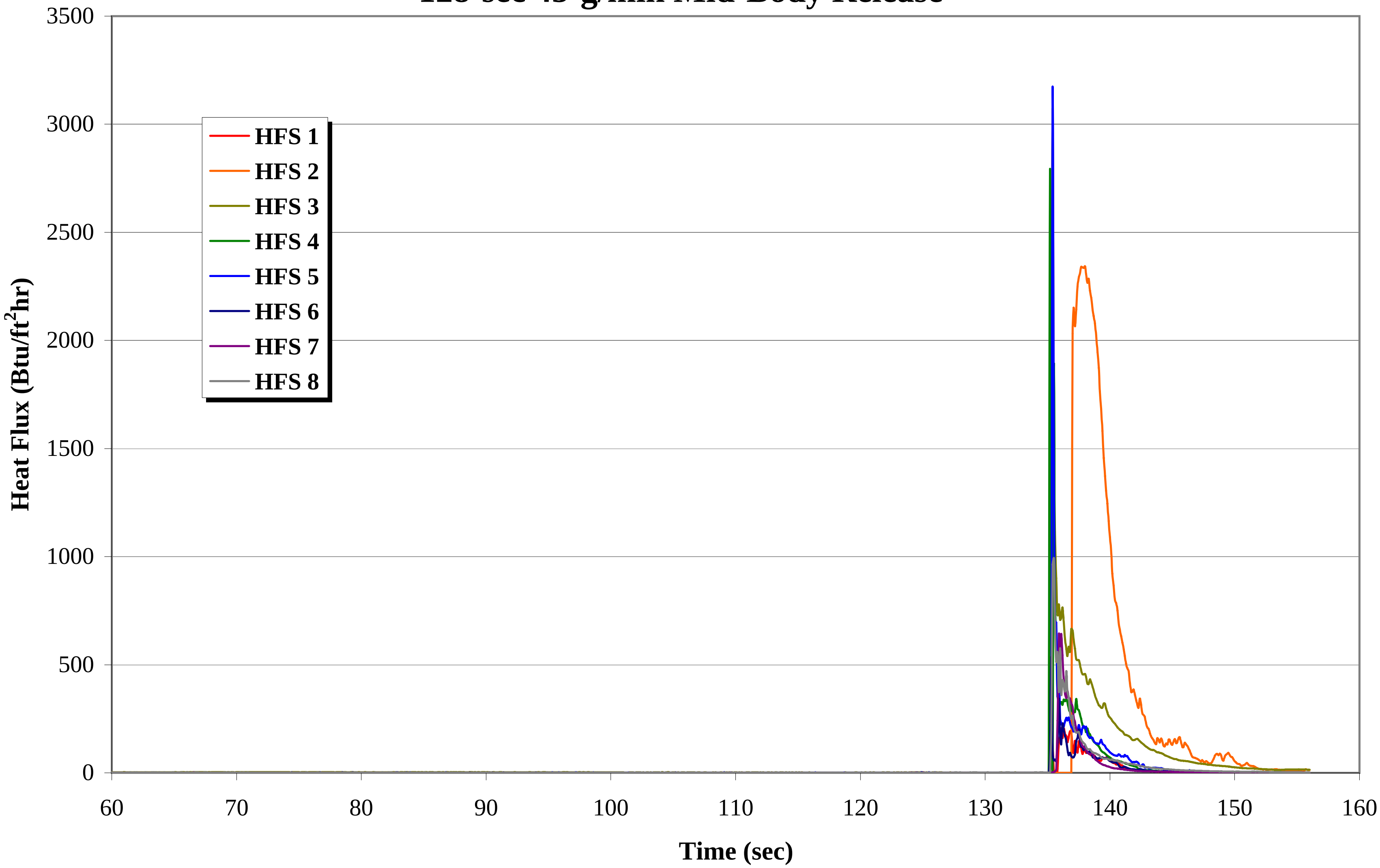
Test Date: October 27, 2005
Test ID: 300MVF1-8

128-sec 45-g/min Mid-Body Release



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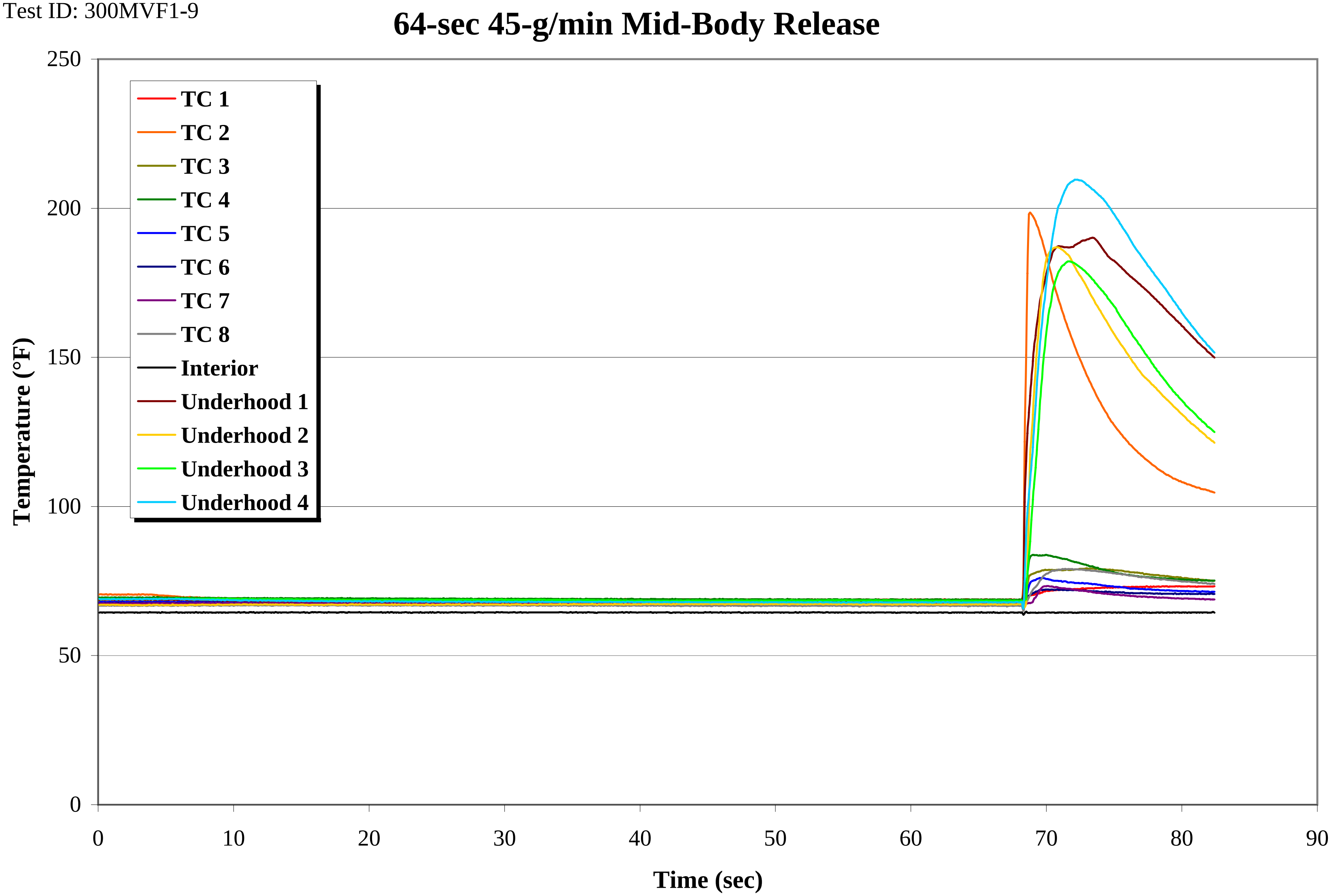

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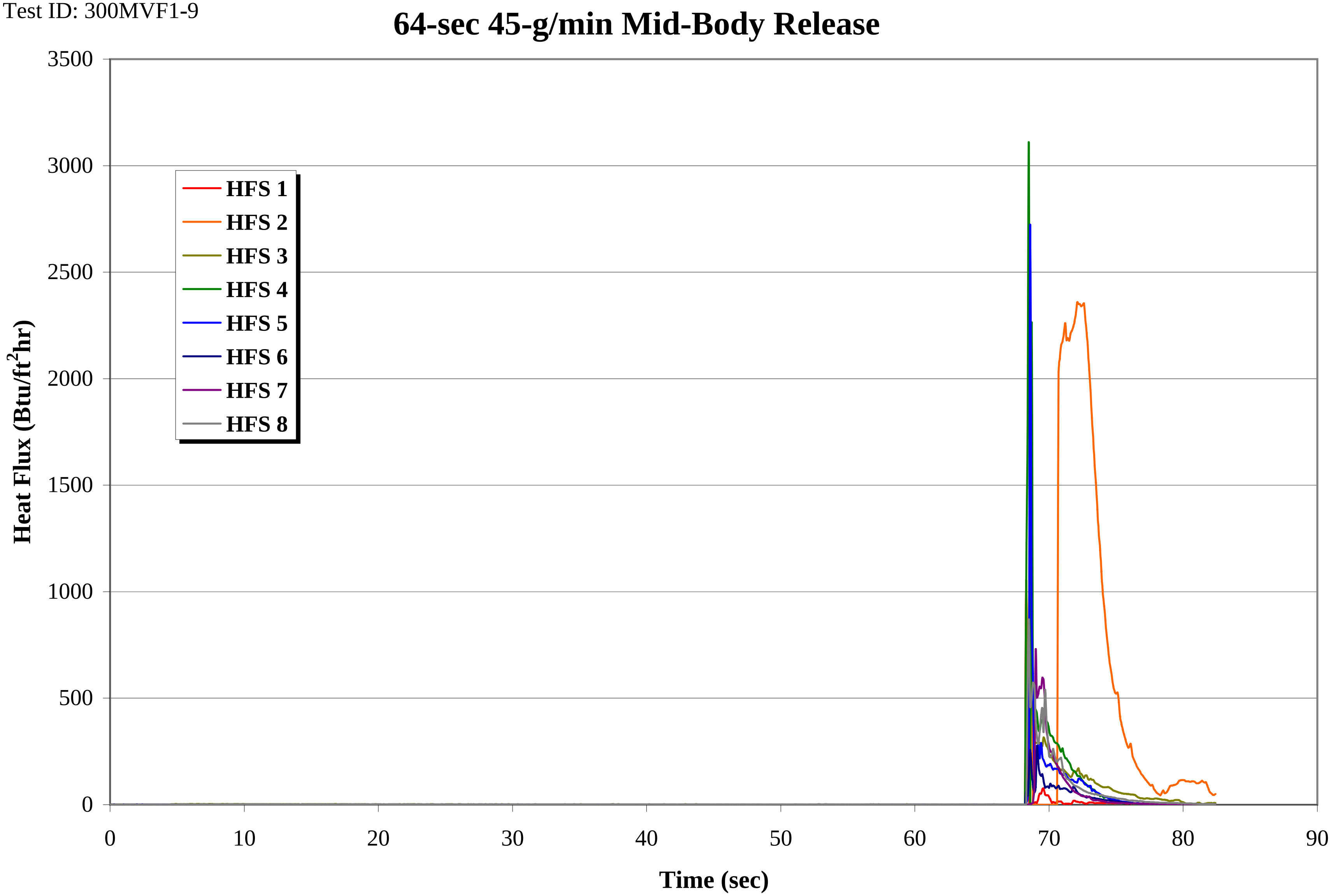

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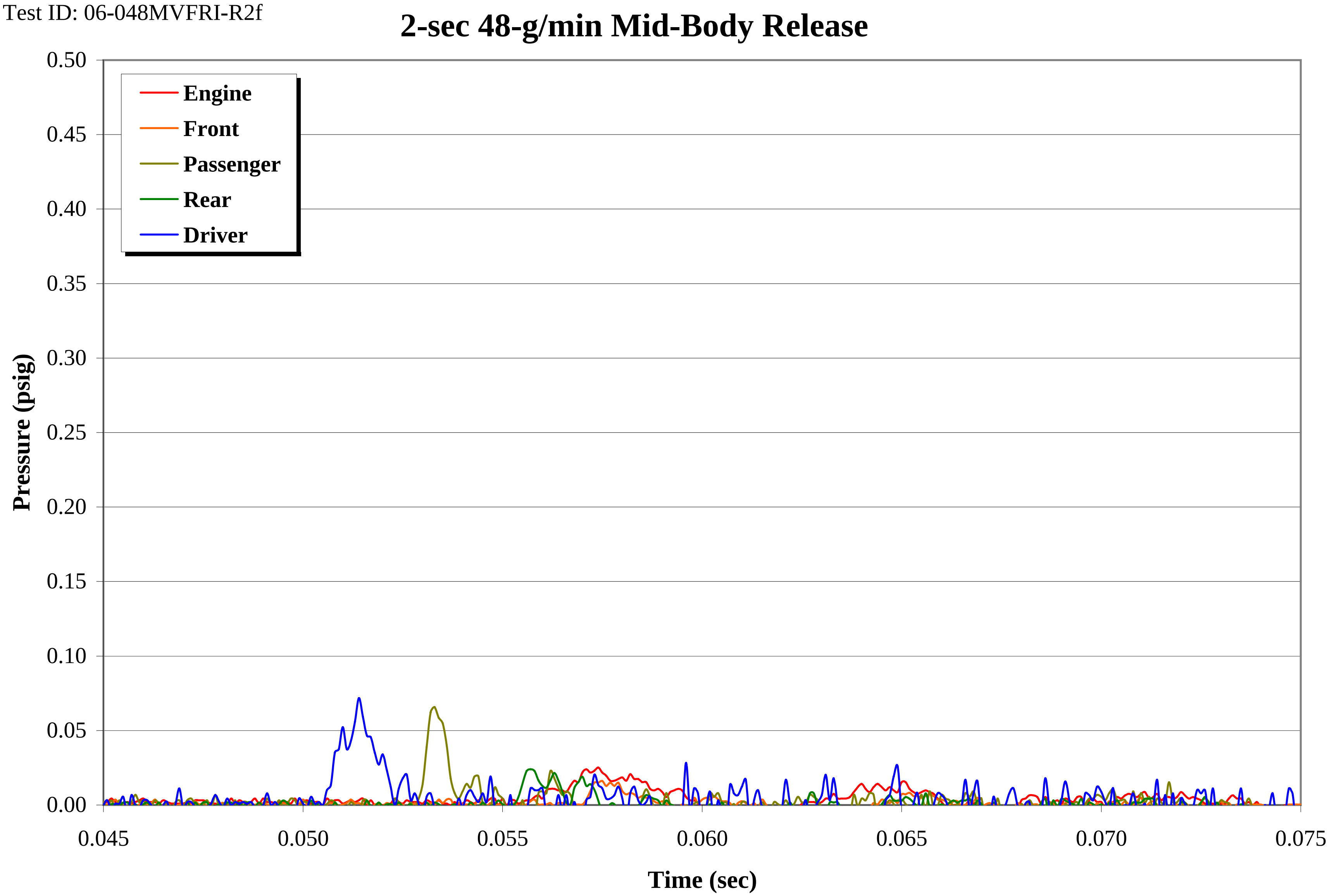

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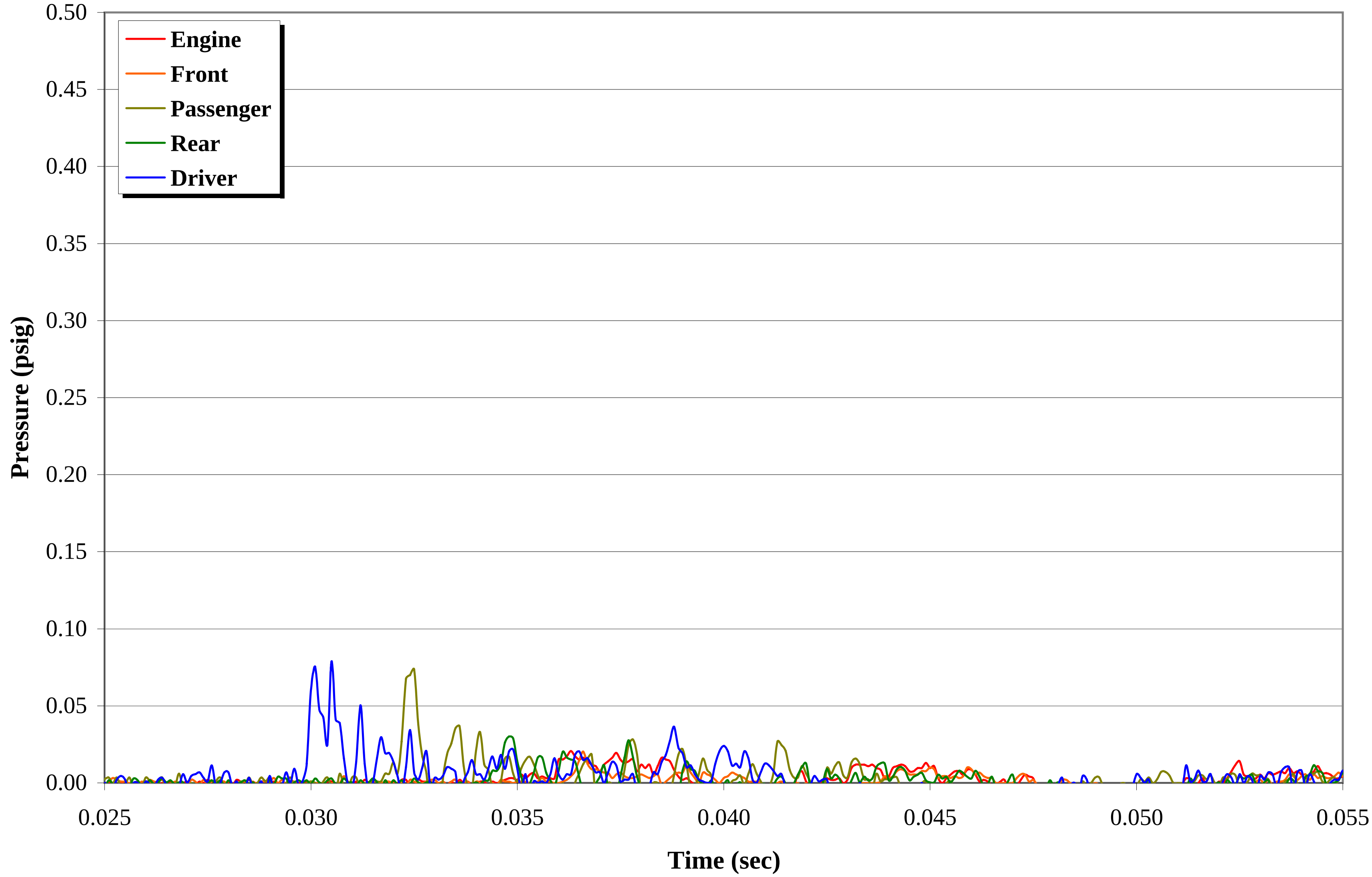
4-sec 48-g/min Mid-Body Release



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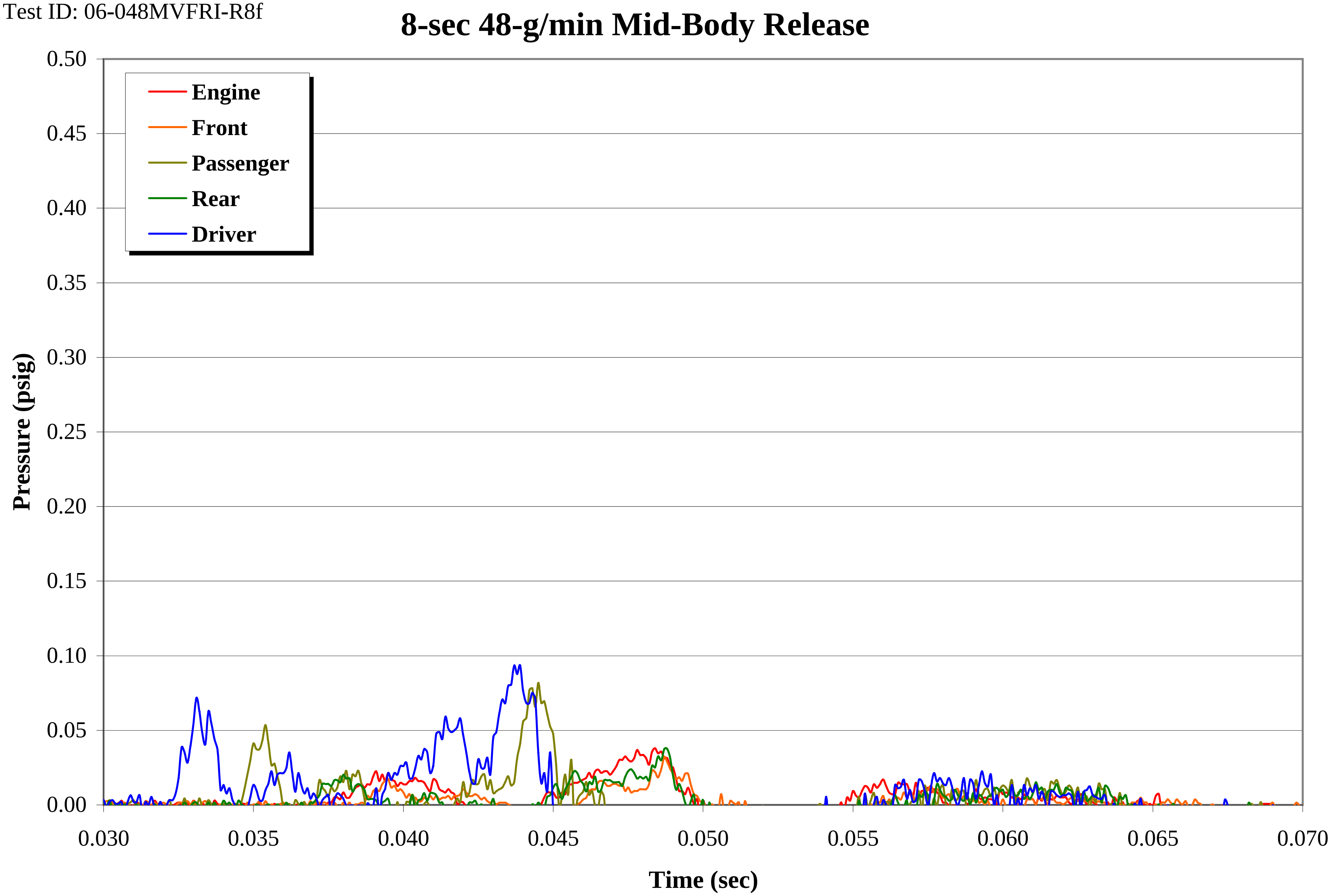

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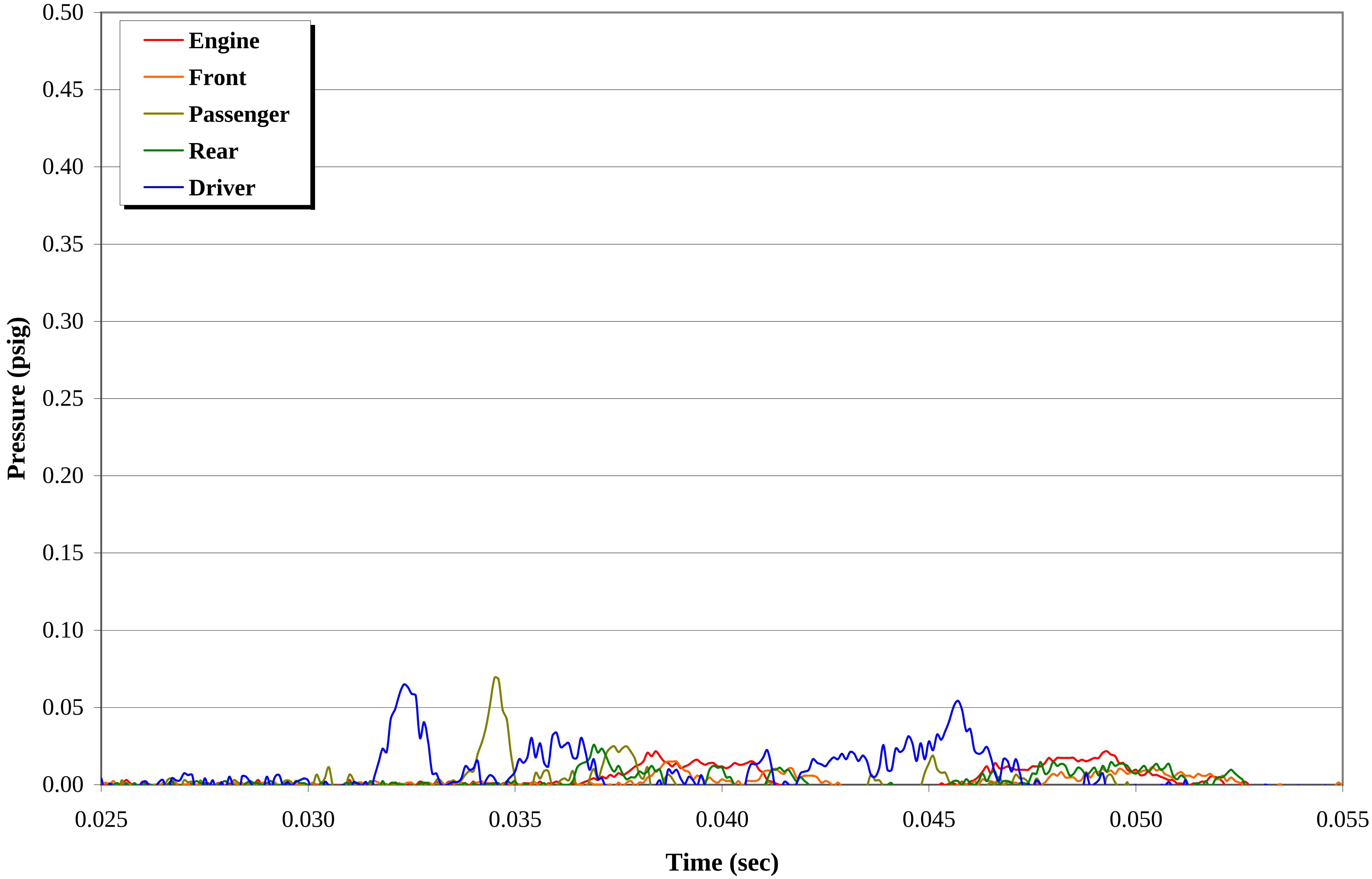
16-sec 48-g/min Mid-Body Release



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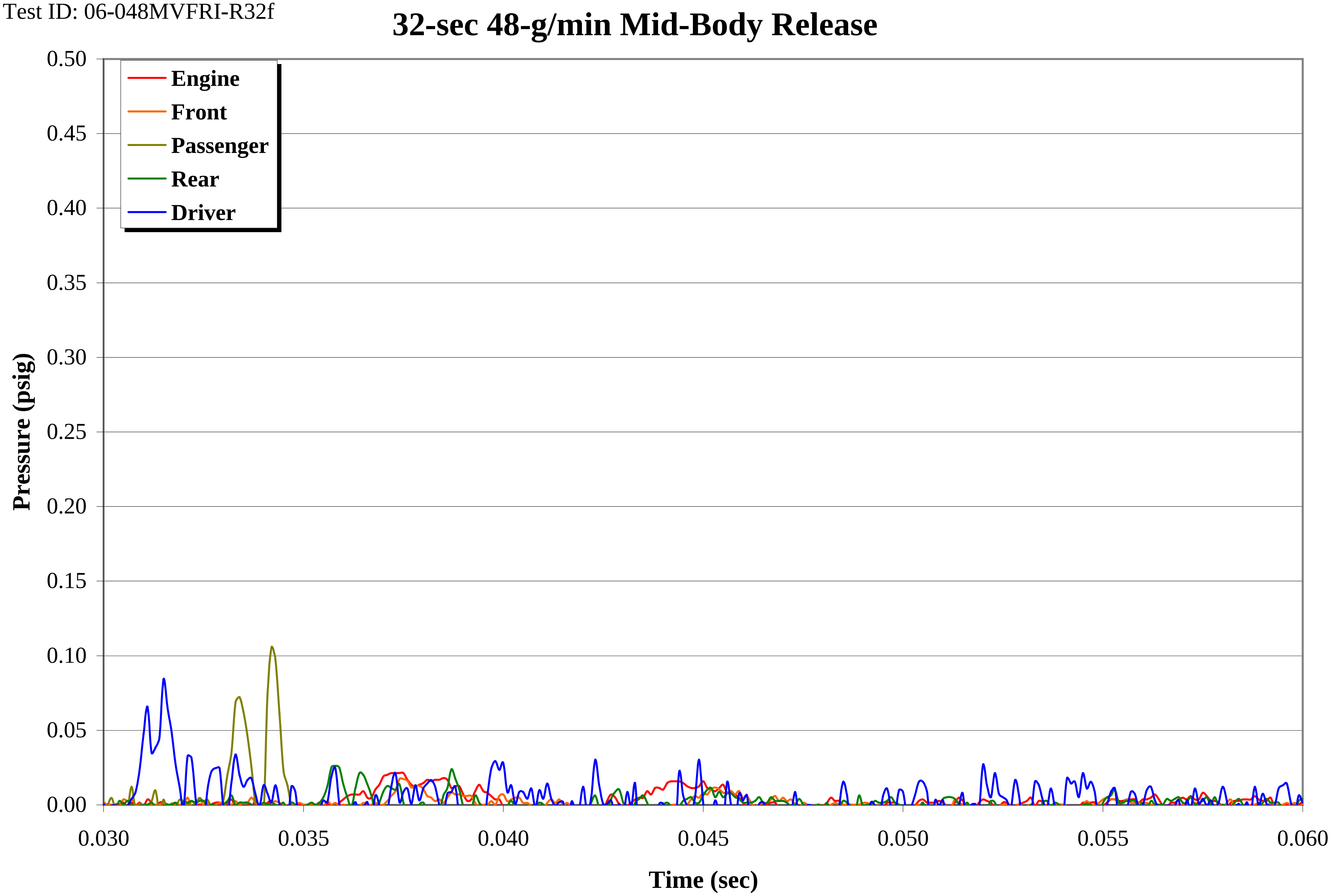

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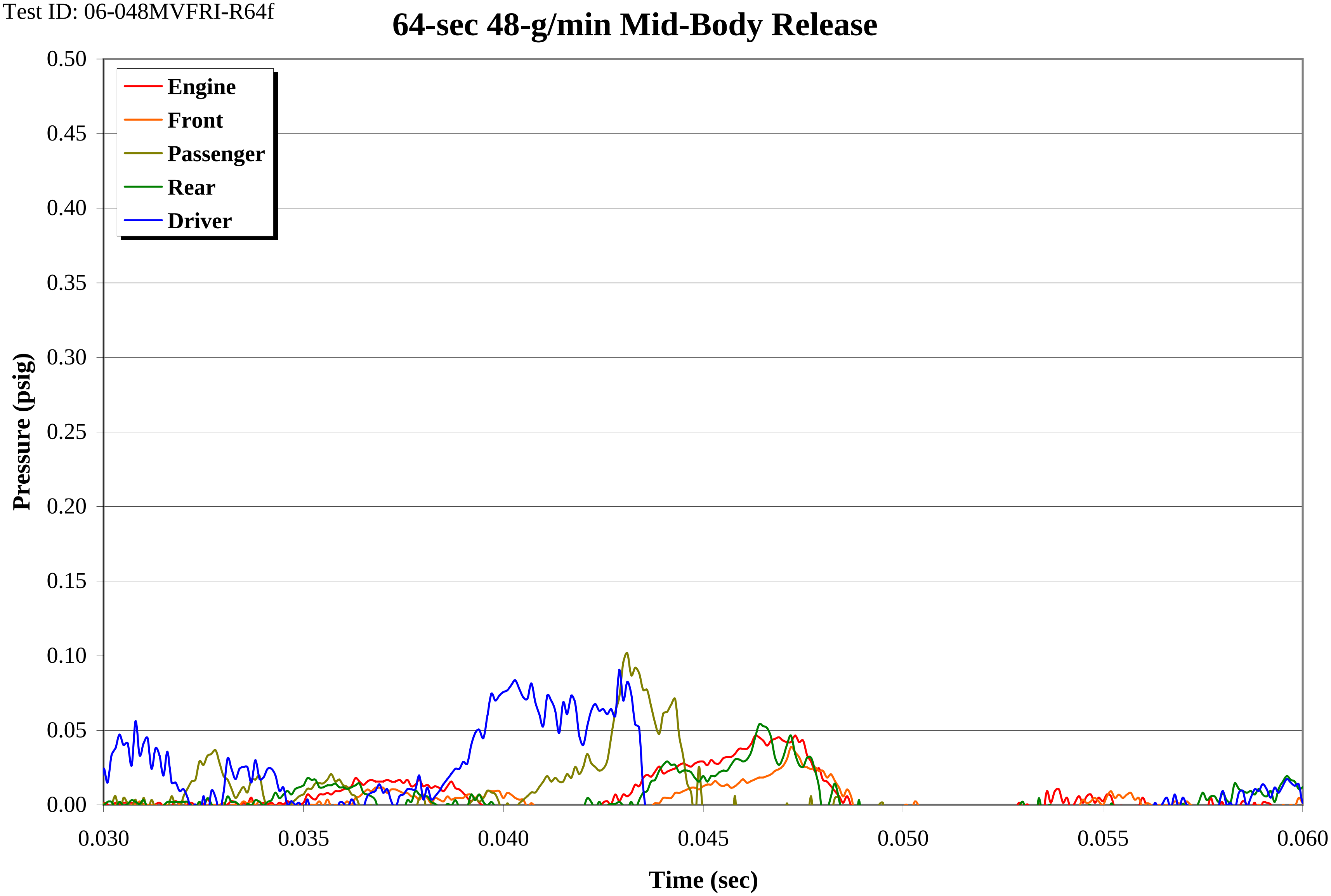

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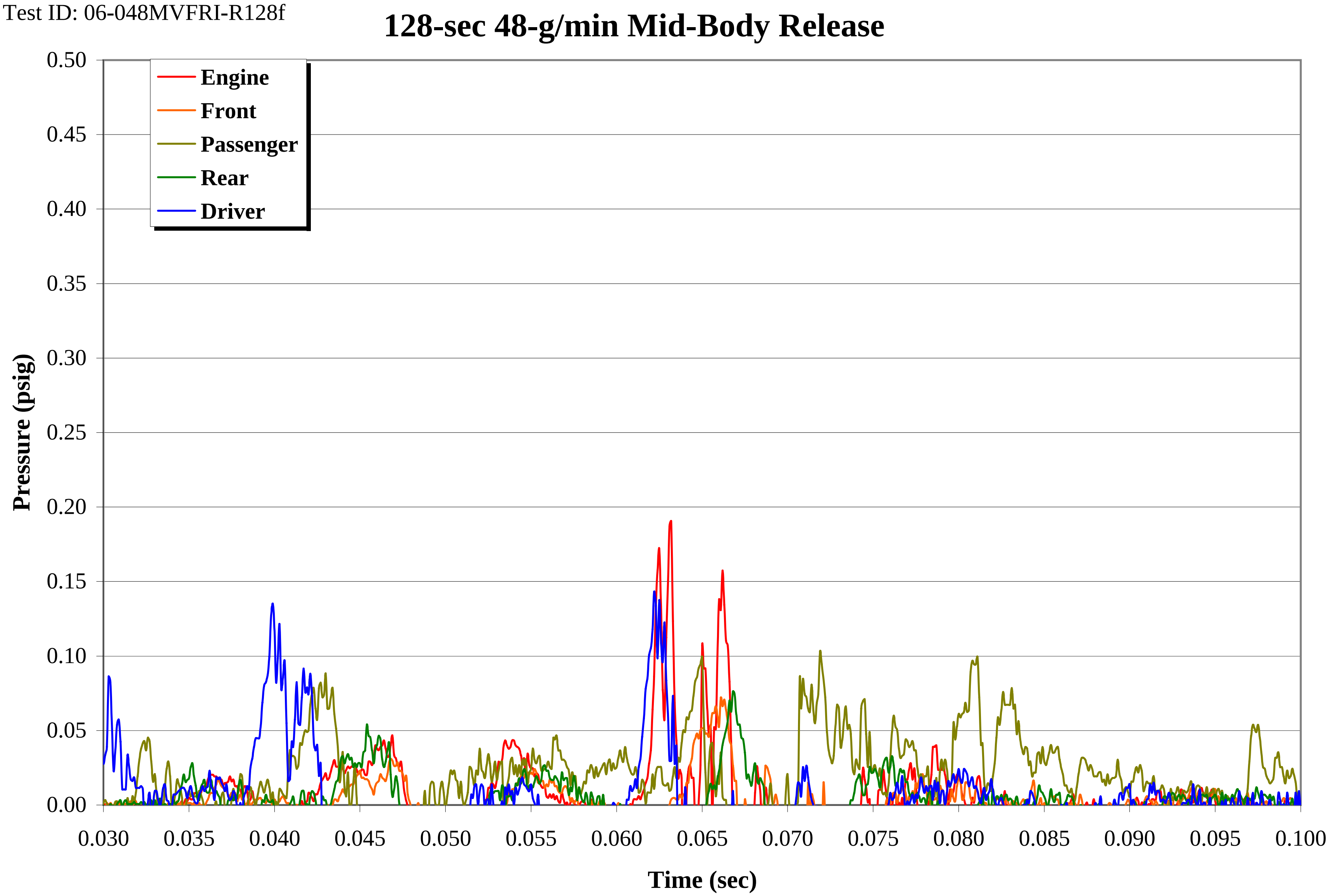

APPENDIX B

SERIES 2 GRAPHICAL TEST DATA

(CONSISTING OF 24 PAGES)

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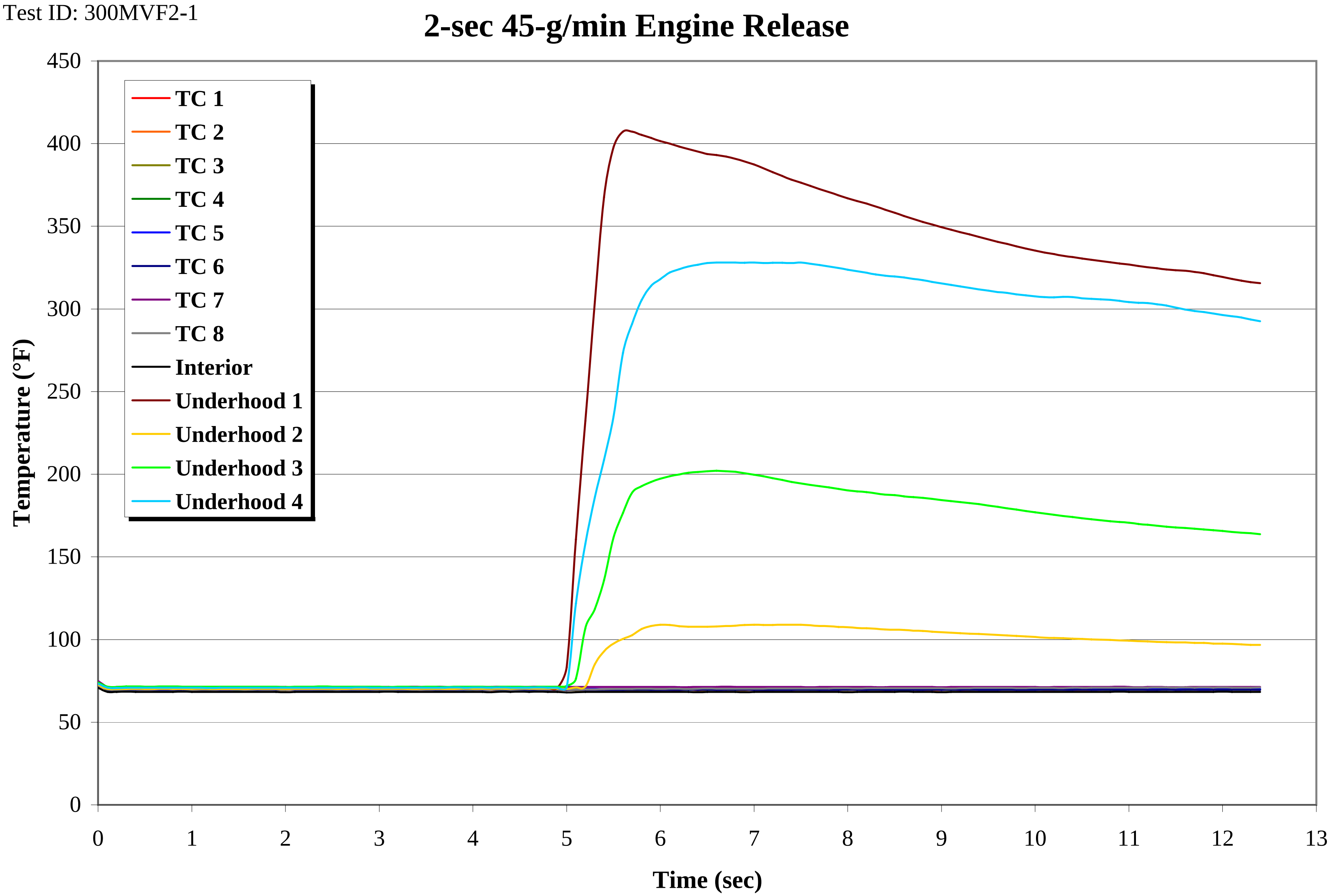

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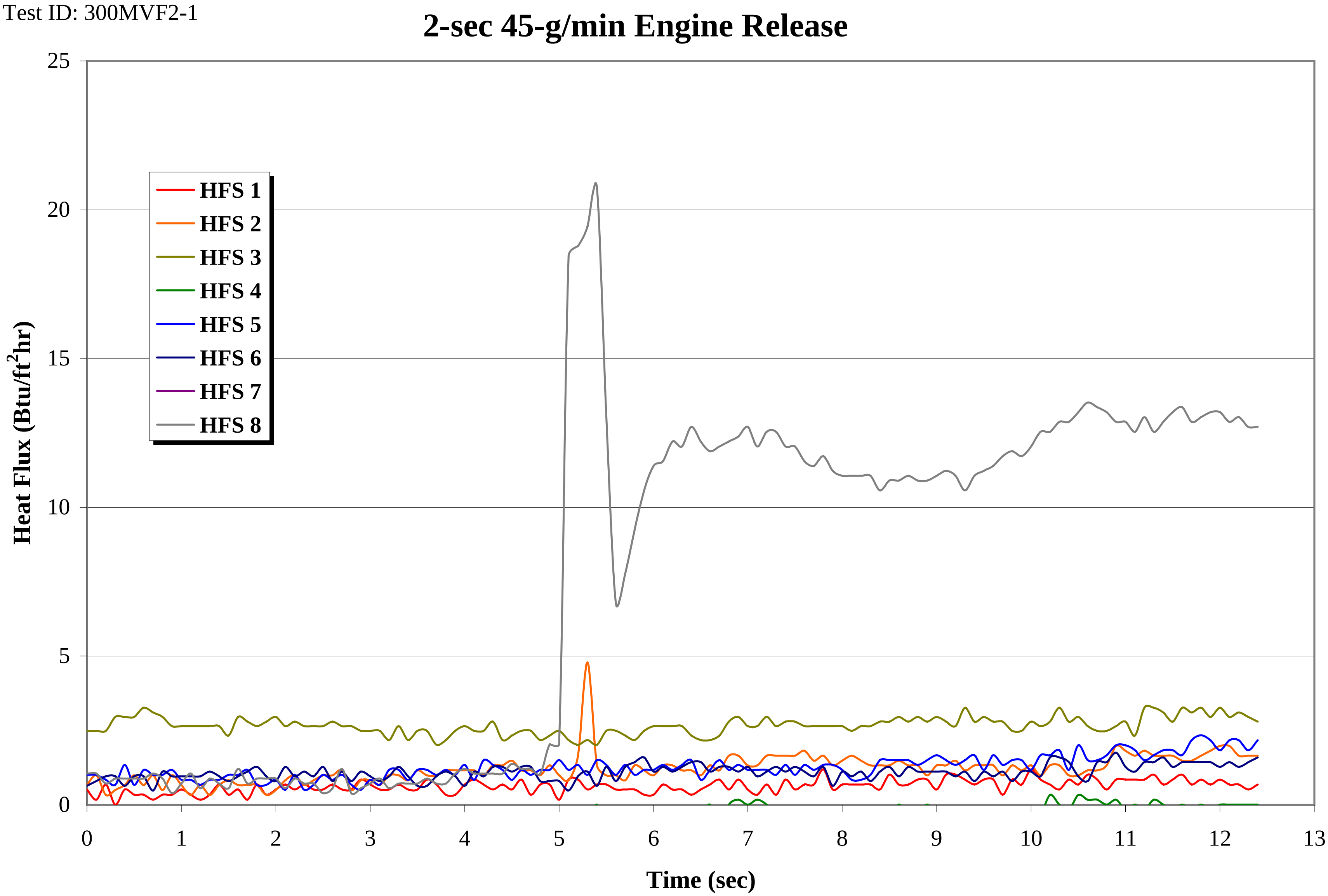

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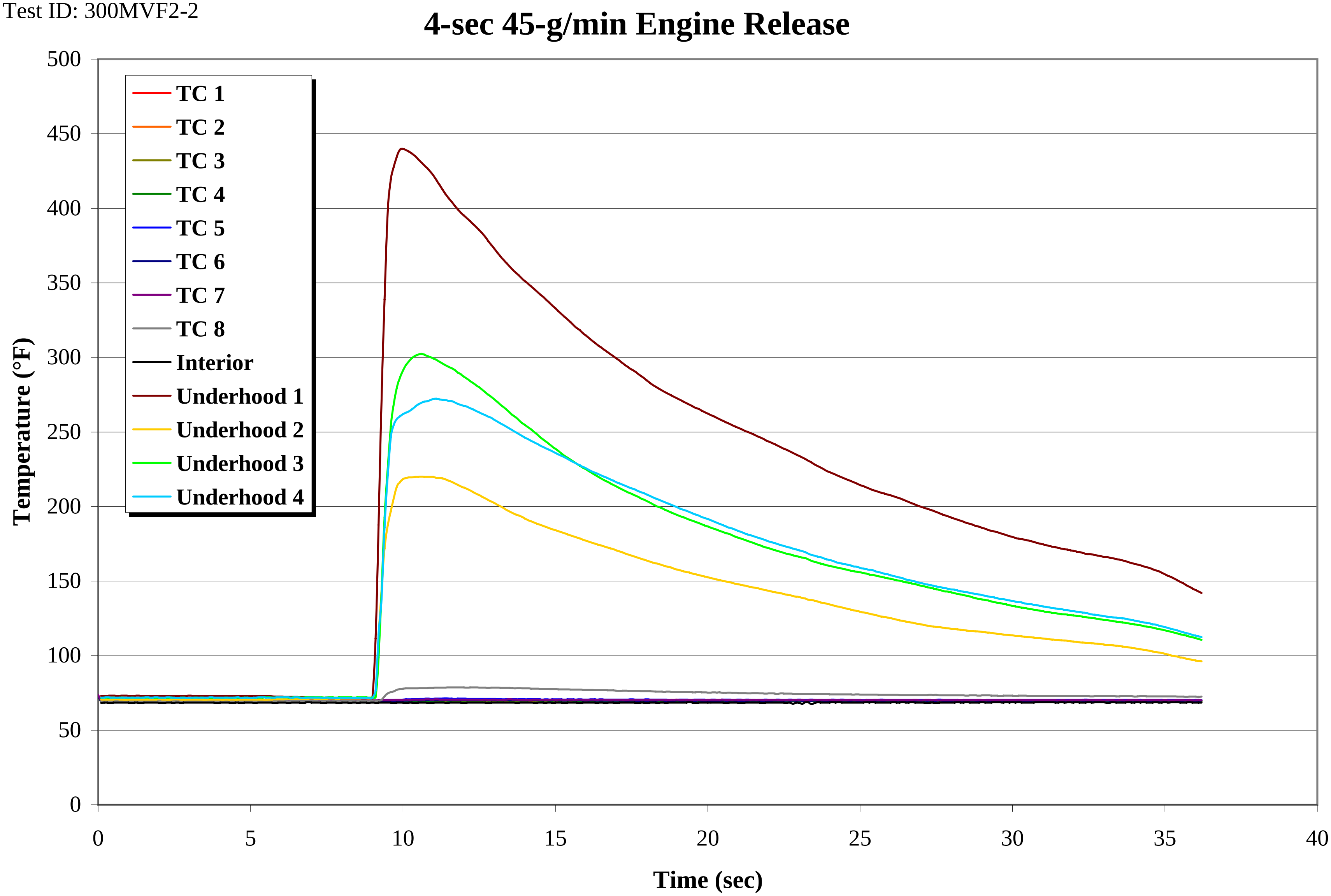

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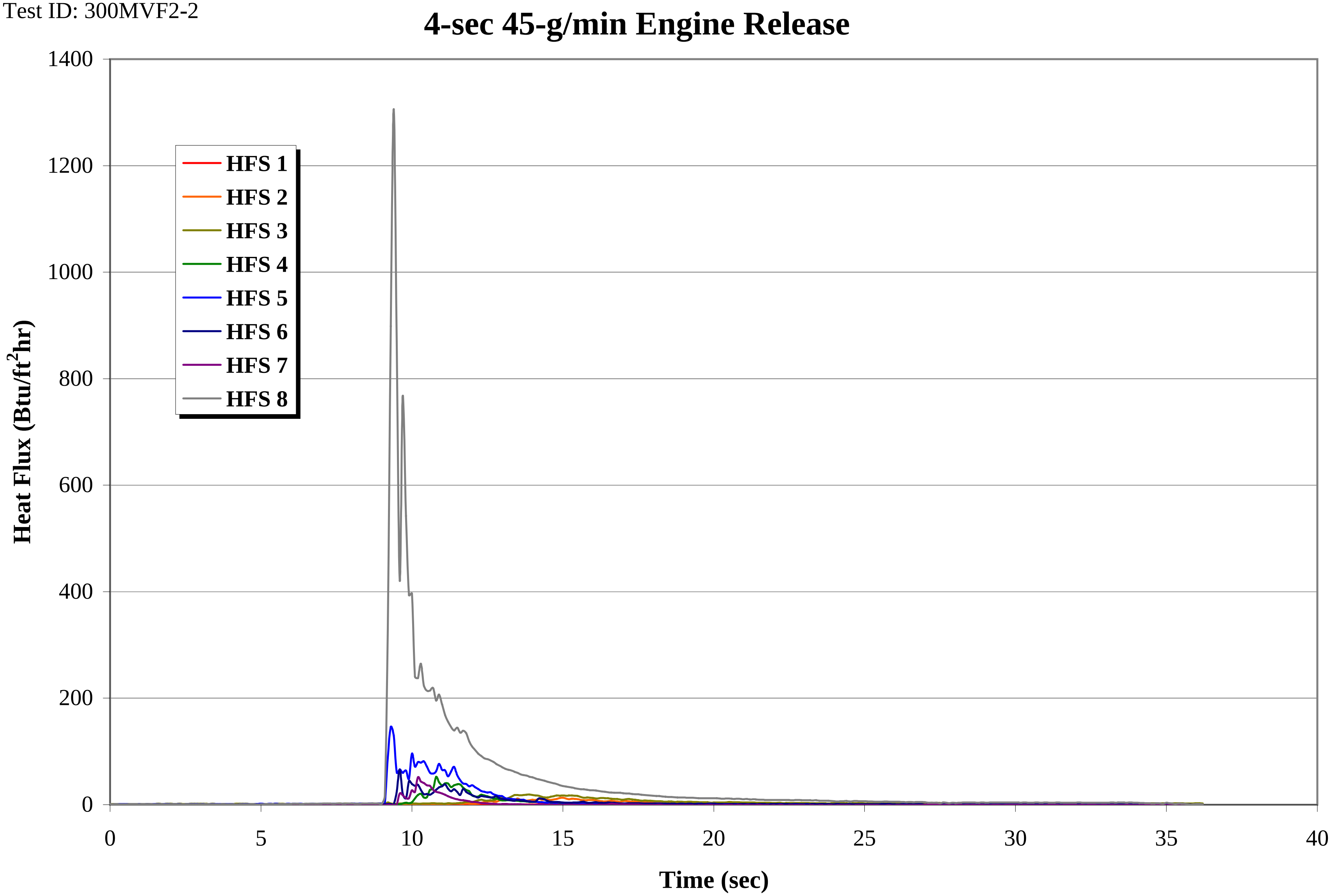

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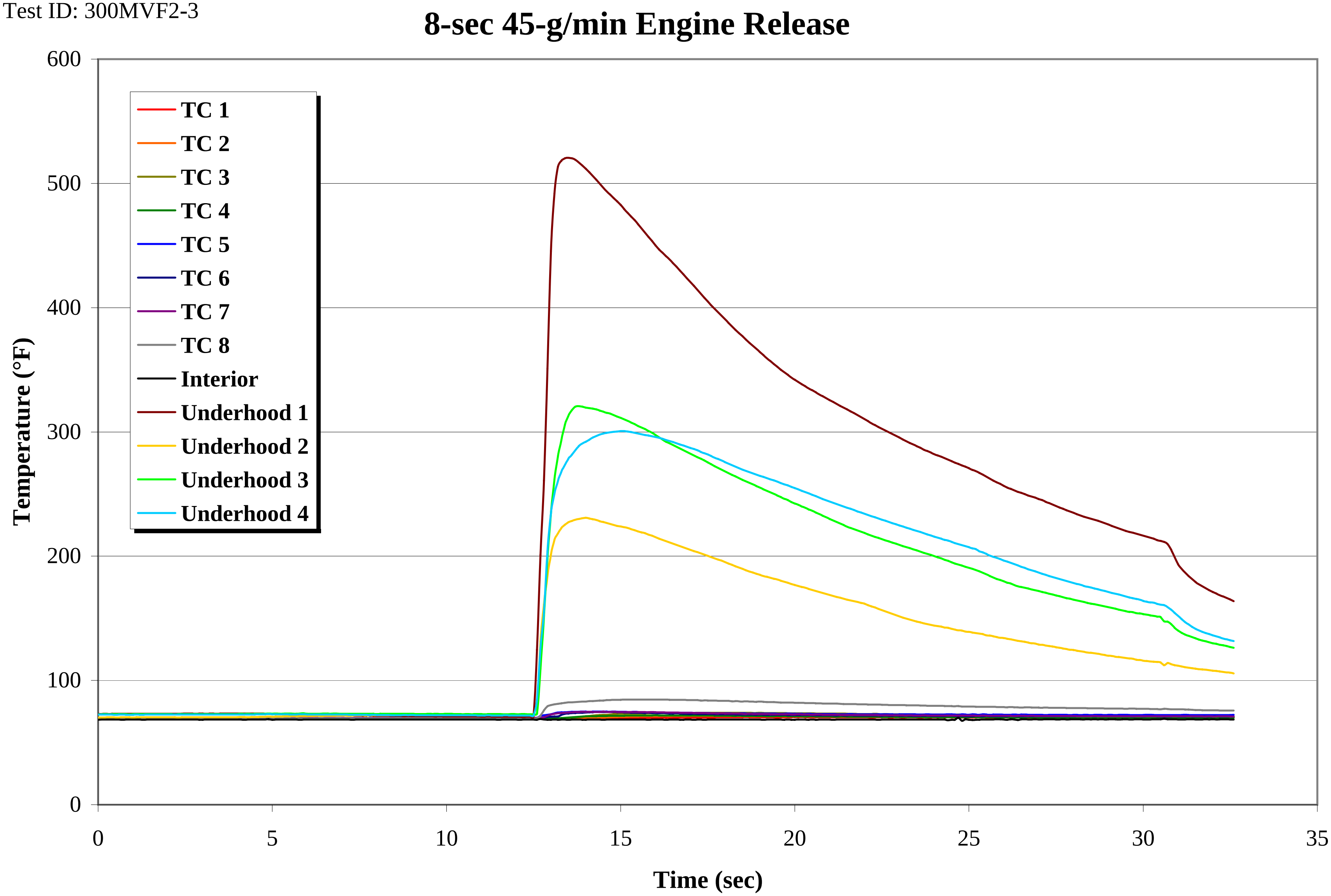

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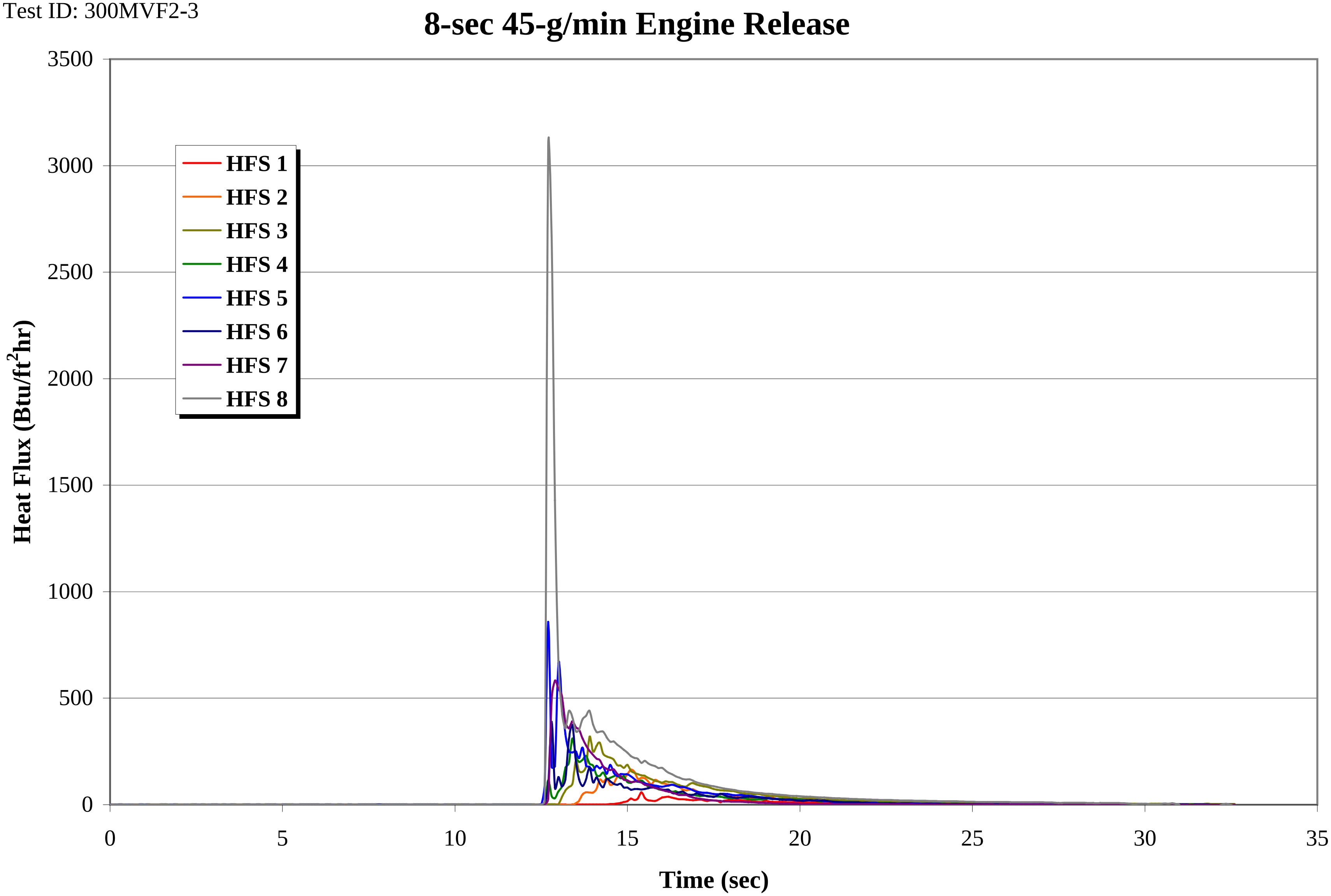

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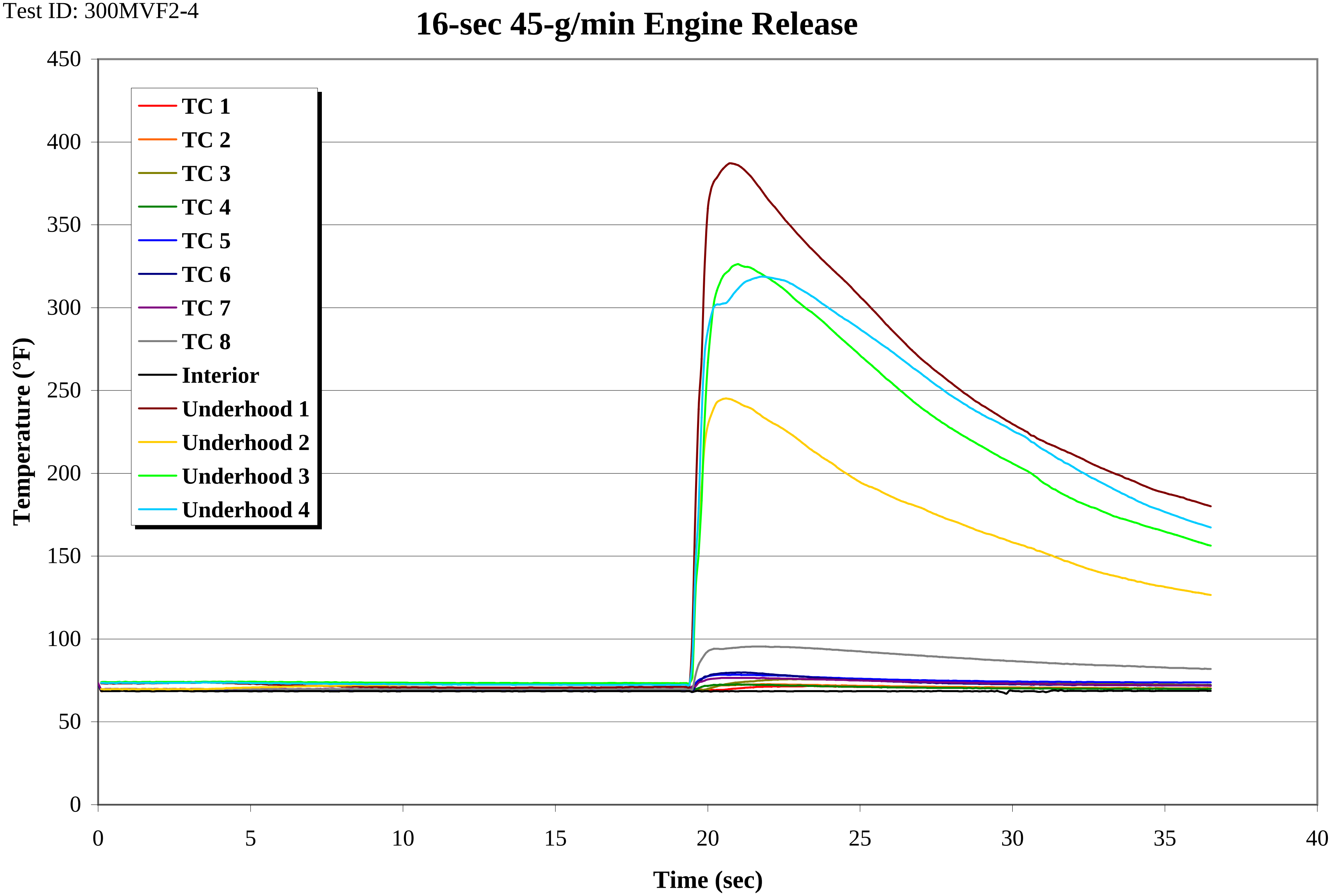

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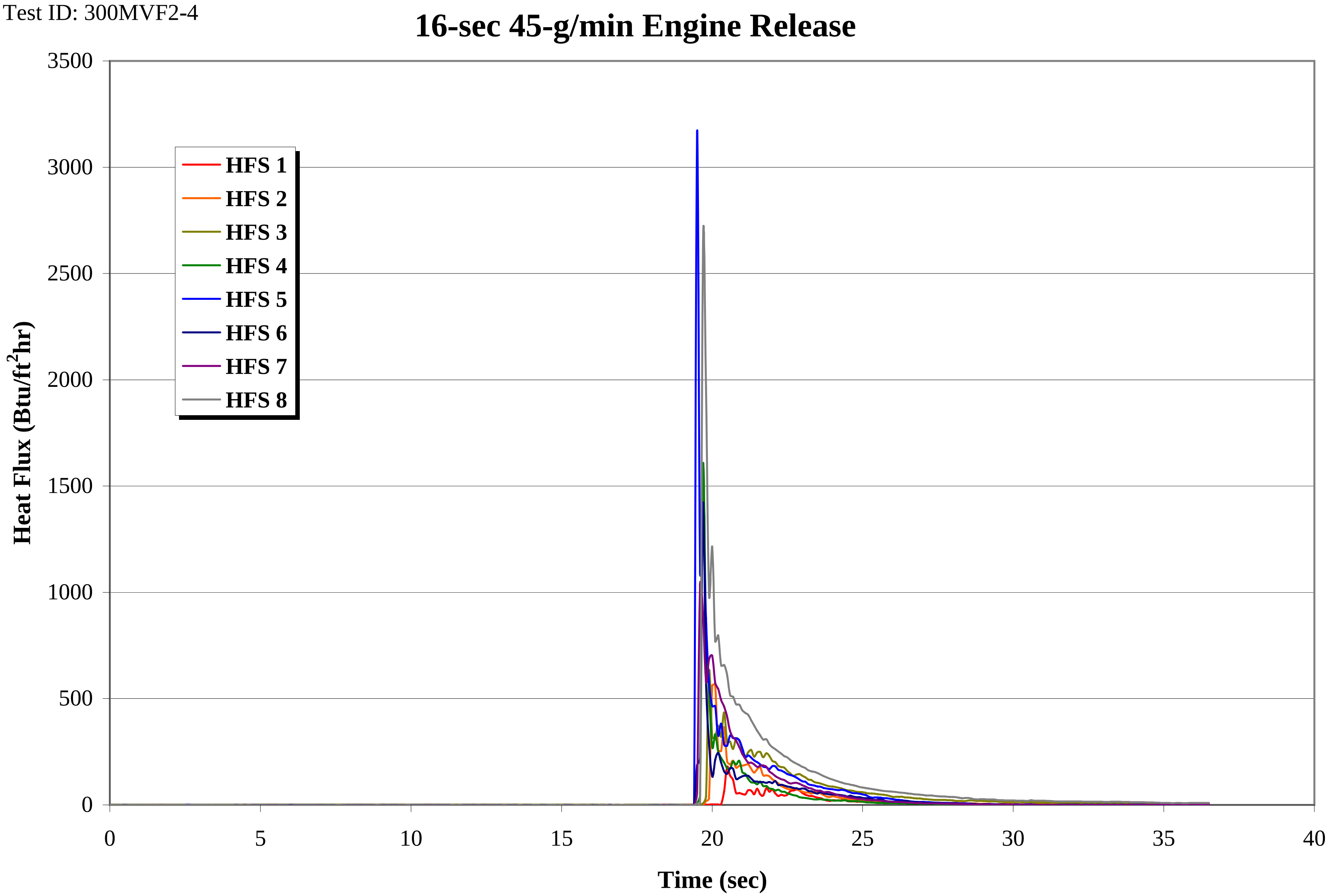

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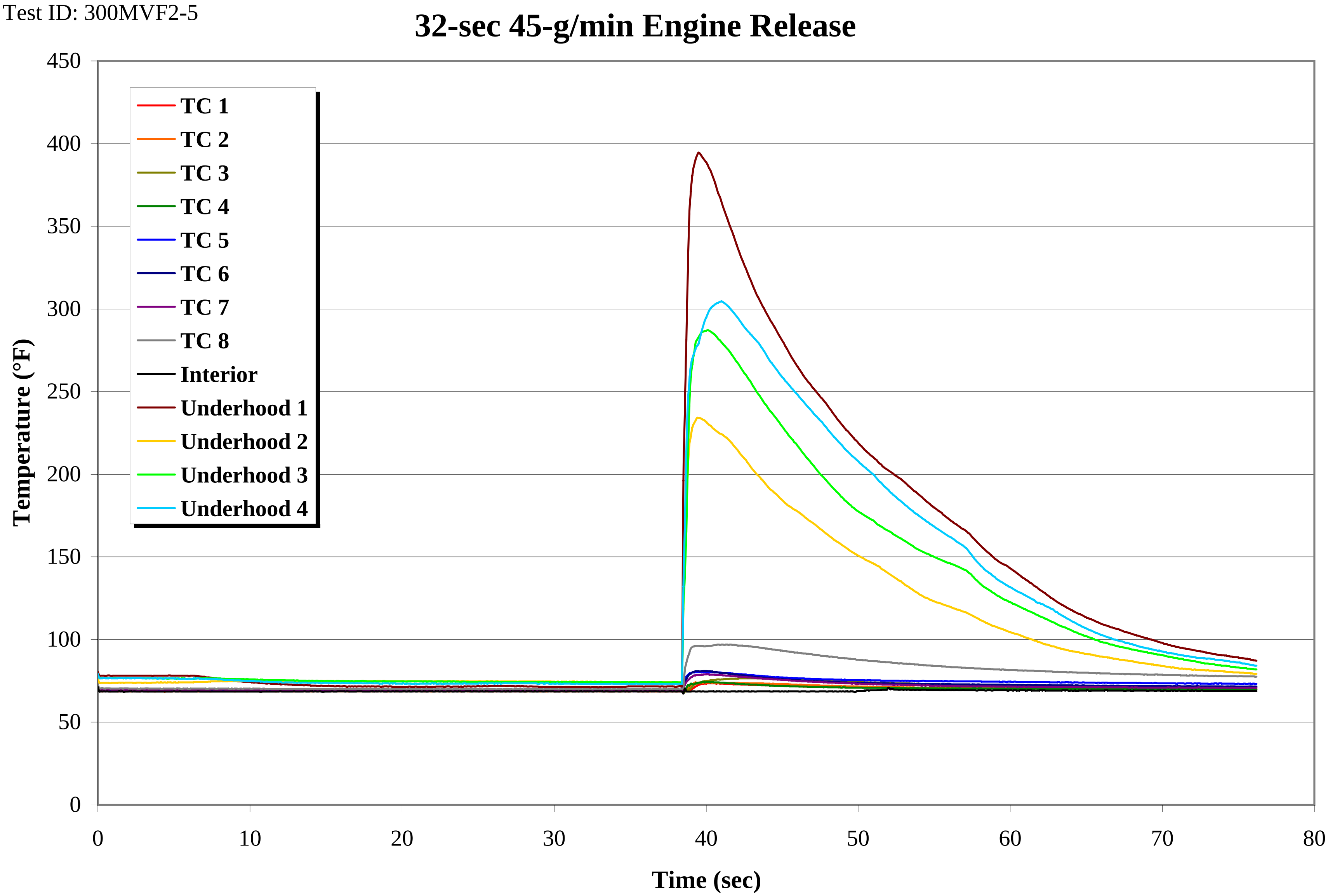

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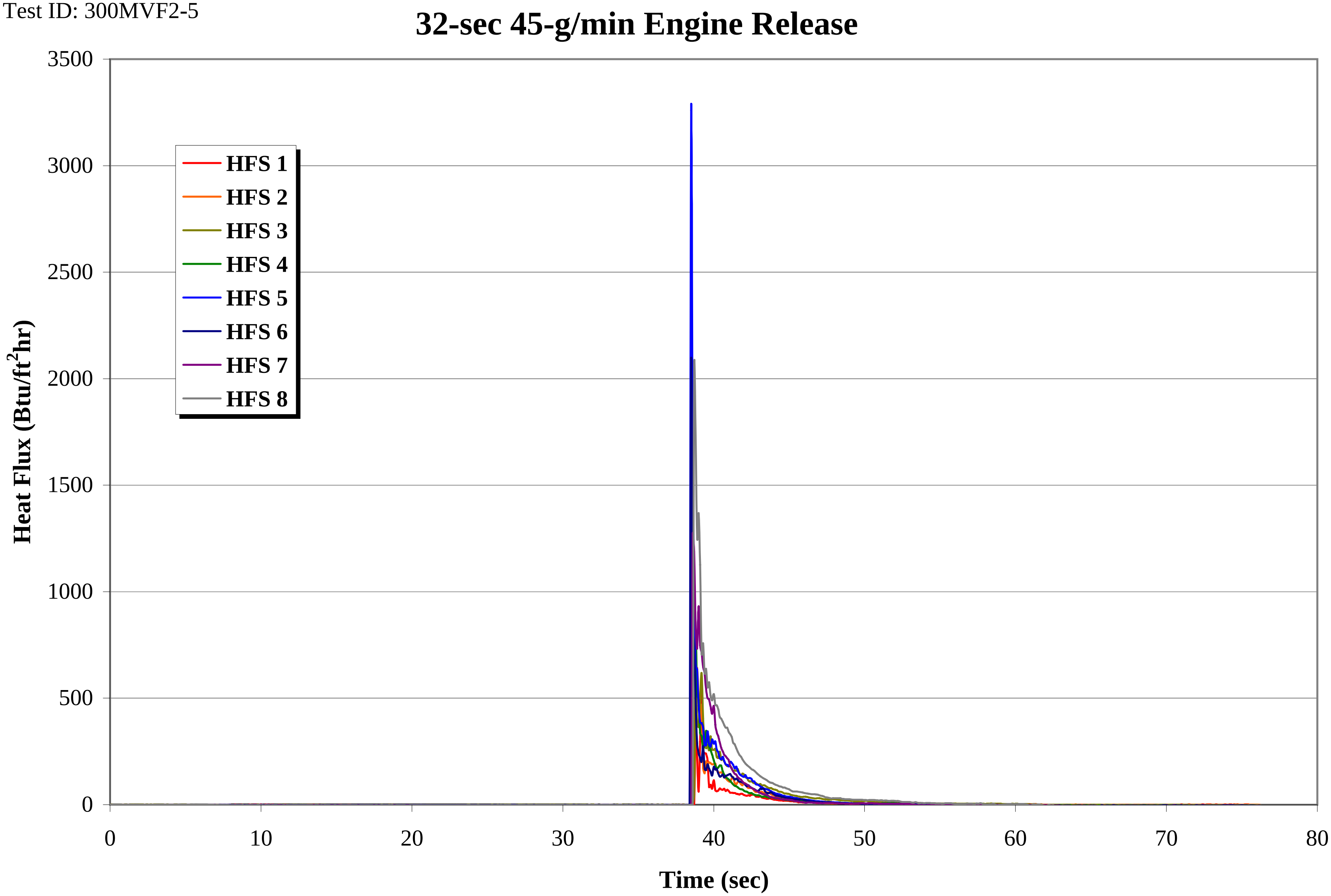

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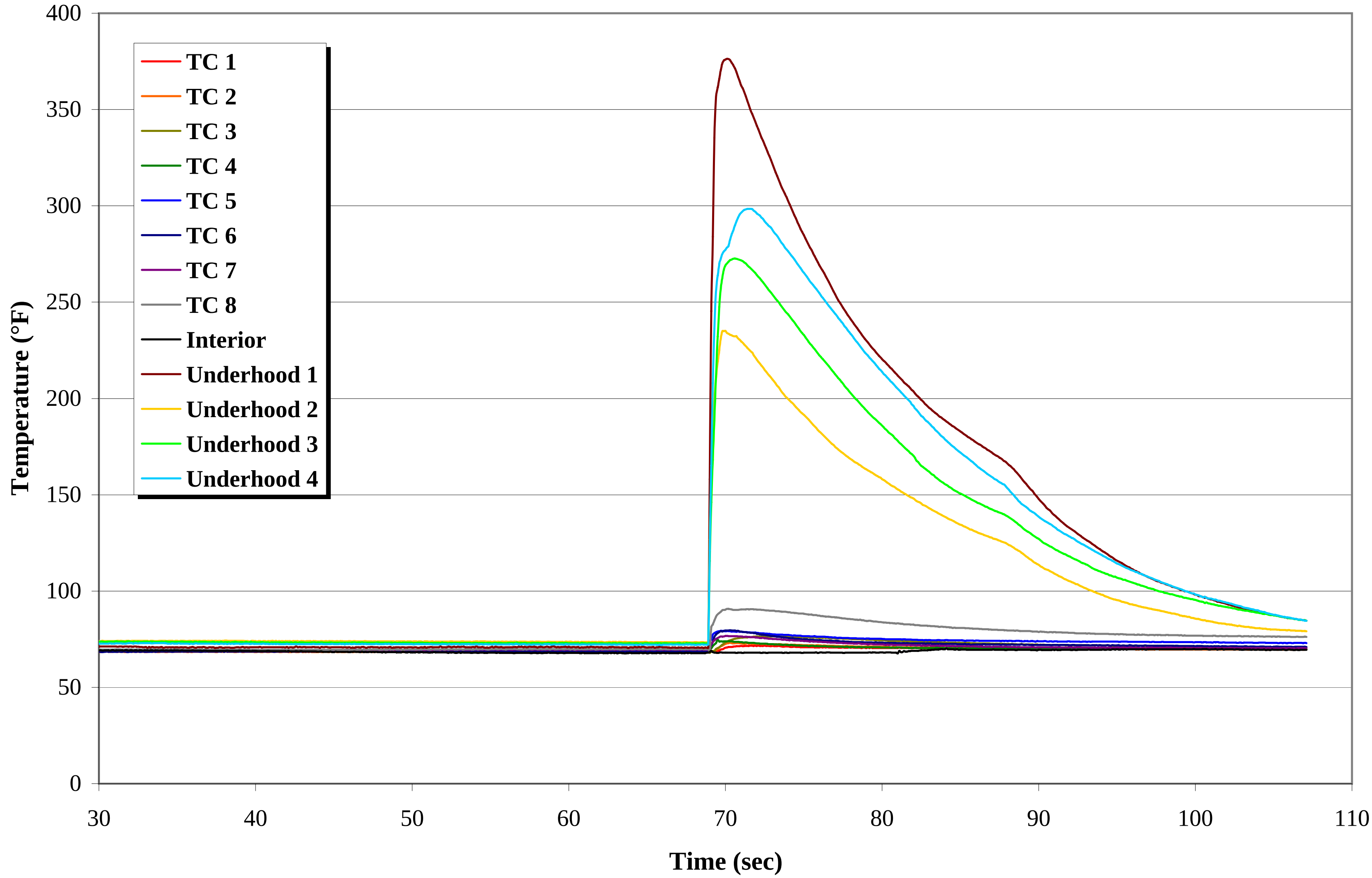
64-sec 45-g/min Engine Release



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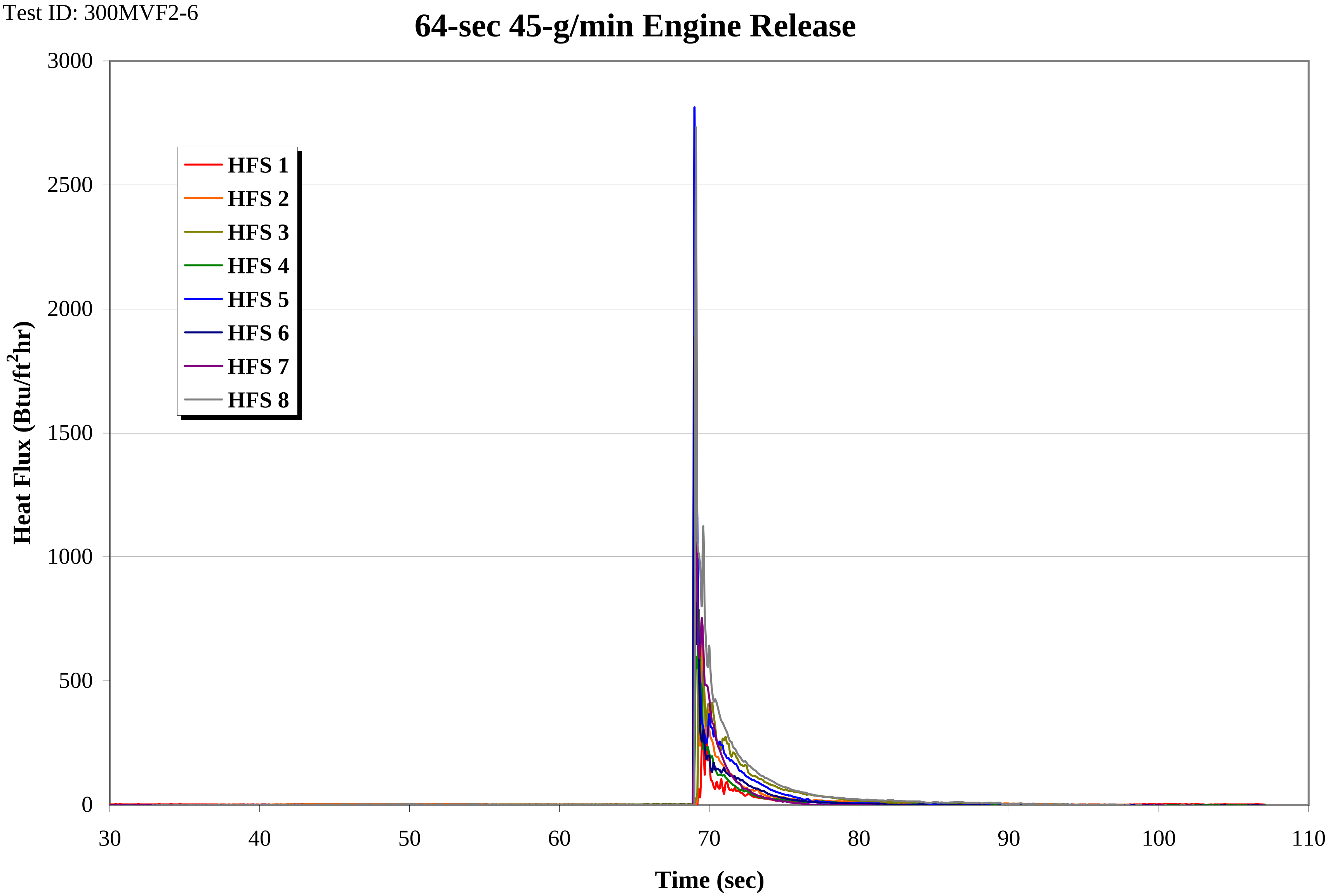

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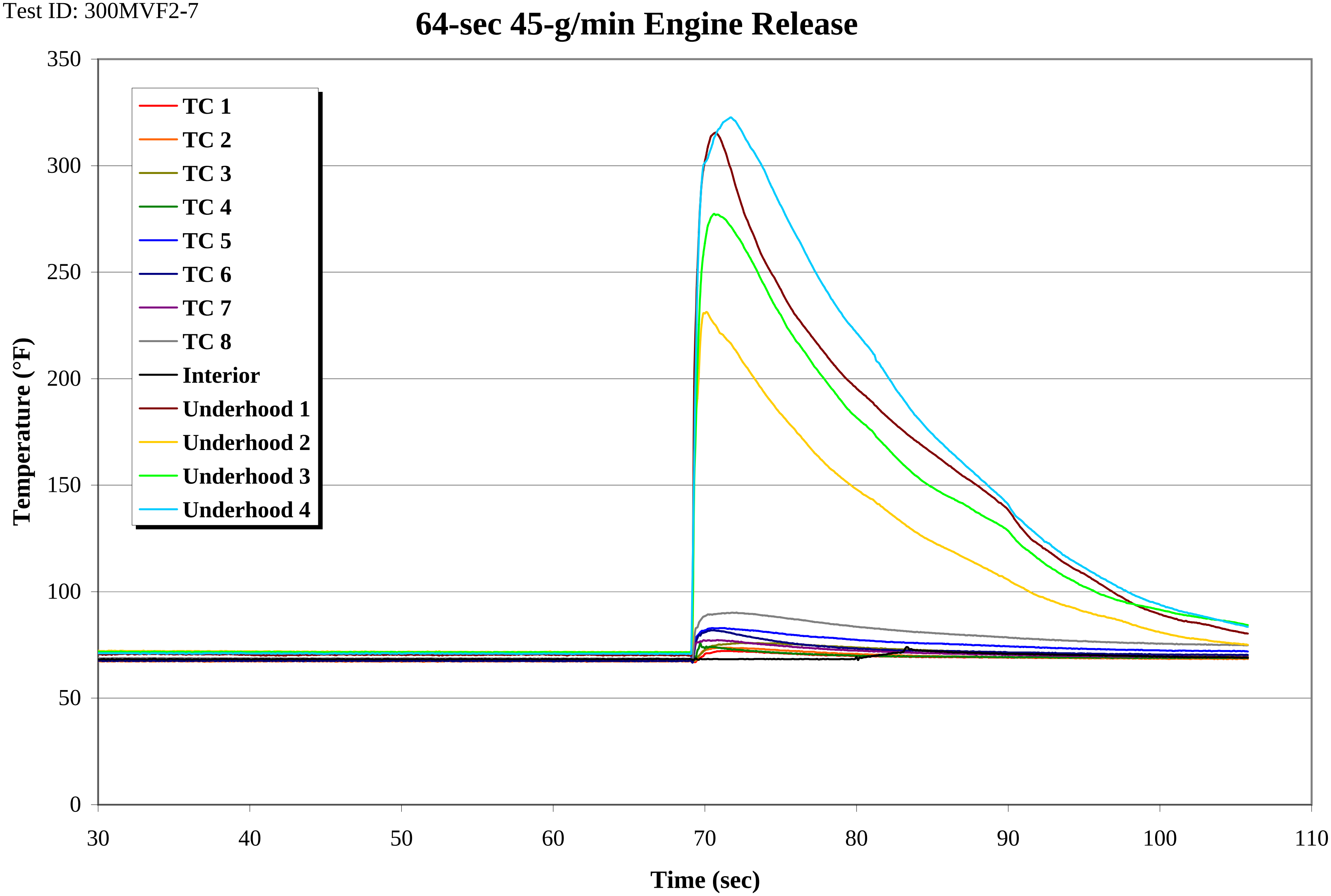

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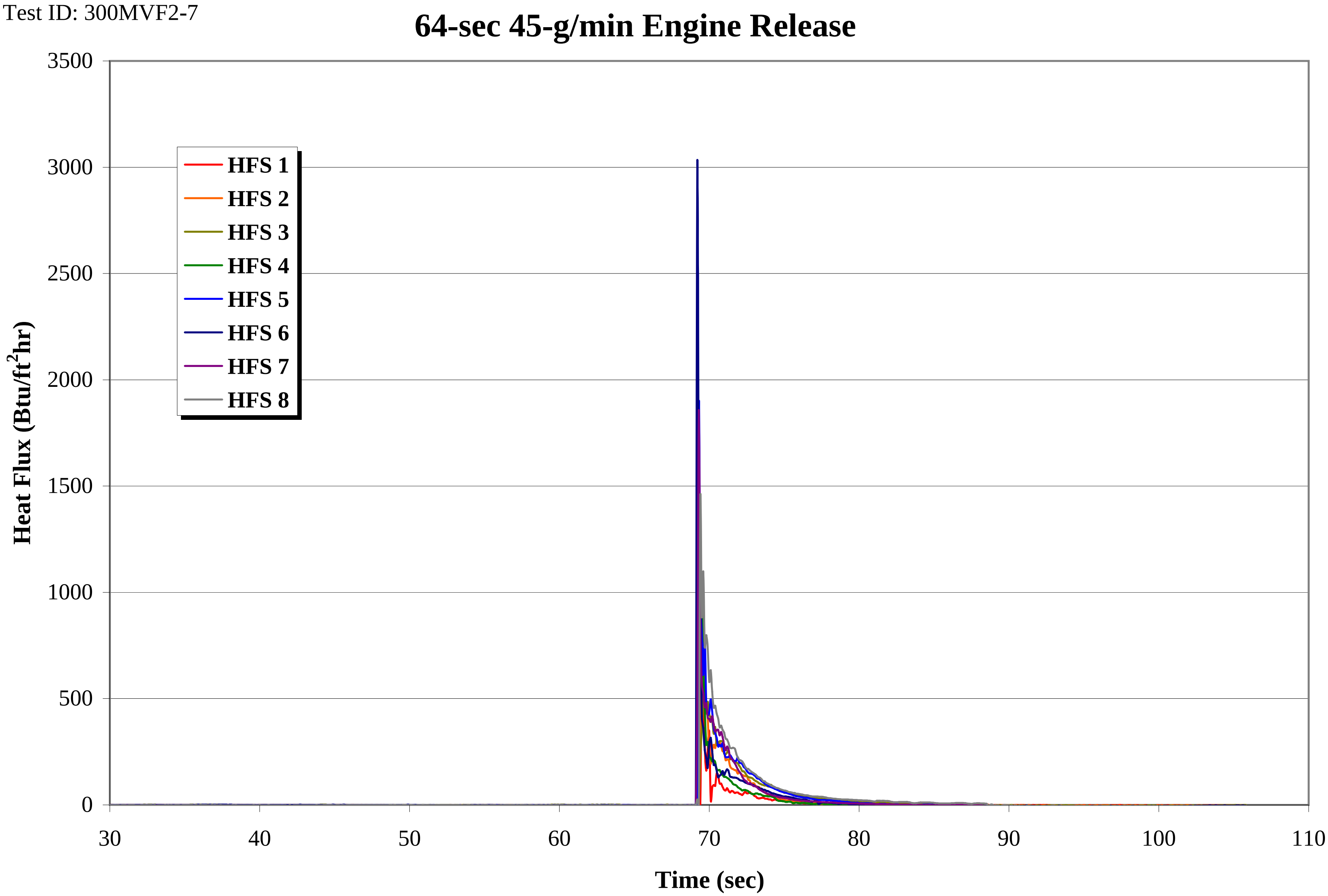

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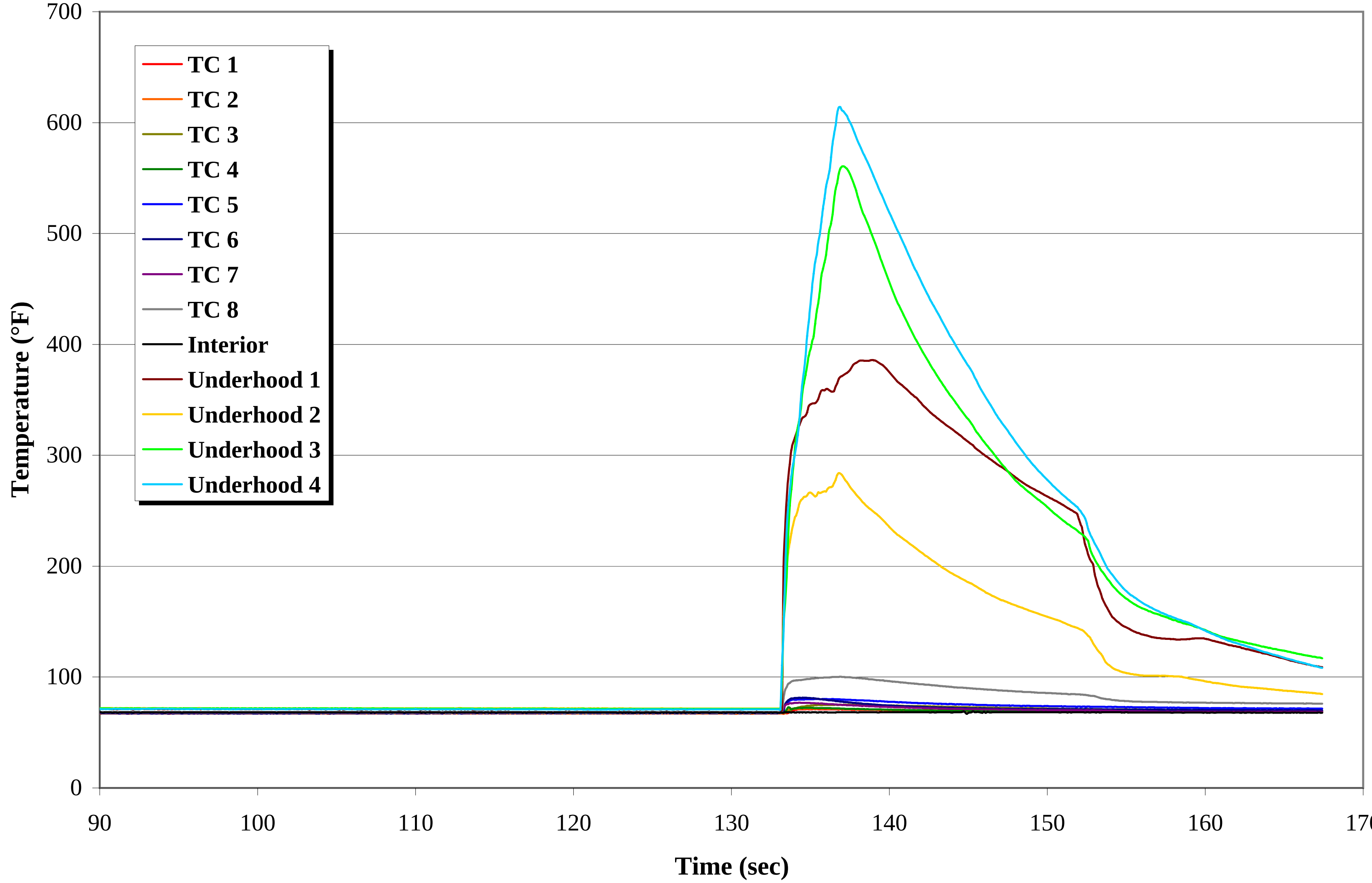
128-sec 45-g/min Engine Release



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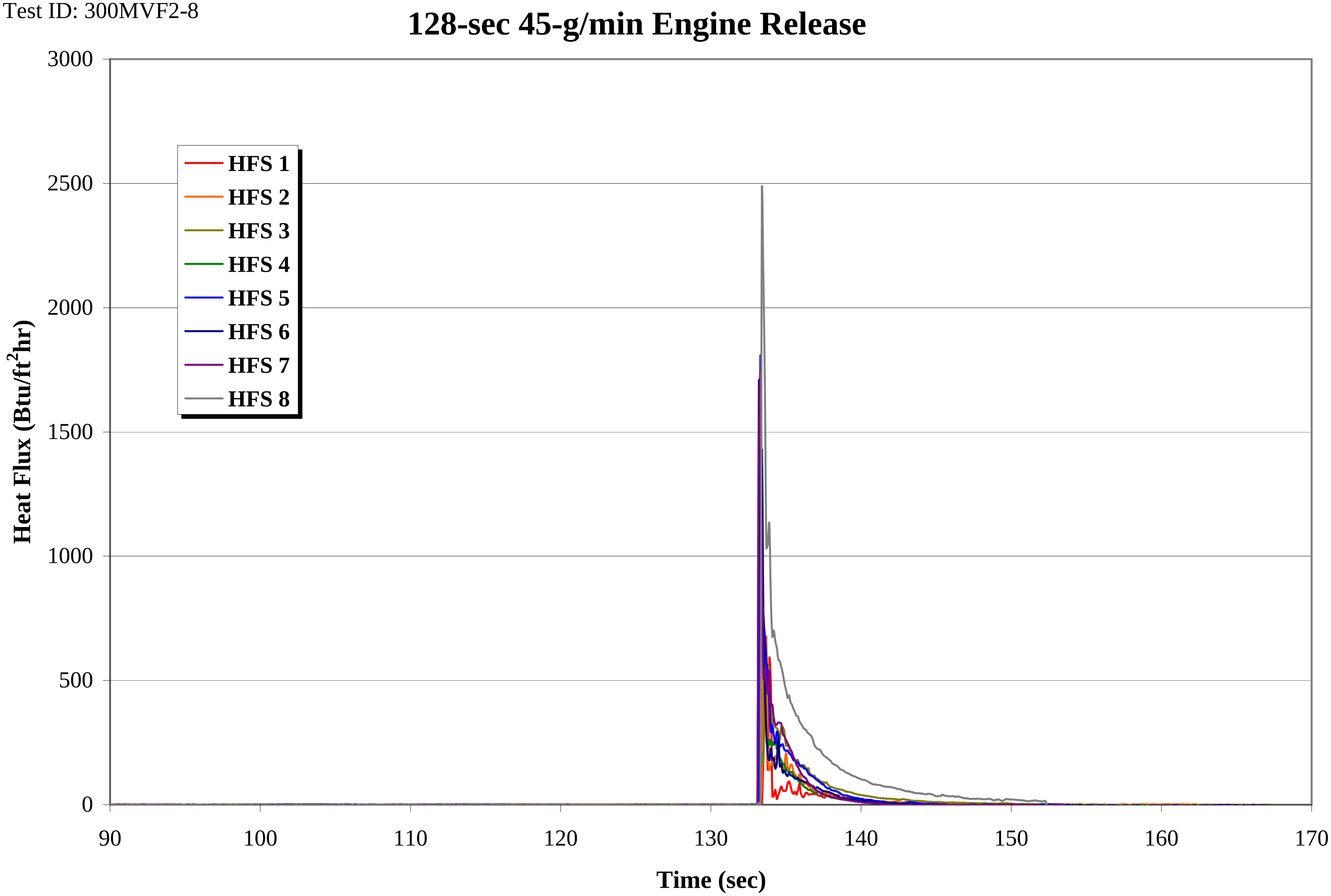

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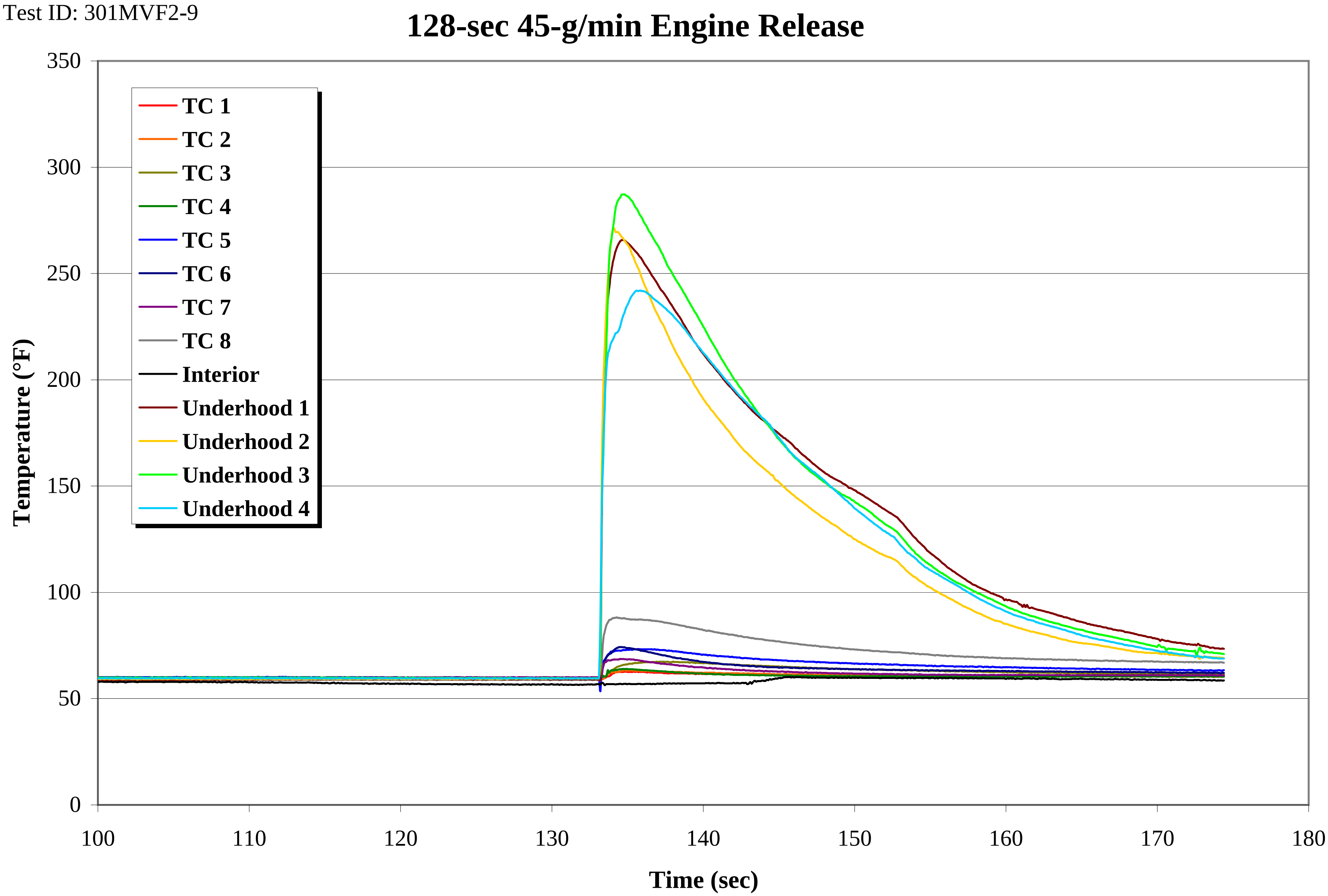

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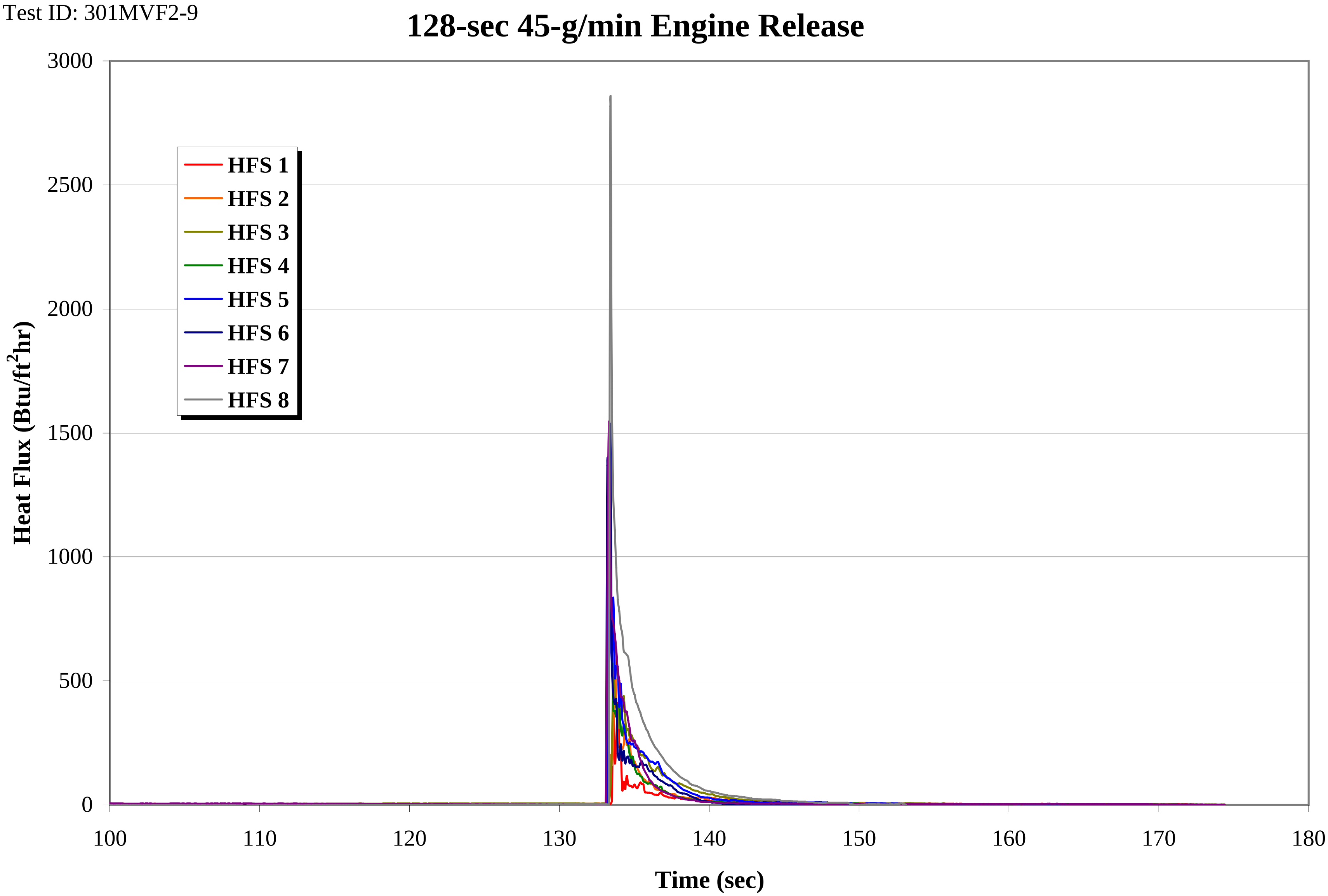

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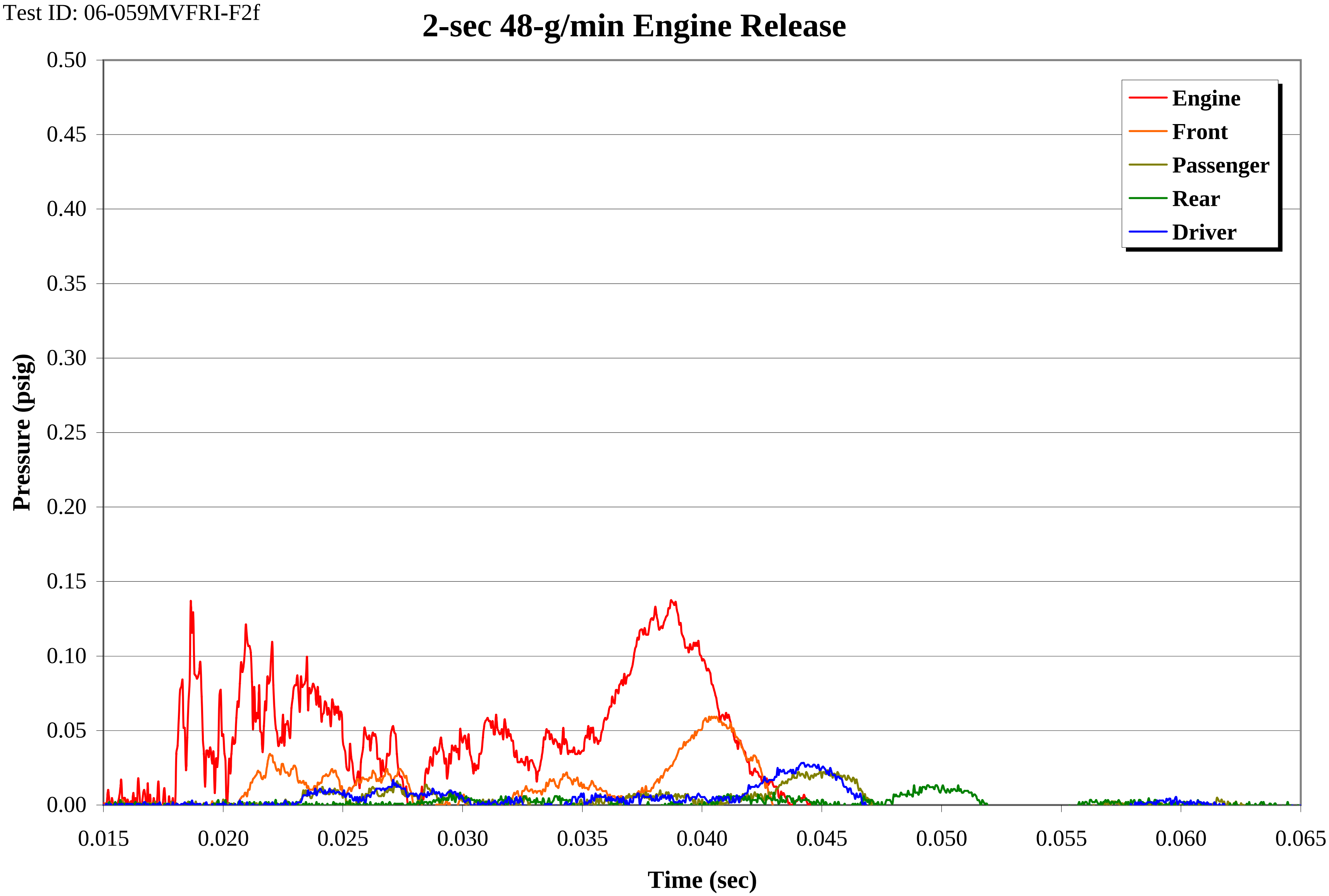

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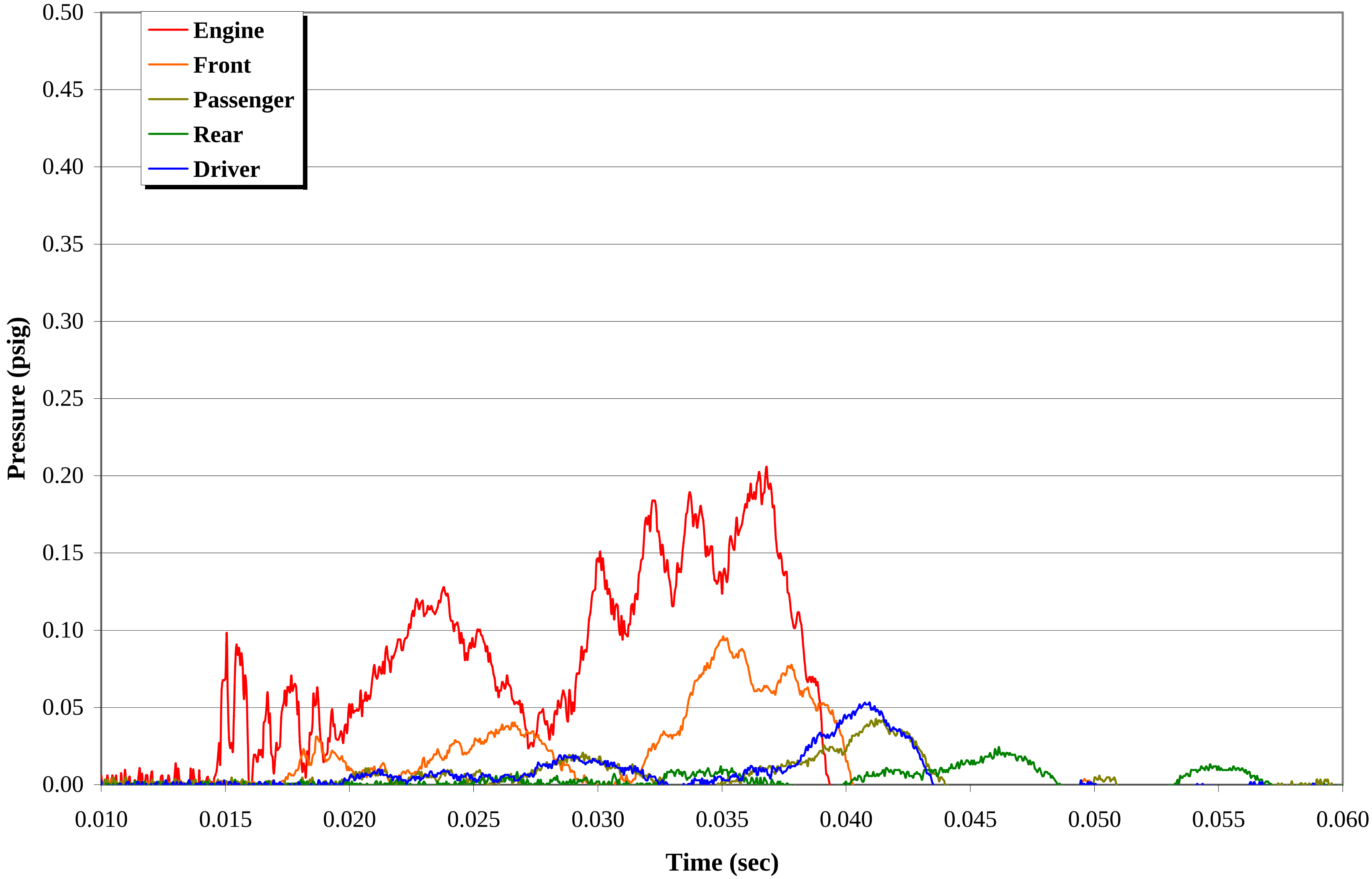
4-sec 48-g/min Engine Release



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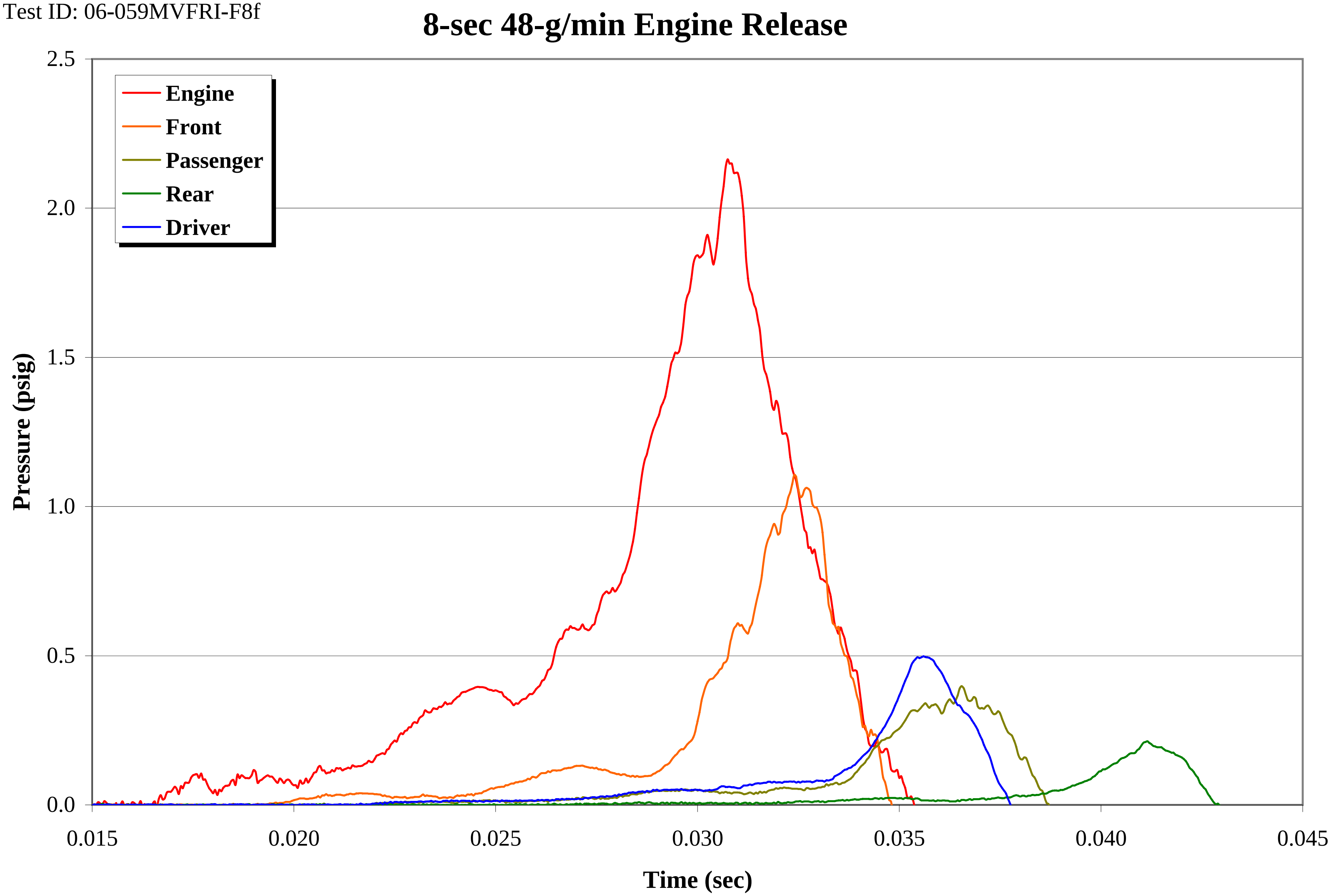

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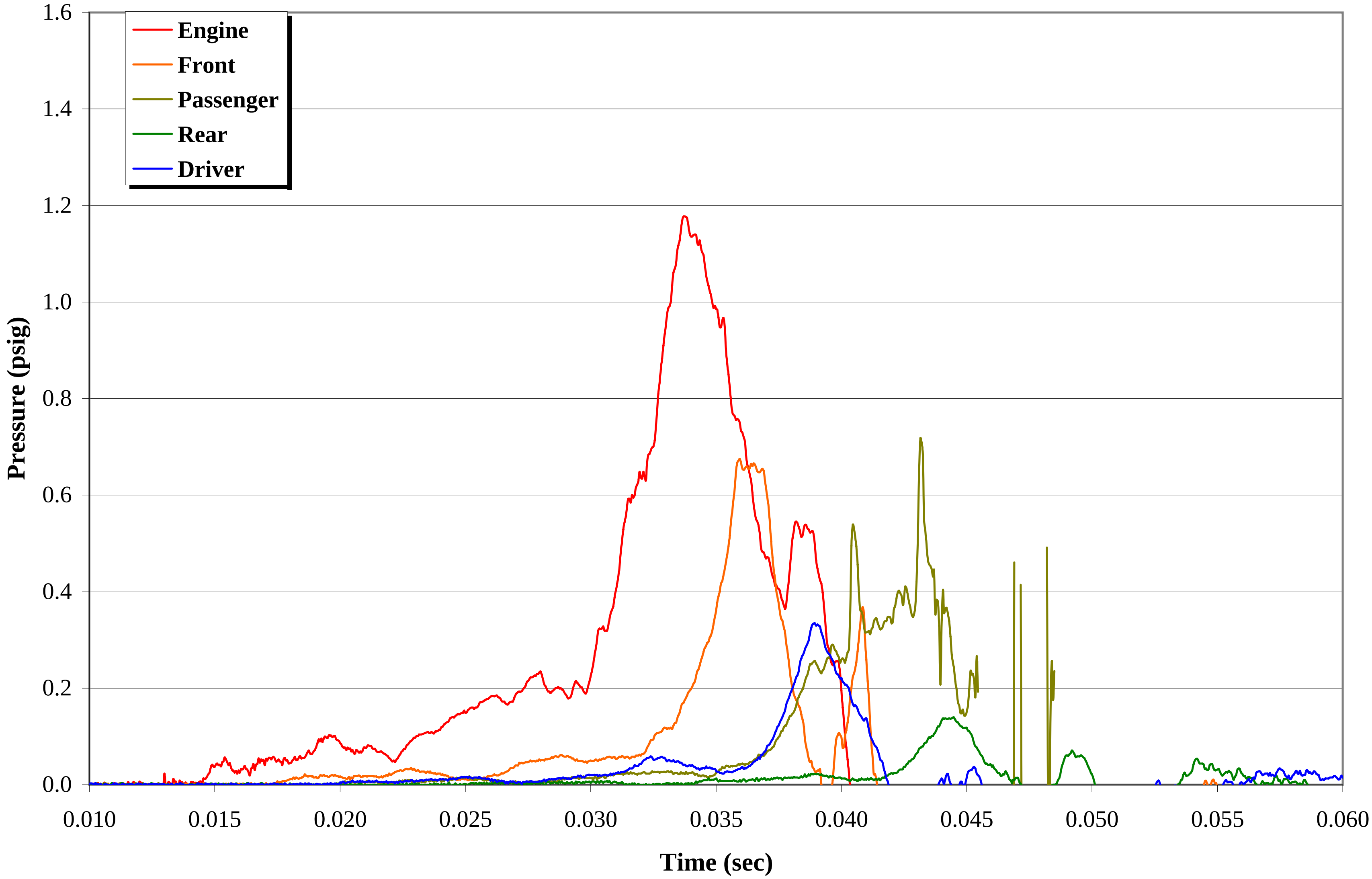
Test ID: 06-059MVFRI-F16f

16-sec 48-g/min Engine Release



Motor Vehicle Fire Research Institute
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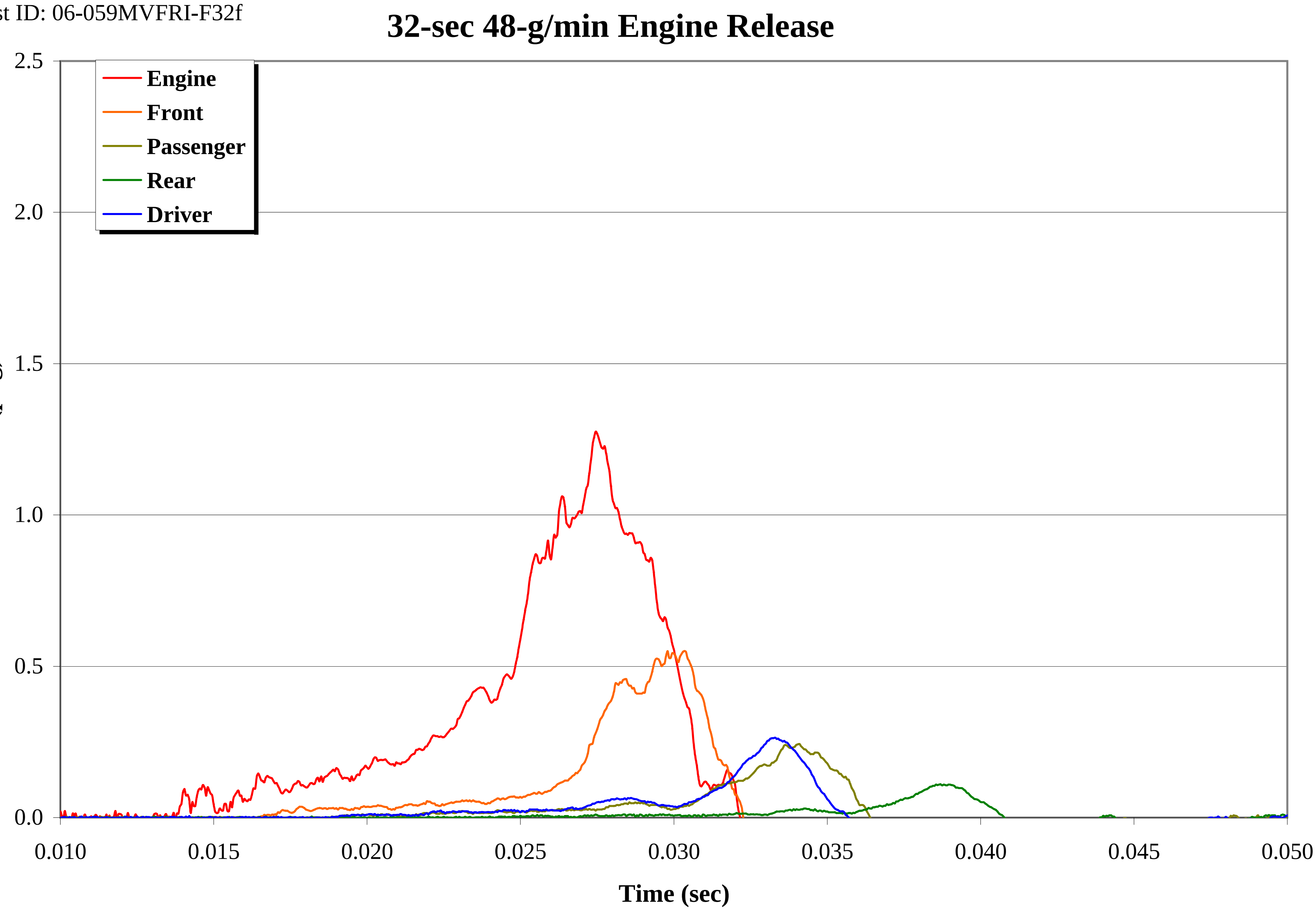

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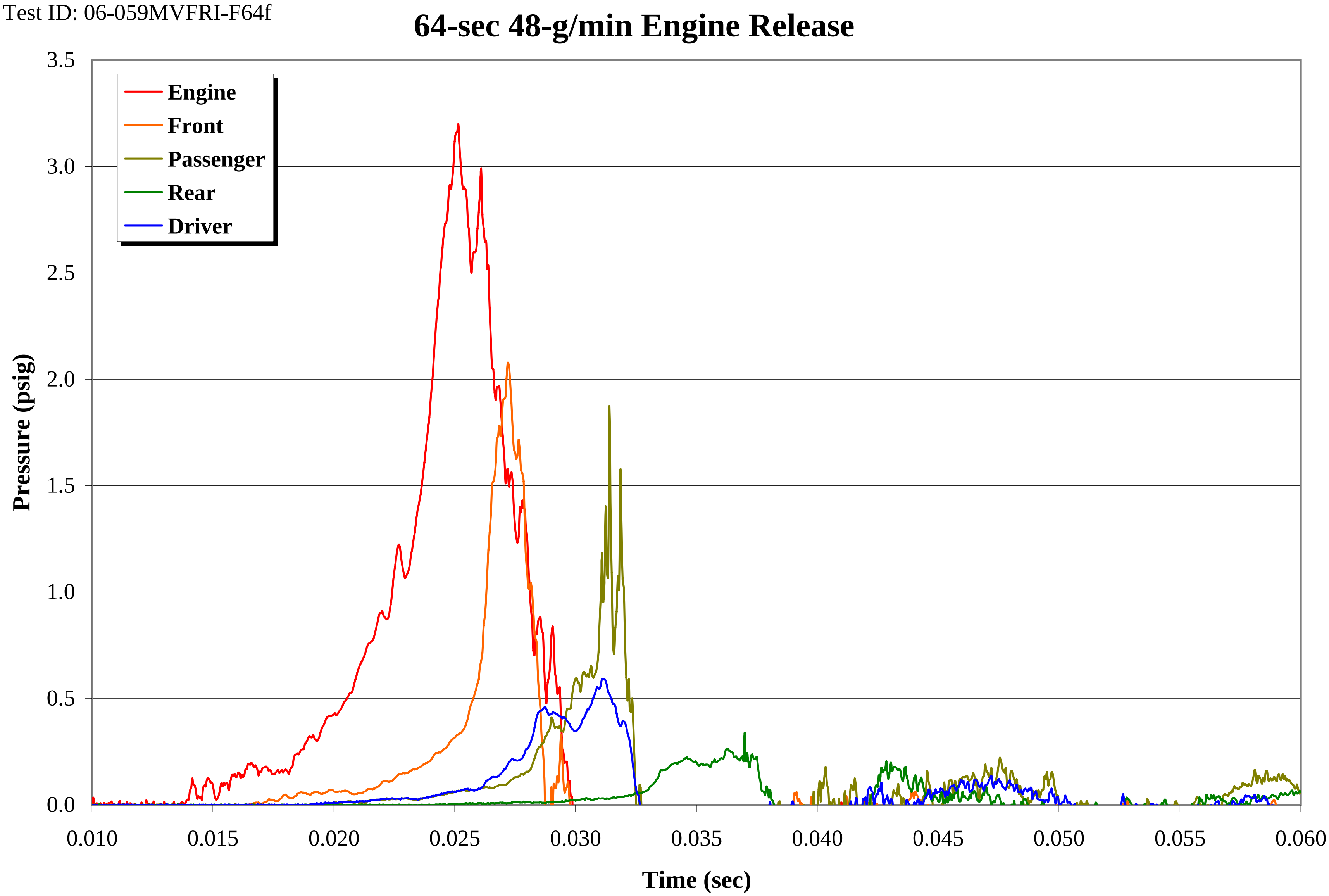
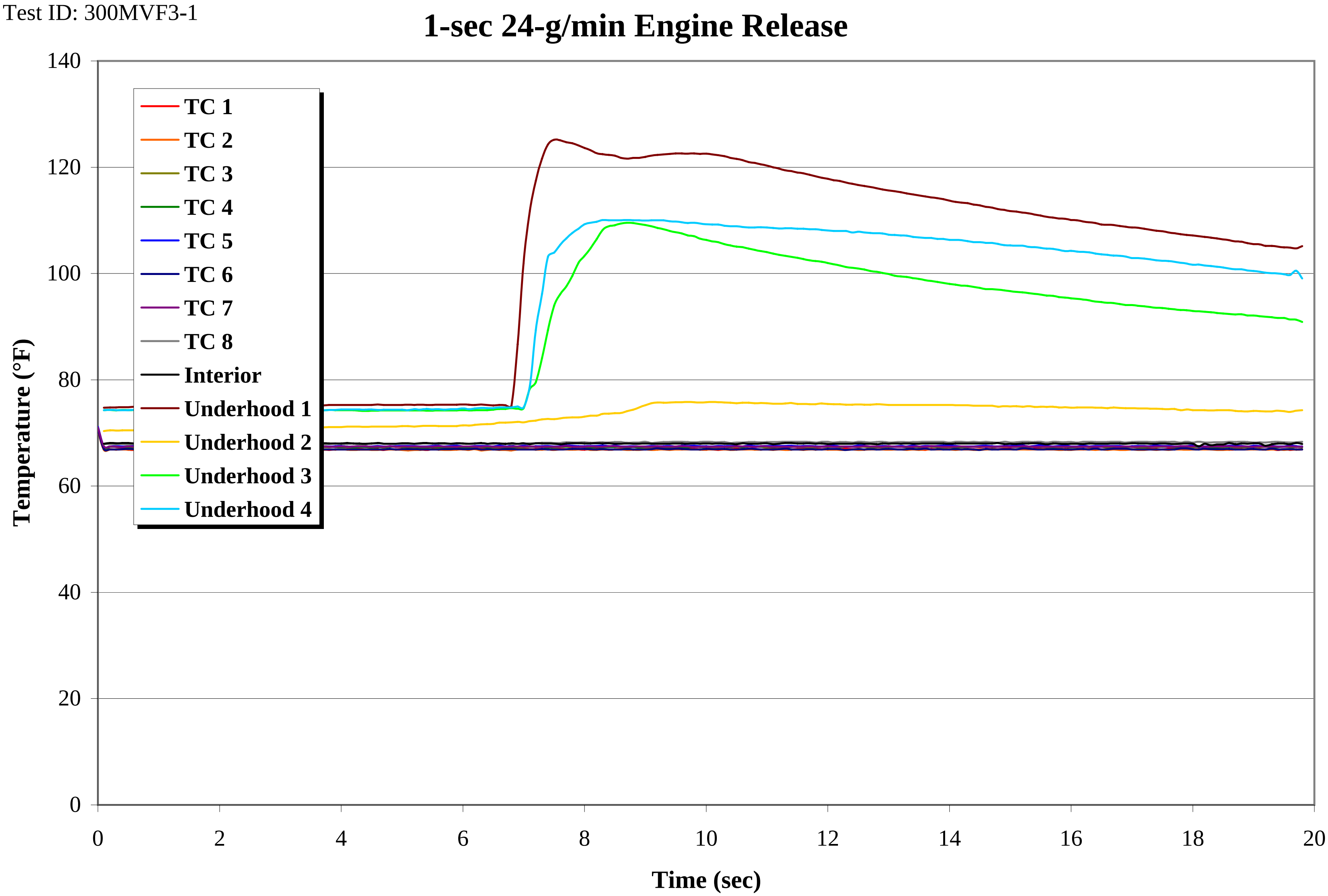


APPENDIX C

SERIES 3 GRAPHICAL TEST DATA

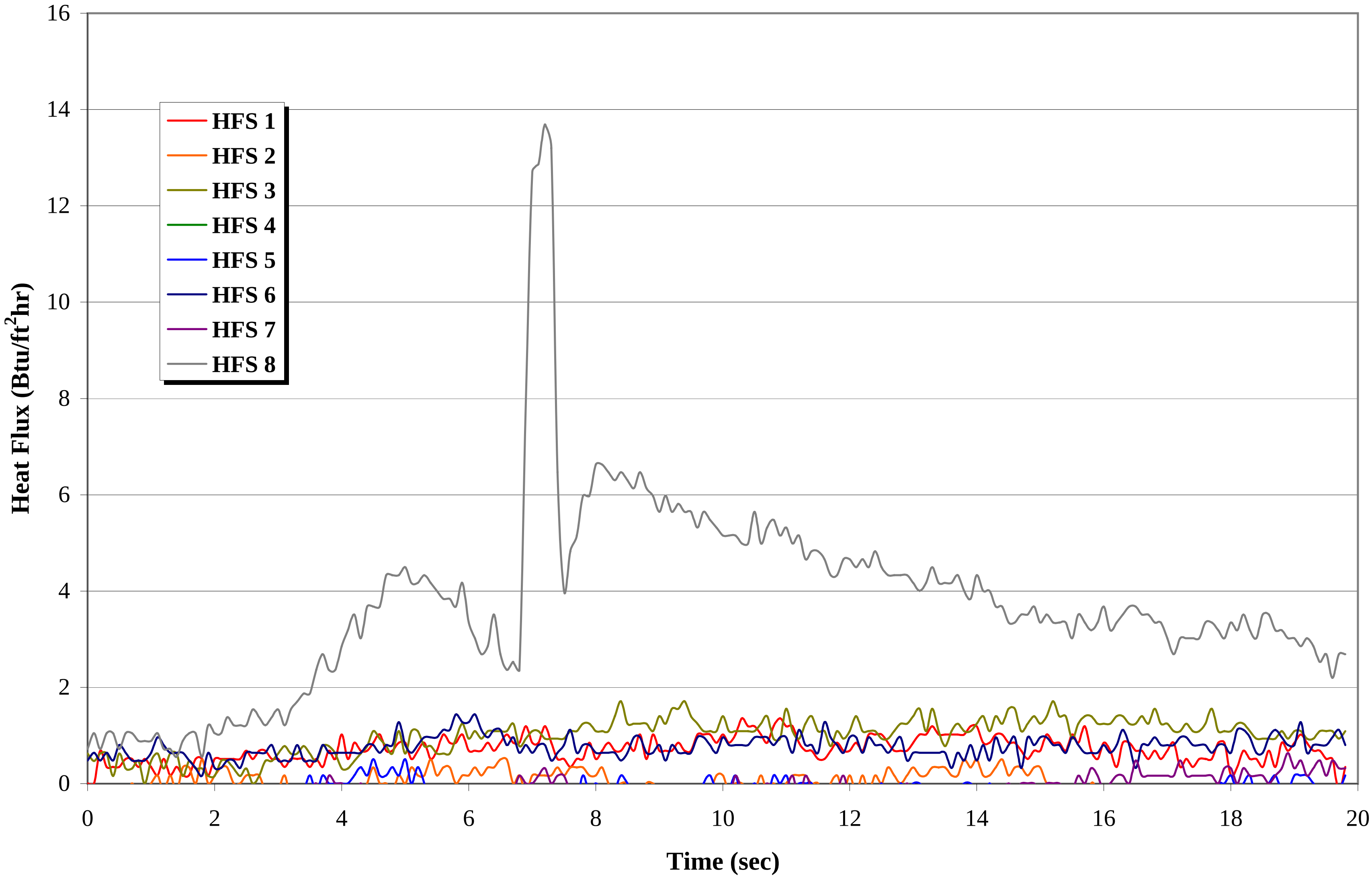
(CONSISTING OF 25 PAGES)

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-1



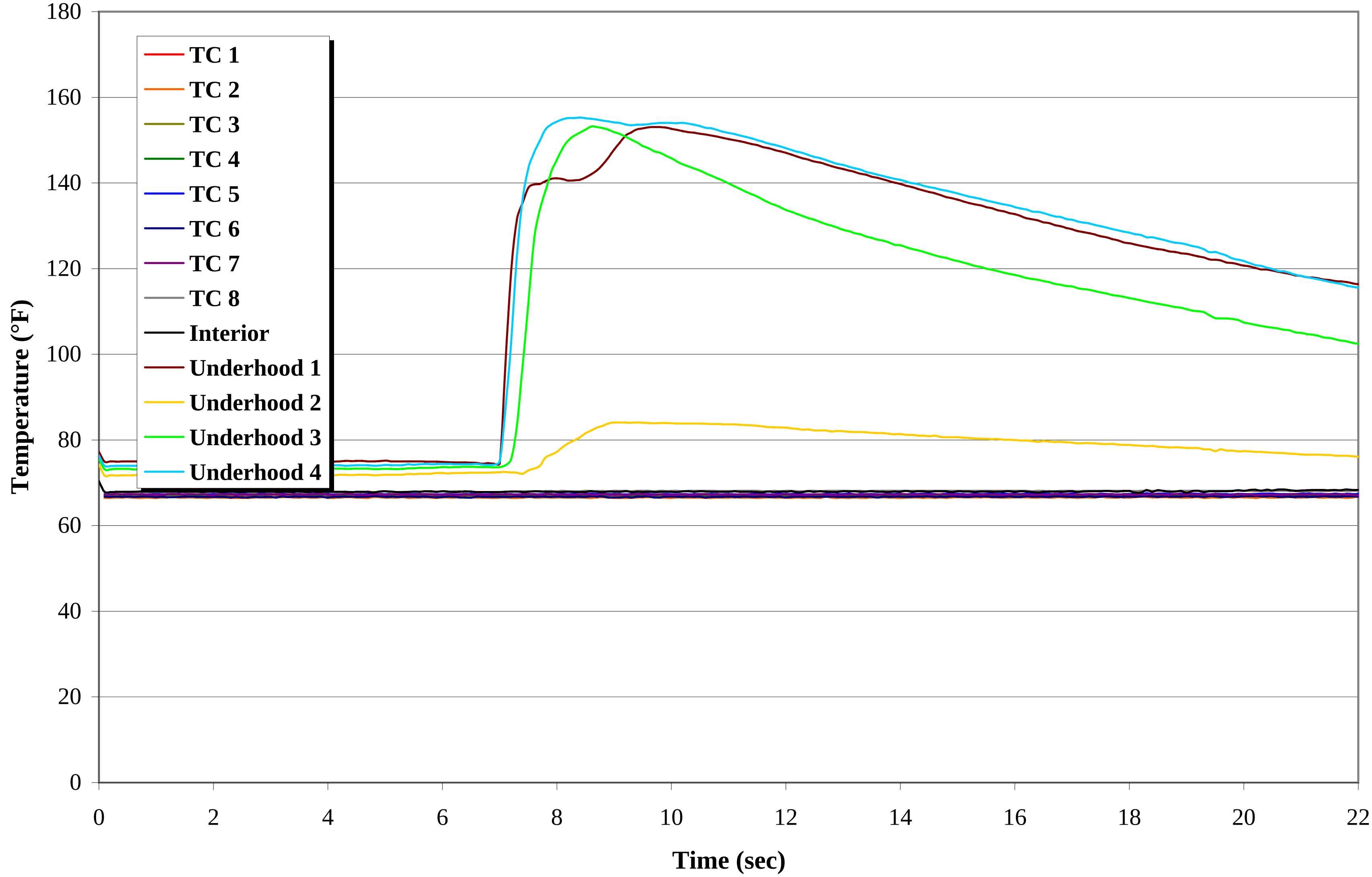
Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-1

1-sec 24-g/min Engine Release

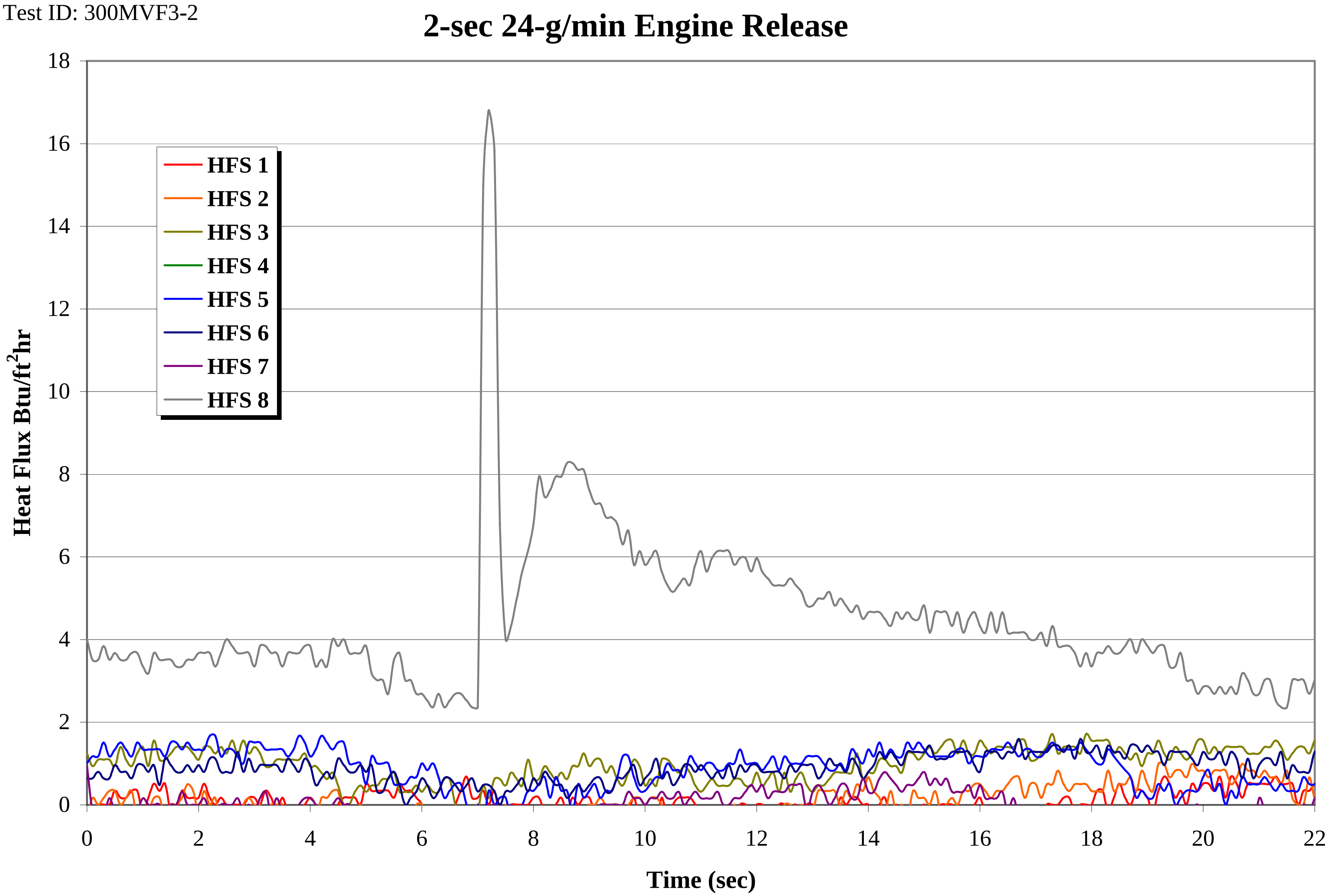


Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-2

2-sec 24-g/min Engine Release



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-2



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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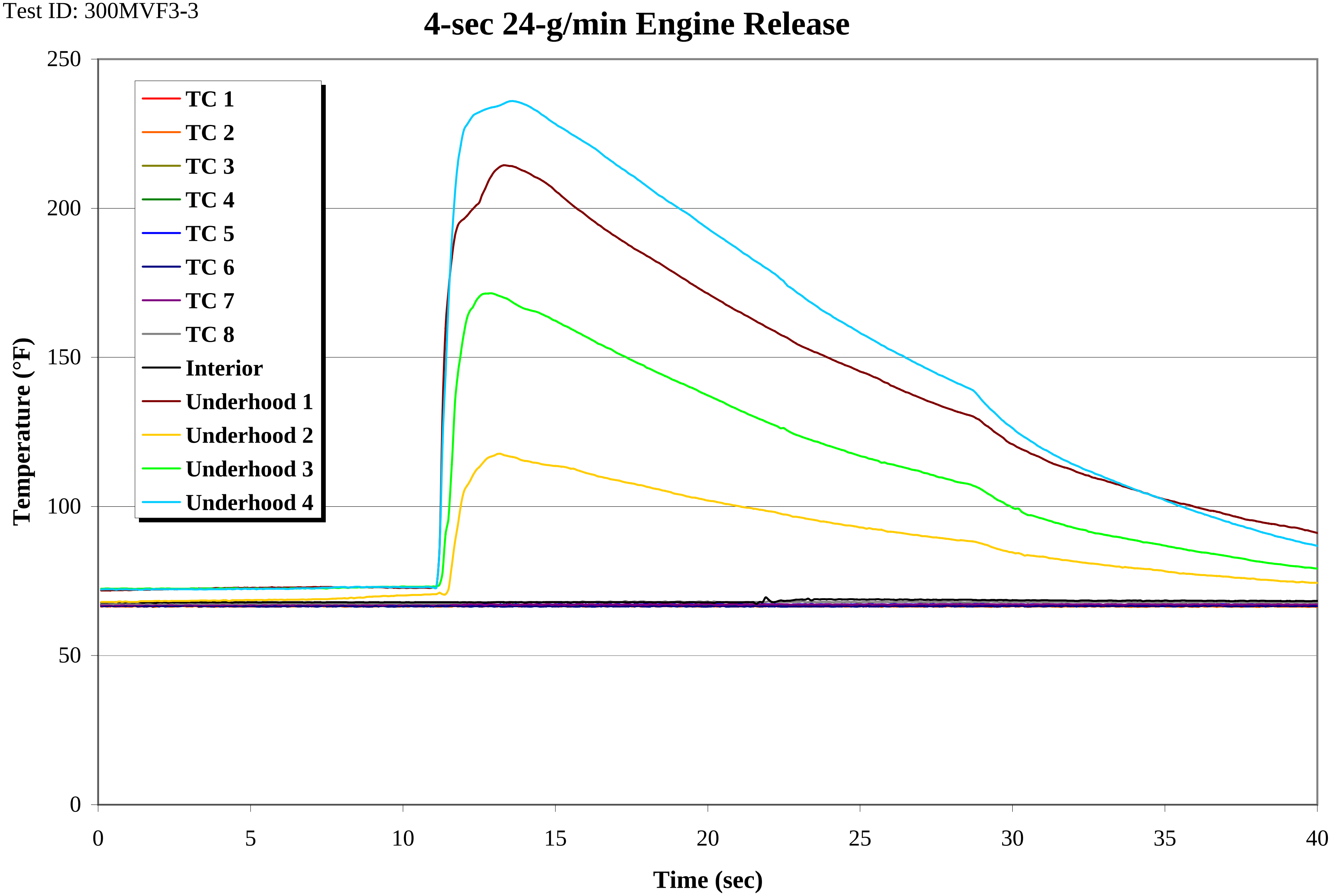
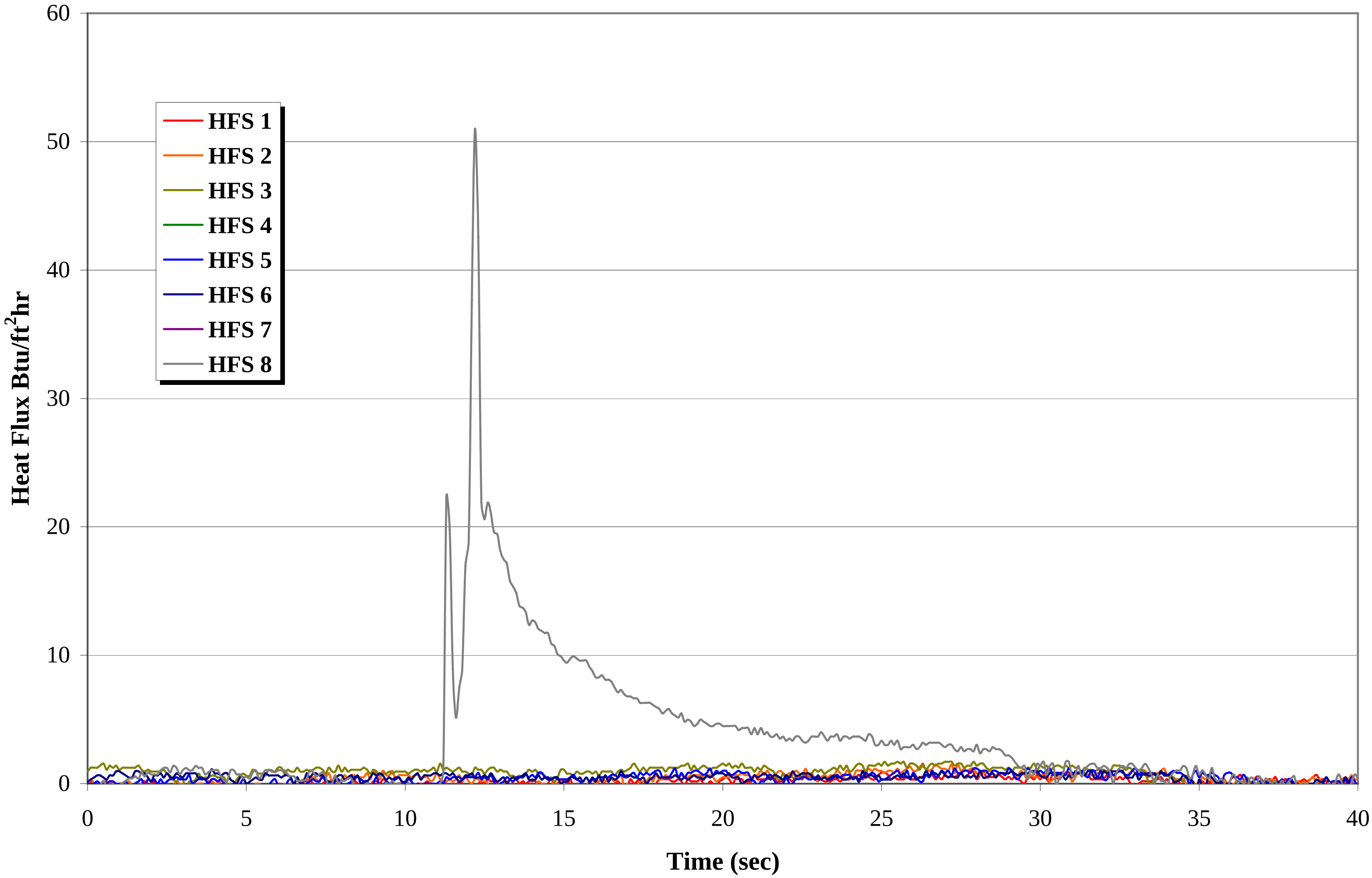
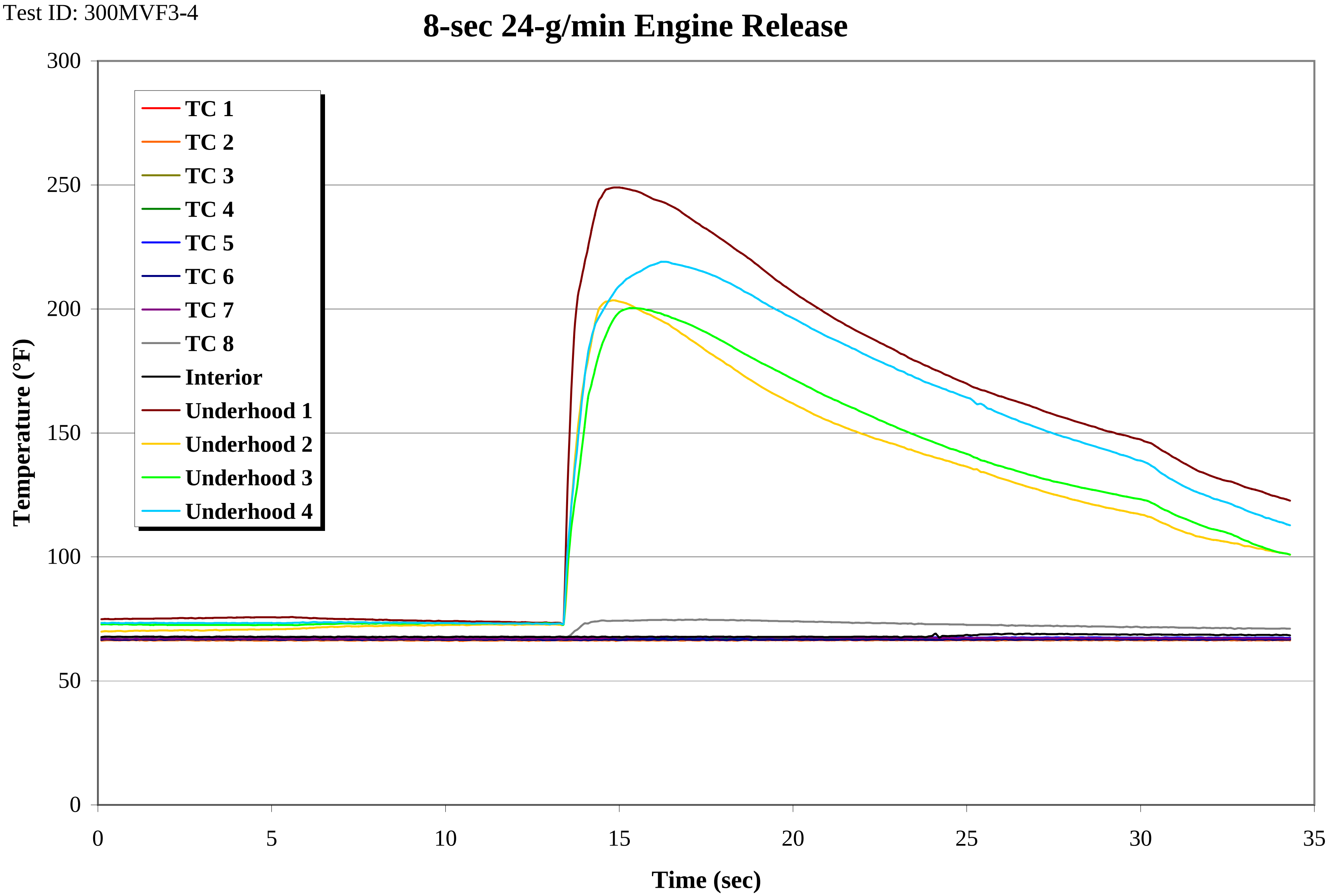


Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-3

4-sec 24-g/min Engine Release



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-4



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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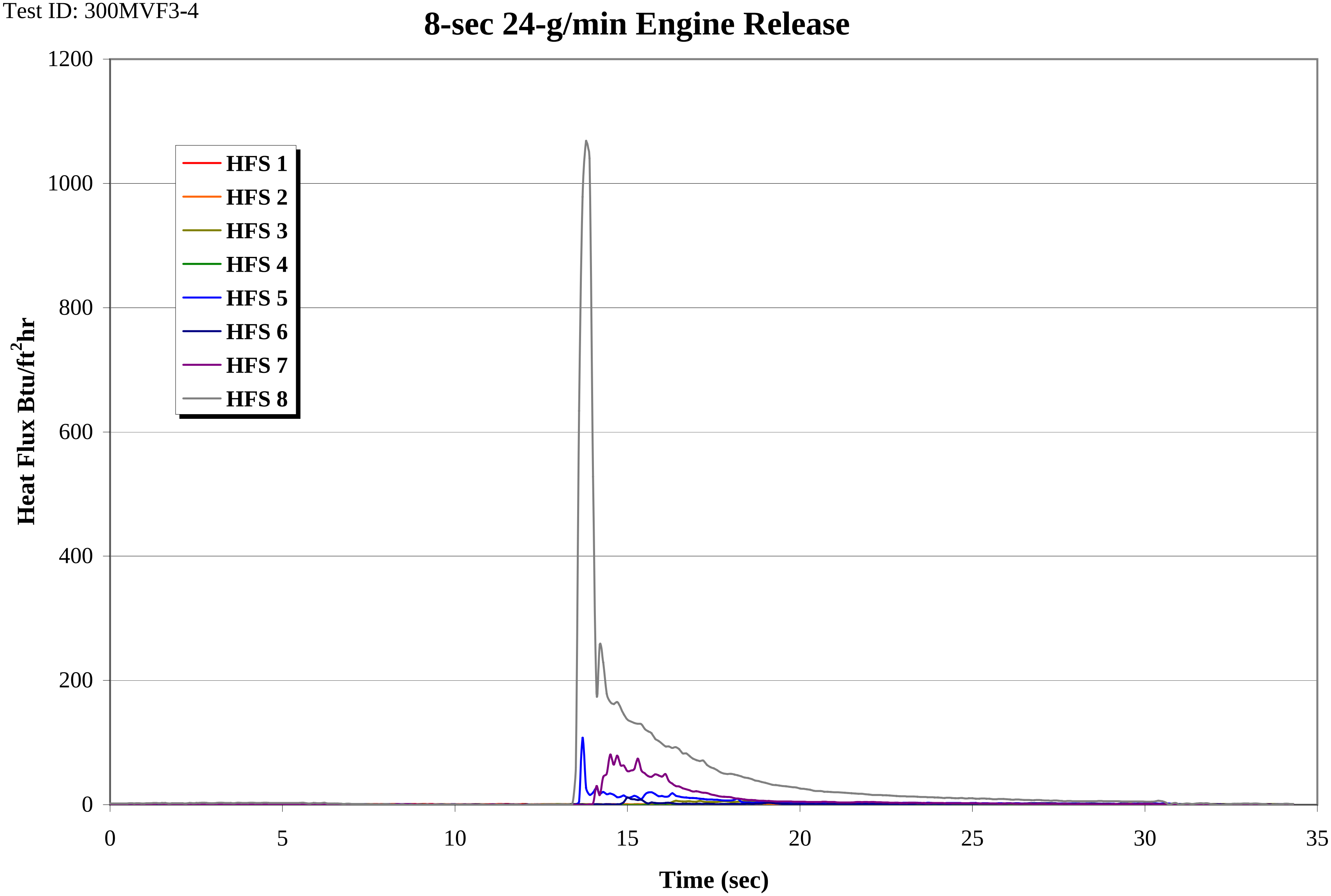

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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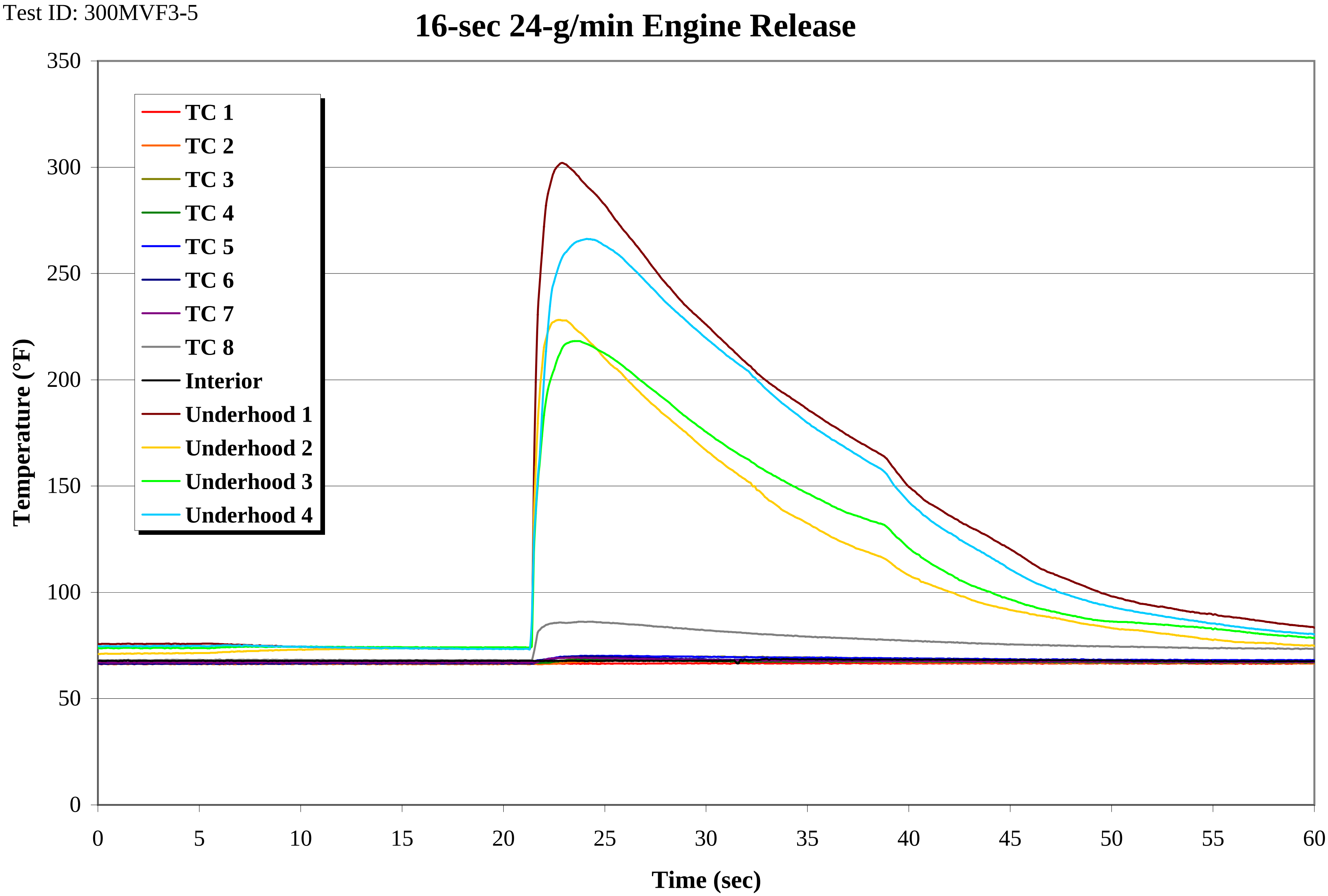

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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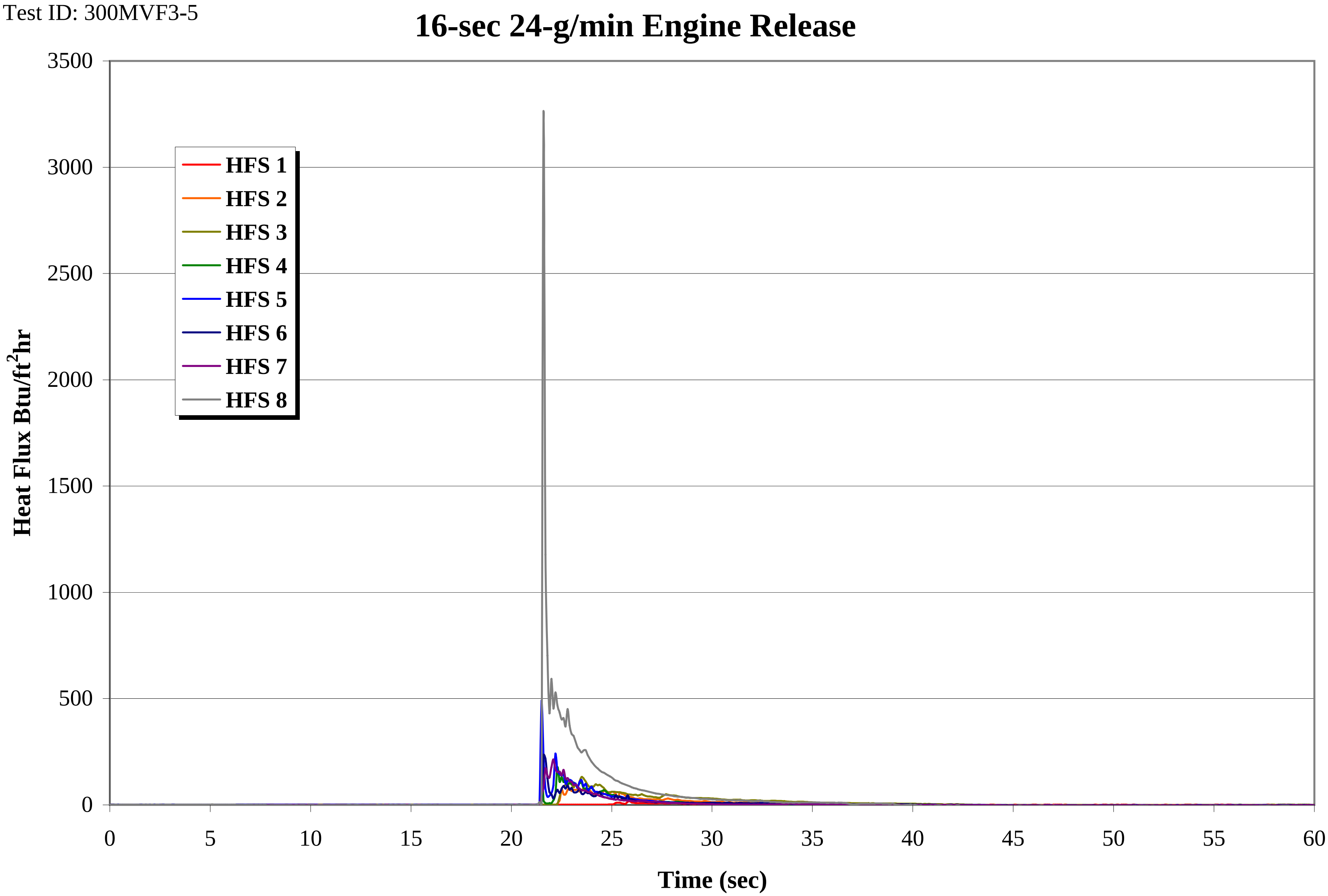

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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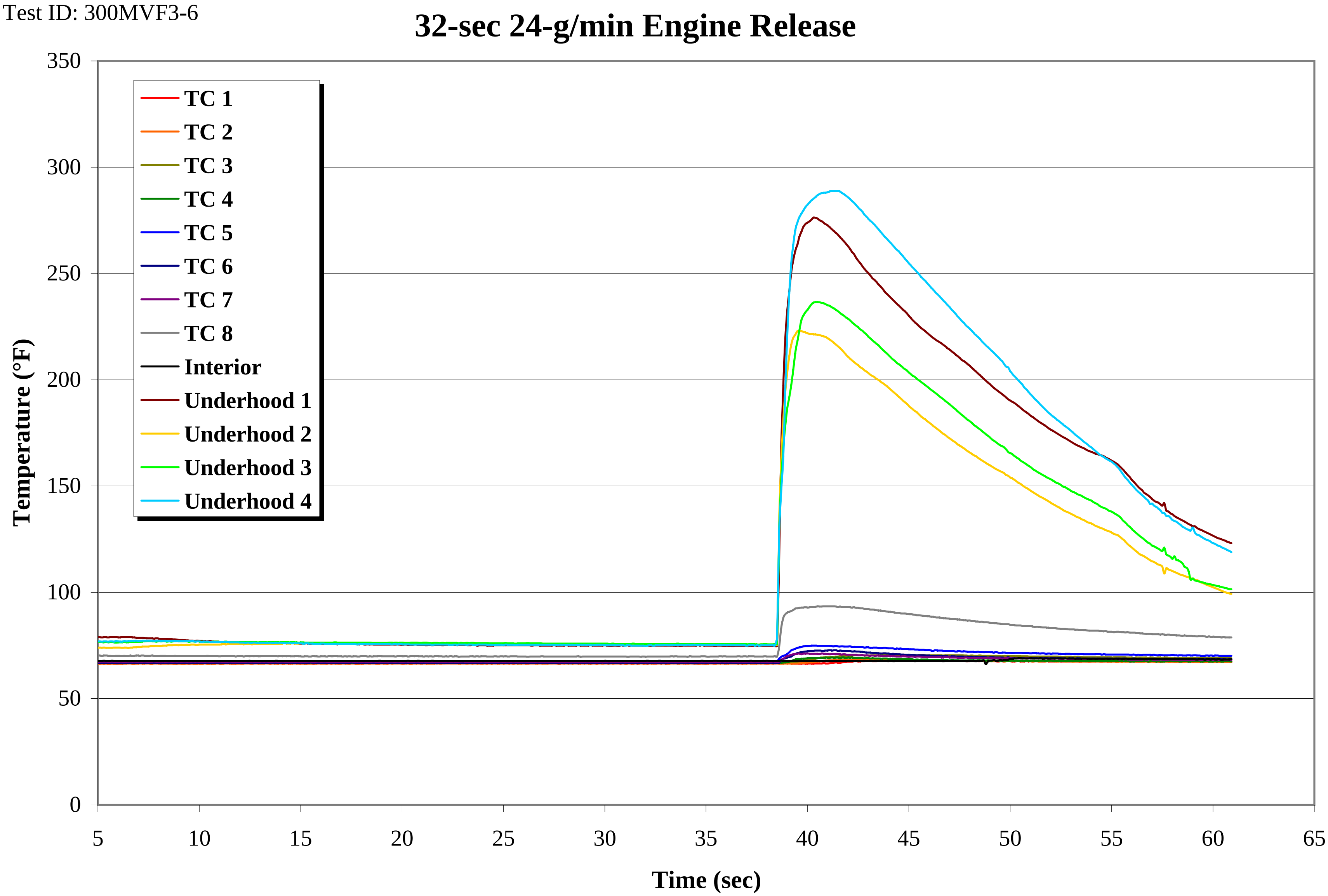

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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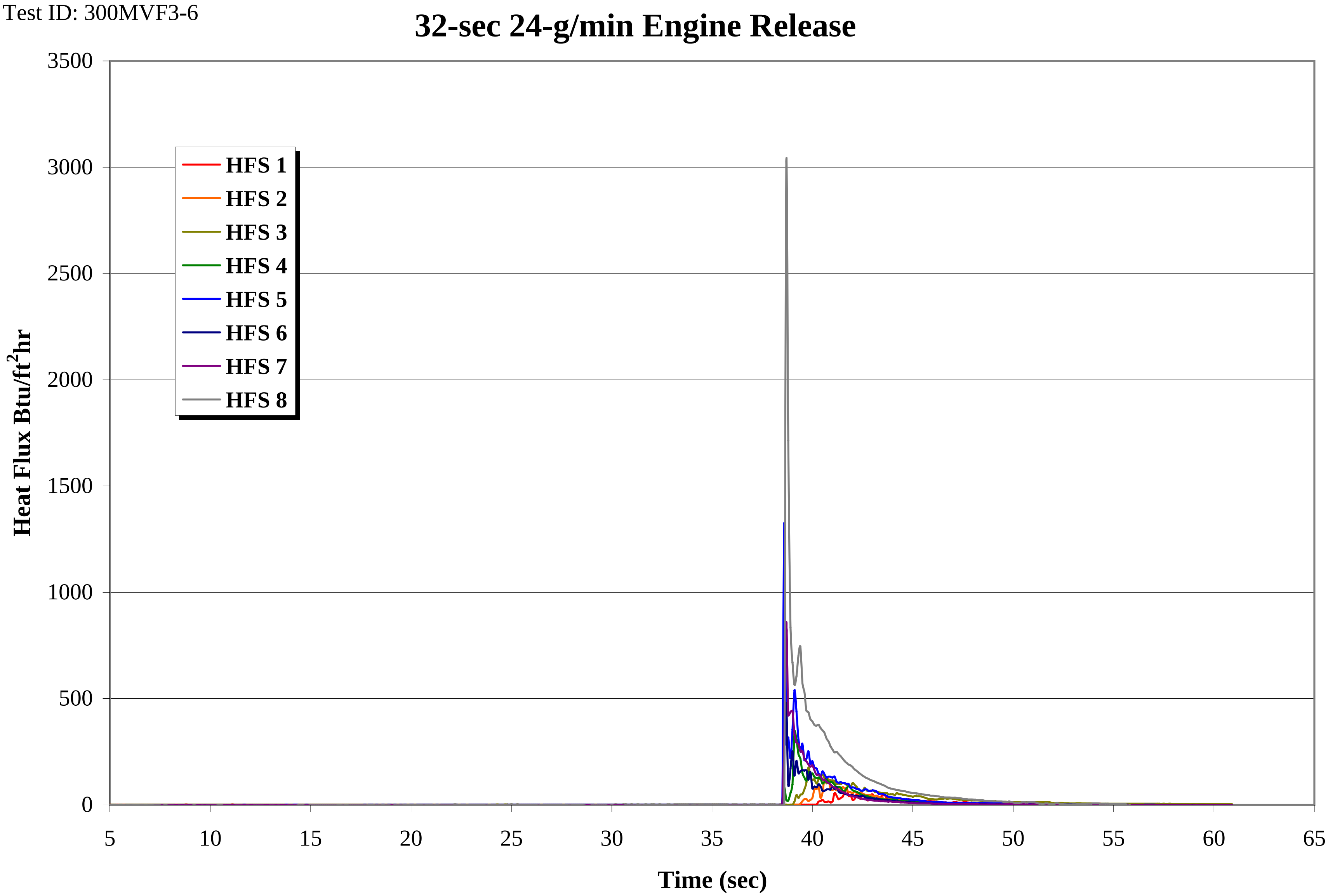
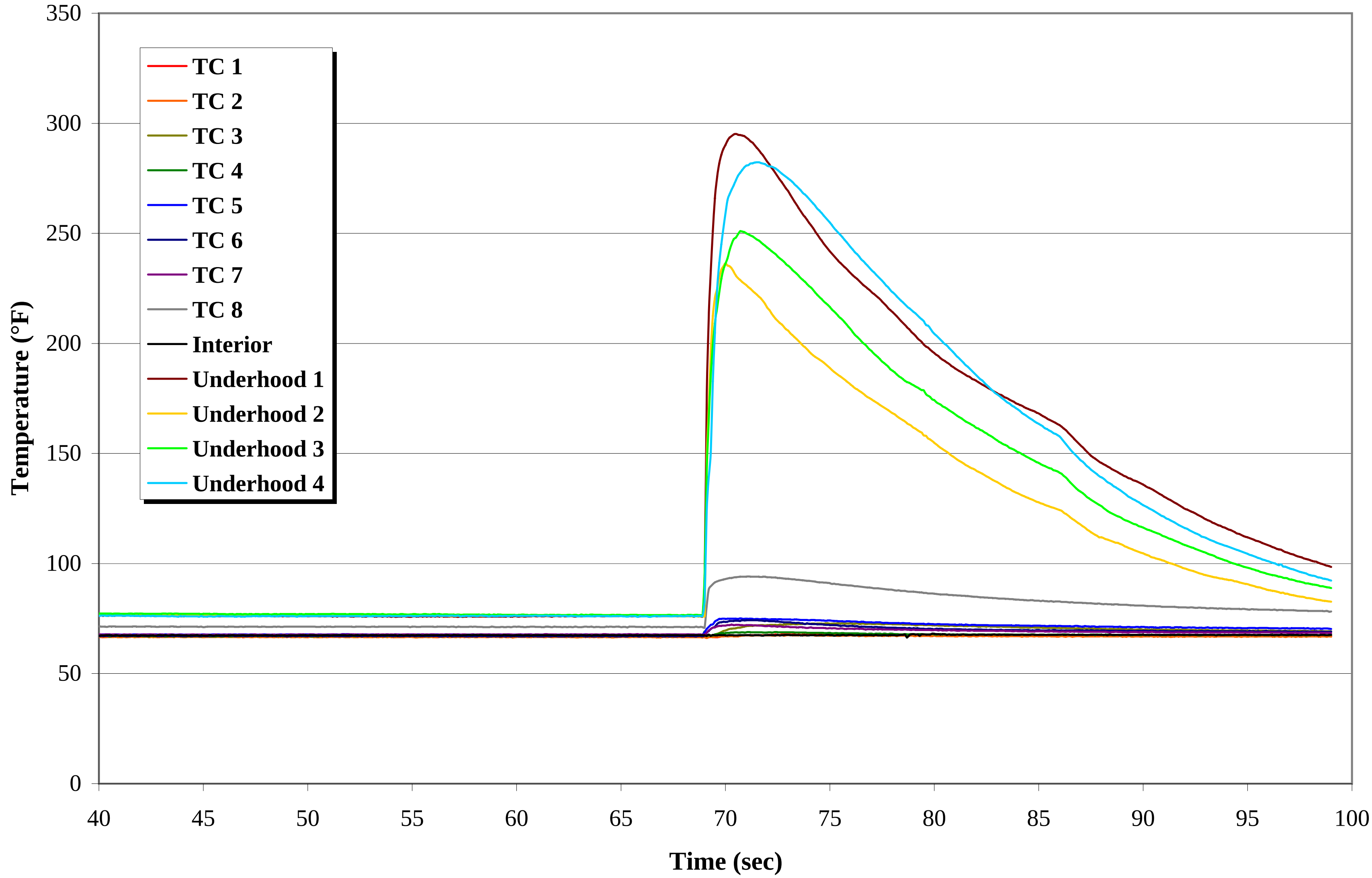


Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
Test ID: 300MVF3-7

64-sec 24-g/min Engine Release



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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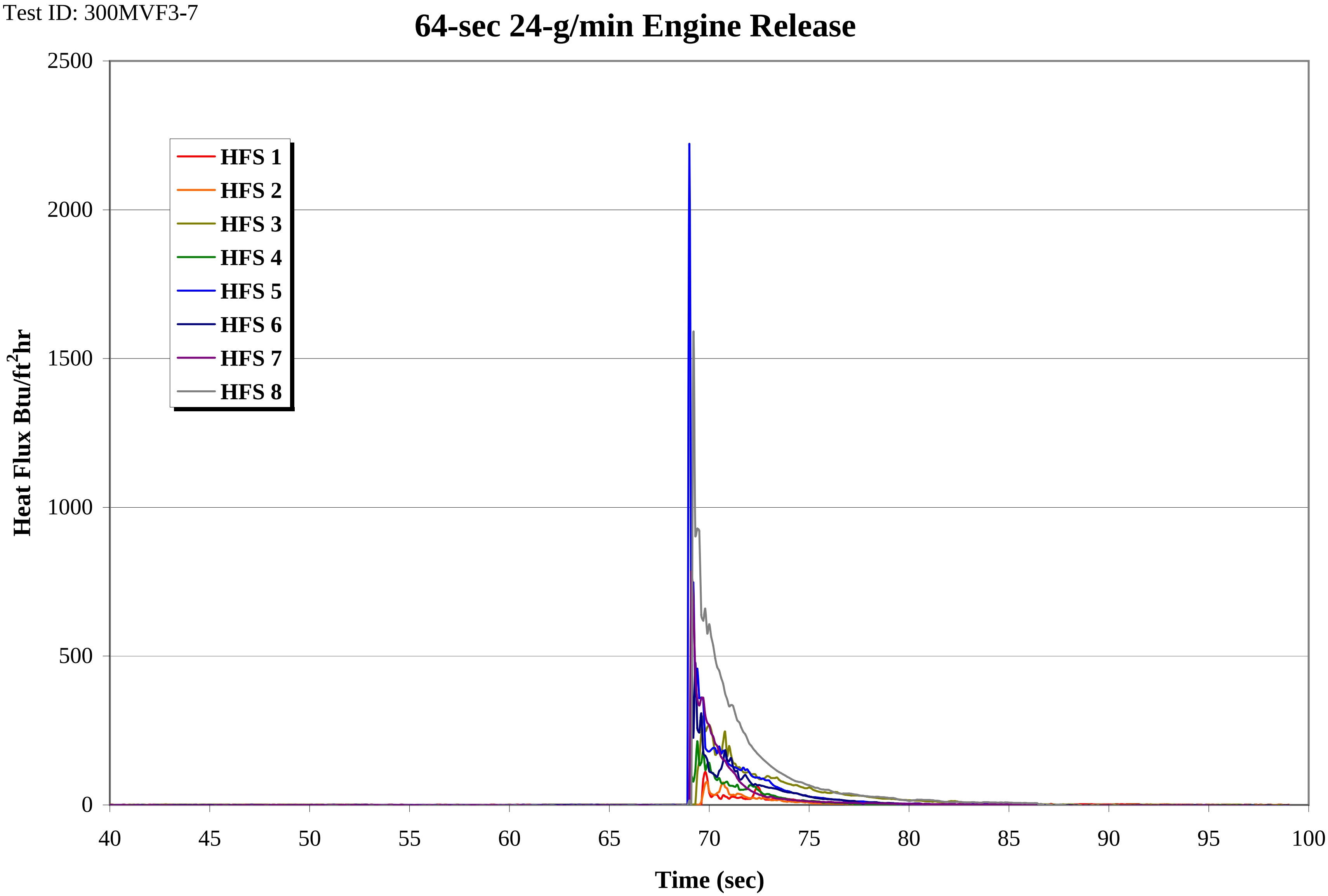

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 27, 2005
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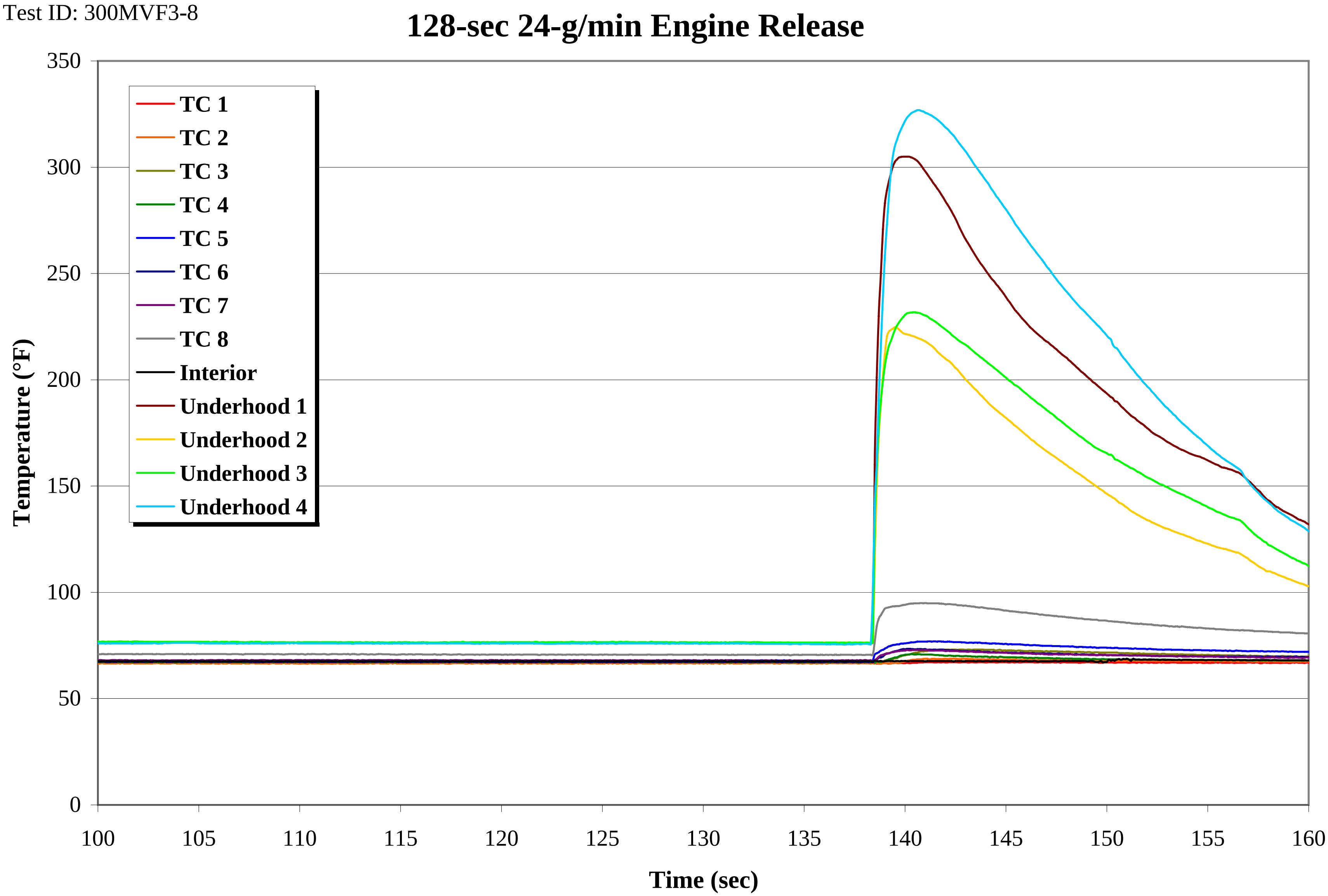

Motor Vehicle Fire Research Institute
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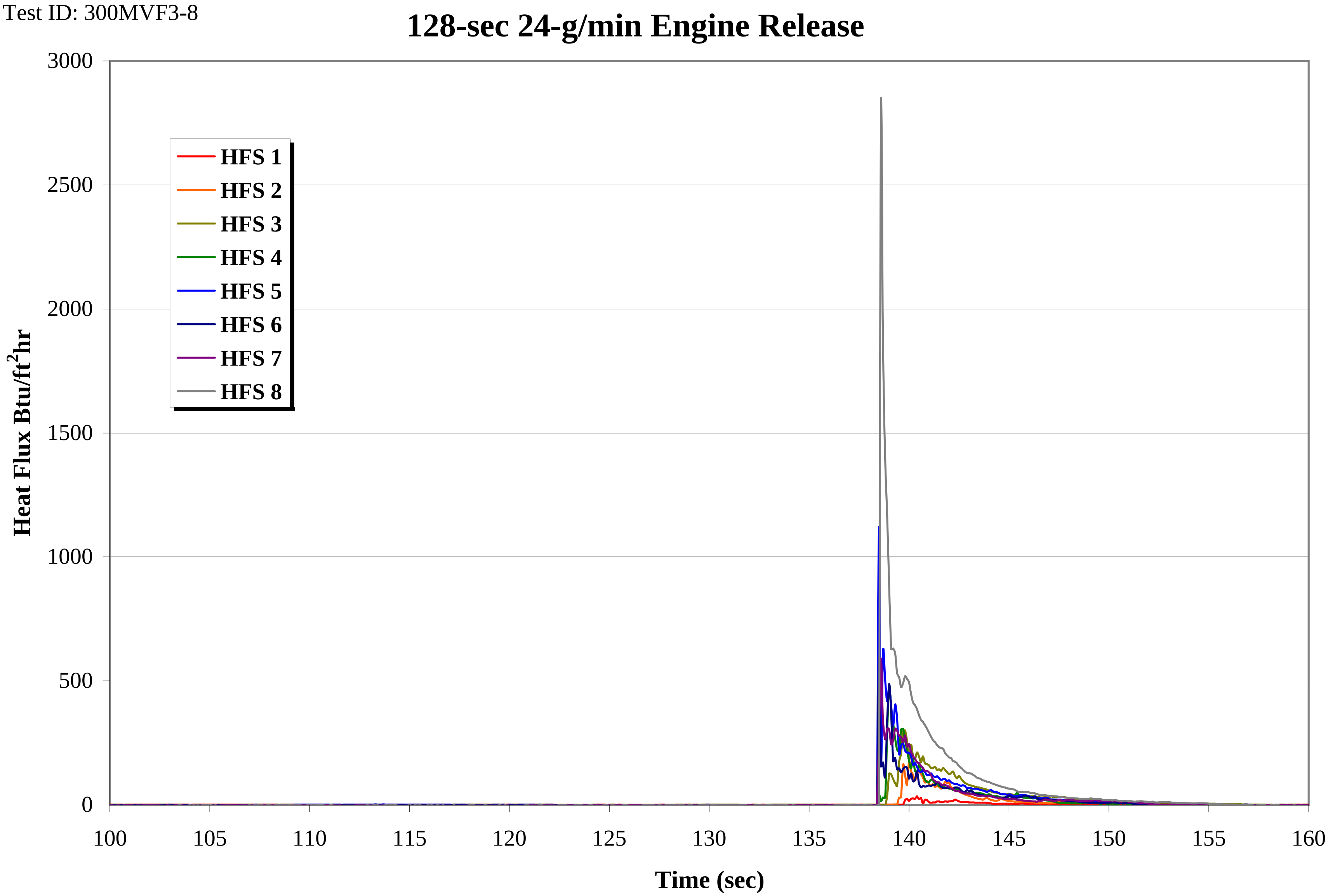

Motor Vehicle Fire Research Institute
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Test Date: October 27, 2005
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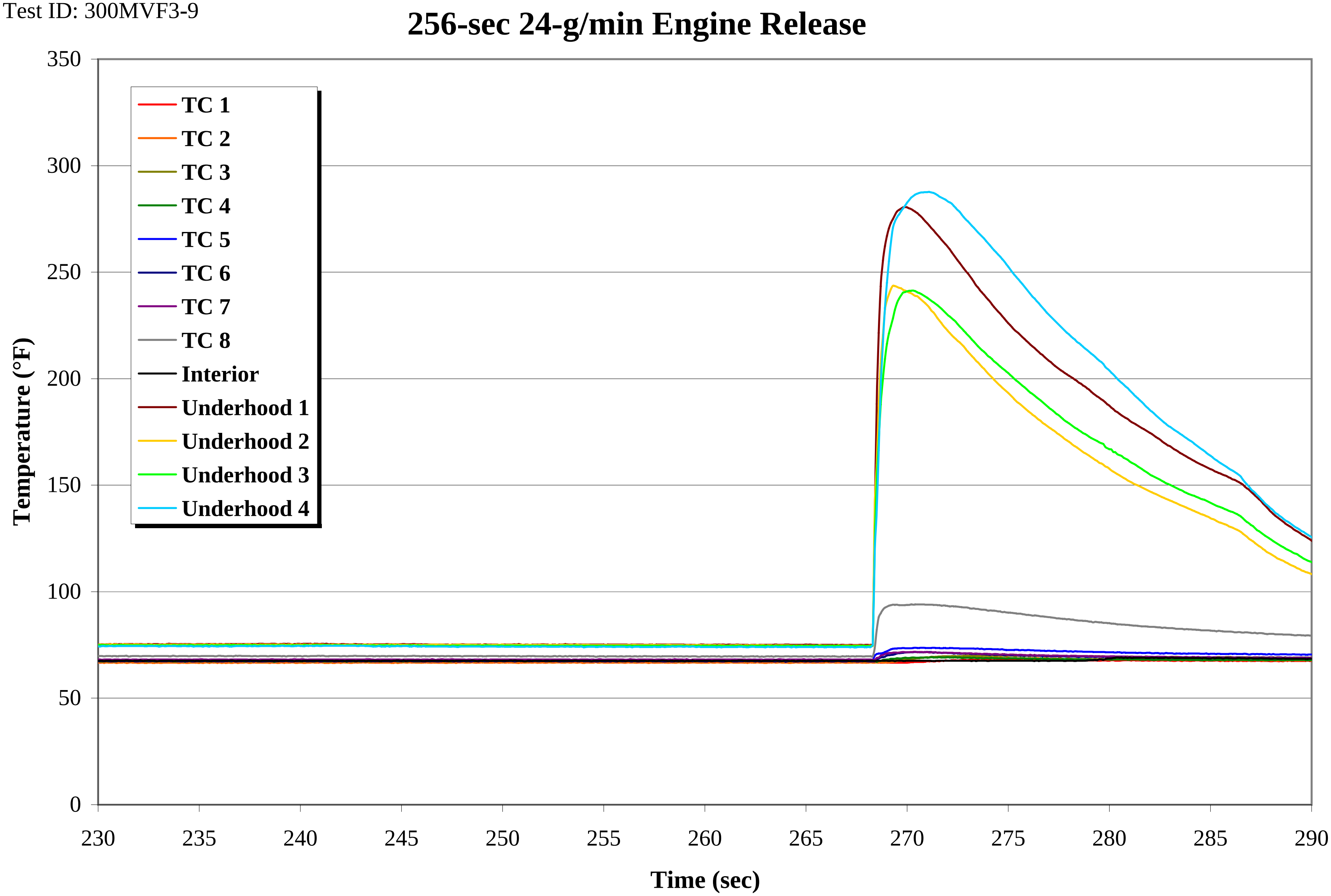

Motor Vehicle Fire Research Institute
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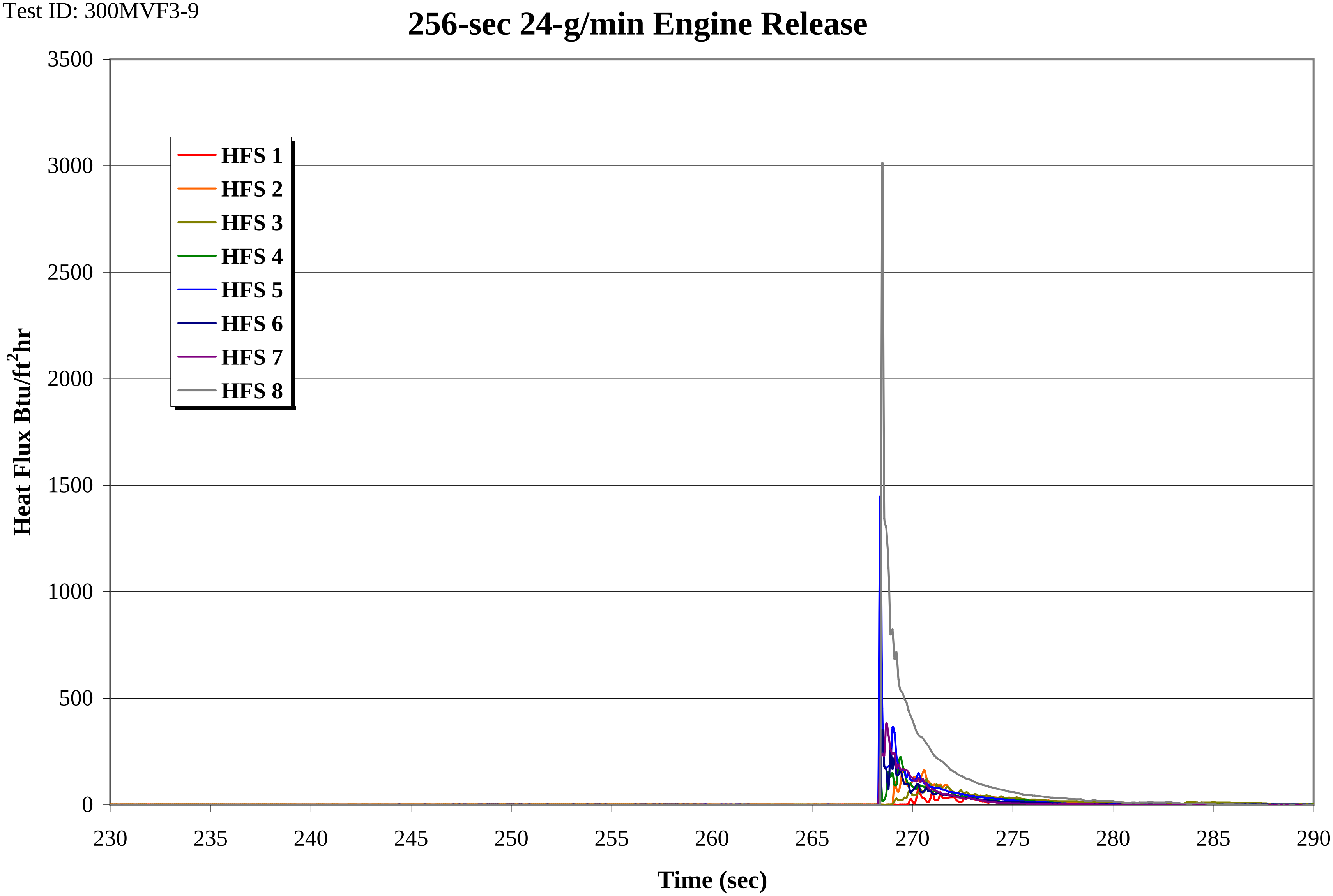

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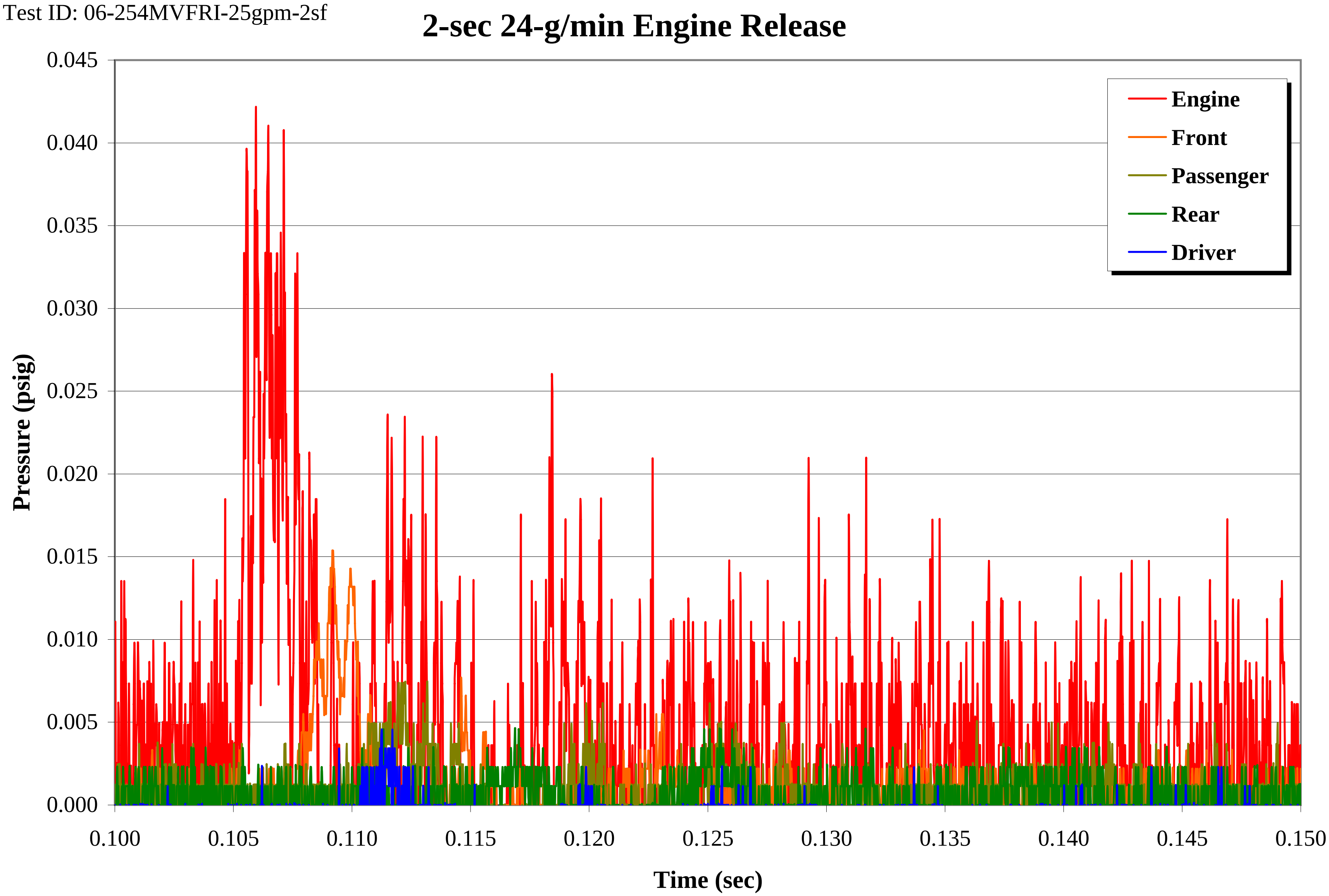

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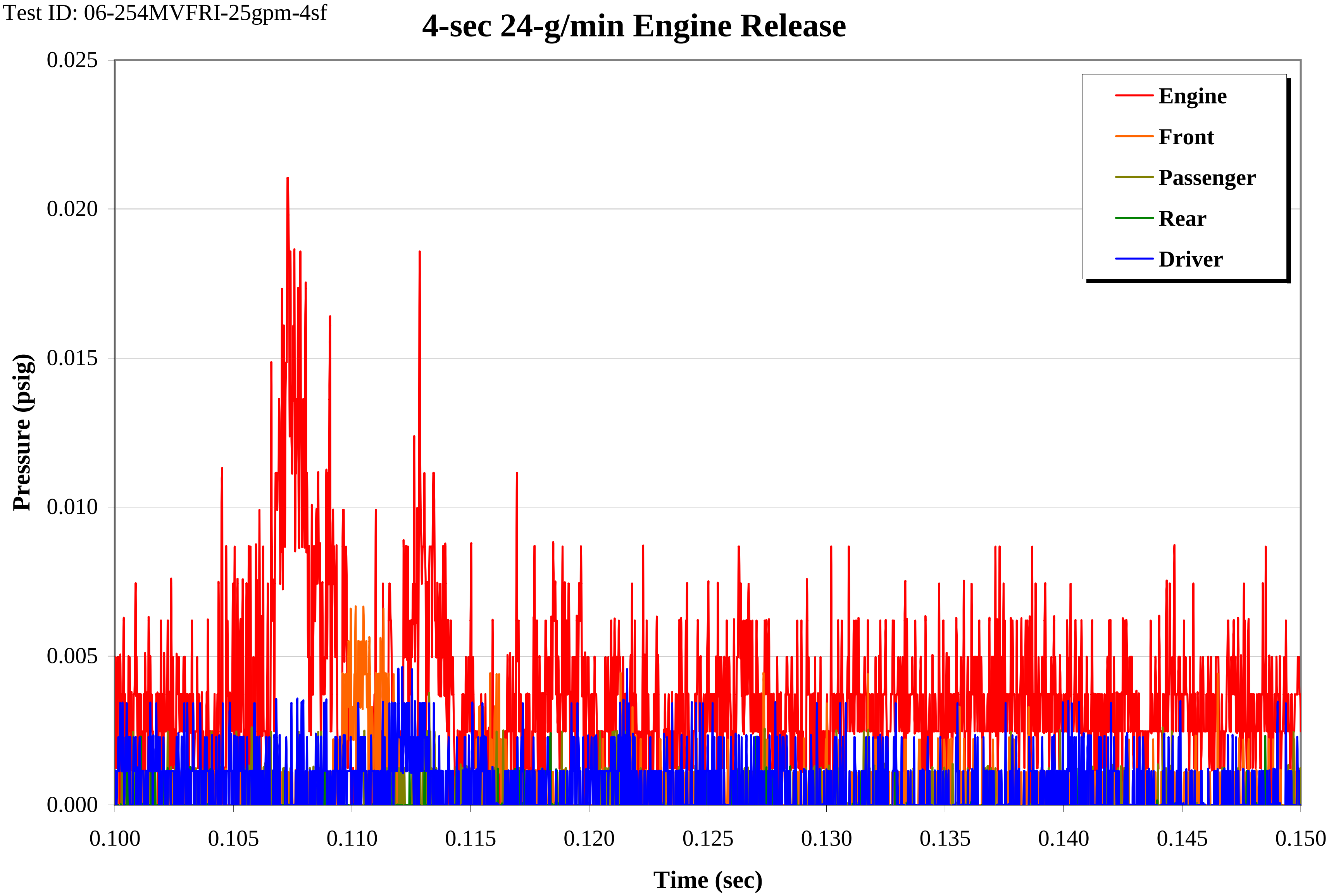

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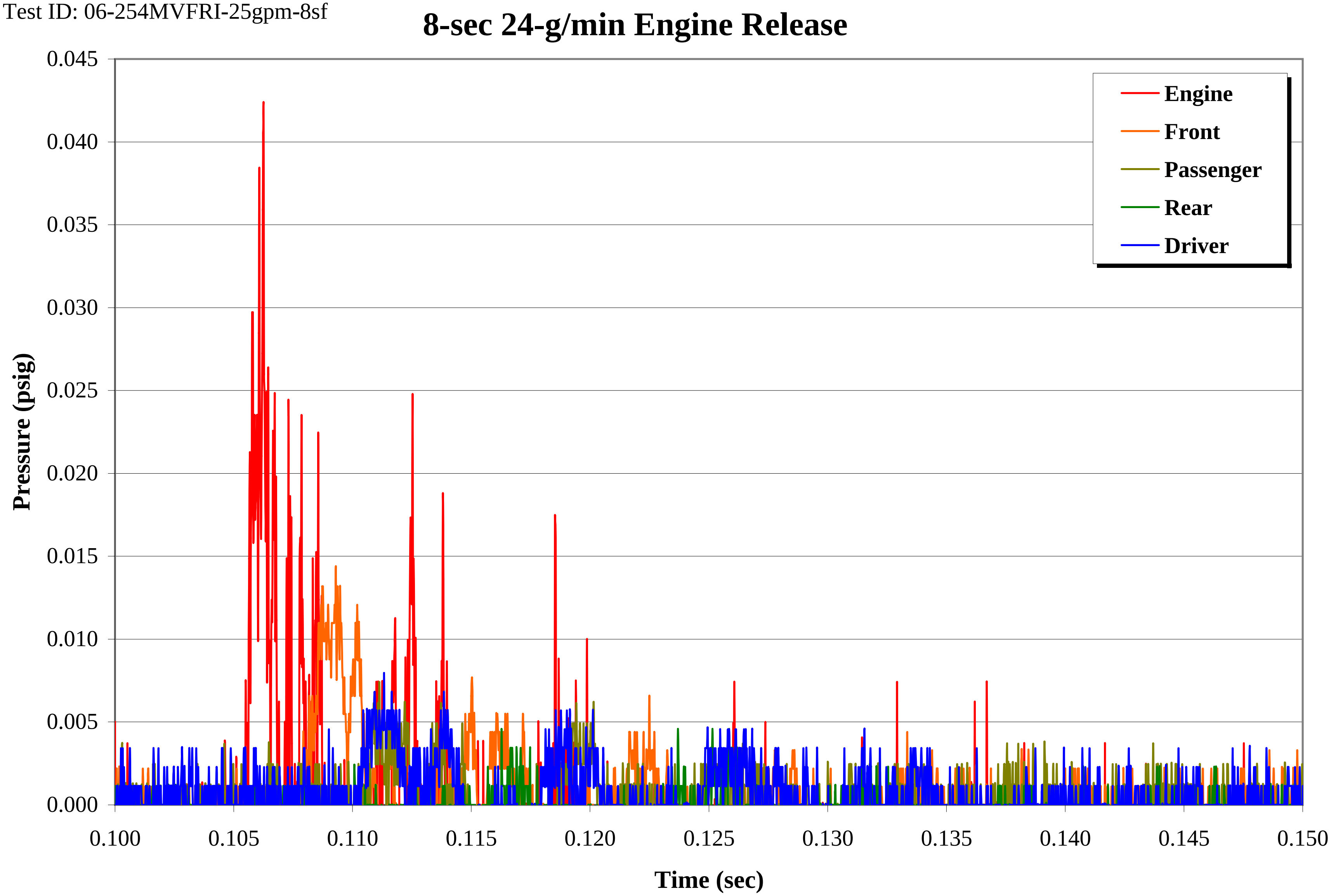

Motor Vehicle Fire Research Institute
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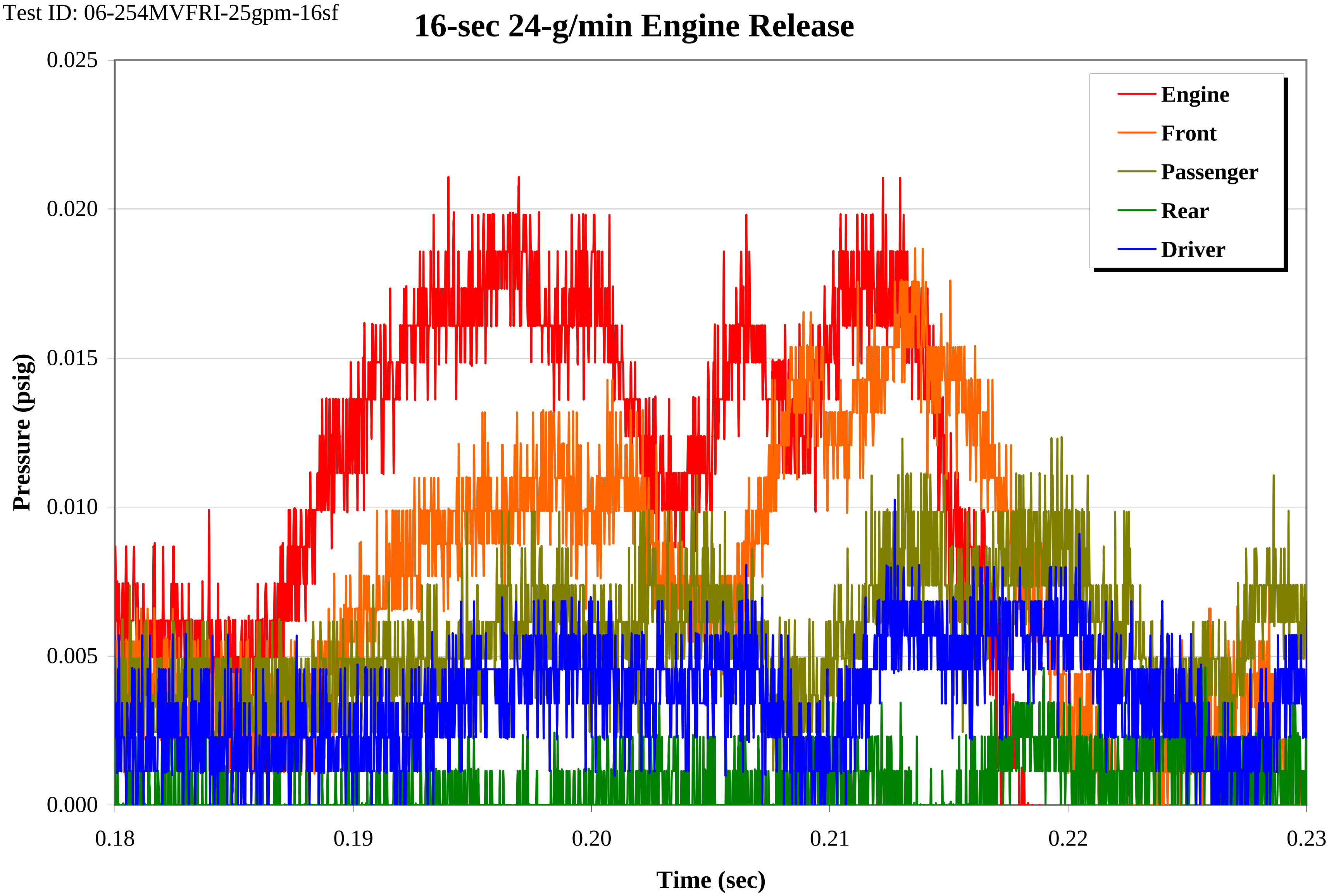

Motor Vehicle Fire Research Institute
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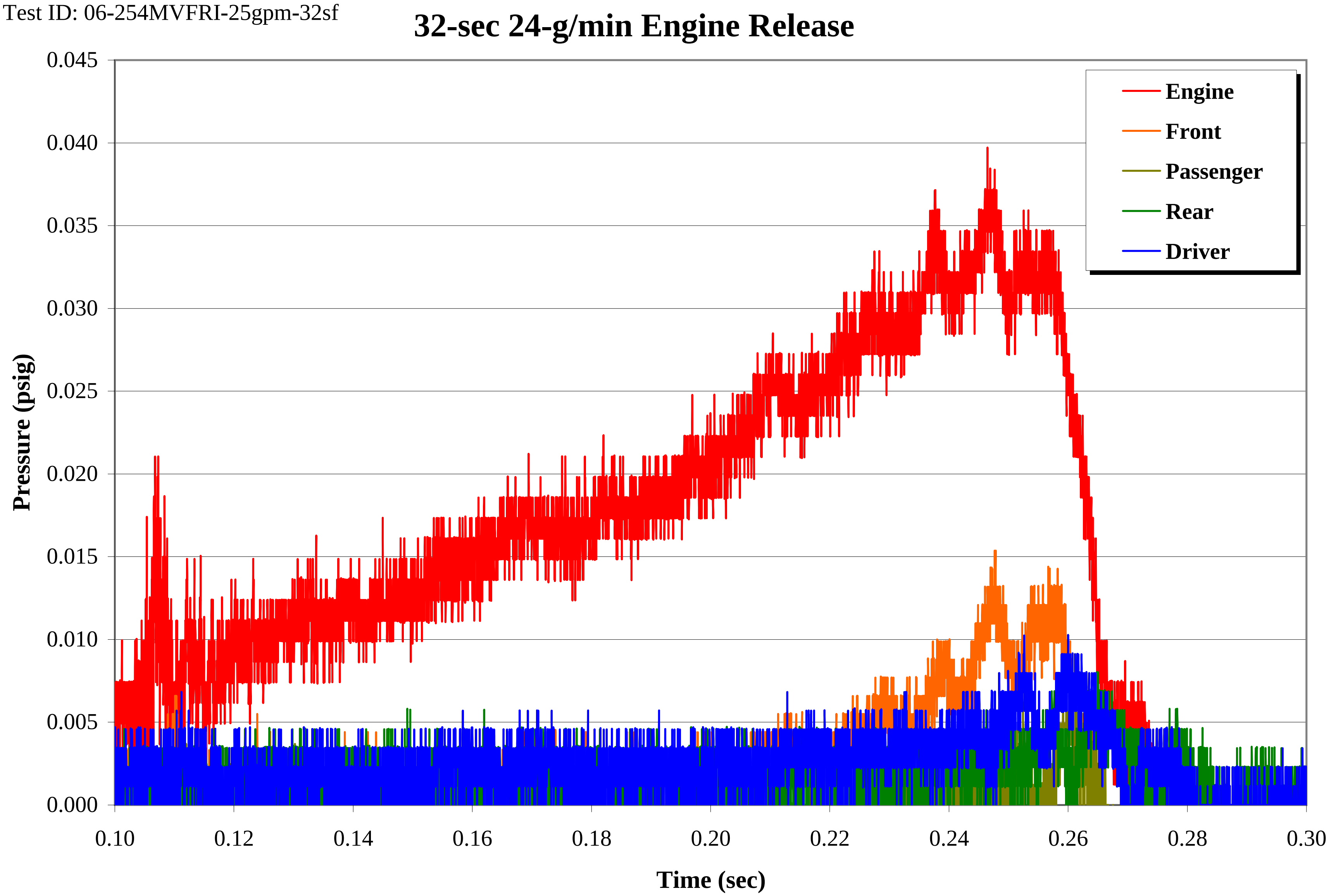

Motor Vehicle Fire Research Institute
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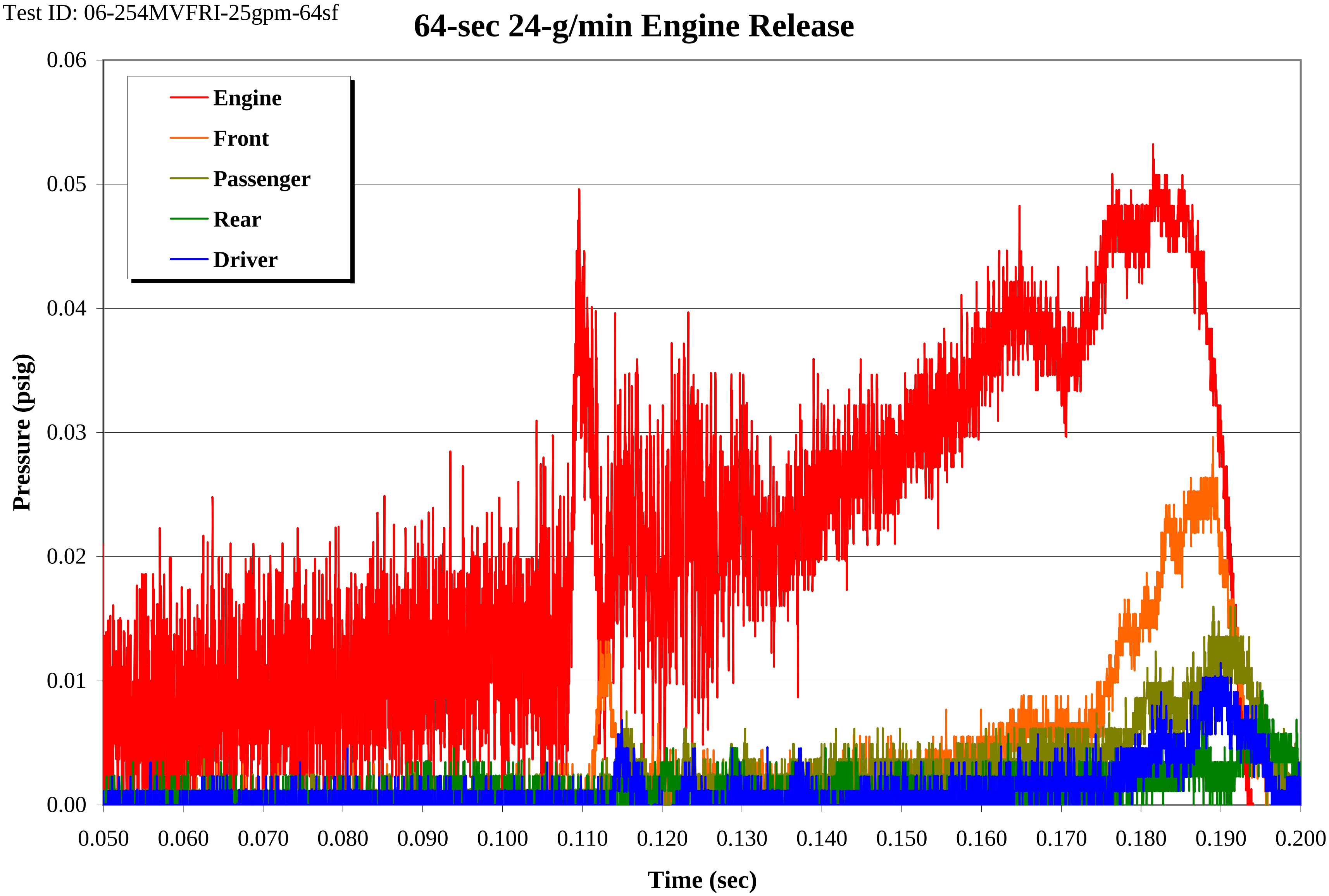

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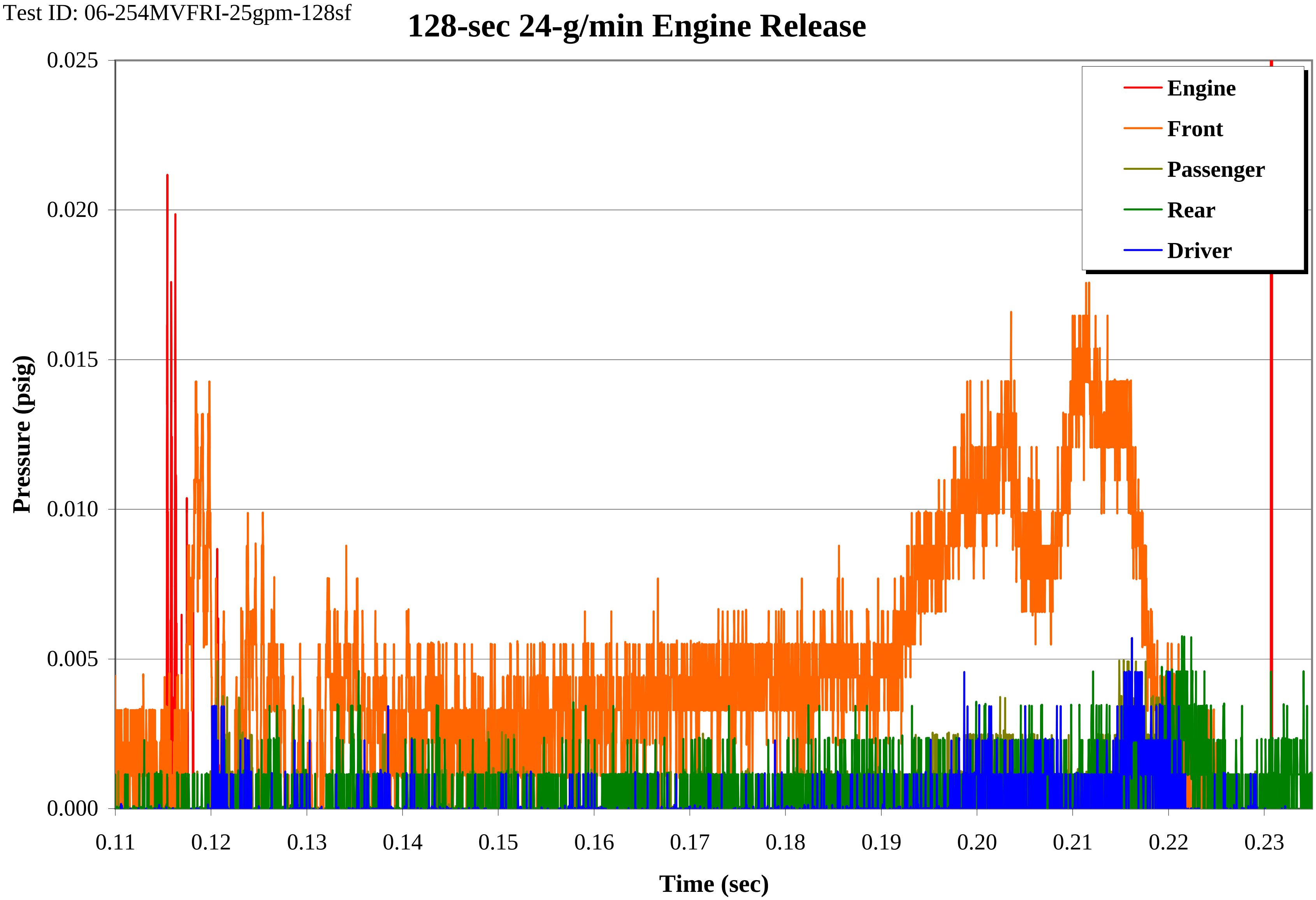

APPENDIX D

SERIES 4 GRAPHICAL TEST DATA

(CONSISTING OF 8 PAGES)

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SwRI Project No. 01.06939.01.004
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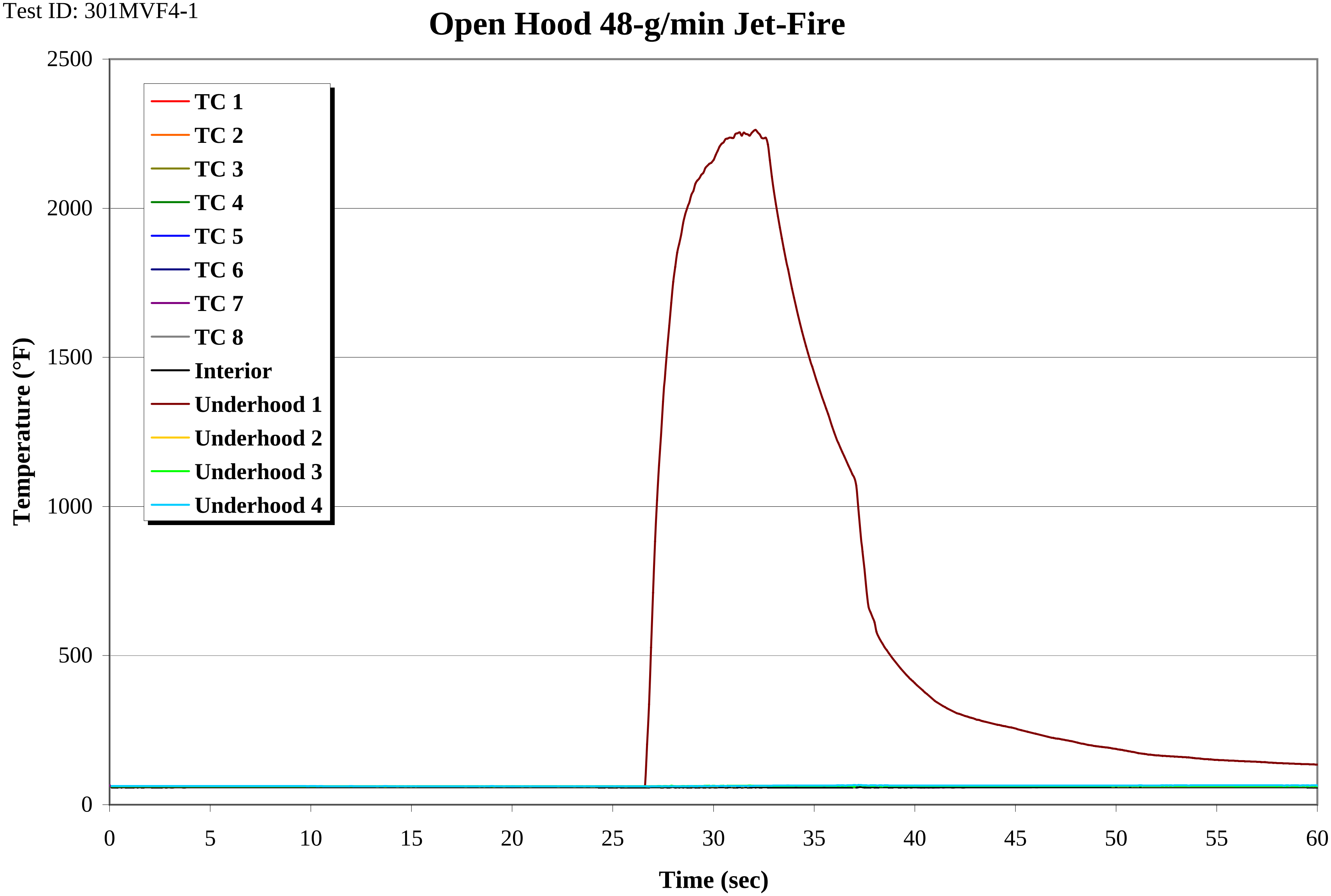

Motor Vehicle Fire Research Institute
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Test Date: October 28, 2005
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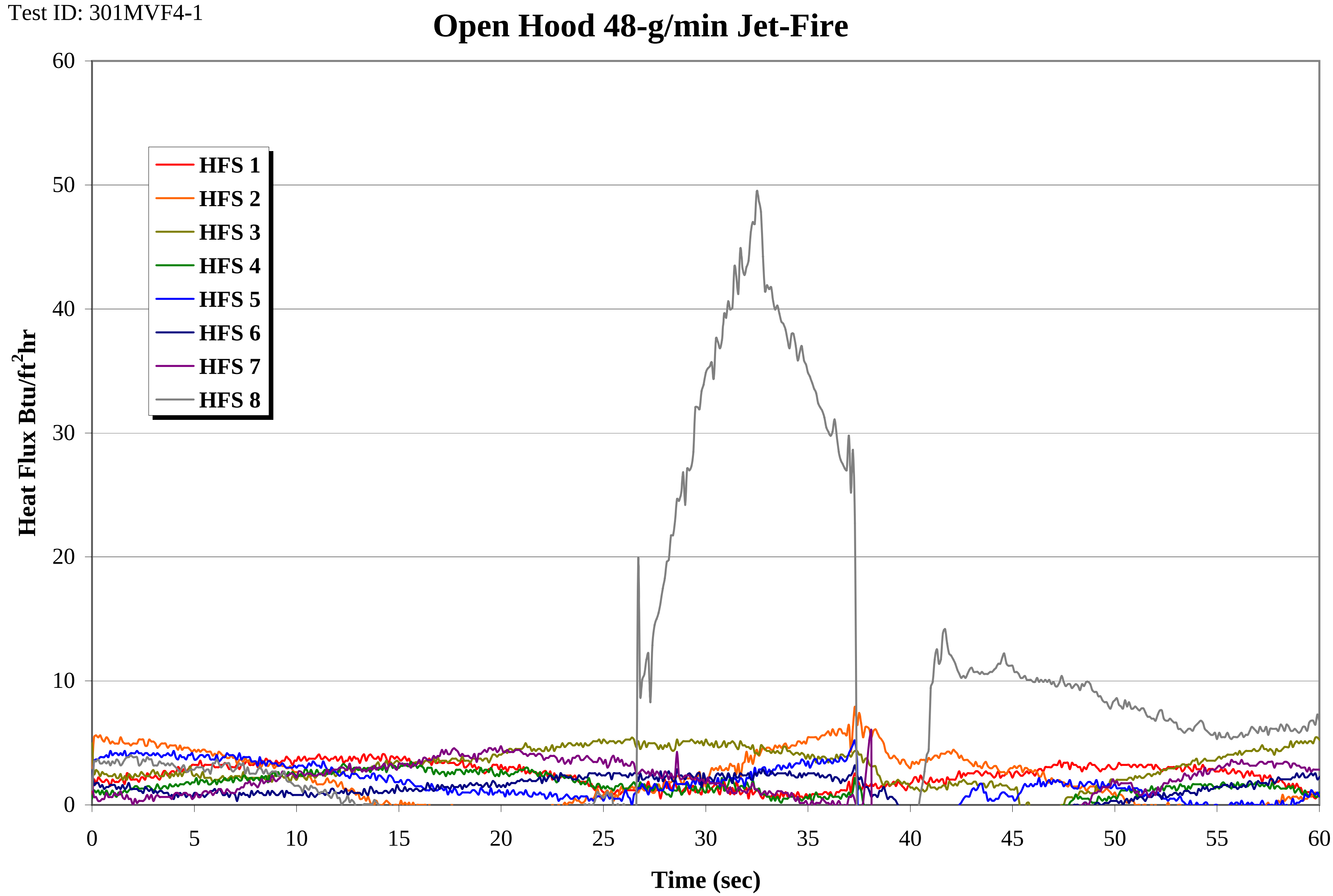

Motor Vehicle Fire Research Institute
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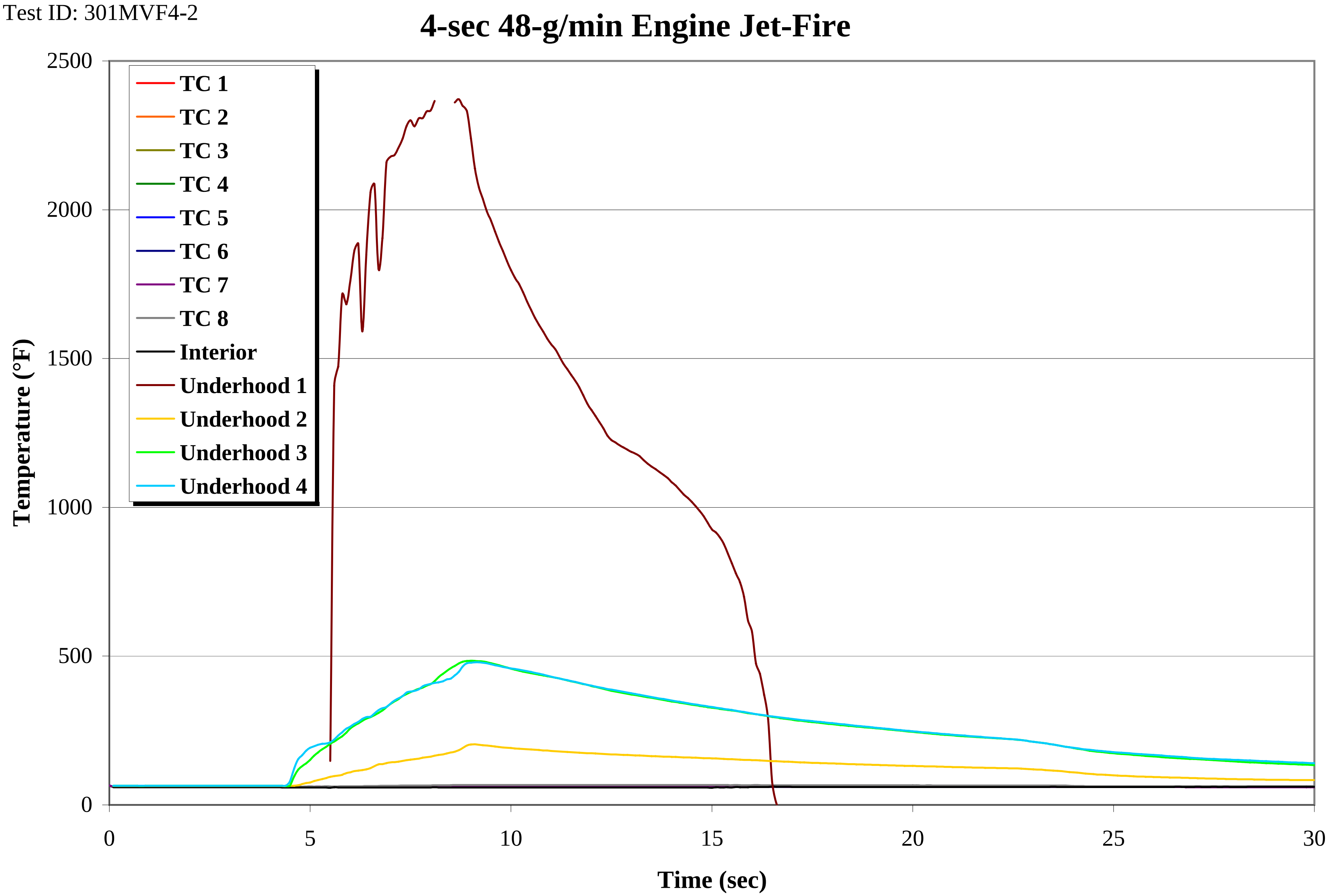

Motor Vehicle Fire Research Institute
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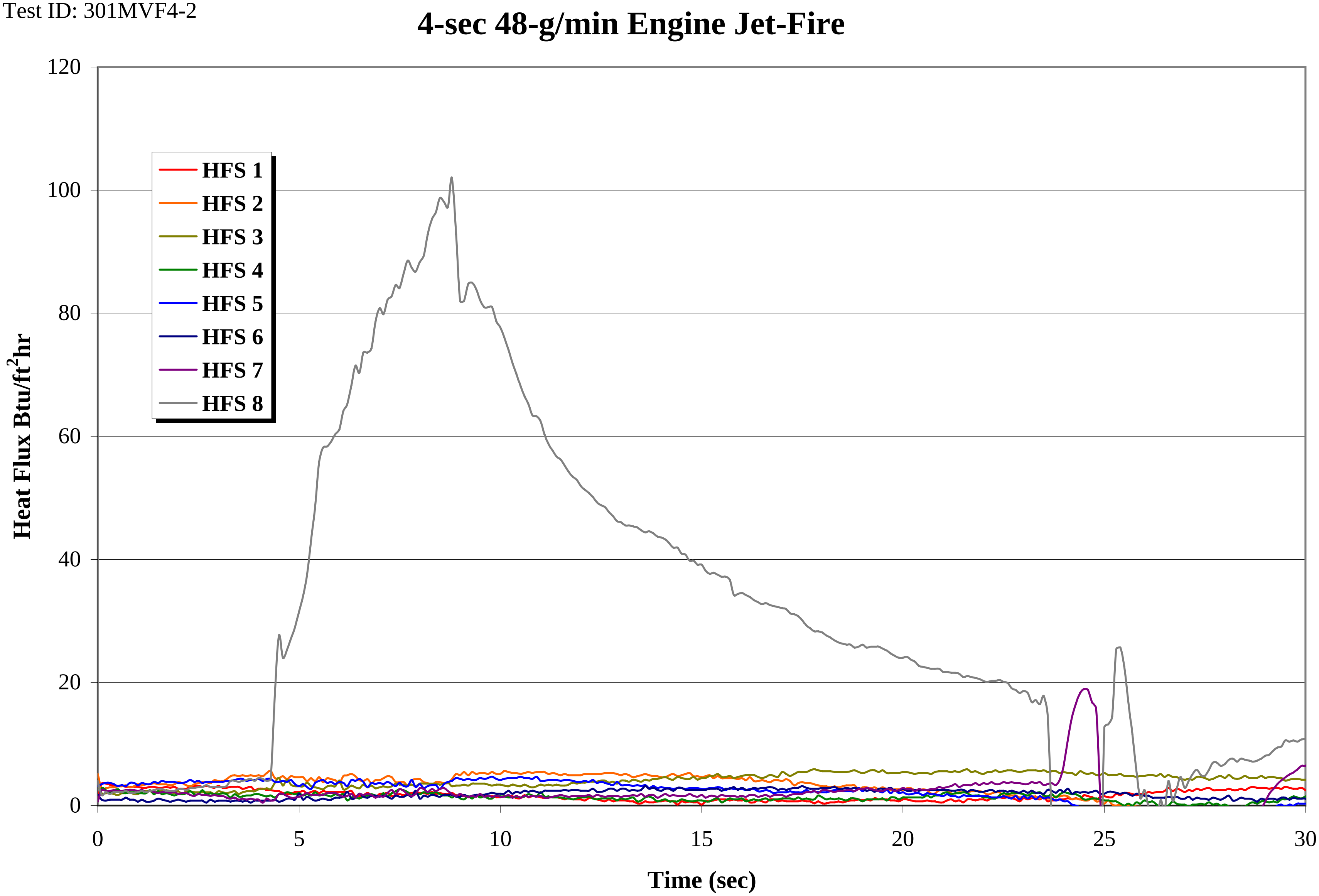
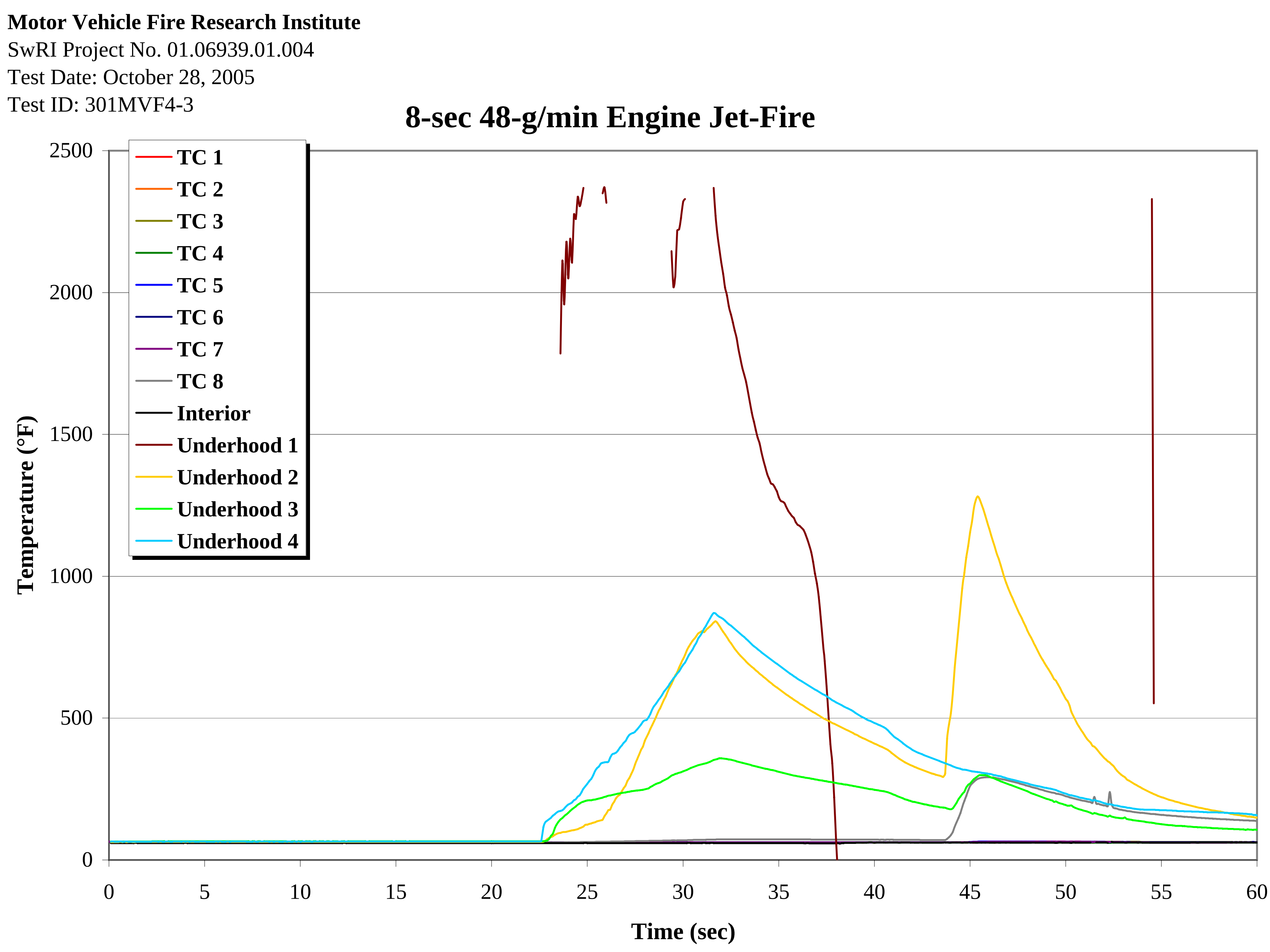
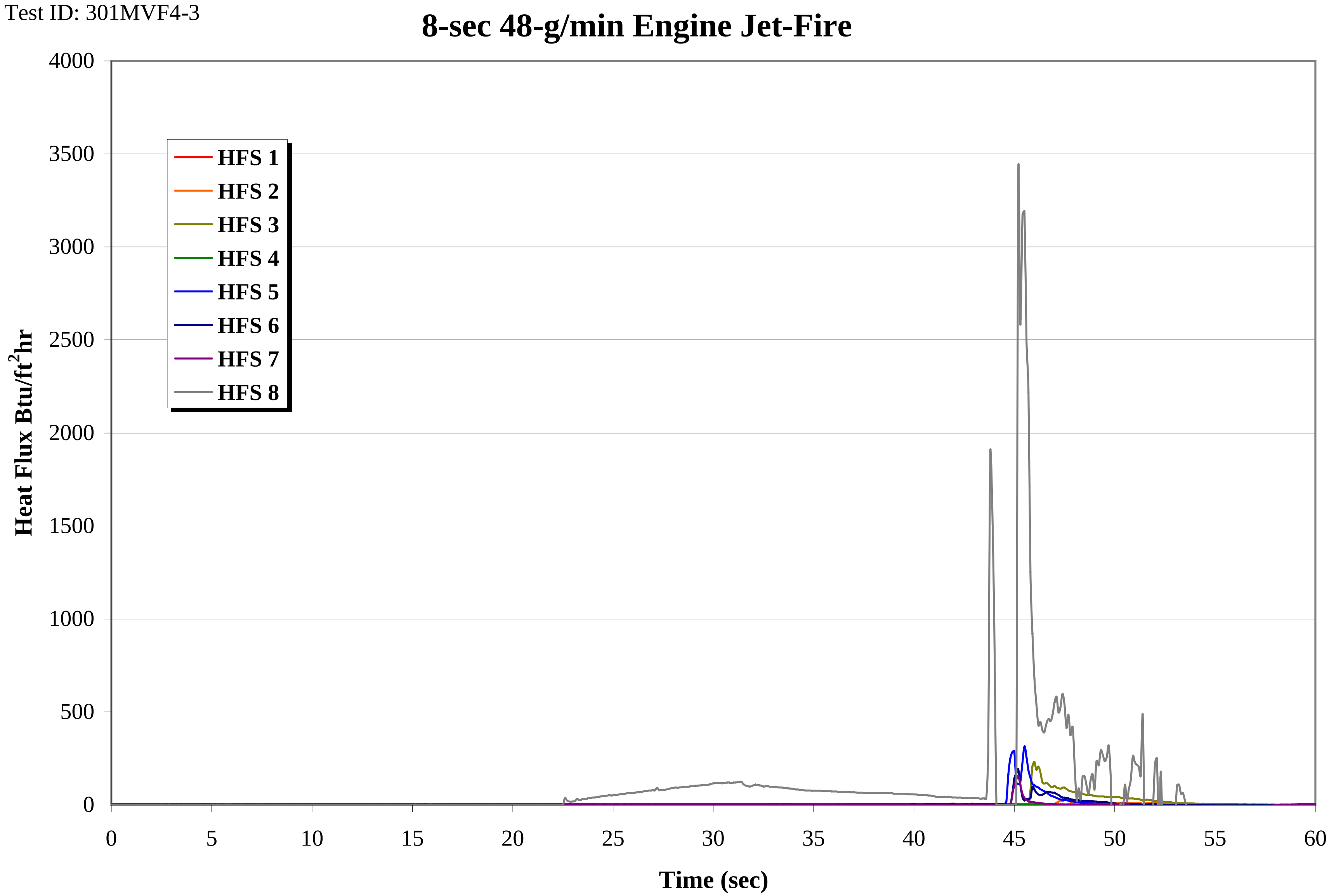



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 28, 2005
Test ID: 301MVF4-3
8-sec 48-g/min Engine Jet-Fire
Temperature (°F)
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
55
60
Time (sec)
TC 1
TC 2
TC 3
TC 4
TC 5
TC 6
TC 7
TC 8
Interior
Underhood 1
Underhood 2
Underhood 3
Underhood 4

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 28, 2005
Test ID: 301MVF4-3



Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
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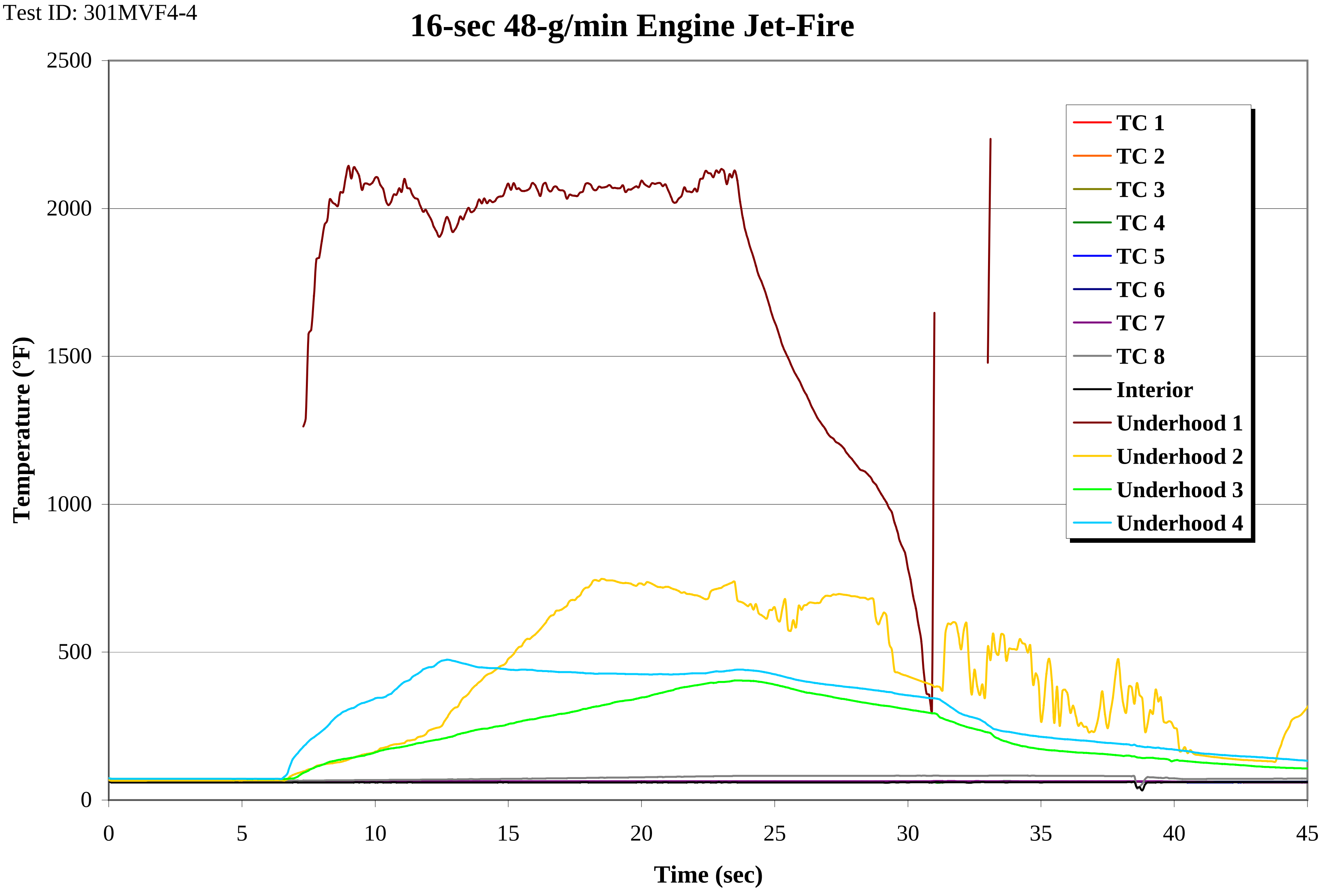

Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
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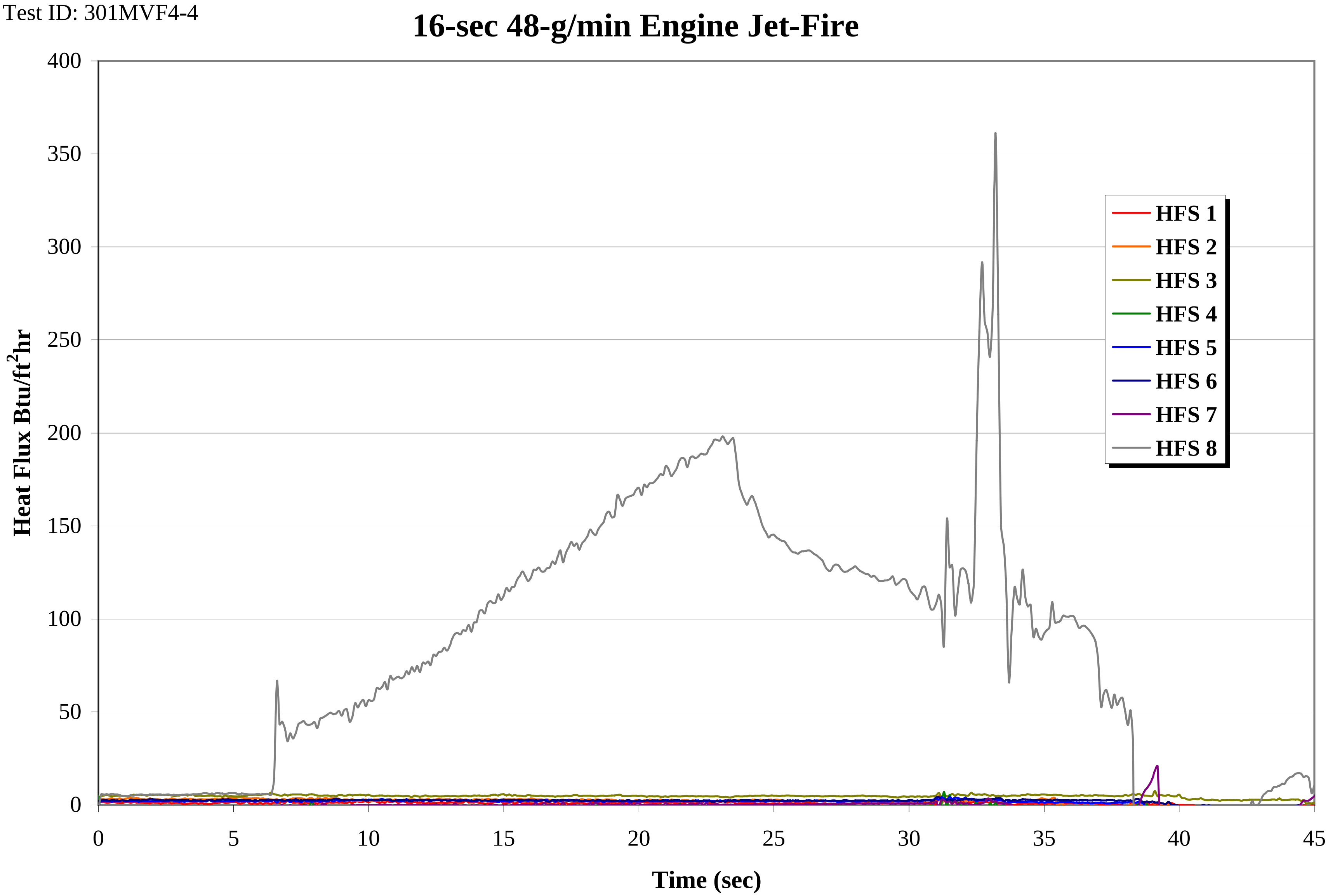

APPENDIX E

SERIES 5 GRAPHICAL TEST DATA

(CONSISTING OF 8 PAGES)

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SwRI Project No. 01.06939.01.004
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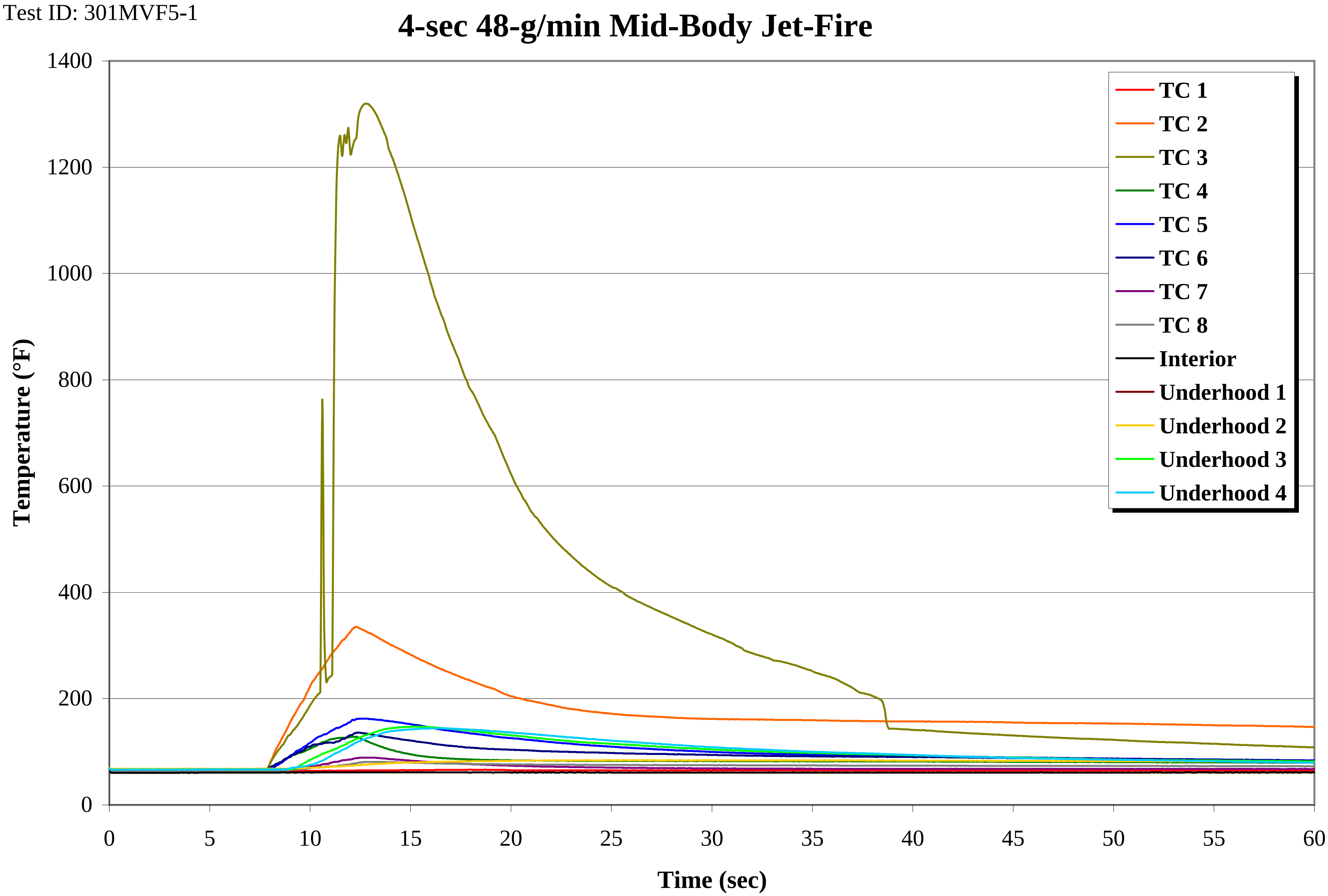
Test ID: 301MVF5-1



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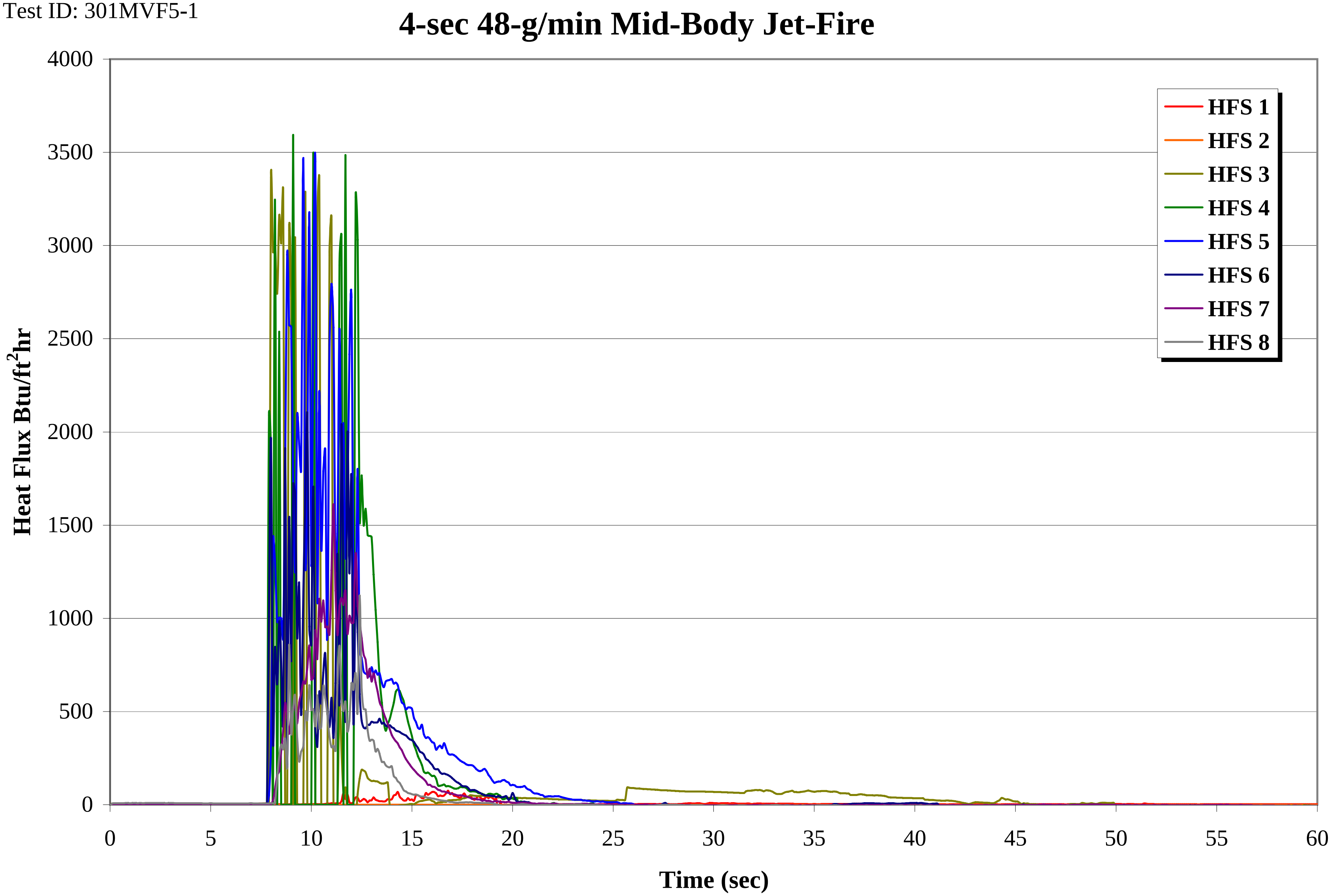

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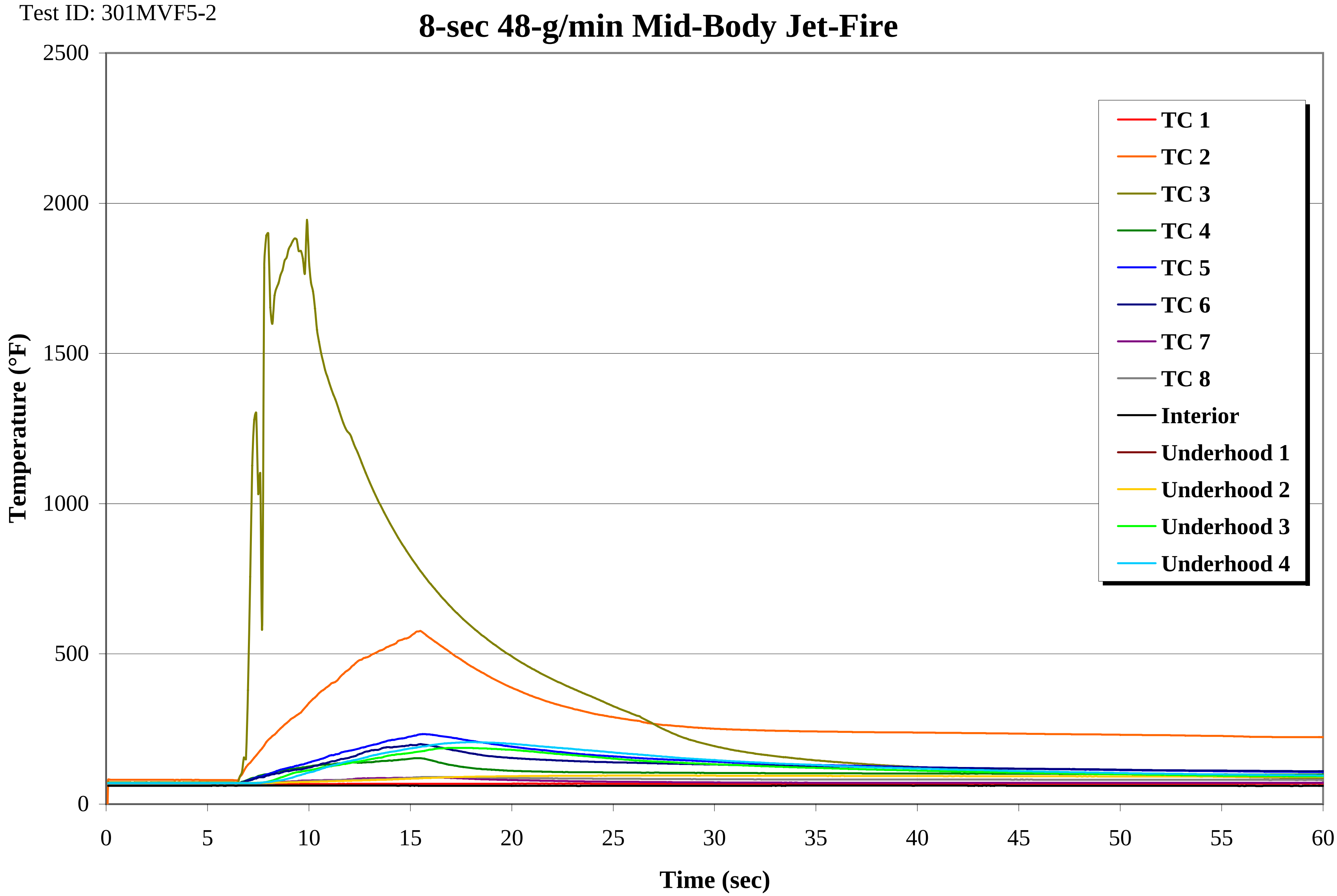

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SwRI Project No. 01.06939.01.004
Test Date: October 28, 2005
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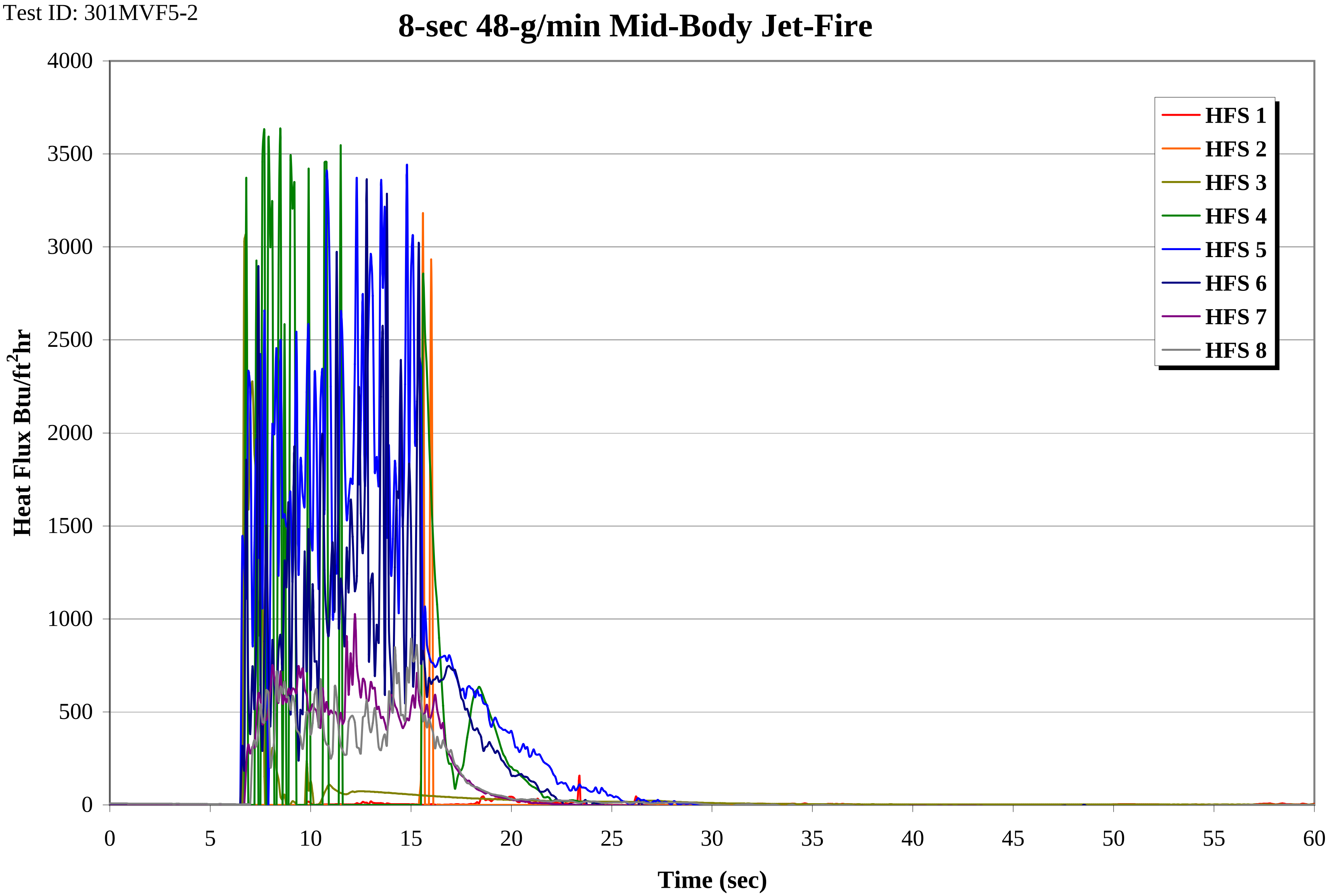

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SwRI Project No. 01.06939.01.004
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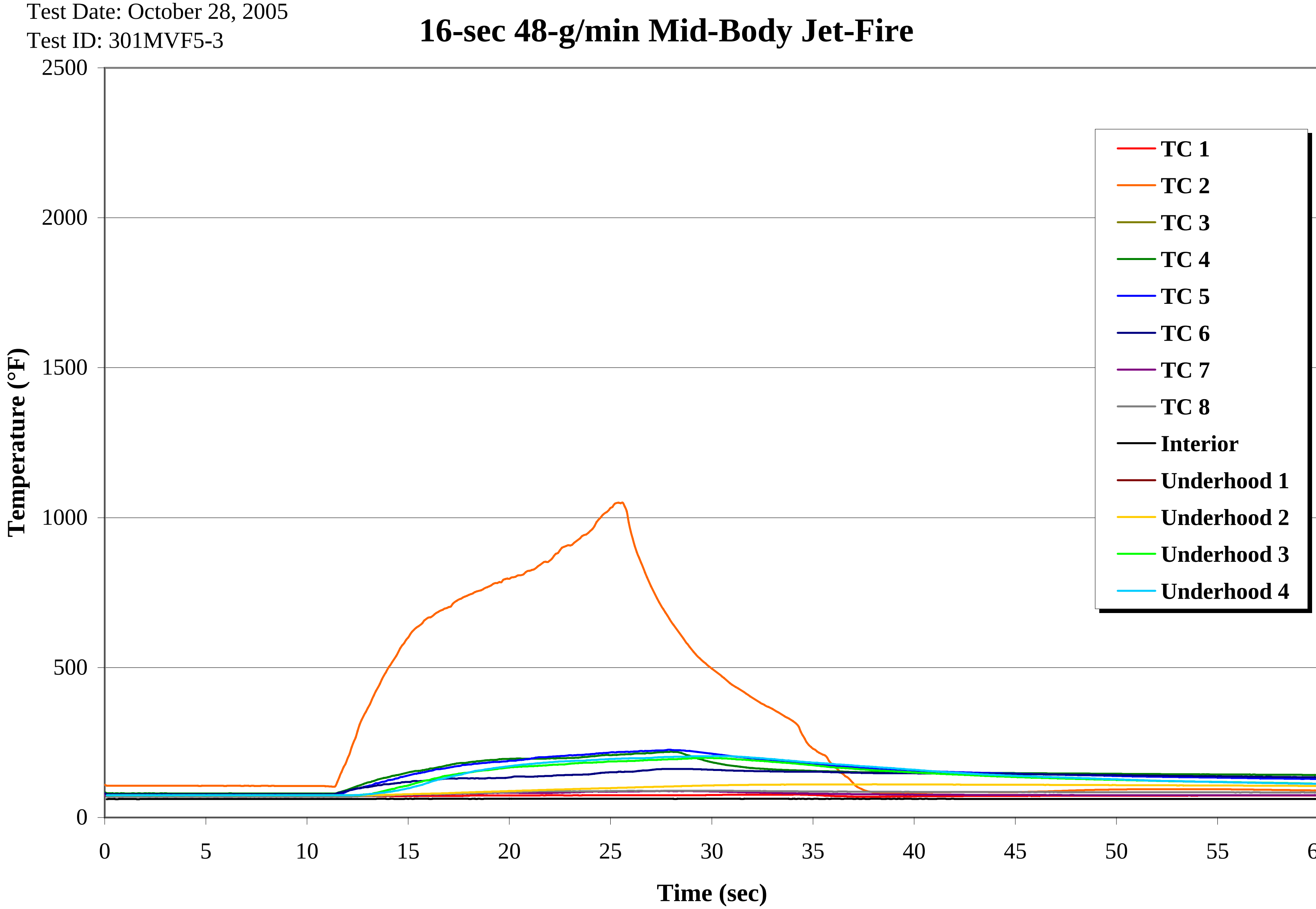
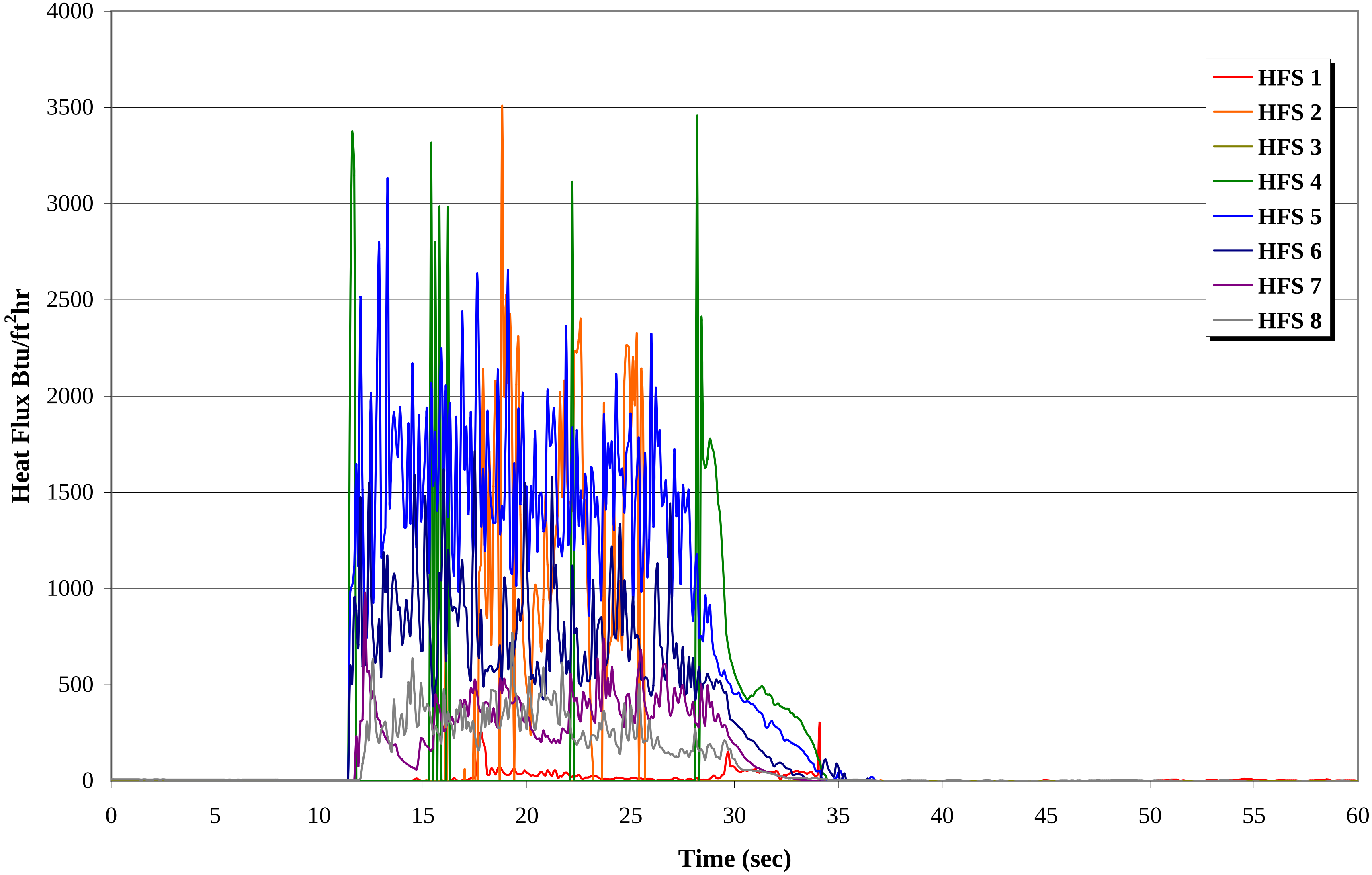


Motor Vehicle Fire Research Institute
SwRI Project No. 01.06939.01.004
Test Date: October 28, 2005
Test ID: 301MVF5-3

16-sec 48-g/min Mid-Body Jet-Fire



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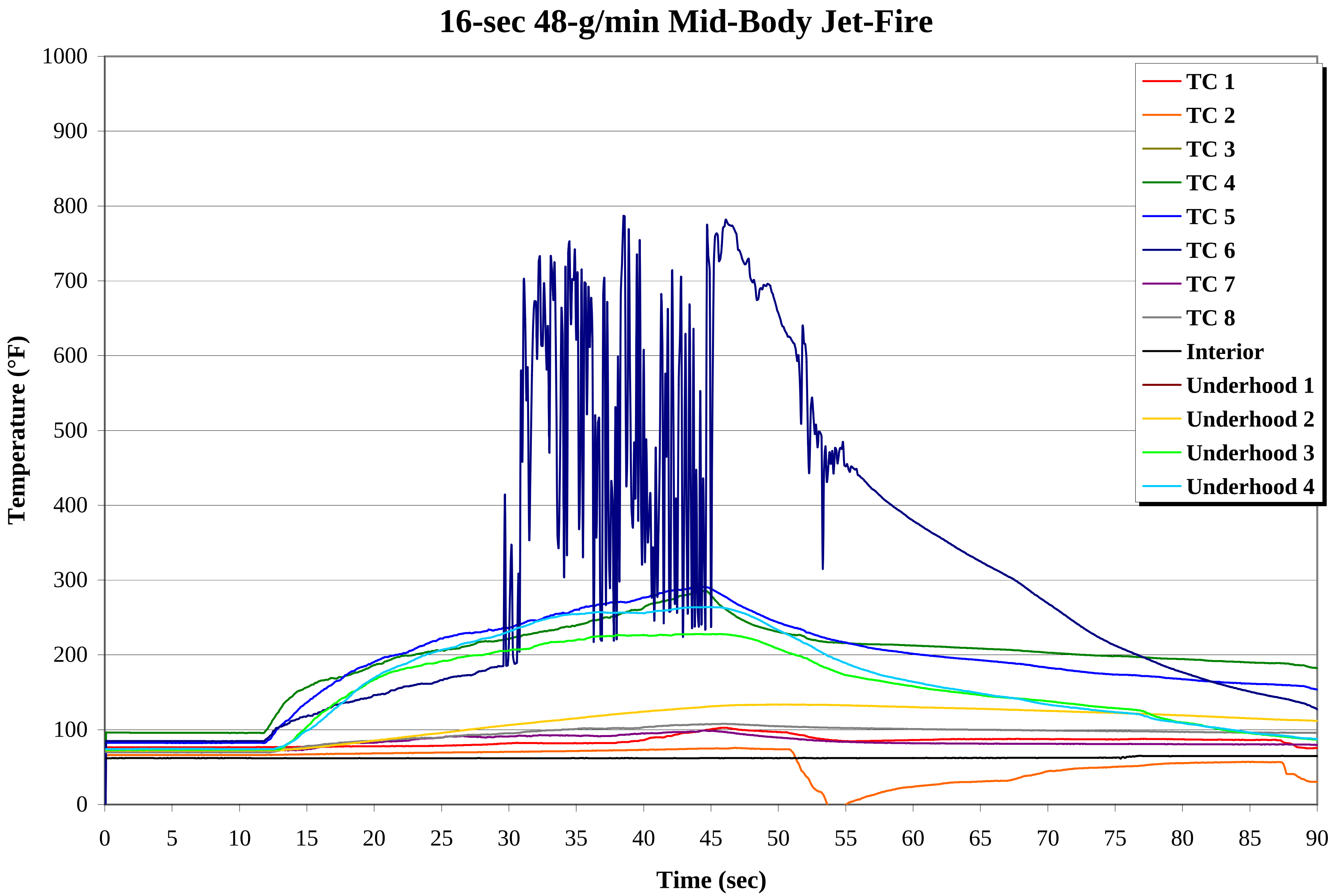

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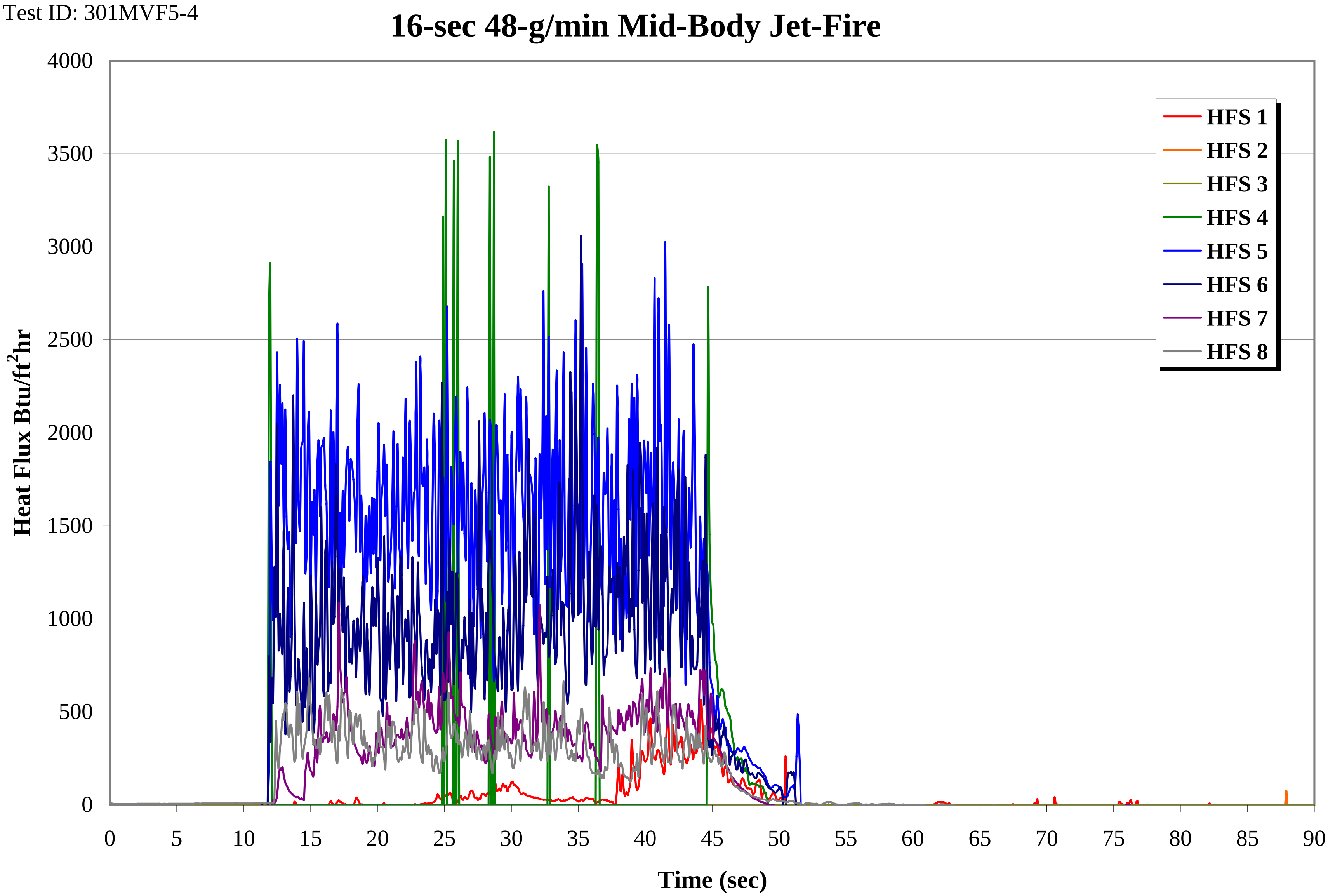

APPENDIX F

PHOTOGRAPHIC DOCUMENTATION

(CONSISTING OF 6 PAGES)

Figure F-1. Overall Test Setup.

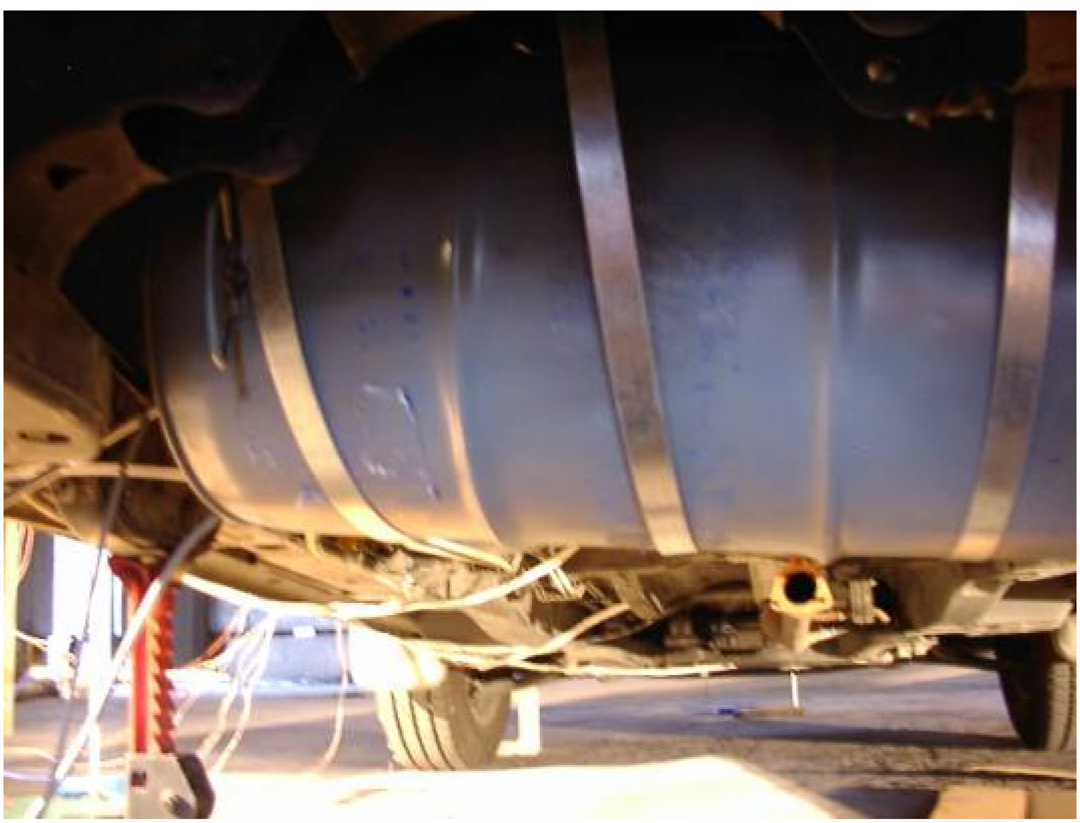

Figure F-2. Simulated Cylinder.

Figure F-3. Mid-Body Nozzle Location.

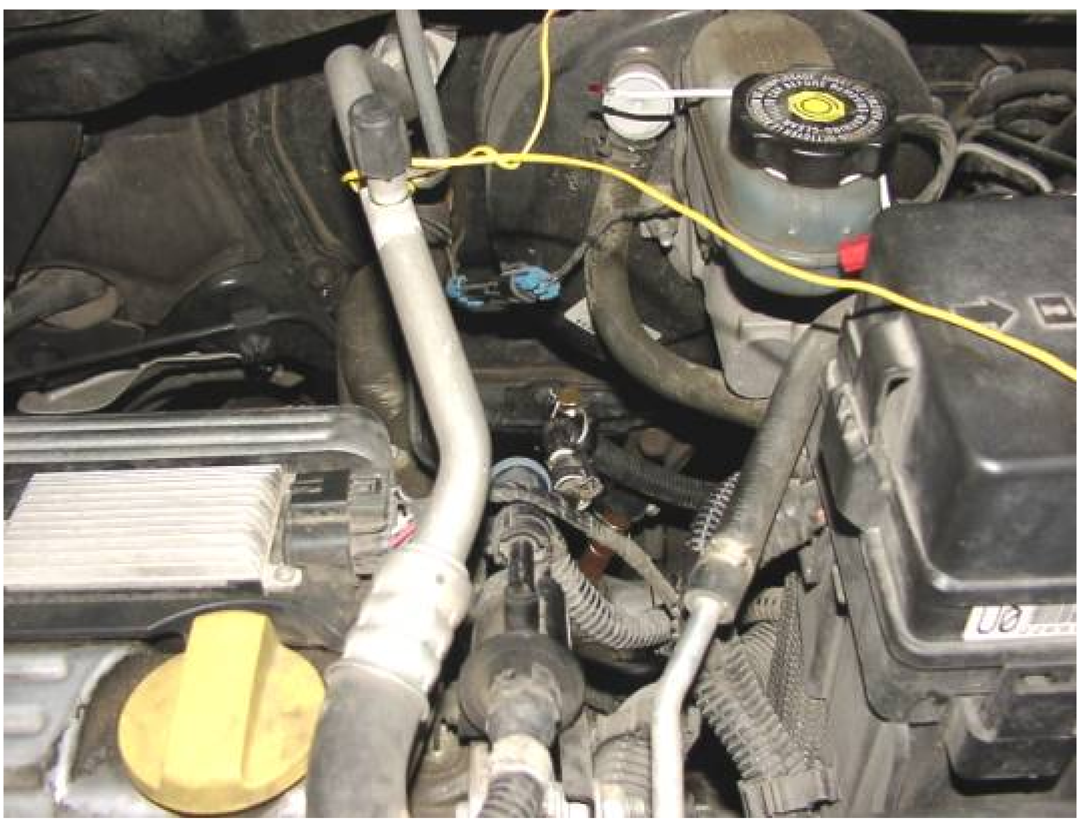

Figure F-4. Underhood Nozzle Location.

Figure F-5. Underhood Test Arrangement.

Figure F-6. Damage to Hood Liner Following Series 3 Tests.

Figure F-7. Jet-Fire Length During Open Hood Test.

Figure F-8. Effects of Jet-Fire With Hood Closed.

Figure F-9. Damage to Underside of Hood Liner Following Series 4 Tests.

Figure F-10. Damage to Topside of Hood Following Series 4 Tests.

Figure F-11. View of Jet-Fire on Underside of Vehicle.

Figure F-12. Continued Flaming of Plastic Component, Glowing Metal Components.