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High Pressure Earth Storable Rocket Technology Program—Hipes Options 1/2 Report

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TRW Space and Technology Division, Redondo Beach, California

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HIGH PRESSURE EARTH STORABLE ROCKET TECHNOLOGY PROGRAM

HIPES OPTIONS 1&2 FINAL REPORT

1.0 SUMMARY

The High Pressure Earth Storable Rocket Technology (HIPES) Option 1 Program was initiated in January 1995 after completion of the Basic Program and winning the downselect. The program was restructured in the first quarter 1995 to emphasize the development of a low cost, high performance N_2O_4-MMH 100 lbf thrust class engine. The program consisted of design, fabrication and testing of engine hardware. The results of the program can be summarized as follows:

- Injector designs included the typical TRW pintle injector using slots and a low cost version using orifices instead of slots.
- Nominal chamber pressure and a 20% increase in chamber pressure were evaluated by the use of different throats in addition to the effect of L*.
- A powder metallurgy rhenium thrust chamber was designed and fabricated using a more cost effective approach.
- A platinum (20% rhodium) thrust chamber was designed and fabricated using a cost effective manufacturing approach. The thrust chamber was a backup to the powder metallurgy rhenium thrust chamber pending successful completion of coating and test firing.
- A total of 124 tests was conducted using a R512E coated columbium chamber and water-cooled nozzle with N_2O_4-MMH demonstrating stable high projected performance.
  - Slotted pintle injector performance
    Nominal Pc/L* - Isp_{∞}=325.9 lbf-sec/lbm (ε=204) @ Wt=0.359 lbm/sec
    Increased Pc - Isp_{∞}=327.7 lbf-sec/lbm (ε=204) @ Wt=0.359 lbm/sec
    Increased Pc - Isp_{∞}=329.6 lbf-sec/lbm (ε=275) @ Wt=0.359 lbm/sec.
  - Orifice pintle injector (reduced cost injector) performance
    Nominal Pc/L* - Isp_{∞}=320.2 lbf-sec/lbm (ε=204) @ Wt=0.355 lbm/sec
    Increased Pc/L* - Isp_{∞}=325.9 lbf-sec/lbm (ε=204) @ Wt=0.353 lbm/sec
    Increased Pc/L* - Isp_{∞}=327.8 lbf-sec/lbm (ε=275) @ Wt=0.353 lbm/sec
  - Both injectors analytically are compatible with the powder metallurgy thrust chamber
- A total of 17 tests was successfully conducted using the bolt-on coated powder metallurgy rhenium chamber accumulating 4789 seconds operating time with a maximum firing duration of 700 seconds with N_2O_4-MMH. A total of 10,019 seconds was accumulated on this powder metallurgy rhenium chamber including 5230 seconds with N_2O_4-N_2H_4 on the SSRT Program (NASA/CR-1998-206605). High performance was achieved correlating within 0.5% with the water-cooled nozzle at the same flowrates.
  Isp_{∞}=323 lbf-sec/lbm (ε=204) at Wt=0.355 lbm/sec at nominal Pc/L*
  Isp_{∞}=326.5 lbf-sec/lbm (ε=275) at Wt=0.355 lbm/sec at nominal Pc/L*

- A total of 48 tests was conducted with the engineering model engine accumulating 8085 seconds with a maximum firing duration of 1200 seconds with N_2O_4-MMH. High stable performance was achieved based on projections from measured C*and projected C_f.
  Isp_{∞}=323 lbf-sec/lbm (ε=204) to 326.5 lbf-sec/lbm (ε=350) for Wt=0.325 lbm/sec & O/F=1.60
  Isp=326 lbf-sec/lbm (ε=204) to 330 lbf-sec/lbm (ε=350) for Wt=0.325 lbm/sec & O/F=1.65

2.0 INTRODUCTION

Earth storable propulsion has been the mainstay for spacecraft applications for the past forty years. Technology has been continually evolving to achieve higher performance as mission demands have grown. The introduction of the dual mode system (N_2O_4-N_2H_4) system provided one of the last significant earth storable propulsion system improvements available. The dual mode system uses a bipropellant liquid apogee engine for apogee circularization and insertion and various forms of hydrazine thrusters for attitude control stationkeeping including electrothermal and arcjets wherein the hydrazine for both the main engine and control system (ACS) are integrated into the same tank or tanks. TRW has qualified and flown on satellites (ANIK and Intelsat) 100 lbf thrust engines with performance of 314.6 lbf-sec/lbm and has qualified and delivered/installed LAE's of >320 lbf-sec/lbm on the AXAF spacecraft. As a result, the potential for further improvements results from higher pressure due to the potential for higher C_f and C* allowing the use of higher temperature materials, reduced length and volume of the engine and potential weight savings. It has also become clear that the use of higher pressure is the only method of using the high performance engine due to volume and length constraints on certain spacecraft applications (i.e., small lightweight spacecraft).

The scope of the HIPES program includes four phases - basic and three options.

The basic program was successfully completed in late 1994 and reported in NASA CR 195449 dated March 1995. The results of the HIPES Basic Program can be summarized as follows:

- HIPES 50 lbf thrust engine operating at a chamber pressure of 500 psia will benefit Mediumsats and Lightsats with their minimum volume and length constraints allowing major increases in payloads.
- Three types of thrust chambers (heatsink, water-cooled and powder metallurgy rhenium) were successfully evaluated using four high performance injectors.
- A total of 76 hot fire tests accumulating 1674 seconds was conducted to evaluate performance and thermal characteristics at varying chamber pressures (400-600 psia).
- High projected performance was demonstrated based on measured C* and projected C_f:
  - Isp_{∞}=337 lbf-sec/lbm (ε=150) using N_2O_4-N_2H_4
  - Isp_{∞}=329 lbf-sec/lbm (ε=150) using N_2O_4-MMH

The Option 1 Program was redirected by NASA-LeRC to emphasize the development of a low cost, high performance N_2O_4-MMH 100 lbf thrust class LAE engine. The specific tasks of the Option 1 Program were:

Task 5. High Performance Advanced Rocket Engine Design

- Design 100 lbf thrust class N_2O_4-MMH high performance rocket engine hardware using water-cooled nozzle and radiation cooled chamber with high performance injectors for performance and thermal evaluations.
- Design advanced thrust chambers using reduced cost fabrication techniques for powder metallurgy (PM) rhenium and investigate the feasibility of using platinum (20% rhodium) wrought material as a backup.

Task 6. High Performance Advanced Rocket Engine Fabrication

- Fabricate the hardware designed in Task 5
  - Injector hardware
  - Thrust chamber (Cb radiation cooled chamber and water-cooled nozzle)
  - Platinum (20% rhodium) thrust chamber
  - Initiate fabrication of reduced cost powder metallurgy rhenium thrust chamber

Task 7. High Performance Advanced Rocket Engine Tests

- Conduct test program to optimize injector performance with thermal characteristics compatible with operation in the PM rhenium or platinum (20% rhodium) thrust chambers.
- Analyze the test results to assess performance and thermal characteristics.

The Option 2 program was redirected to demonstrate an engineering model engine as a technology demonstrator with N_2O_4-MMH at the 100 lbf thrust level. This engine shall incorporate the high performing low cost injector developed in Option 1 and the technologies developed on both SSRT and HIPES programs. This Option 2 program consisted of the following tasks:

TASK 8 Design of Advanced Engineering Model Engine

- Design high performance engineering model engine using the technologies developed on SSRT and HIPES programs
- Engine shall be designed in a configuration to maximize nozzle length
- Optimize engine to maximize performance
- Engine shall use N_2O_4-MMH in 100 lbf thrust class

TASK 9 Fabricate an Advanced Engineering Model Engine

- Fabricate a low cost and low pressure drop injector
- Modify the powder metallurgy rhenium thrust chamber fabricated in Option 1 to operate at increased chamber pressure with a short nozzle attached
- Fabricate injector-valve interface block to allow maximum length nozzle in flight configuration
- Use available TRW valves (individual solenoid valves qualified for TRW engines)

TASK 9 Test the Advanced Engineering Model Engine

- Conduct test matrix to assess engine performance over a range of conditions
- Conduct long duration tests to assess durability

This final report presents the results of the Option 1 and Option 2 programs.

3.0 OPTION 1 RESULTS

3.1. High Performance Engine Development

3.1.1. Design

The pintle injector was designed to utilize different configurations of fuel tips and different sleeves to achieve different oxidizer gaps to enable evaluations at various velocities and momentums. Five different fuel tips were designed including three slotted configurations and two reduced cost orifice type injectors (another orifice type injector was available from the SSRT program). Three different types of thrust chambers were designed. A workhorse thrust chamber was designed to evaluate injector performance and assess nozzle heat transfer. This thrust chamber consisted of a R512E coated C103 chamber welded to the C103 injector body. The nozzle was water-cooled and bolted to the chamber. Two different throat liners were designed to allow testing at nominal chamber pressure and at 120% nominal chamber pressure to assess the impact of increased chamber pressure. In addition a water-cooled spool section was designed to allow for increased L* and length. High temperature radiation cooled thrust chambers were also designed. These included a coated powder metallurgy rhenium thrust chamber using a lower cost fabrication approach and a platinum (20%rhodium) thrust chamber as a backup.

3.1.1.1. Injectors

The five injector tips included three slotted elements consisting of two of 48 slots and one of 60 slots. The three low cost elements (including one from the SSRT program) consisted of two of 48 orifices/row and another of 60 orifices/row. After testing the discrete element orifice type injectors, the two injectors of 48 orifices/row were modified to add another row of orifices to reduce the fuel pressure drop and momentum.

3.1.1.2 Thrust Chambers

The three types of thrust chambers used in the evaluations were:

- Columbium chamber with water-cooled nozzle

  The C103 chamber was coated with R512E silicide coating (Hitemco) and electron beam welded to the C103 injector body. The chamber had thermocouple bosses in the center of the chamber so temperatures could be measured to assess headend thermal characteristics. The water-cooled nozzle was designed so that two different throat liners could be used to assess performance and thermal characteristics at nominal and 120% nominal chamber pressure. Both were used in the test program. The water-cooled spool section was designed to increase the length (L*) to assess the performance increase. This spool section was used downstream of the chamber between the C103 columbium chamber and water-cooled nozzle.

- Platinum (20% rhodium) thrust chamber

  The platinum (20% rhodium) thrust chamber was designed with a flange (also platinum-20% rhodium) for the nominal chamber pressure operation. The thrust chamber was designed to use a HfO_2 external coating to increase the emissivity. This thrust chamber was designed as a backup thrust chamber to the powder metallurgy rhenium thrust chamber in case problems occurred.

- Powder metallurgy rhenium thrust chamber

The powder metallurgy rhenium thrust chamber was designed to operate at nominal chamber pressure incorporating the same diameter as the baseline thrust chambers. The powder metallurgy rhenium thrust chamber was designed to be fabricated using a low cost approach and in the same manner as the previously tested PM rhenium thrust chamber which accumulated over 10,000 seconds firing time. The thrust chamber upon completion of fabrication was then coated with the electrodeposited coatings of iridium internally/externally and rhodium internally in the chamber section. The thrust chamber was then subjected to thermal treatment and then coated externally with HfO_2 for high emissivity. This powder metallurgy rhenium chamber fabrication/coating process is covered by patent No. 5,720,451 dated 2-24-98.

3.1.2. Fabrication

The injector hardware was fabricated to the design discussed in 3.1.1. The C103 chamber was fabricated and coated with R512E silicide coating. The chamber was then electron beam welded to the C103 injector body. The water-cooled nozzle was fabricated. The testing could now be initiated. The powder metallurgy rhenium chamber was fabricated by Rhenium Alloys Inc. but left uncoated pending the results of the hot fire tests using the SSRT PM rhenium chamber. The platinum (20% rhodium) thrust chamber was fabricated by Engelhard by spinning the thrust chamber and welding on the flange and then coated externally with HfO_2 for high emissivity.

3.1.3. Hot Fire Testing

The workhorse thrust chamber was mated with the injectors as shown in Figure 3-1. A total of 124 tests was conducted with N_2O_4-MMH to assess the performance of the engine with the various injectors. Initial testing with the orifice pintle injectors gave low performance. The injectors (X-1 and X-2) were then modified to add another row of orifices (designated X-4 and X-5) and tested. The results of all tests indicated the slotted injector gave slightly better performance but the orifice injector (X-4) was almost as good but lower cost. The details of testing are discussed in 3.2.

3.2. Test Results

3.2.1. High Performance Injectors

High performance injectors were tested in the workhorse engine in a test series of 124 tests using N_2O_4-MMH. The results are presented in Table 3-1. The data was corrected for heat loss due to the water-cooled nozzle. A correction was made for heat loss to predict the performance that should be attained with the powder metallurgy rhenium thrust chamber using a two-zone model which accounted for the wall zone temperatures along the chamber length. The results indicated the following:

- The slotted injector (-2) generated the best performance with the results presented in Figure 3-2. The specific impulse (Isp projected for ε=204) was indicated as 325.9 lbf-sec/lbm at Wt=0.359 lbm/sec and baseline L* and chamber pressure. Increasing the Pc/L* resulted in an

Isp increase of 0.55% (1.8 s) to 327.7 lbf-sec/lbm. If additional length is available, the Isp could be increased another 0.58% (1.9 s) to 329.6 lbf-sec/lbm using $\varepsilon=275$.

- The discrete element (orifice) pintle injector (X-4) generated high performance as shown in Figure 3-3 which was comparable to the slotted injector but lower in cost. The projected specific impulse (Isp_ projected for $\varepsilon=204$) was 320.2 lbf-sec/lbm at nominal Pc/L*. Increasing the Pc/L* resulted in an increase in Isp by 1.78% (5.7 s) to 325.9 lbf-sec/lbm. If additional length is available, the Isp could be increased further by 0.58% (1.9 s) to 327.8 lbf-sec/lbm using $\varepsilon=275$.
- As a result of this testing, the discrete element X-4 injector was selected as the baseline for all future N_2O_4-MMH testing using the coated powder metallurgy rhenium thrust chamber.

3.2.2. PM Rhenium Chamber Test Results

The SSRT coated powder metallurgy rhenium thrust chamber (Figure 3-4) was tested with N_2O_4-MMH using the X-4 injector (discrete element) after SSRT program testing with N_2O_4-N_2H_4. This chamber had accumulated 5230 seconds in 44 tests on SSRT with a maximum duration of 600 seconds and was in excellent condition. The chamber was then tested on HIPES using N_2O_4-MMH and was successfully tested for an added 4789 seconds accumulated test time in 17 tests with a maximum duration of 700 seconds. This resulted in a total accumulated time of 10,019 seconds in 61 total tests and the chamber was in excellent condition.

The testing on HIPES was initiated using the short snout which was the configuration used to evaluate the injector in the columbium chamber and water-cooled nozzle as discussed in 3.2.1. The test results indicated very good agreement (within <1%) with the water-cooled nozzle as presented in Figure 3-5. The rest of the testing was conducted with the long snout which was the corrective action taken to resolve the TRW DM-LAE thermal anomaly. This long snout demonstrated thermal stability in all the testing conducted on both the SSRT and HIPES programs as well as other TRW programs. High performance was demonstrated as shown in Figure 3-6 which indicated C*=5500-5550 at total flowrates of 0.33-0.36 lbm/sec with wall temperatures below 3500F which was well below the iridium coated rhenium thrust chamber capability. The projected specific impulse (Isp) was 321-324 lbf-sec/lbm ($\varepsilon=204$) as shown in Figure 3-7. If additional length is available, the performance could be increased as shown in Figure 3-8 to 324-327 lbf-sec/lbm ($\varepsilon=275$).

3.2.3. Summary of Test Results

The discrete element pintle injector demonstrated high performance in a columbium chamber and water-cooled nozzle. Increasing the Pc/L* increased the performance significantly more. This high performing injector was then tested in the coated powder metallurgy rhenium thrust chamber (baseline Pc and Dt) accumulating >10,000 seconds of firing time thus demonstrating the viability of the powder metallurgy rhenium thrust chamber. In addition there was excellent agreement with the water-cooled nozzle and the rhenium thrust chamber performance data. These results indicated the powder metallurgy rhenium thrust chamber is a viable high temperature capability thrust chamber achieving high performance eliminating the need for the backup platinum-rhodium thrust chamber. However, even higher performance can be achieved using added L* with attendant higher chamber pressure which would also allow greater nozzle expansion.

TABLE 3-1
HIPES TEST PROGRAM
C*&Isp based on 2-ZONE MODEL(N2O4-MMH)

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
4364	5	0.00955	0.0018	1.42	0.3653	115.5	5405	5457	160.3	168.7	44.8	53.2	316.3
4365	15	0.00955	0.0018	1.423	0.3677	116.2	5404	5467	161.1	170.3	44.8	54.1	316.9
4366	15	0.00955	0.0018	LOST DATA-COMPUTER PROBLEM									
4367	15	0.00955	0.0018	1.62	0.3287	103.7	5393	5466	142.7	141.2	39.1	37.6	316.8
4368	15	0.00955	0.0018	1.632	0.3292	104.7	5422	5495	141.7	141.6	37	36.9	318.5
4369	15	0.00955	0.0018	1.63	0.3685	117.5	5447	5518	163	164.8	45.5	47.3	319.9
4370	15	0.00955	0.0018	1.6274	0.3686	117.5	5446	5517	162.6	164.8	45.1	47.3	319.8
4371	15	0.00955	0.0018	1.628	0.3686	117.5	5445	5516	162.9	164.9	45.5	47.4	319.7
4372	15	0.00955	0.002	1.614	0.3671	116.1	5403	5470	160.9	167.8	44.8	51.7	317.1
4373	15	0.00955	0.0022	1.468	0.3102	96.9	5335	5403	128.7	133.7	31.8	36.8	313.2
4374	15	0.00955	0.0022	1.62	0.3685	116.9	5421	5494	163.3	165.3	46.4	48.4	318.5
4375	15	0.00955	X-1	1.603	0.327	100	5221	5284	135.9	165.4	35.9	65.4	306.3
4376	15	0.00955	X-1	1.7393	0.3291	101.3	5255	5321	140	162.3	38.7	61	308.5
4377	15	0.00955	X-1	1.8685	0.3298	102.2	5298	5370	143	160.4	40.8	58.2	311.3
4378	15	0.00955	X-1	1.8676	0.3878	122.8	5416	5496	177.6	201.4	54.8	78.6	318.6
4379	15	0.00955	X-1	1.6122	0.3881	122.5	5398	5472	172	215	49.5	92.5	317.2
4380	15	0.00955	X- 2	1.6165	0.328	101	5259	5331	137.1	133.2	36.2	32.2	309.0
4381	15	0.00955	X-2	1.6241	0.3589	111.2	5293	5368	154.5	149.9	43.3	38.7	311.2
4382	15	0.00955	X-2	1.621	0.387	120.8	5340	5418	170.6	166.4	49.8	45.6	314.1
4383	15	0.00955	X-2	1.6215	0.4172	131.1	5374	5454	188.2	185.1	57.1	54.1	316.1
4384	15	0.0085	X-1	1.6235	0.3291	102.2	5311	5383	142.9	168.5	40.7	66.3	312.0
4385	15	0.0085	X-1	1.6283	0.3591	113	5380	5457	160.8	191	47.8	78	316.3
4386	15	0.0085	X-1	1.6171	0.3878	123.1	5434	5515	177.8	214	54.7	90.9	319.7
4387	15	0.0085	X-1	1.5008	0.3577	111.6	5336	5408	156.1	195.8	44.5	84.2	313.5
4388	15	0.0085	X-1	1.6937	0.3563	111.9	5371	5448	160	185.6	48.1	73.7	315.8
4389	15	0.0085	X-1	1.6153	0.3581	112.2	5360	5435	159.2	190.3	47	78.1	315.0
4390	15	0.0085	X-1	1.7418	0.3585	113	5392	5473	162.5	185.4	49.5	72.4	317.3
4391	15	0.0085	X-3	1.6079	0.3269	103.8	5434	5520	142.8	138.3	39.1	34.5	320.0
4392	15	0.00955	X-3	1.6118	0.3274	103.2	5391	5467	138.6	137.2	35.4	34	316.9
4393	15	0.00955	X-3	1.6181	0.358	113.3	5414	5494	155.2	153.1	42	39.9	318.5

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
4394	15	0.00955	X-3	1.6172	0.388	122.8	5420	5508	171.4	169.3	48.6	46.5	319.3
4395	15	0.00955	X-3	1.4966	0.3572	112.9	5409	5488	152.2	155.5	39.3	42.6	318.1
4396	15	0.00955	X-3	1.6892	0.3272	103.5	5413	5497	135.4	103.5	36.2	32	318.7
4397	15	0.00955	-1/.0029	1.7046	0.329	105.9	5509	5592	143.3	138.3	37.4	32.5	324.1
4398	15	0.00955	-1/.0029	1.6192	0.3304	106.5	5519	5604	143	140.9	36.5	34.4	324.8
4399	15	0.00955	-1/.0029	1.6241	0.3578	115.4	5523	5607	157.7	155.9	42.3	40.5	325.0
4400	15	0.00955	-1/.0029	1.6265	0.3883	125.4	5534	5608	174.9	173.4	49.5	48	325.1
4401	15	0.00955	-2/.0029	1.618	0.3306	107	5540	5626	143.1	144.9	36.1	38	326.1
4402	15	0.00955	-2/.0029	1.6201	0.3569	115.6	5548	5629	157.2	160.2	41.6	44.6	326.3
4403	15	0.00955	-2/.0029	1.6244	0.3882	125.7	5549	5620	174.4	178.6	48.8	52.9	325.8
4404	15	0.00955	-2/.0029	1.5004	0.3869	125.1	5540	5620	170.8	181.5	45.7	56.4	325.8
4405	15	0.00955	-3/.0027	1.6305	0.331	106.3	5497	5582	142.8	145.7	36.5	39.5	323.6
4406	15	0.00955	-3/.0027	1.5062	0.3283	105.4	5496	5582	139.3	147.1	33.9	41.7	323.6
4407	15	0.0116	-3/.003	1.6341	0.3323	106.3	5479	5562	138.3	141.9	32	35.6	322.4
4408	15	0.0116	-3/.003	1.6343	0.3594	114.8	5472	5551	151.6	156.4	36.9	41.6	321.8
4409	15	0.0116	-3/.003	1.6301	0.389	123.9	5462	5533	166.6	173	42.7	49	320.7
4410	15	0.0116	-3/.003	1.5064	0.3889	124.2	5477	5550	164.4	176.8	40.2	52.7	321.7
4411	15	0.00955	-2/.0024	1.6249	0.3315	106.9	5518	5604	143.9	151.5	37	44.7	324.8
4412	15	0.00955	-2/.0024	1.6178	0.3574	115.5	5537	5620	158	168.2	42.5	52.7	325.8
4413	15	0.00955	-2/.0024	1.6199	0.3882	125.8	5556	5635	175.4	188.2	49.6	62.3	326.6
4414	15	0.00955	-2/.0024	1.5047	0.3881	125.3	5532	5612	171.9	192.2	46.7	66.9	325.3
4415	15	0.00955	-2/.0024	1.6981	0.3576	116	5557	5638	159.8	165.8	43.8	49.8	326.8
4416	15	0.0116	-2/.003	1.6148	0.3292	106.3	5530	5613	137	141.1	30.7	34.9	325.4
4417	15	0.0116	-2/.003	1.6256	0.3583	115.8	5542	5622	152.1	157	36.3	41.2	325.9
4418	15	0.0116	-2/.003	1.6164	0.3876	125.4	5551	5624	167.2	174.2	41.8	48.8	326.0
4419	15	0.0116	-2/.003	1.4961	0.3885	125.1	5521	5596	165	178.3	40	53.3	324.4
4420	15	0.0116	-2/.003	1.6991	0.3588	115.6	5527	5601	153.6	155.7	37.9	40.1	324.7
4421	15	0.0116	-2/.003	1.5004	0.3583	115.2	5512	5592	149.6	160.2	34.4	45	324.1
4422	15	0.0116	-2/.003	1.6152	0.2985	96.1	5514	5600	122.1	124.9	26	28.8	324.6
4423	15	0.0116	-2/.003	1.6176	0.3878	125.3	5543	5616	167.5	174.4	42.2	49.1	325.5

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
4424	15	0.0116	-2/.003	1.6109	0.387	125	5544	5617	167	174	42	49	325.6
	20	0.0116	-2/.003	1.6121	0.3873	125.1	5544	5614	167.1	174.2	42	49.1	325.4
	25	0.0116	-2/.003	1.613	0.3874	125.2	5545	5615	167.1	174.3	41.9	49.1	325.5
	30	0.0116	-2/.003	1.6137	0.3874	125.2	5546	5616	167.2	174.4	42	49.2	325.5
	35	0.0116	-2/.003	1.6136	0.3876	125.3	5546	5616	167.1	174.4	41.9	49.1	325.5
	40	0.0116	-2/.003	1.6143	0.3876	125.3	5546	5616	167.2	174.4	42	49.1	325.5
	45	0.0116	-2/.003	1.6142	0.3877	125.3	5546	5613	167.2	174.5	41.9	49.2	325.4
	50	0.0116	-2/.003	1.6981	0.3877	125.3	5545	5611	167.2	174.5	41.9	49.2	325.2
	55	0.0116	-2/.003	1.6148	0.3877	125.3	5547	5612	167.2	174.5	41.9	49.1	325.3
	59	0.0116	-2/.003	1.6149	0.3877	125.4	5548	5614	167.3	174.5	41.9	49.2	325.4
4425	15	0.00955	E449554-2	1.6452	0.3318	105	5417	5501	142.1	122.8	37.1	17.9	318.9
4426	15	0.00955	E449554-2	1.6273	0.3582	113.4	5422	5501	156.7	135.8	43.4	22.4	318.9
4427	15	0.00955	E449554-2	1.5001	0.3574	113.1	5418	5497	153.1	136.6	40	23.5	318.6
4428	15	0.0116	E449554-2	1.6179	0.3293	103.4	5376	5457	134.3	121.1	30.9	17.7	316.3
4429	15	0.0116	E449554-2	1.6162	0.3278	103.2	5388	5470	133.5	120.5	30.4	17.3	317.1
4430	15	0.0116	E449554-2	1.6077	0.327	103	5391	5473	133.1	120.2	30.2	17.2	317.2
4431	15	0.0116	E449554-2	1.6266	0.3594	113.6	5414	5494	149.9	134.2	36.3	20.6	318.5
4432	15	0.0116	E449554-2	1.4942	0.3274	102.7	5366	5448	131.1	121.1	28.5	18.4	315.8
4433	15	0.0116	-2/0.0029	1.6377	0.3297	106.6	5536	5621	137.8	144.3	31.3	37.7	325.8
4434	15	0.0116	-2/0.0029	1.6206	0.3566	115.4	5544	5626	151.5	160	36.2	44.6	326.1
4435	15	0.0116	-2/0.0029	1.6192	0.3886	125.9	5554	5634	168.1	178.9	42.2	53	326.6
4436	15	0.0116	-2/0.0029	1.496	0.3571	115.2	5525	5607	149.4	163.5	34.2	48.3	325.0
						L* TESTS							
4437	15	0.0116	-2/0.0029	1.6085	0.3269	105.6	5529	5641	136.1	143	30.5	37.4	327.0
4438	15	0.0116	-2/0.0029	1.6296	0.358	115.9	5546	5652	152.3	160.3	36.3	44.3	327.6
4439	15	0.0116	-2/0.0029	1.6168	0.3869	125	5534	5636	166.4	177.2	41.4	52.2	326.7
4440	15	0.0116	-2/0.0029	1.5012	0.3581	115.3	5513	5619	149.6	163.5	34.3	48.1	325.7
4441	15	0.0116	-2/0.0029	1.7223	0.3614	116.5	5522	5635	154.8	159.8	38.3	43.3	326.6
4442	15	0.00955	X-3	1.6176	0.3278	103.8	5417	5524	139.4	137.5	35.6	33.7	320.2
4443	15	0.00955	X-3	1.6212	0.3573	113.8	5454	5560	155.7	153.3	41.9	39.5	322.3
4444	15	0.00955	X-3	1.617	0.3869	122.9	5441	5540	171.5	168.7	48.6	45.8	321.1
4445	15	0.00955	X-3	1.5011	0.3575	114	5459	5565	153.7	156.2	39.7	42.1	322.6
4446	15	0.00955	X-3	1.7046	0.3579	114.1	5459	5571	157.6	151.4	43.6	37.5	322.9
4447	15	0.0085	X-1	1.6216	0.3281	103	5369	5475	142.6	168.9	39.6	65.9	317.4
4448	15	0.0085	X-1	1.6217	0.3575	113.5	5433	5537	160.1	191.2	46.6	77.7	321.0
4449	15	0.0085	X-1	1.626	0.388	124.3	5488	5590	178.4	214.9	54.1	90.6	324.0

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
						HIGH Pc TESTS							
4450	15	0.0085	X-1	1.6273	0.3274	122.8	5337	5395	162.4	188	39.6	65.2	312.7
4451	15	0.0085	X-1	1.6216	0.3581	136.5	5427	5484	182.9	214.2	46.4	77.7	317.9
4452	15	0.0085	X-1	1.6124	0.3866	149.1	5500	5551	202.3	239.4	53.2	90.3	321.8
4453	15	0.00955	X-3	1.6015	0.3272	124.6	5425	5485	160	157.7	35.4	33.1	317.9
4454	15	0.00955	X-3	1.6466	0.3602	137.7	5452	5502	181.1	177	43.5	39.3	318.9
4455	15	0.00955	X-3	1.633	0.3862	147.2	5440	5490	196.2	192.3	48.9	45.1	318.2
4456	15	0.00955	X-3	1.4919	0.3556	136.3	5466	5528	175.6	177.9	39.3	41.7	320.4
4457	15	0.0116	-2/0.0029	1.6002	0.3277	128	5567	5633	158.1	165.6	30.1	37.6	326.5
4458	15	0.0116	-2/0.0029	1.6252	0.3588	140.5	5589	5654	176.6	185.3	36	44.7	327.7
4459	15	0.0116	-2/0.0029	1.6492	0.3859	151.6	5612	5674	193.5	203.1	41.8	51.4	328.9
4460	15	0.0116	-2/0/0029	1.5213	0.3562	139.3	5581	5651	173.2	186.4	33.9	47	327.6
4461	15	0.0116	-2/0.0029	1.7106	0.3594	141.2	5607	5674	178.4	183.7	37.3	42.6	328.9
						HIGH Pc/L* TESTS							
4511	5	0.00955	X-5	1.6084	0.3239	123.9	5461	5560	158.8	138.7	34.9	14.8	322.3
4512	15	0.00955	X-5	1.6048	0.3273	125.1	5555	5578	160.3	140.3	35.2	15.2	323.3
4513	15	0.00955	X-5	1.506	0.3291	125.8	5459	5555	159.8	141.8	34	16	322.0
	20	0.00955	X-5	1.5035	0.3286	125.6	5457	5553	159.5	141.6	33.9	16	321.9
	25	0.00955	X-5	1.4998	0.3283	125.5	5457	5553	159.2	141.4	33.7	15.9	321.9
	30	0.00955	X-5	1.4985	0.3284	125.4	5450	5546	159.2	141.4	33.8	16	321.5
4514	15	0.0116	X-5	1.6215	0.3313	126.1	5435	5531	157.2	140.4	31	14.2	320.6
	20	0.0116	X-5	1.6241	0.332	126.3	5432	5529	157.4	140.6	31.1	14.3	320.5
	30	0.0116	X-5	1.6181	0.3311	125.4	5407	5504	156.7	140.1	31.3	14.6	319.0
	40	0.0116	X-5	1.6234	0.3319	126.4	5439	5536	157.3	140	30.9	13.6	320.9
	50	0.0116	X-5	1.6183	0.3311	126.1	5438	5535	156.9	139.7	30.8	13.6	320.8
	60	0.0116	X-5	1.6166	0.3309	125.9	5431	5528	156.7	139.5	30.8	13.7	320.4
4515	15	0.0116	X-5	1.6122	0.3559	135.7	5448	5544	171.4	152.1	35.7	16.4	321.4
	20	0.0116	X-5	1.6074	0.3554	135.6	5450	5544	171	151.9	35.4	16.3	321.4
	30	0.0116	X-5	1.6098	0.3557	135.7	5450	5544	171.3	152.1	35.5	16.3	321.4
	40	0.0116	X-5	1.6136	0.3562	135.8	5444	5538	171.4	152	35.6	16.3	321.0
	50	0.0116	X-5	1.6139	0.3563	135.9	5449	5543	171.5	152.2	35.5	16.3	321.3
	60	0.0116	X-5	1.6112	0.3559	135.5	5436	5529	170.9	151.7	35.4	16.3	320.5
4516	15	0.0116	X-5	1.6134	0.3867	147.3	5444	5533	189.1	166.4	41.7	19.1	320.7
	20	0.0116	X-5	1.6111	0.3864	147	5436	5525	188.7	166.1	41.5	19.1	320.3
	35	0.0116	X-5	1.6114	0.3867	146.6	5417	5507	188.2	165.8	41.5	19.2	319.2
4517	15	0.0116	X-4	1.6101	0.327	123.9	5401	5502	154.3	149.1	30.4	25.2	318.9
	20	0.0116	X-4	1.6091	0.3268	123.8	5401	5500	154.2	149	30.4	25.2	318.8
	30	0.0116	X-4	1.6075	0.3263	123.6	5397	5496	153.9	148.8	30.3	25.2	318.6
	40	0.0116	X-4	1.6068	0.3263	123.6	5398	5498	153.7	148.7	30.1	25.2	318.7

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
4518	15	0.0116	X-4	1.6152	0.3865	149.4	5520	5617	191.6	184.9	42.2	35.5	325.6
	20	0.0116	X-4	1.6157	0.3866	149.4	5518	5613	191.6	184.8	42.3	35.5	325.4
	30	0.0116	X-4	1.6163	0.3867	149.4	5516	5611	191.8	184.9	42.4	35.5	325.2
	40	0.0116	X-4	1.617	0.3868	149.4	5514	5609	191.8	184.9	42.4	35.6	325.1
4519	15	0.0116	X-4	1.6012	0.3263	123.4	5391	5493	153.6	148.8	30.2	25.4	318.4
	20	0.0116	X-4	1.6012	0.3265	123.4	5389	5491	153.7	148.8	30.3	25.4	318.3
	30	0.0116	X-4	1.6017	0.3267	123.3	5379	5481	153.7	148.9	30.4	25.6	317.7
	40	0.0116	X-4	1.6027	0.3268	123.3	5381	5483	153.8	148.9	30.5	25.5	317.8
4520	15	0.0116	X-4	1.6175	0.3559	136.5	5471	5573	172.7	166.4	36.3	29.9	323.0
	20	0.0116	X-4	1.6193	0.3561	136.5	5471	5573	172.9	166.5	36.5	29.9	323.0
	30	0.0116	X-4	1.6027	0.3564	136.5	5466	5568	173	166.4	36.5	29.9	322.8
	40	0.0116	X-4	1.6216	0.3565	136.5	5464	5565	172.9	166.5	36.4	30	322.6
4521	15	0.0116	X-4	1.6073	0.3864	150.1	5549	5648	192.6	185.4	42.5	35.3	327.4
	20	0.0116	X-4	1.6082	0.3866	150.1	5548	5647	192.5	185.5	42.4	35.3	327.3
	30	0.0116	X-4	1.61	0.3869	150.2	5544	5643	192.7	185.6	42.5	35.5	327.1
	40	0.0116	X-4	1.6109	0.3869	150.2	5545	5641	192.7	185.6	42.5	35.4	327.0
4522	15	0.0116	X-4	1.621	0.4175	162.1	5550	5643	211.2	202.8	49	40.7	327.1
	20	0.0116	X-4	1.6228	0.4178	162.2	5549	5642	211.3	202.8	49.1	40.6	327.0
	30	0.0116	X-4	1.6234	0.418	162.3	5548	5641	211.2	203	48.9	40.7	327.0
	40	0.0116	X-4	1.623	0.4183	162.2	5543	5635	211.3	203	49.1	40.8	326.6
4523	15	0.0116	X-4	1.6143	0.3412	130.1	5440	5543	163.2	157.7	33.1	27.6	321.3
	20	0.0116	X-4	1.6168	0.3414	130.1	5437	5540	163.3	157.7	33.2	27.6	321.1
	30	0.0116	X-4	1.6185	0.3417	130.2	5436	5539	163.6	157.8	33.4	27.5	321.1
	40	0.0116	X-4	1.6186	0.342	130.2	5432	5538	163.6	157.7	33.4	27.5	321.0
4524	15	0.0116	X-4	1.4911	0.3416	129.6	5410	5512	161	159.3	31.4	29.7	319.5
	20	0.0116	X-4	1.492	0.3418	129.6	5407	5509	161	159.4	31.4	29.7	319.3
	30	0.0116	X-4	1.4935	0.342	129.6	5403	5505	161.1	159.5	31.5	29.9	319.1
	40	0.0116	X-4	1.4957	0.3421	129.6	5401	5502	161.1	159.3	31.5	29.8	318.9
4525	15	0.0116	X-4	1.7192	0.3416	130.8	5465	5569	165.9	156.9	35.1	26.2	322.8
	20	0.0116	X-4	1.7213	0.3418	130.9	5464	5568	166	156.9	35.2	26	322.8
	30	0.0116	X-4	1.7238	0.3419	130.9	5462	5566	166.1	156.9	35.2	26.1	322.6
	40	0.0116	X-4	1.7236	0.3421	131	5465	5567	166.2	157	35.2	26	322.7
4526	15	0.00955	X-4	1.6082	0.3273	125.8	5485	5591	161.9	152.2	36.1	26.4	324.1
	20	0.00955	X-4	1.6099	0.3274	125.9	5487	5593	161.9	152.3	36.1	26.4	324.2
	30	0.00955	X-4	1.6109	0.3274	126	5490	5596	162	152.4	36	26.4	324.4
	40	0.00955	X-4	1.6107	0.3275	125.9	5487	5596	162	152.5	36	26.5	324.4
4527	15	0.00955	X-4	1.5931	0.3533	136.4	5514	5619	178.5	167.5	42	31.1	325.7
	20	0.00955	X-4	1.5941	0.3534	136.6	5518	5622	178.4	167.6	41.8	31	325.9
	30	0.00955	X-4	1.5952	0.3535	136.6	5518	5622	178.5	167.7	41.8	31.1	325.9
	40	0.00955	X-4	1.5958	0.3536	136.7	5521	5625	178.7	167.8	41.9	31.1	326.1

TEST #	DUR	Do	Df	O/F	Wt	Pc	C*	C*(hl)	PIO	PIF	DPox	DPf	Isp(v)
4528	15	0.00955	X-4	1.6161	0.3871	150.5	5554	5655	200.7	187.2	50.2	36.7	327.8
	20	0.00955	X-4	1.6169	0.3872	150.5	5554	5655	200.7	187.3	50.2	36.8	327.8
	30	0.00955	X-4	1.6177	0.3874	150.6	5554	5655	200.7	187.3	50.1	36.7	327.8
	40	0.00955	X-4	1.6181	0.3875	150.6	5553	5648	200.7	187.4	50.1	36.8	327.4
4529	15	0.00955	X-4	1.6055	0.4155	161.9	5571	5670	218.9	204.2	57	42.3	328.7
	20	0.00955	X-4	1.6065	0.4158	162.1	5572	5671	219.1	204.3	57	42.3	328.7
	30	0.00955	X-4	1.6073	0.416	162.2	5573	5668	219.3	204.5	57.1	42.3	328.6
	40	0.00955	X-4	1.6087	0.4162	162.3	5573	5668	219.2	204.6	57	42.4	328.6
4530	15	0.00955	X-4	1.7246	0.3555	138.2	5554	5655	182.6	167.6	44.4	29.4	327.8
	20	0.00955	X-4	1.7262	0.3556	138.3	5556	5657	182.8	167.6	44.6	29.4	327.9
	30	0.00955	X-4	1.7267	0.3557	138.3	5556	5657	182.8	167.7	44.5	29.3	327.9
	40	0.00955	X-4	1.7264	0.356	138.4	5556	5657	182.9	167.7	44.5	29.3	327.9
						B/L Pc & L*							0.0
4531	15	0.0955	X-4	1.6125	0.3259	103.3	5431	5504	141.7	130	38.4	26.6	319.0
	20	0.0955	X-4	1.6131	0.3261	103.5	5435	5511	141.9	130.1	38.4	26.7	319.5
	30	0.0955	X-4	1.6145	0.3263	103.5	5433	5512	142.2	130.3	38.7	26.8	319.5
	40	0.0955	X-4	1.6153	0.3264	103.5	5430	5510	142	130	38.5	26.5	319.4
4532	15	0.0955	X-4	1.5958	0.3546	112.7	5443	5523	154.6	143.9	41.9	31.2	320.1
	20	0.0955	X-4	1.5967	0.3548	112.7	5442	5524	154.7	143.9	42	31.1	320.2
	30	0.0955	X-4	1.5973	0.355	112.7	5440	5524	154.9	144.2	42.1	31.4	320.2
	40	0.0955	X-4	1.5973	0.3551	112.9	5447	5531	154.8	144	41.9	31.1	320.6
4533	15	0.0955	X-4	1.6167	0.3873	123.8	5481	5559	174.2	160.4	50.4	36.6	322.2
	20	0.0955	X-4	1.6179	0.3875	123.9	5481	5561	174.1	160.6	50.2	36.7	322.3
	30	0.0955	X-4	1.6193	0.3876	124	5484	5566	174.1	160.6	50.1	36.6	322.6
	40	0.0955	X-4	1.62	0.3877	124	5481	5564	174.2	160.6	50.3	36.7	322.5
4534	15	0.0955	X-4	1.5904	0.4124	133.3	5545	5619	190.4	175.6	57.1	42.3	325.7
	20	0.0955	X-4	1.5926	0.4129	133.4	5543	5619	190.5	175.7	57.1	42.3	325.7
	30	0.0955	X-4	1.5897	0.4125	133.5	5549	5627	190.6	176	57.2	42.6	326.2
	40	0.0955	X-4	1.5912	0.4126	133.5	5550	5628	190.6	176	57.1	42.5	326.2
4535	15	0.0955	X-4	1.7202	0.3565	114.2	5489	5562	158.8	143.8	44.6	29.6	322.4
	20	0.0955	X-4	1.7222	0.3567	114.3	5491	5567	158.8	143.9	44.5	29.6	322.7
	30	0.0955	X-4	1.7238	0.357	114.3	5490	5567	158.9	144.1	44.6	29.7	322.7
	40	0.0955	X-4	1.7242	0.3571	114.3	5488	5566	158.9	144.1	44.5	29.8	322.6
4536	15	0.0955	X-4	1.6114	0.3277	104.2	5447	5519	142.8	131.2	38.6	27	319.9
	20	0.0955	X-4	1.6125	0.3277	104.2	5448	5522	142.9	131.3	38.7	27.1	320.1
	30	0.0955	X-4	1.6128	0.3278	104.1	5444	5520	142.9	131.3	38.7	27.1	320.0
	40	0.0955	X-4	1.6124	0.3277	103.9	5434	5509	142.9	131.2	38.9	27.2	319.3

Figure 3-1 Workhorse Engine

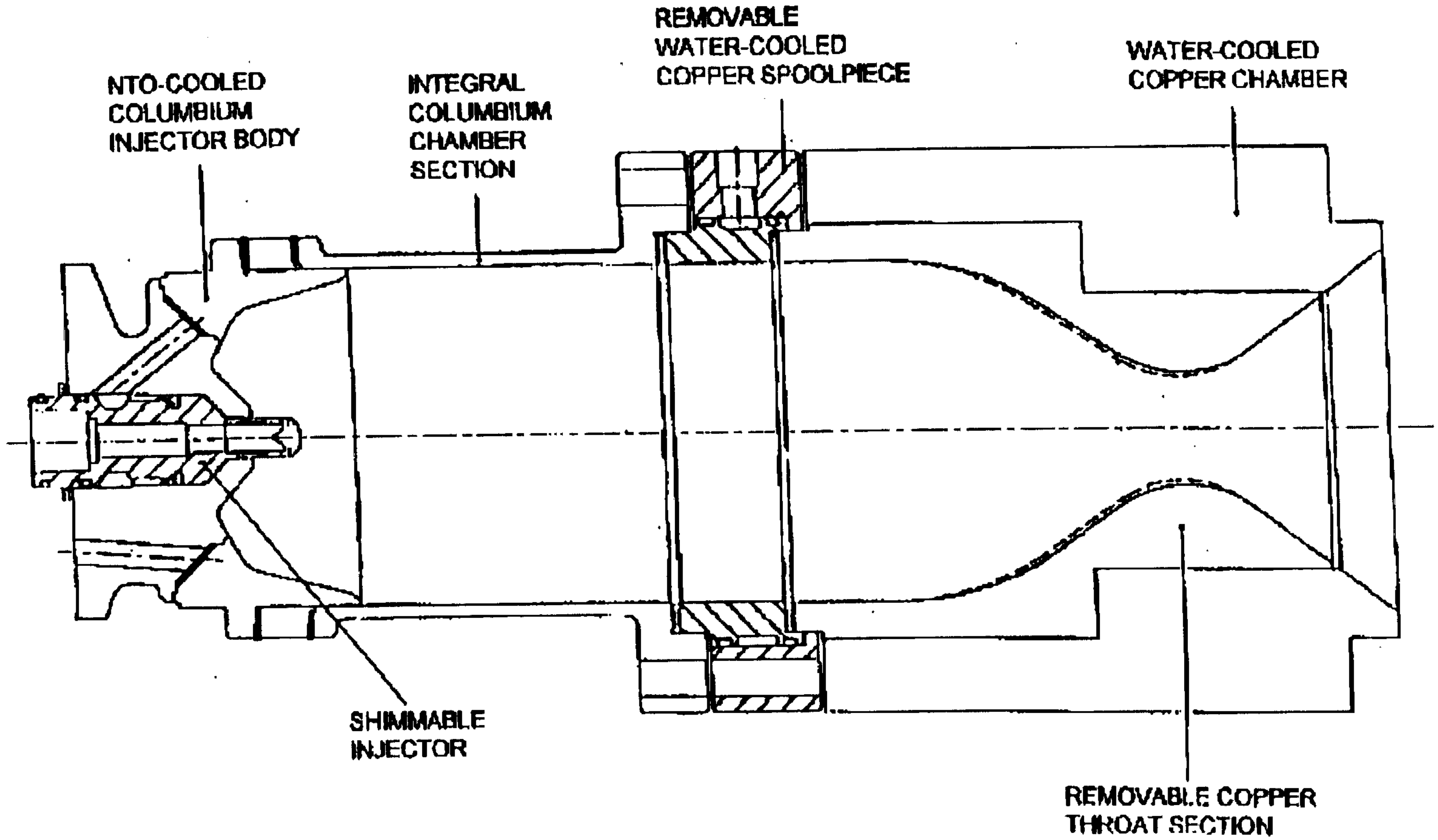
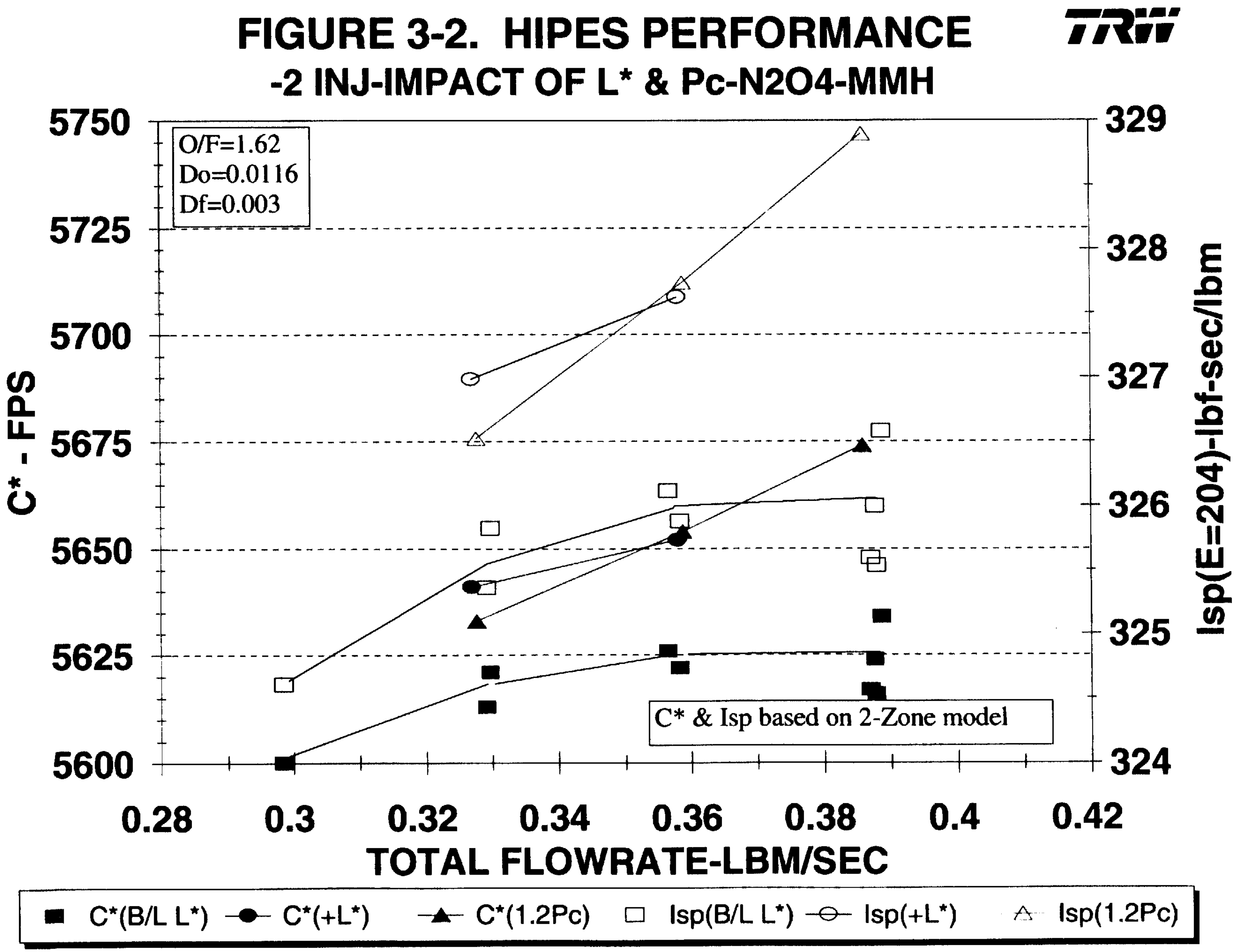


FIGURE 3-2. HIPES PERFORMANCE
-2 INJ-IMPACT OF L* & Pc-N2O4-MMH



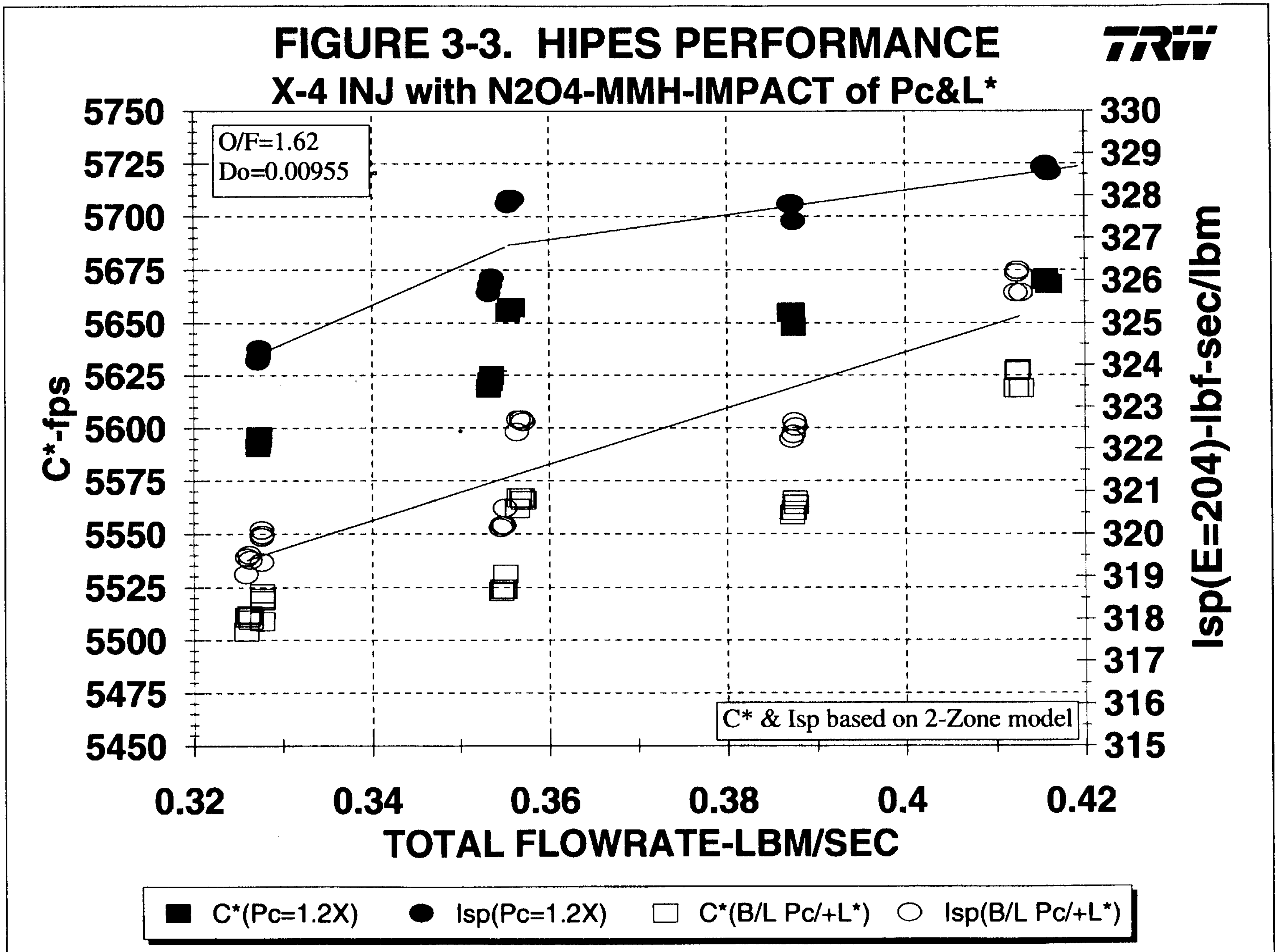


FIGURE 3-3. HIPES PERFORMANCE
X-4 INJ with N2O4-MMH-IMPACT of Pc&L*
TRW
O/F=1.62
Do=0.00955
C* & Isp based on 2-Zone model
C*-fps
5750
5725
5700
5675
5650
5625
5600
5575
5550
5525
5500
5475
5450
Isp(E=204)-lbf-sec/lbm
330
329
328
327
326
325
324
323
322
321
320
319
318
317
316
315
0.32
0.34
0.36
0.38
0.4
0.42
TOTAL FLOWRATE-LBM/SEC
C*(Pc=1.2X)
Isp(Pc=1.2X)
C*(B/L Pc/+L*)
Isp(B/L Pc/+L*)

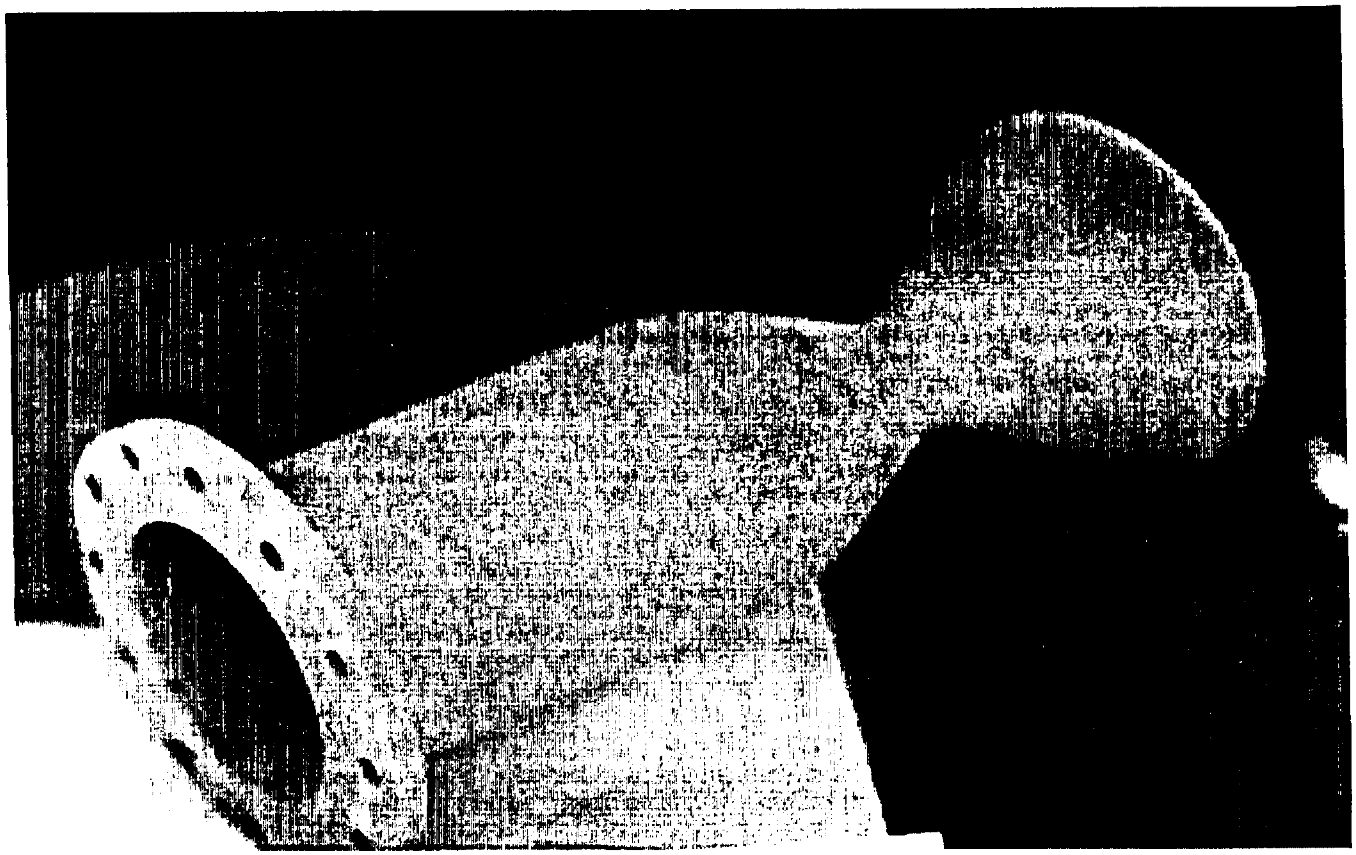


Figure 3-4 Powder Metallurgy Rhenium Thrust Chamber

TABLE 3-2. HIPES OPTION 1 PM RHENIUM ENGINE TESTS(N2O4-MMH)
SHORT SNOUT

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4958	X-4	5	4.6	1.6246	0.3242	102.7	5501	321.4	159	131.7	2215	0.0096
4959	X-4	20	5	1.6327	0.3271	103.5	5498	321.3	160.7	132.9	2293	0.0096
			10	1.6193	0.3255	102.8	5511	322.0	159.3	132.2	2871	
			19.5	1.6235	0.3256	102.8	5546	324.1	159.4	132	3325	
4960	X-4	20	5	1.5232	0.3264	102.5	5450	318.5	156.4	133.7	2133	0.0096
			10	1.512	0.3251	101.9	5460	319.0	155.1	133.1	2611	
			19.5	1.5206	0.3262	102.5	5488	320.7	156.2	133.7	2969	

TABLE 3-3. HIPES OPTION 1 PM RHENIUM ENGINE TESTS(N2O4-MMH)
LONG SNOUT

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4961	X-4	20	5	1.5359	0.3277	102.7	5443	318.0	157.9	134	2056	0.0115
			10	1.5237	0.3256	102	5460	319.0	158.3	133.1	2651	
			19.5	1.5272	0.3265	102.4	5477	320.0	157	133.6	2959	
4962	X-4	20	5	1.5701	0.3256	102.2	5448	318.3	157.6	132.3	2135	0.0115
			10	1.5749	0.3262	102.4	5471	319.7	158.2	132.7	2648	
			19.5	1.5706	0.3255	102.3	5488	320.7	157.8	132.4	2952	
4963	X-4	20	5	1.6127	0.3266	102.7	5460	319.0	159.5	132.3	2173	0.0115
			10	1.6115	0.3262	102.5	5480	320.2	159.1	132	2700	
			19.5	1.6205	0.3269	102.9	5503	321.6	159.9	132.4	3064	
4964	X-4	24	5	1.6285	0.3602	114.1	5512	322.1	183.2	149.7	2421	0.0115
			10	1.6235	0.3594	113.7	5529	323.1	182.3	149.3	2992	
			19.5	1.6275	0.3599	113.7	5540	323.7	182.6	149.4	3385	
			23	1.6241	0.3596	113.6	5543	323.9	182.2	149.2	3430	
4965	X-4	120	5	1.6201	0.3278	103.2	5470	319.6	160.7	133	2275	0.0115
			9	1.6167	0.3274	103	5484	320.4	160.3	132.8	2693	
			19	1.6152	0.3269	102.8	5502	321.5	160	132.6	3087	
			59	1.62	0.3277	103.1	5506	321.7	160.5	132.8	3190	
			89	1.6268	0.3286	103.4	5512	322.1	161.3	133.3	3225	
			117	1.6227	0.3282	103.3	5513	322.1	160.9	133.1	3273	

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4966	X-4	120	5	1.6002	0.3266	102.7	5467	319.4	159.4	132.6	2262	0.0115
			9	1.5939	0.3258	102.4	5479	320.2	158.6	132.3	2662	
			19	1.5967	0.326	102.6	5503	321.6	158.9	132.4	3056	
			59	1.6041	0.3269	102.8	5502	321.5	159.5	132.7	3130	
			89	1.5882	0.3278	103.1	5502	321.5	159.8	133.4	3143	
			117	1.5885	0.3281	103.2	5504	321.6	160.1	133.6	3175	
4967	X-4	120	5	1.5861	0.3598	113.9	5510	322.0	181.6	150.4	2503	0.0115
			9	1.5864	0.3595	113.7	5529	323.1	181.3	150.2	2930	
			19	1.5852	0.3596	113.7	5538	323.6	181.3	150.1	3323	
			59	1.5867	0.3601	113.8	5541	323.8	181.8	150.3	3414	
			89	1.5855	0.36	113.8	5544	323.9	181.7	150.3	3451	
			117	1.5958	0.359	113.5	5546	324.1	181.4	149.7	3463	
4968	X-4	600	5	1.5772	0.3219	100.7	5443	318.0	155.3	130.4	2342	0.0115
			10	1.5759	0.3217	100.8	5463	319.2	155.3	130.4	2718	
			20	1.5751	0.3217	100.8	5475	319.9	155.2	130.4	2973	
			30	1.5773	0.322	100.9	5478	320.1	155.4	130.4	3036	
			40	1.5767	0.322	100.9	5478	320.1	155.4	130.5	3049	
			60	1.5777	0.3224	101.1	5483	320.4	155.9	130.7	3053	
			90	1.5801	0.3225	101.1	5484	320.4	156.1	130.7	3057	
			120	1.5902	0.3228	101.7	5495	321.1	157.5	131.4	3101	
			180	1.5767	0.3218	100.9	5485	320.5	155.6	130.4	3051	
			240	1.5756	0.322	101	5488	320.7	155.9	130.7	3043	
			300	1.5647	0.3232	101.3	5483	320.4	156.4	131.5	3048	
			400	1.563	0.3228	101.1	5479	320.2	156.1	131.2	3045	
			500	1.5586	0.3226	101	5476	320.0	155.8	131.2	3063	
			595	1.5611	0.3231	101.1	5477	320.0	156.2	131.4	3087	

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4969	X-4	600	5	1.5732	0.3402	107	5474	319.9	167.5	140.1	2401	0.0115
			10	1.5767	0.3406	107.3	5498	321.3	168	140.3	2783	
			20	1.5772	0.3407	107.3	5508	321.8	168.1	140.4	3041	
			30	1.5839	0.3407	107.3	5511	322.0	168.3	140.2	3111	
			40	1.5942	0.3401	107.1	5511	322.0	168.1	139.7	3168	
			60	1.5904	0.3399	107	5514	322.2	168.1	139.7	3189	
			90	1.5865	0.3394	106.8	5513	322.1	167.7	139.5	3203	
			120	1.5712	0.3403	107.1	5512	322.1	167.9	140.3	3198	
			180	1.5687	0.3401	107.1	5513	322.1	167.7	140.3	3190	
			240	1.5687	0.3401	107.1	5514	322.2	167.7	140.2	3197	
			300	1.5672	0.3402	107	5511	322.0	167.6	140.3	3204	
			400	1.5821	0.3394	106.8	5513	322.1	167.6	139.6	3252	
			500	1.5873	0.3404	107.2	5519	322.5	168.5	140.1	3328	
			595	1.5838	0.3399	107	5520	322.5	168.1	140	3325	
4970	X-4	600	5	1.5978	0.3239	101.7	5463	319.2	157.4	131.1	2401	0.0115
			10	1.5954	0.3236	101.6	5482	320.3	157	131	2790	
			20	1.5961	0.3237	101.7	5495	321.1	157.2	131	3051	
			30	1.5984	0.324	101.8	5496	321.1	157.4	131.1	3089	
			40	1.6031	0.3245	102	5501	321.4	157.9	131.3	3137	
			60	1.6037	0.3247	102.1	5507	321.8	158.3	131.5	3147	
			90	1.6048	0.3248	102.2	5506	321.7	158.5	131.6	3158	
			120	1.5968	0.3239	101.8	5504	321.6	157.8	131.3	3161	
			180	1.5993	0.3243	102	5507	321.8	158.1	131.5	3183	
			240	1.5991	0.3243	102	5508	321.8	158.2	131.5	3207	
			300	1.5973	0.3241	102	5512	322.1	158	131.5	3217	
			400	1.5977	0.3242	102	5511	322.0	158.2	131.6	3230	
			500	1.5967	0.3242	101.9	5508	321.8	158.1	131.5	3247	
			595	1.5972	0.3242	101.9	5506	321.7	158.2	131.6	3244	

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4971	X-4	600	5	1.5632	0.35	110.4	5492	320.9	173.9	145.4	1587	0.0115
			10	1.5666	0.3503	110.6	5514	322.2	174.2	145.5	2496	
			20	1.5643	0.35	110.4	5519	322.5	174	145.3	3118	
			30	1.5634	0.3501	110.4	5522	322.7	173.9	145.3	3162	
			40	1.5642	0.3503	110.5	5521	322.6	174.1	145.5	3175	
			60	1.5675	0.3508	110.6	5523	322.7	174.8	145.6	3209	
			90	1.5641	0.3504	110.5	5526	322.9	174.5	145.6	3220	
			120	1.5767	0.3497	110.3	5528	323.0	174.5	145.1	3265	
			180	1.5735	0.3494	110.3	5531	323.2	174.2	144.9	3275	
			240	1.574	0.3494	110.3	5530	323.1	174.2	144.9	3288	
			300	1.5699	0.3491	110.1	5529	323.1	173.9	144.8	3285	
			400	1.5692	0.3492	110.1	5525	322.8	173.9	144.9	3282	
			500	1.5699	0.3494	110.1	5523	322.7	174	145	3292	
			595	1.5706	0.3495	110.1	5521	322.6	174.1	145.1	3296	
4972	X-4	600	5	1.5926	0.3386	106.5	5476	320.0	167.1	138.6	2538	0.0115
			10	1.5944	0.339	106.7	5497	321.2	167.5	138.8	2928	
			20	1.5942	0.339	106.6	5508	321.8	167.4	138.7	3205	
			30	1.5961	0.3392	106.6	5505	321.7	167.5	138.7	3270	
			40	1.5962	0.3391	106.5	5505	321.7	167.4	138.7	3274	
			60	1.5982	0.3393	106.7	5511	322.0	168.1	139	3289	
			90	1.5878	0.3405	107.1	5513	322.1	168.6	139.8	3283	
			120	1.5852	0.3402	107.1	5515	322.3	168.4	139.8	3301	
			180	1.5851	0.3399	106.9	5511	322.0	168.1	139.5	3305	
			240	1.5882	0.3399	107	5516	322.3	168.3	139.5	3327	
			300	1.5974	0.3388	106.6	5517	322.4	167.9	138.8	3359	
			400	1.5848	0.3397	106.8	5511	322.0	168	139.5	3340	
			500	1.5912	0.3409	107.2	5516	322.3	169.2	140	3375	
			595	1.5912	0.3411	107.3	5516	322.3	169.4	140.1	3380	

TEST NO A4-XXXX	INJ	DUR SEC	DATA SEC	O/F	Wt LBM/SEC	Pc PSIA	C* FPS	Isp-SEC E=204	PIO PSIA	PIF PSIA	Tt(max) F	Do IN
4973	X-4	600	5	1.6223	0.3385	106.7	5490	320.8	168.1	138.2	2578	0.0115
			10	1.6215	0.3387	106.8	5509	321.9	168.3	138.3	2969	
			20	1.6208	0.3387	106.6	5521	322.6	168	138.1	3258	
			30	1.6915	0.3388	106.6	5514	322.2	168.1	138.2	3307	
			40	1.6216	0.3389	106.6	5515	322.3	168.2	138.2	3314	
			60	1.6273	0.3396	107	5525	322.8	169.2	138.7	3345	
			90	1.6288	0.3401	107.2	5528	323.0	169.6	138.9	3370	
			120	1.6339	0.3407	107.4	5529	323.1	170.2	139.2	3396	
			180	1.625	0.3396	107	5525	322.8	169.1	138.7	3362	
			240	1.6178	0.3387	106.7	5525	322.8	168.4	138.5	3352	
			300	1.6161	0.3388	106.8	5526	322.9	168.5	138.6	3357	
			400	1.613	0.3384	106.6	5523	322.7	168	138.4	3331	
			500	1.6139	0.3386	106.5	5517	322.4	168.1	138.4	3339	
			595	1.6143	0.3387	106.6	5520	322.5	168.2	138.5	3336	
4974	X-4	700	5	1.5852	0.3266	102.5	5465	319.3	158.9	132.4	2425	0.0115
			10	1.5873	0.3267	102.7	5487	320.6	159.2	132.5	2784	
			20	1.5891	0.327	102.8	5498	321.3	159.3	132.6	3041	
			30	1.589	0.3271	102.8	5498	321.3	159.3	132.6	3111	
			40	1.5893	0.327	102.7	5498	321.3	159.3	132.6	3128	
			60	1.5881	0.3272	102.8	5500	321.4	159.7	132.7	3131	
			90	1.5891	0.3272	102.9	5506	321.7	159.9	132.9	3153	
			120	1.5888	0.3272	102.9	5507	321.8	159.9	132.9	3168	
			180	1.5901	0.3273	102.9	5508	321.8	160.1	133	3194	
			240	1.5896	0.3278	103.1	5510	322.0	160.4	133.3	3214	
			300	1.5882	0.3276	103.1	5511	322.0	160.3	133.2	3220	
			400	1.5817	0.3267	102.7	5504	321.6	159.4	132.4	3173	
			500	1.5927	0.3273	102.9	5506	321.7	160.2	133.1	3209	
			595	1.5904	0.3274	102.9	5504	321.6	160.2	133.1	3216	
			695	1.589	0.3275	102.9	5505	321.7	160.2	133.2	3214	

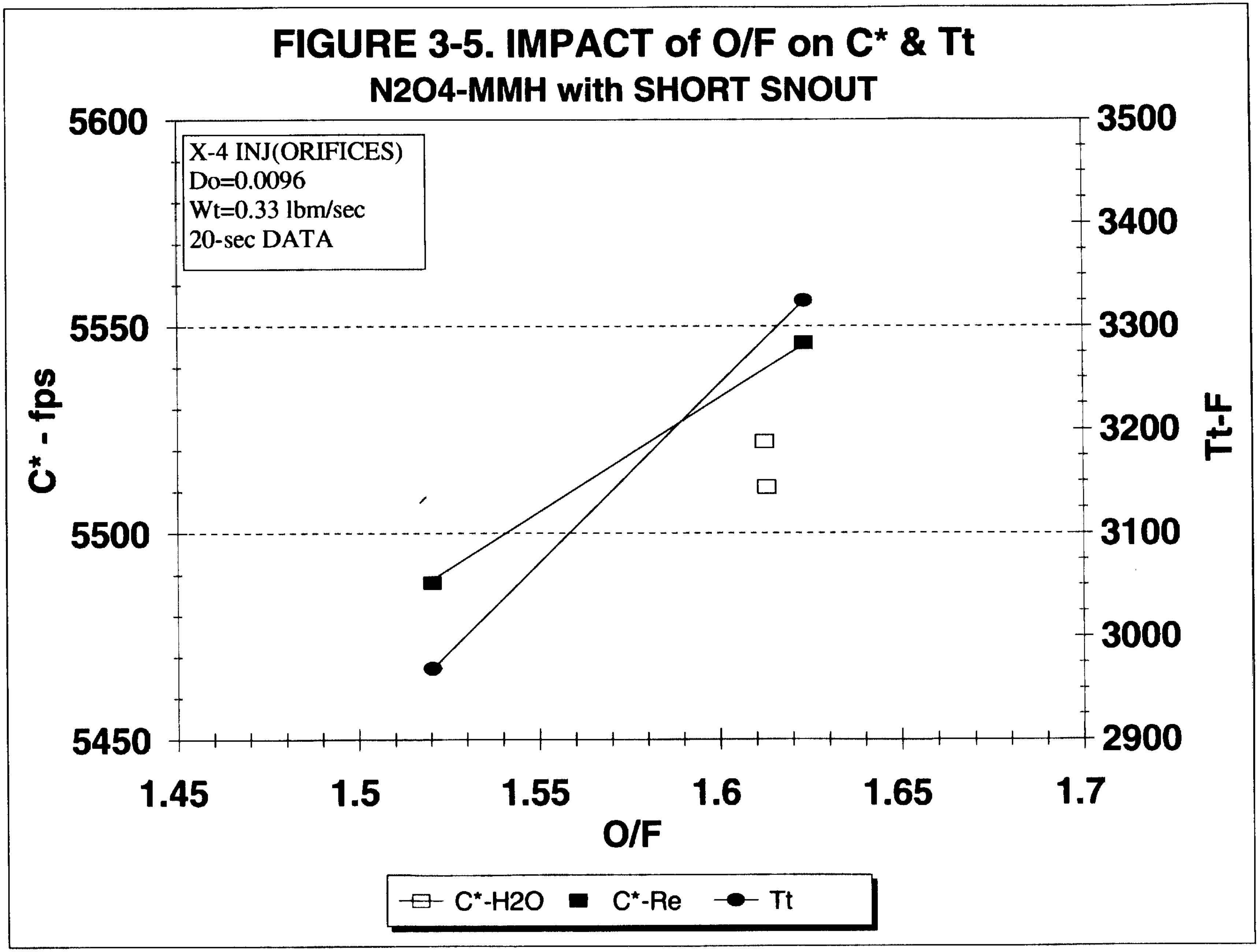


FIGURE 3-5. IMPACT of O/F on C* & Tt
N2O4-MMH with SHORT SNOUT
X-4 INJ(ORIFICES)
Do=0.0096
Wt=0.33 lbm/sec
20-sec DATA
C* - fps
5600
5550
5500
5450
Tt-F
3500
3400
3300
3200
3100
3000
2900
1.45
1.5
1.55
1.6
1.65
1.7
O/F
C*-H2O
C*-Re
Tt

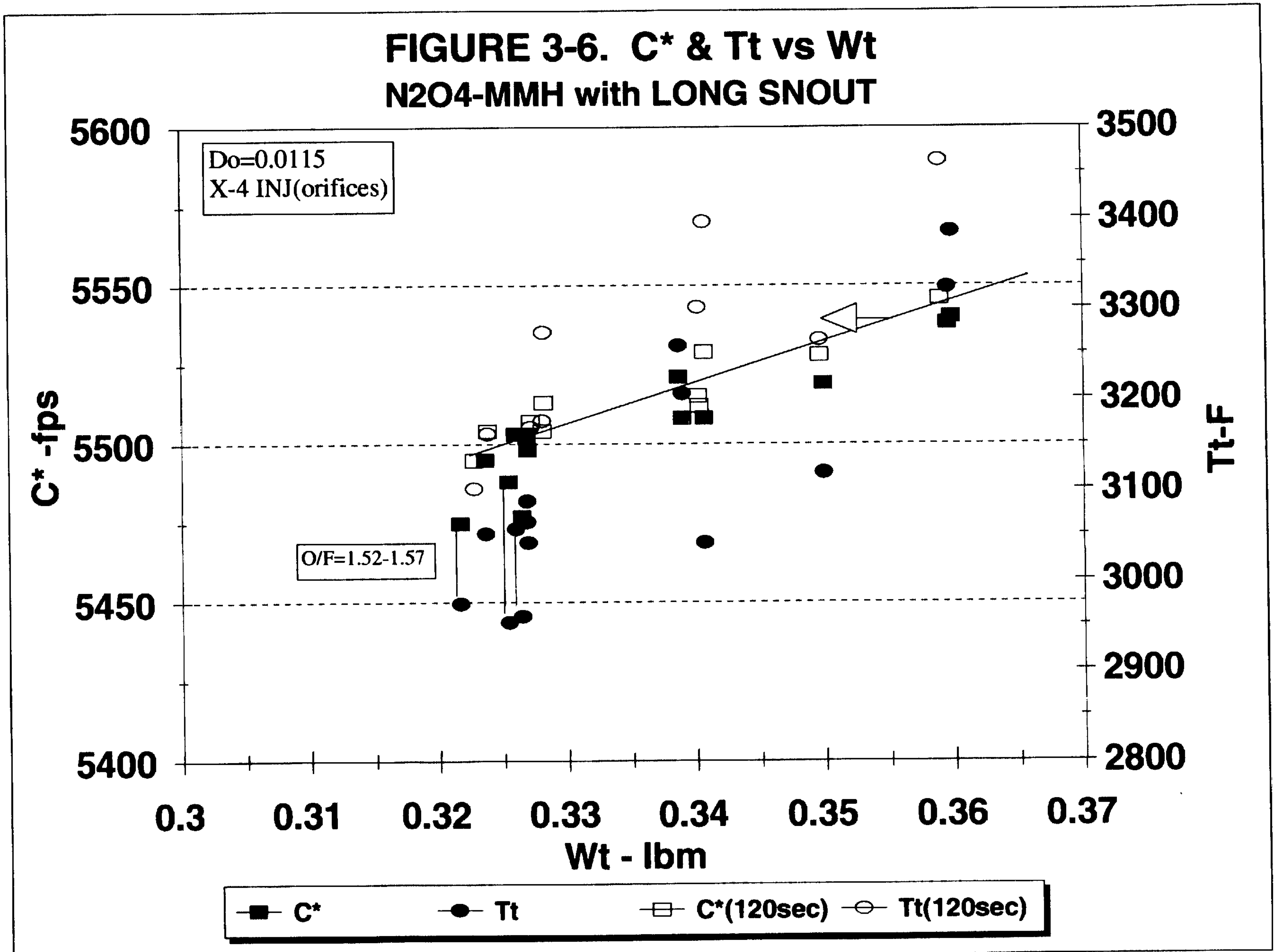


FIGURE 3-6. C* & Tt vs Wt
N2O4-MMH with LONG SNOUT
Do=0.0115
X-4 INJ(orifices)
O/F=1.52-1.57
C* -fps
5600
5550
5500
5450
5400
Tt-F
3500
3400
3300
3200
3100
3000
2900
2800
0.3
0.31
0.32
0.33
0.34
0.35
0.36
0.37
Wt - lbm
C*
Tt
C*(120sec)
Tt(120sec)

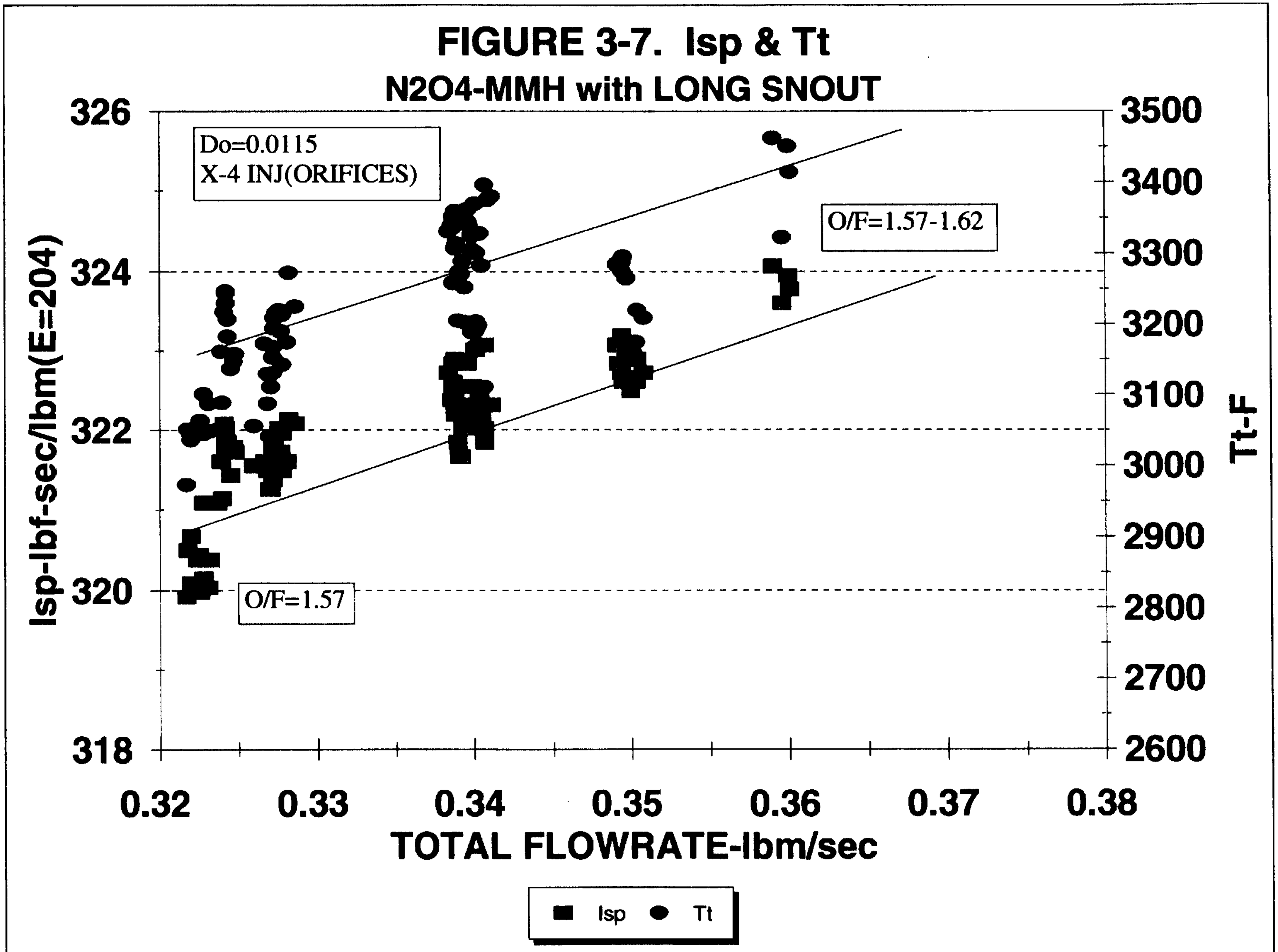


FIGURE 3-7. Isp & Tt
N2O4-MMH with LONG SNOUT
Do=0.0115
X-4 INJ(ORIFICES)
O/F=1.57-1.62
O/F=1.57
Isp-lbf-sec/lbm(E=204)
326
324
322
320
318
Tt-F
3500
3400
3300
3200
3100
3000
2900
2800
2700
2600
0.32
0.33
0.34
0.35
0.36
0.37
0.38
TOTAL FLOWRATE-lbm/sec
Isp
Tt

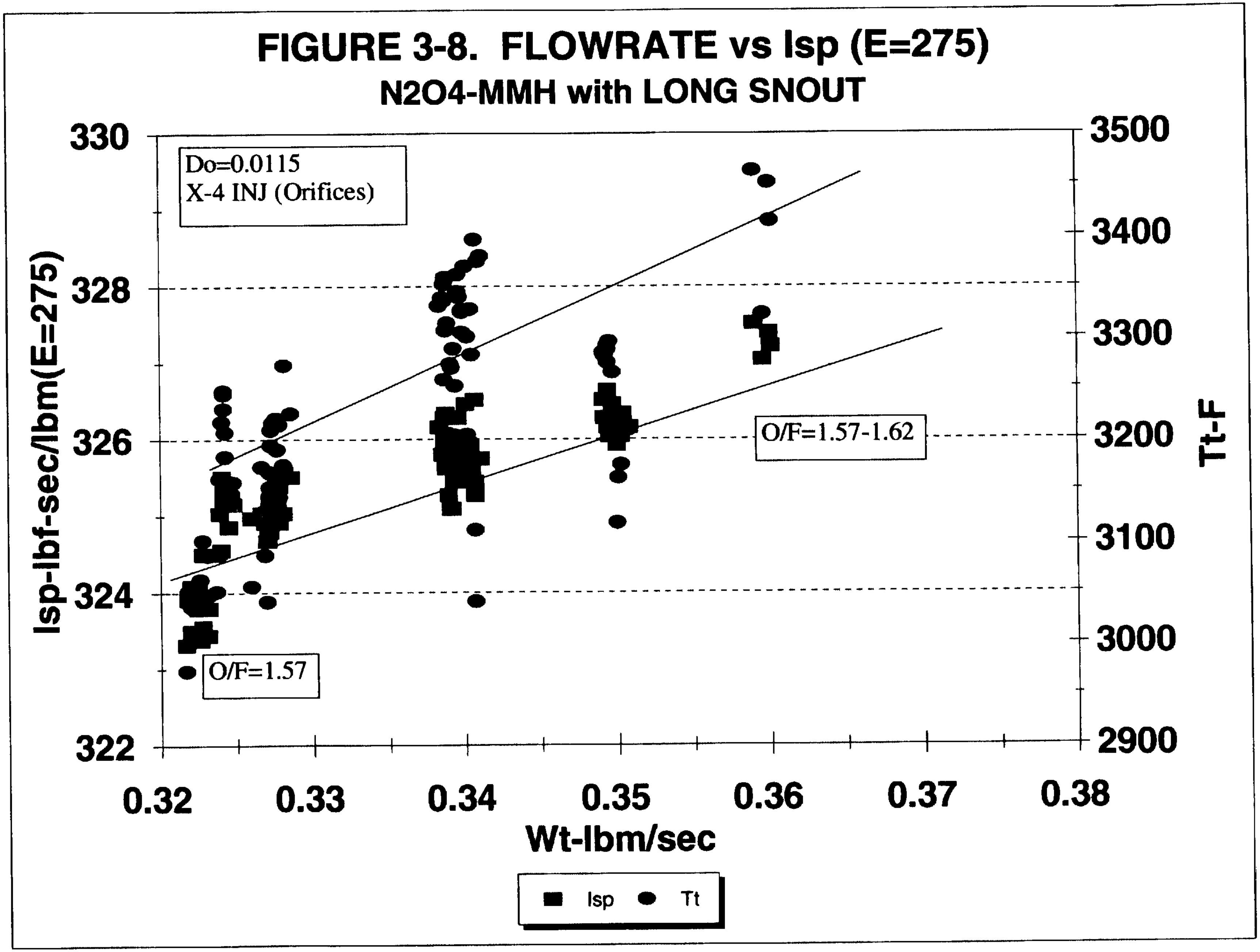


FIGURE 3-8. FLOWRATE vs Isp (E=275)
N2O4-MMH with LONG SNOUT
Do=0.0115
X-4 INJ (Orifices)
O/F=1.57
O/F=1.57-1.62
Isp-lbf-sec/lbm(E=275)
330
328
326
324
322
3500
3400
3300
3200
3100
3000
2900
Tt-F
0.32
0.33
0.34
0.35
0.36
0.37
0.38
Wt-lbm/sec
Isp
Tt

4.0 OPTION 2 RESULTS

4.1. Engineering Model Engine Development

4.1.1. Design

The HIPES Option 2 Program was redirected to develop a N_2O_4-MMH engineering model engine using the high performance injector and the technologies developed on both the SSRT and HIPES programs. The intent of this engineering model engine was to demonstrate an advanced engine as a technology demonstrator. The engine objectives were :

- Incorporate a high performance N_2O_4-MMH injector
- Utilize the low cost discrete element pintle injector approach
- Utilize engine pressure drops compatible with spacecraft propulsion systems
- Incorporate coated powder metallurgy rhenium thrust chamber into engine concept
- Utilize inertia welded joints for attachment of injector and nozzle to powder metallurgy rhenium thrust chamber
- Utilize a partial nozzle to demonstrate joint/durability
- Evaluate the engineering model engine by hot fire testing for 3000 seconds to demonstrate the viability of the concept as a precursor to DVT/Qual

The philosophy used for this engine design was based on the following:

- The engineering model engine was to serve as a technology demonstrator using N_2O_4-MMH
- The engine design was to serve as a precursor to the flight-type engine
- The engine inlet pressures were designed for compatibility with commercial spacecraft with maximum inlet pressures of 240 psia and chamber pressure of 150 psia
- The engine was designed for compatibility with simultaneous valve open/close characteristics
- The engine was designed for commercial spacecraft vibration
- The engine was designed for reduced cost producibility

4.1.1.1 Thrust Chamber

Powder metallurgy rhenium was selected as the material of construction for the thrust chamber due to its excellent structural characteristics (i.e. low cycle fatigue and isotropic metallurgy – see NASA/CR-1998-206605), producibility and reduced cost compared to CVD rhenium. The coatings used on the powder metallurgy rhenium chamber included electrodeposited iridium internally and externally with rhodium internally in the chamber and plasma sprayed hafnium oxide externally for high emissivity. This was based on the excellent results obtained on full scale ring evaluation indicating viability and subsequent hot fire tests at NASA-LeRC on 5 lbf thrust GO_2-GH_2 engine accumulating >41,000 seconds of firing operation at wall temperatures of 3200-3460F with essentially no degradation as determined by SEM analysis post test. In addition, the bolt-on SSRT powder metallurgy rhenium chamber was successfully fired for >10,000 seconds and was in excellent condition post fire test. The powder metallurgy rhenium thrust chamber for the engineering model engine utilized the HIPES Option 1 rhenium chamber reworked as follows:

- The throat was reworked to incorporate the smaller throat to achieve high performance by operation at 120% nominal Pc

- The injector end flange was removed to utilize inertia welded ring for attachment
- The nozzle end was modified to utilize inertia welded ring for attachment of the partial nozzle

The inertia welded ring was selected for joining based on full scale rings evaluated indicating viability. Temperature cycling and high strength (20.5 ksi) post cycling was obtained. Inertia welding was the lowest cost method of attachment and inspectable using NDT for production.

4.1.1.2 Injector

The high performance low cost discrete element orifice type pintle injector used during Option 1 was the selected design. This injector used orifices instead of slots and eliminated parts and assembly operations thereby reducing cost. The orifice configuration was the same as Option 1. During TRW IR&D deposits formed on the sleeve from N_2O_4 reactions which caused hot areas. The corrective action was to protect the sleeve from these reactions by using an extended snout which basically reduced the skip distance of the oxidizer. This same corrective action was implemented into the engineering model engine. The sleeve utilized titanium to eliminate a braze joint and allow an electron beam weld of the titanium sleeve to the injector body (C103). This resulted in a lower cost more producible injector. The injector was designed for reduced pressure drop at higher oxidizer flowrates and to allow more thermal margin for the regenerative cooling loop by operation at higher chamber pressure. A design review was held internally and then with NASA-LeRC and then approval was given by NASA-LeRC to fabricate the engineering model engine.

4.1.2. Fabrication

The engineering model engine was fabricated to the design of 4.1.1. Certain problems occurred during fabrication which impacted the final configuration. The injector-chamber inertia welded ring was the major problem. First the columbium section of the inertia welded ring became contaminated during the coating process. Secondly a test to assess ductility after subjection to thermal conditioning and thermal cycling indicated brittleness. Consequently, a decision was made to evaluate the engineering model engine by using a bolt-on configuration with a flange at the injector headend to prevent failure during the test evaluation. Therefore, the coated flange from the previously fired powder metallurgy rhenium chamber (tested for >10,000 seconds) was removed and electron beam welded to the powder metallurgy rhenium chamber for the engineering model engine. The nozzle end inertia welded ring attaching the partial nozzle to the rhenium chamber nozzle end was left attached since a failure of this part would not cause a catastrophic failure of the engine. The thrust chamber was coated with hafnium oxide for high emissivity. Figure 4-1 shows the engineering model engine configuration. Photographs of the engineering model engine are presented in Figure 4-2 for the subassemblies and 4-3 for the engine.

4.1.3. Hot Fire Testing

The HIPES engineering model engine was test fired to assess performance and thermal characteristics. The test program was completed in July 1998. A total of 48 tests was conducted accumulating a total of 8085 seconds with all demonstrating stable operation. Seven durability tests were conducted to demonstrate thermal stability which was successfully demonstrated including 1000-seconds and 1200-seconds tests. A summary of the engineering model tests is presented in

Table 4-1. Two series were conducted to evaluate two different oxidizer snout configurations. The smaller oxidizer gap was designed for lower engine total flowrates while the larger oxidizer gap was designed for larger engine total flowrates.

4.1.3.1 Smaller Oxidizer Gap Test Results

The smaller oxidizer gap (0.0105 inch) was tested to assess performance and thermal characteristics. The results are presented in Figures 4-4 through 4-9.

- High performance was demonstrated as presented in Figures 4-4 and 4-5. The results indicated 97.2% C* was achieved at O/F=1.6 and Wt=0.30 lbm/sec. At O/F=1.65 and Wt=0.30 lbm/sec, 97.8% C* was achieved. Increasing the total flowrate (Wt=0.35 lbm/sec), 98.7% C* was achieved at O/F=1.6.
- Throat maximum temperatures are presented in Figure 4-6. The 60-second tests produced the data presented in Figure 4-6. The maximum throat temperature at Wt=0.30 lbm/sec and O/F=1.60 was 3230F. At O/F=1.65 and Wt=0.30, the maximum throat temperature increased to 3350F. Increasing the total flowrate (Wt=0.35 lbm/sec), the maximum throat temperature increased to 3530F at O/F=1.60. Durability testing produced the data of 4-6A. The data indicated the impact due to long duration was an increase in throat maximum temperature of ~170F from 60-second tests to the long duration tests (260-900 second tests-one-260 seconds, one-600 seconds and three-900 seconds).
- The oxidizer engine inlet pressures based on tests are presented in Figure 4-7. At maximum total flowrate (Wt=0.35 lbm/sec) and maximum nominal O/F=1.65, the oxidizer inlet pressure required was Pin=209 psia. At lower nominal flowrate (Wt=0.30 lbm/sec), the oxidizer Pin=174 psia at O/F=1.65. In both cases, a trim orifice should be used which would add an additional 10 psia. Therefore, the maximum oxidizer Pin=220 psia at Wt=0.35 lbm/sec at O/F=1.65.
- The fuel engine inlet pressures based on tests are presented in Figure 4-8. At maximum total flowrate (Wt=0.35 lbm/sec) and minimum nominal O/F=1.60, the fuel inlet pressure Pin=172 psia. At lower nominal flowrate (Wt=0.30 lbm/sec), the fuel Pin=145 psia at O/F=1.60. In both cases, a trim orifice should be used which would add an additional 10 psia. Therefore, the maximum fuel Pin=182 psia. Since this inlet pressure is below the oxidizer Pin, the trim orifice would be increased to maintain balanced inlet pressures.
- The projected vacuum specific impulse (Isp) based on measured C* and TRW measured C_f on LAE with N_2O_4-MMH is presented in Figure 4-9. The Isp values for ε=245-350 are projected based on the same % theoretical C_f as that obtained at ε=204. This indicated the engine achieved high performance. For Wt=0.325 lbm/sec and O/F=1.60, the Isp ranged from 323 lbf-sec/lbm (ε=204) to Isp=326.5 lbf-sec/lbm (ε=350). Increasing the O/F=1.65 and Wt=0.325 lbm/sec, the Isp ranged from Isp=326 lbf-sec/lbm (ε=204) to Isp=330 lbf-sec/lbm (ε=350).

4.1.3.2 Larger Oxidizer Gap Test Results

The larger oxidizer gap (0.0125 inch) was tested to assess performance and thermal characteristics. The results are presented in Figures 4-10 through 4-14.

- The larger oxidizer gap was devoted to testing higher flowrates only. Figure 4-10 presents the C* data and indicated the C* is essentially constant over a range of O/F=1.5-1.7 and is high in performance (97.5% theoretical).

- Figure 4-11 presents the maximum throat temperatures for both 60-second tests as well as the increase noted for very long duration tests (1000-1200 seconds). The maximum temperatures were approximately 125F lower than the temperatures obtained with the smaller oxidizer gap at the same conditions. The maximum throat temperature was 3300F for 60-second tests at Wt=0.325 lbm/sec and O/F=1.60. Increasing the total flowrate (Wt=0.35 lbm/sec) at O/F=1.60 resulted in an increase in maximum throat temperatures to 3550F for 60-second tests. At Wt=0.35 lbm/sec and O/F=1.65, the maximum throat temperature was increased to 3660F for 60-second tests. At Wt=0.325 lbm/sec and O/F=1.60, the 1200-second test resulted in a maximum throat temperature of 3457F or 157F increase over the same 60-second test.
- The oxidizer inlet pressures based on tests are presented in Figure 4-12. The data is very similar to the smaller gap data – within 1 psi indicating the engine inlet pressure is 210 psia and 220 psia with trim orifice.
- The fuel inlet pressures based on tests are presented in Figure 4-13. The data is very similar to the smaller gap data – within 3 psi. Therefore, the engine trim orifice would be sufficiently large to balance the oxidizer and fuel inlet pressures (220 psia).
- The projected vacuum specific impulse (Isp) which is presented in Figure 4-14 was based on the same assumptions as the smaller oxidizer gap. Since the C* was essentially constant, the Isp projections were made for a constant C* (97.5% theoretical). At O/F=1.6, the Isp ranged from 322.5 lbf-sec/lbm (ε=204) to 326.2 lbf-sec/lbm (ε=350). Increasing the O/F=1.65, the Isp ranged from 323.7 lbf-sec/lbm (ε=204) to 327.5 lbf-sec/lbm (ε=350).

4.1.4. Post Hot Fire Testing Observations

Upon completion of the test program accumulating 8085 seconds, a number of visual observations were noted which are summarized as follows:

- External Observations
  Hafnium oxide original color was dark gray and the only remaining original color remains for one inch from the chamber inlet.
  Chamber to convergent nozzle appears lighter gray
  Throat region is now white
  Throat region to nozzle exit appears gray – close to original color
  At upstream throat region weld where smaller throat diameter insert was welded, there is a crack in the hafnium oxide that appears ready to flake
  Inertia weld (nozzle end) looks fine
- Internal Observations
  One localized spot in the bottom of chamber (1x3/4 inch spot) appears to have loss of rhodium.
  Iridium appears very rough and globular from end of rhodium coating to the throat
  Throat looks good
  Inertia weld looks fine
- Overall
  Chamber looks okay but not as good as first powder metallurgy thrust chamber (very fine condition post fire after >10,000 seconds)
  Hafnium oxide changes in coloration and emissivity are of somewhat concern

Program was successful accumulating >8000 seconds and mapped performance and thermal characteristics over a range of conditions including six tests of 600-1200 seconds with high performance and stable operation.

5.0 CONCLUSIONS

The HIPES Options 1 and 2 Programs demonstrated the viability of the use of the TRW pintle injector for N_2O_4-MMH LAE's in the 100 lbf thrust class with high performance, excellent thermal stability and stable operation with no damping devices. A low cost version of the pintle injector was developed making the injector more highly producible and cost effective. A powder metallurgy rhenium advanced thrust chamber was developed and demonstrated high performance in two chambers with accumulated firing times of >8000 seconds and >10,000 seconds. The coating system was developed and demonstrated on both thrust chambers. The powder metallurgy rhenium thrust chamber and coating system was patented (No. 5,720,451 dated 2-24-98).

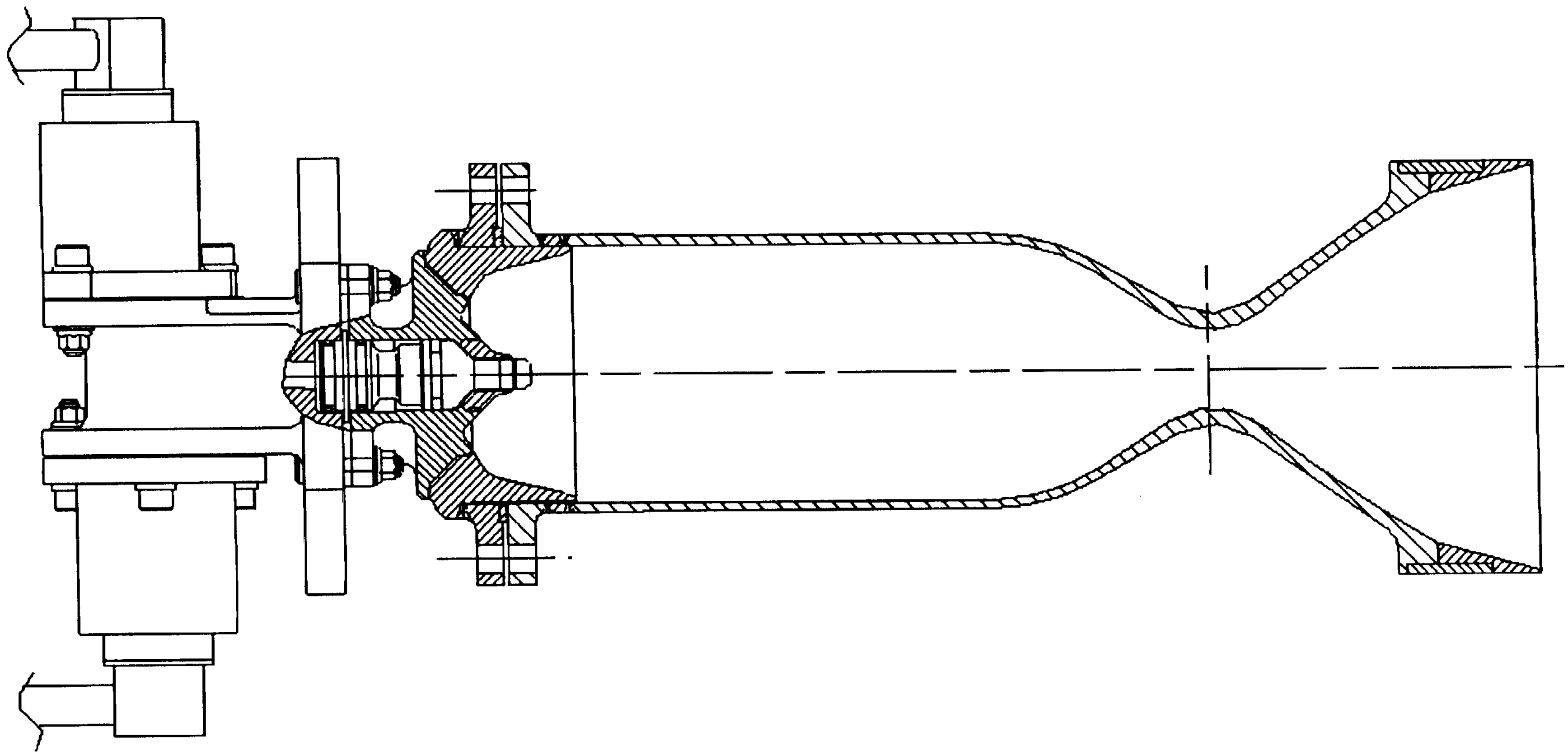


FIGURE 4-1 HIPES ENGINEERING MODEL ENGINE

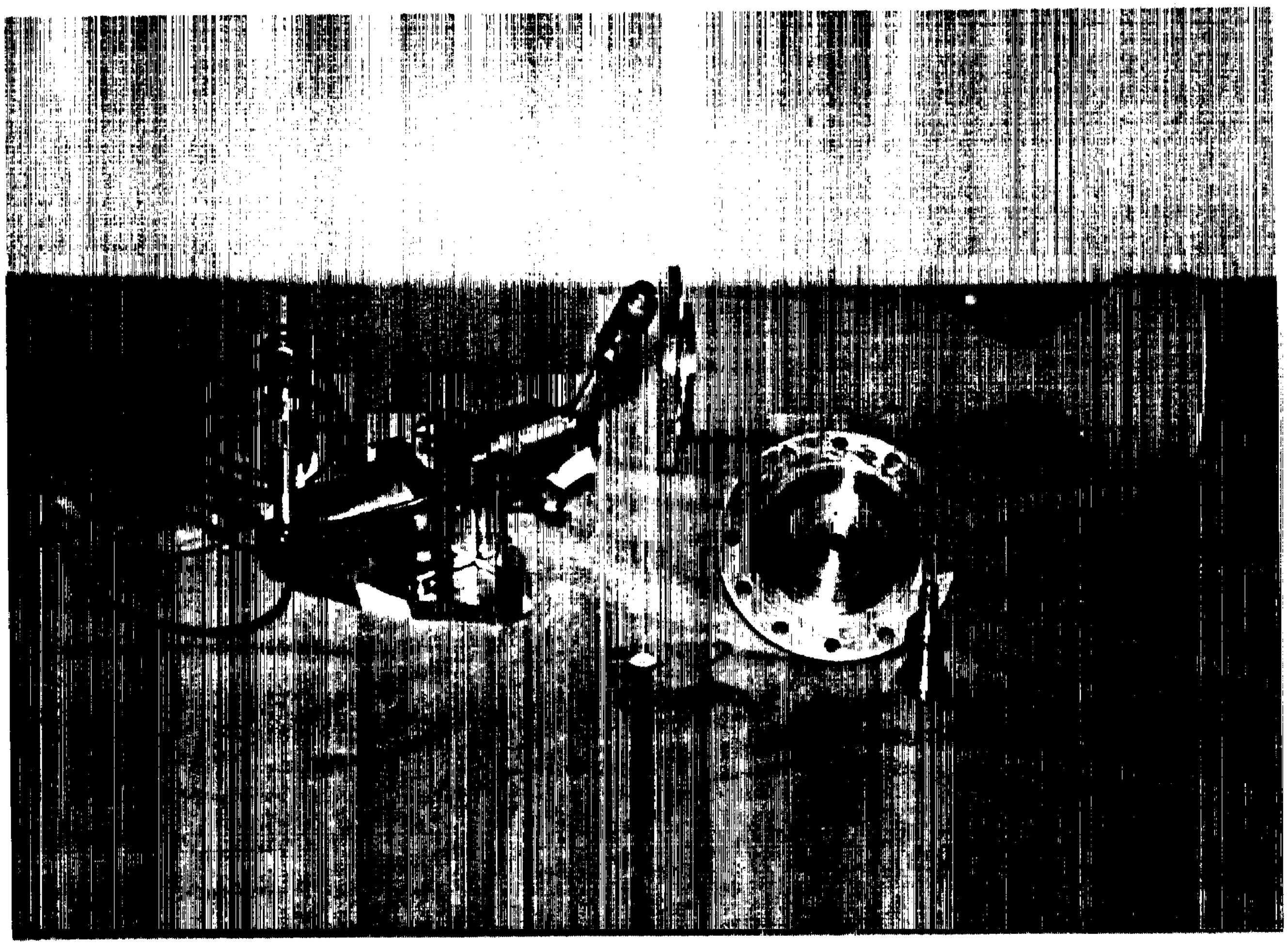


Figure 4-2. HIPES Eng'g Model Engine Subassemblies

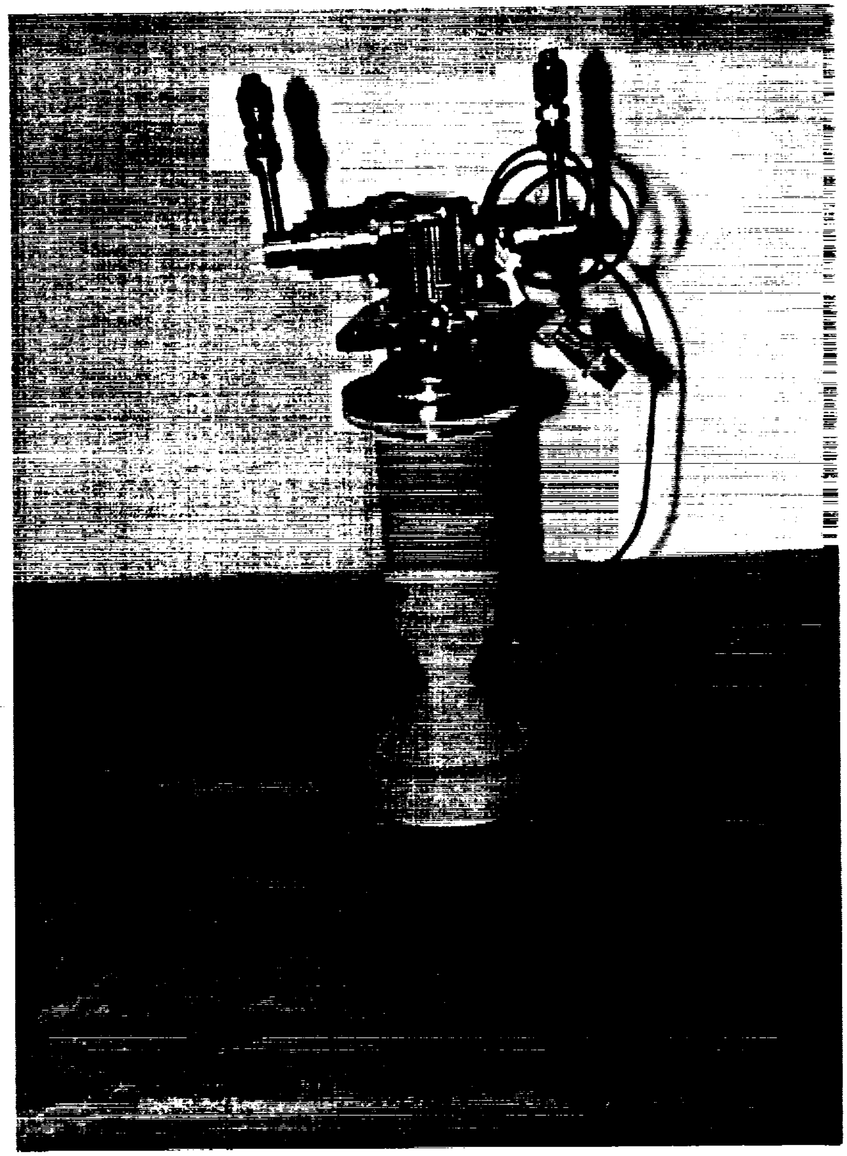


Figure 4-3. HIPES Eng'g Model Engine

TABLE 4-1. HIPES OPTION 2 ENG'G MODEL ENGINE TEST DATA

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
4980	5	4.5	1.554	0.2794	0.17	0.1094	106.8	5473	151.8	133.8	0.0105	2060	143
4981	10	4.5	1.563	0.2784	0.1698	0.1086	106.3	5474	151.6	132.8	0.0105		
		9.5	1.553	0.2772	0.1686	0.1086	106.1	5510	150.9	132.4	0.0105	2649	233
4982	30	9.4	1.561	0.2774	0.1691	0.1083	106.2	5511	151.2	132.1	0.0105		
		29.6	1.562	0.2776	0.1693	0.1084	106.4	5529	151.4	132.4	0.0105	2986	460
4983	60	10	1.555	0.2754	0.1676	0.1078	105.3	5507	149.7	131.2	0.0105		
		30	1.553	0.2756	0.1677	0.1079	105.5	5524	149.9	131.5	0.0105		
		59	1.554	0.2758	0.1678	0.108	105.5	5522	150.1	131.1	0.0105	3000	684
4984	60	10	1.56	0.2995	0.1825	0.117	114.9	5533	167.7	145.8	0.0105		
		30	1.559	0.2995	0.1825	0.1171	114.9	5545	167.6	145	0.0105		
		59	1.56	0.2997	0.1826	0.1171	114.9	5542	167.6	142.2	0.0105	3185	673
4985	60	10	1.56	0.3001	0.1828	0.1173	115.2	5545	167.9	145.2	0.0105		
		30	1.558	0.3002	0.1828	0.1173	115.3	5550	167.9	145.3	0.0105		
		59	1.557	0.3002	0.1828	0.1174	115.3	5549	167.8	148.1	0.0105	3153	639
4986	60	10	1.55	0.3241	0.197	0.1271	124.9	5562	186	160	0.0105		
		30	1.5476	0.3239	0.1968	0.1272	124.8	5574	185.9	160	0.0105		
		59	1.546	0.3239	0.1967	0.1272	124.7	5573	185.7	161.4	0.0105	3331	674
4987	60	10	1.597	0.2759	0.1697	0.1063	105.7	5515	151.2	130.1	0.0105		
		30	1.595	0.2758	0.1695	0.1063	105.7	5532	151.2	130.3	0.0105		
		59	1.595	0.276	0.1696	0.1063	105.6	5526	151.2	132.6	0.0105	3071	712
4988	60	10	1.598	0.2994	0.1842	0.1152	115.2	5549	168.4	144.2	0.0105		
		30	1.597	0.2993	0.184	0.1153	115.3	5569	168.3	144.3	0.0105		
		59	1.597	0.2996	0.1842	0.1154	115.4	5568	168.4	143	0.0105	3225	718
4989	60	10	1.603	0.3251	0.2002	0.1249	125.5	5576	188.3	159.6	0.0105		
		30	1.602	0.3251	0.2001	0.125	125.6	5595	188.4	159.8	0.0105		
		59	1.601	0.3252	0.2002	0.125	125.4	5584	188.3	158.7	0.0105	3429	726
4990	60	10	1.656	0.2759	0.172	0.1039	105.9	5535	152.4	129.7	0.0105		
		30	1.643	0.2747	0.1707	0.1039	105.5	5551	151.4	129.3	0.0105		
		59	1.641	0.2747	0.1707	0.104	105.6	5552	151.4	129.5	0.0105	3157	743
4991	60	10	1.657	0.3006	0.1875	0.1132	115.8	5559	171.1	143.8	0.0105		
		30	1.657	0.3008	0.1876	0.1132	116.0	5582	171.2	144.1	0.0105		
		59	1.653	0.3005	0.1872	0.1133	115.9	5582	170.9	144.4	0.0105	3354	768

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
4992	60	10	1.667	0.3013	0.1884	0.113	116.3	5575	171.4	144.1	0.0105		
		30	1.658	0.3004	0.1874	0.113	115.9	5590	170.5	143.8	0.0105		
		59	1.656	0.30	0.1871	0.113	115.8	5587	170.1	145.4	0.0105	3298	782
4993	60	10	1.657	0.3251	0.2027	0.1223	125.6	5589	189.8	158.2	0.0105		
		30	1.654	0.3249	0.2025	0.1224	125.6	5603	189.5	158.2	0.0105		
		59	1.656	0.3252	0.2027	0.1224	125.7	5604	189.9	160.1	0.0105	3531	750
4994	60	10	1.7001	0.2747	0.173	0.1018	105.7	5549	152.6	128.4	0.0105		
		30	1.6998	0.2749	0.1731	0.1018	105.8	5568	152.8	128.5	0.0105		
		59	1.70	0.2749	0.1731	0.1018	105.7	5563	152.7	130.7	0.0105	3264	776
4995	60	10	1.705	0.3009	0.1896	0.1112	116.0	5571	172.3	143.2	0.0105		
		30	1.698	0.3002	0.1889	0.1113	115.9	5595	171.7	143.1	0.0105		
		59	1.697	0.3002	0.1889	0.1113	116.0	5598	171.7	144.2	0.0105	3456	850
4996	60	10	1.601	0.2508	0.1544	0.0964	95.75	5495	133.8	115.8	0.0105		
		30	1.596	0.2506	0.1541	0.0965	95.79	5516	133.7	115.9	0.0105		
		59	1.596	0.2508	0.1542	0.0966	95.96	5522	133.8	118.3	0.0105	2946	726
4997	60	10	1.716	0.2515	0.1589	0.0926	94.7	5435	136.9	116.5	0.0105		
		30	1.712	0.2514	0.1587	0.0927	96.48	5549	136.6	115.3	0.0105		
		59	1.708	0.2513	0.1585	0.0928	96.44	5549	136.4	116.7	0.0105	3194	858
4998	60	10	1.578	0.2528	0.1547	0.0981	96.45	5491	134.8	117.3	0.0105		
		30	1.565	0.2518	0.1537	0.0982	96.14	5506	134.0	116.9	0.0105		
		59	1.565	0.2521	0.1538	0.0983	96.56	5525	134.4	118.6	0.0105	2875	723
4999	60	10	1.559	0.2512	0.153	0.0982	95.93	5494	133.1	116.7	0.0105		
		30	1.538	0.2493	0.1511	0.0983	95.17	5509	131.4	115.9	0.0105		
		59	1.536	0.2493	0.151	0.0983	95.24	5509	131.6	119.2	0.0105	2899	685
5000	60	10	1.559	0.3006	0.1831	0.1175	115.9	5560	168.9	145.5	0.0105		
		30	1.553	0.3002	0.1826	0.1176	115.8	5578	168.7	145.5	0.0105		
		59	1.551	0.3001	0.1825	0.1176	115.9	5583	168.6	147.5	0.0105	3181	726
5001	60	10	1.652	0.3008	0.1874	0.1134	116.2	5580	171.7	144.1	0.0105		
		30	1.651	0.3007	0.1873	0.1135	116.4	5606	171.7	144.4	0.0105		
		59	1.652	0.3011	0.1875	0.1135	116.6	5611	172.2	145	0.0105	3420	800
5002	60	10	1.503	0.3502	0.2103	0.1399	136.1	5620	206.2	177.9	0.0105		
		30	1.502	0.3502	0.2102	0.14	136.2	5635	206.3	178.2	0.0105		
		59	1.503	0.3505	0.2105	0.1401	136.5	5642	206.7	180	0.0105	3468	687

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
5003	60	10	1.553	0.3511	0.2136	0.1375	136.6	5630	208.9	177.1	0.0105		
		30	1.5496	0.3509	0.2133	0.1376	136.6	5644	208.5	177.2	0.0105		
		59	1.5501	0.3511	0.2134	0.1377	136.2	5625	208.5	179.3	0.0105	3570	740
5004	60	10	1.597	0.3494	0.2149	0.1346	135.7	5626	209.0	174.7	0.0105		
		30	1.597	0.3494	0.215	0.1346	135.8	5636	209.1	174.9	0.0105		
		59	1.595	0.3496	0.2149	0.1347	135.5	5624	208.9	176.7	0.0105	3632	784
5005	600	9	1.597	0.2997	0.1843	0.1154	115.6	5570	169.2	144.3	0.0105		
		29	1.597	0.2999	0.1844	0.1155	115.8	5590	169.5	144.5	0.0105		
		59	1.598	0.30	0.1845	0.1155	115.9	5591	169.6	144.7	0.0105		
		89	1.599	0.3003	0.1847	0.1155	116	5593	169.8	144.9	0.0105		
		119	1.60	0.3004	0.1849	0.1156	116.1	5594	170.0	145	0.0105		
		179	1.60	0.3006	0.185	0.1156	116.2	5596	170.1	145.1	0.0105		
		239	1.597	0.3003	0.1847	0.1156	116.2	5600	170	145.1	0.0105		
		299	1.598	0.3004	0.1848	0.1157	116.3	5603	170	145.1	0.0105		
		399	1.596	0.3004	0.1847	0.1157	116.3	5606	170.2	145.2	0.0105		
		499	1.593	0.3001	0.1844	0.1158	116.3	5611	170.1	145.2	0.0105		
		594	1.593	0.3002	0.1844	0.1158	116.4	5615	170.3	145.3	0.0105	3424	909
5006	900	9	1.649	0.3008	0.1872	0.1136	116.3	5591	171.5	144.1	0.0105		
		29	1.638	0.2998	0.1861	0.1136	116	5604	170.5	143.8	0.0105		
		59	1.637	0.2998	0.1861	0.1137	115.9	5601	170.5	143.9	0.0105		
		89	1.638	0.30	0.1863	0.1137	116	5603	170.6	144	0.0105		
		119	1.638	0.30	0.1863	0.1137	116.1	5607	170.8	144.2	0.0105		
		179	1.636	0.2999	0.1861	0.1138	116.1	5606	170.6	144.2	0.0105		
		239	1.635	0.30	0.1862	0.1138	116.1	5607	170.6	144.3	0.0105		
		299	1.633	0.30	0.186	0.1139	116.2	5613	170.8	144.4	0.0105		
		399	1.631	0.2997	0.1858	0.1139	116.2	5618	170.9	144.4	0.0105		
		499	1.687	0.3062	0.1922	0.114	118.8	5629	177.2	147.2	0.0105		
		599	1.68	0.3056	0.1916	0.114	118.6	5630	176.6	147	0.0105	3591	1005
		699	1.678	0.3054	0.1914	0.1141	118.6	5632	176.5	147	0.0105		
		799	1.677	0.3055	0.1914	0.1141	118.7	5635	176.5	147.1	0.0105		
		894	1.677	0.3055	0.1914	0.1141	118.9	5644	176.8	147.3	0.0105	3435	992

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
5007	260	9	1.656	0.2756	0.1718	0.1038	106	5548	152.6	129.1	0.0105		
		29	1.651	0.2752	0.1714	0.1038	106.1	5576	152.6	129.3	0.0105		
		59	1.651	0.2753	0.1715	0.1039	106.3	5585	153.1	129.6	0.0105		
		89	1.649	0.2752	0.1713	0.1039	106.3	5594	153.2	129.8	0.0105		
		119	1.65	0.2753	0.1714	0.1039	106.4	5591	153.1	129.8	0.0105		
		179	1.647	0.2751	0.1712	0.1039	106.0	5576	152.5	129.4	0.0105		
		239	1.645	0.2749	0.171	0.1039	106.3	5593	152.9	129.7	0.0105		
		259	1.646	0.2749	0.171	0.1039	106.2	5590	152.9	129.7	0.0105	3340	928
5008	900	9	1.552	0.3252	0.1977	0.1274	126.0	5601	188.2	160.5	0.0105		
		29	1.55	0.325	0.1975	0.1275	126.1	5620	188.3	160.7	0.0105		
		59	1.549	0.3249	0.1974	0.1275	126.0	5618	188.2	160.8	0.0105		
		89	1.545	0.3246	0.1971	0.1275	125.9	5620	188	160.8	0.0105		
		119	1.546	0.3247	0.1971	0.1275	126.0	5621	188	160.9	0.0105		
		179	1.545	0.3246	0.1971	0.1276	126.4	5641	189	161.4	0.0105		
		239	1.544	0.3246	0.197	0.1276	125.9	5621	187.9	160.9	0.0105		
		299	1.544	0.3246	0.197	0.1276	126.0	5623	188	161	0.0105		
		399	1.543	0.3245	0.1969	0.1276	126.0	5625	188.1	161	0.0105		
		499	1.542	0.3244	0.1968	0.1276	126.0	5628	188.1	161	0.0105		
		599	1.542	0.3244	0.1968	0.1276	126.0	5629	188.2	161	0.0105		
		699	1.542	0.3245	0.1968	0.1277	126.1	5633	188.2	161.1	0.0105		
		799	1.541	0.3244	0.1967	0.1277	126.1	5633	188.2	161.1	0.0105		
		894	1.54	0.3244	0.1967	0.1277	126.2	5638	188.2	161.1	0.0105	3504	861
5009	900	9	1.604	0.326	0.2008	0.1252	126.5	5620	189.9	160.2	0.0105		
		29	1.600	0.3257	0.2004	0.1253	126.4	5631	189.6	160.2	0.0105		
		59	1.598	0.3255	0.2002	0.1253	126.4	5633	189.5	160.3	0.0105		
		89	1.598	0.3257	0.2003	0.1254	126.5	5632	189.5	160.4	0.0105		
		119	1.596	0.3256	0.2002	0.1254	126.5	5634	189.4	160.4	0.0105		
		179	1.595	0.3256	0.2002	0.1255	126.4	5631	189.4	160.4	0.0105		
		239	1.593	0.3255	0.2000	0.1255	126.4	5634	189.3	160.5	0.0105		
		299	1.594	0.3256	0.2000	0.1255	126.4	5632	189.3	160.4	0.0105		
		399	1.592	0.3255	0.1999	0.1256	126.4	5632	189.5	160.5	0.0105		
		499	1.59	0.3255	0.1999	0.1257	126.3	5629	189.6	160.5	0.0105		
		599	1.59	0.3255	0.1998	0.1257	126.4	5633	189.6	160.6	0.0105		
		699	1.589	0.3255	0.1998	0.1257	126.4	5633	189.6	160.6	0.0105		
		799	1.587	0.3255	0.1997	0.1258	126.4	5635	189.6	160.7	0.0105		
		894	1.586	0.3255	0.1997	0.1259	126.5	5638	189.5	160.7	0.0105	3605	1088

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
5010	60	10	1.605	0.3018	0.1859	0.1158	116.1	5566	171.2	145.6	0.0115		
		20	1.604	0.3019	0.1859	0.1159	116.3	5583	171.5	145.9	0.0115		
		58	1.604	0.3021	0.1861	0.116	116.3	5583	171.5	145.5	0.0115	3556	1172
5011	60	10	1.557	0.3016	0.1836	0.1179	116.1	5564	170.0	146.2	0.0115		
		20	1.557	0.3017	0.1838	0.118	116.3	5583	170.3	146.5	0.0115		
		58	1.556	0.3017	0.1837	0.118	116.3	5587	170.4	146.6	0.0115	3463	1177
5012	60	10	1.553	0.3001	0.1825	0.1176	115.3	5545	170.7	145.3	0.0115		
		30	1.548	0.2998	0.1821	0.1176	115.4	5568	170.6	145.5	0.0115		
		58	1.548	0.2999	0.1822	0.1177	115.5	5573	170.8	145.7	0.0115	3347	1127
5013	60	10	1.616	0.3016	0.1863	0.1153	115.9	5554	173.5	144.8	0.0115		
		30	1.611	0.3012	0.1858	0.1153	115.8	5571	173.3	144.9	0.0115		
		58	1.607	0.3008	0.1854	0.1154	115.7	5574	172.9	144.9	0.0115	3479	1297
5014	60	10	1.55	0.3254	0.1978	0.1276	125.2	5562	190.1	160.3	0.0115		
		30	1.548	0.3253	0.1976	0.1277	125.3	5580	190.2	160.7	0.0115		
		58	1.547	0.3253	0.1976	0.1277	125.3	5583	190.2	160.8	0.0115	3469	1145
5015	60	10	1.594	0.3253	0.1999	0.1254	125.3	5575	191.6	159.4	0.0115		
		30	1.594	0.3252	0.1998	0.1254	125.3	5586	191.4	159.5	0.0115		
		58	1.592	0.3251	0.1997	0.1254	125.2	5586	191.2	159.5	0.0115	3529	1214
5016	60	10	1.55	0.2997	0.1822	0.1175	114.7	5516	167.1	143.7	0.0125		
		30	1.549	0.2996	0.1821	0.1176	114.9	5536	167.2	143.9	0.0125		
		58	1.547	0.2994	0.1819	0.1176	114.7	5526	166.8	143.7	0.0125	2990	773
5017	60		1.6	0.325		Lost Data-Computer Problem					0.0125		
5018	60	10	1.603	0.3256	0.2005	0.1251	125	5546	188.6	158	0.0125		
		30	1.6	0.3256	0.2004	0.1252	125	5555	188.5	158.2	0.0125		
		58	1.599	0.3257	0.2004	0.1253	124.9	5551	188.4	158.3	0.0125	3303	933
5019	60	10	1.655	0.3256	0.203	0.1226	125	5549	189.8	156.8	0.0125		
		30	1.655	0.3256	0.2029	0.1226	125	5562	189.9	157.1	0.0125		
		58	1.653	0.3255	0.2028	0.1227	125	5560	189.8	157.1	0.0125	3424	1050
5020	60	10	1.706	0.3259	0.2055	0.1205	125	5551	191.7	155.9	0.0125		
		30	1.7	0.3256	0.205	0.1206	124.8	5556	191.1	155.8	0.0125		
		58	1.698	0.3255	0.2049	0.1207	124.8	5560	191.1	156	0.0125	3561	1055
5021	60	10	1.551	0.3503	0.213	0.1373	134.8	5568	206.8	174.4	0.0125		
		30	1.549	0.3505	0.213	0.1375	134.7	5570	206.6	174.4	0.0125		
		58	1.549	0.3507	0.2131	0.1376	134.7	5565	206.6	174.6	0.0125	3476	819
5022	60	10	1.506	0.351	0.211	0.1401	135.1	5561	205.9	176	0.0125		
		30	1.503	0.3509	0.2107	0.1402	135	5568	205.6	176.1	0.0125		
		58	1.502	0.3509	0.2106	0.1403	134.9	5566	205.4	176.2	0.0125	3372	637

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
5023	60	10	1.605	0.3506	0.216	0.1346	134.8	5563	208.7	172.9	0.0125		
		30	1.602	0.3503	0.2157	0.1346	134.7	5572	208.5	173	0.0125		
		58	1.601	0.3504	0.2157	0.1347	134.7	5570	208.4	173.2	0.0125	3559	937
5024	60	10	1.65	0.3509	0.2185	0.1324	134.8	5565	210.5	172	0.0125		
		30	1.647	0.3507	0.2182	0.1325	134.5	5562	209.9	171.7	0.0125		
		58	1.645	0.3507	0.2181	0.1326	134.5	5563	209.8	171.9	0.0125	3632	990
5025	1200	10	1.603	0.3252	0.2003	0.1249	125	5555	188.5	157.7	0.0125		
		30	1.603	0.3254	0.2004	0.125	125	5561	188.6	157.9	0.0125		
		60	1.604	0.3256	0.2006	0.1251	125	5558	188.8	158.1	0.0125		
		90	1.604	0.3257	0.2006	0.1251	125	5556	188.8	158.2	0.0125		
		120	1.603	0.3257	0.2006	0.1251	125	5555	188.6	158.2	0.0125		
		180	1.603	0.3259	0.2006	0.1252	125.1	5557	188.6	158.3	0.0125		
		240	1.6	0.3255	0.2003	0.1252	125.2	5569	188.5	158.4	0.0125		
		300	1.599	0.3256	0.2003	0.1253	125.3	5571	188.5	158.4	0.0125		
		400	1.597	0.3254	0.2001	0.1253	125.3	5573	188.5	158.4	0.0125		
		500	1.596	0.3253	0.2	0.1253	125.3	5578	188.5	158.5	0.0125		
		600	1.595	0.3253	0.2	0.1254	125.4	5579	188.5	158.5	0.0125		
		700	1.594	0.3253	0.1999	0.1254	125.3	5579	188.3	158.5	0.0125		
		800	1.593	0.3252	0.1998	0.1254	125.4	5583	188.4	158.5	0.0125		
		900	1.591	0.3252	0.1997	0.1255	125.4	5584	188.4	158.6	0.0125		
		100	1.591	0.3252	0.1997	0.1255	125.5	5588	188.4	158.6	0.0125		
		1100	1.589	0.3251	0.1996	0.1256	125.5	5588	188.2	158.6	0.0125		
		1190	1.589	0.3251	0.1995	0.1256	125.6	5597	188.4	158.9	0.0125	3457	1032

Test No A4-XXXX	Dur sec	TimeSlice Sec	O/F	Wt lbm/sec	Wo lbm/sec	Wf lbm/sec	Pc psia	C* fps	PIO psia	PIF psia	Do in.	Tt(max) F	Tch(fl) F
5026	1000	10	1.653	0.3251	0.2026	0.1226	125.3	5578	190.4	157	0.0125		
		30	1.652	0.3253	0.2026	0.1227	125.2	5581	190.3	157	0.0125		
		60	1.653	0.3255	0.2028	0.1227	125.2	5578	190.4	157.2	0.0125		
		90	1.652	0.3255	0.2028	0.1227	125.3	5579	190.4	157.3	0.0125		
		120	1.652	0.3256	0.2028	0.1227	125.4	5583	190.5	157.4	0.0125		
		180	1.652	0.3255	0.2028	0.1228	125.5	5591	190.5	157.5	0.0125		
		240	1.648	0.3251	0.2023	0.1228	125.3	5589	190	157.3	0.0125		
		300	1.648	0.3252	0.2024	0.1228	125.4	5592	190.1	157.4	0.0125		
		400	1.645	0.325	0.2022	0.1229	125.6	5602	190.2	157.6	0.0125		
		500	1.645	0.3249	0.2021	0.1229	125.6	5602	190.1	157.6	0.0125		
		600	1.644	0.3249	0.202	0.1229	125.6	5605	190.1	157.7	0.0125		
		700	1.642	0.3247	0.2018	0.1229	125.5	5601	189.9	157.5	0.0125		
		800	1.642	0.3247	0.2018	0.1229	125.5	5604	189.9	157.5	0.0125		
		900	1.641	0.3247	0.2017	0.1229	125.9	5623	190.3	158	0.0125		
		990	1.64	0.3246	0.2017	0.1229	126	5629	190.4	158.1	0.0125	3562	1009
5027	60	10	1.751	0.326	0.2075	0.1185	126	5603	193.3	156.1			
		30	1.748	0.3257	0.2072	0.1185	126.5	5640	193.6	156.7			
		58	1.746	0.3254	0.2069	0.1185	126.1	5627	192.8	156.3		3680	1094

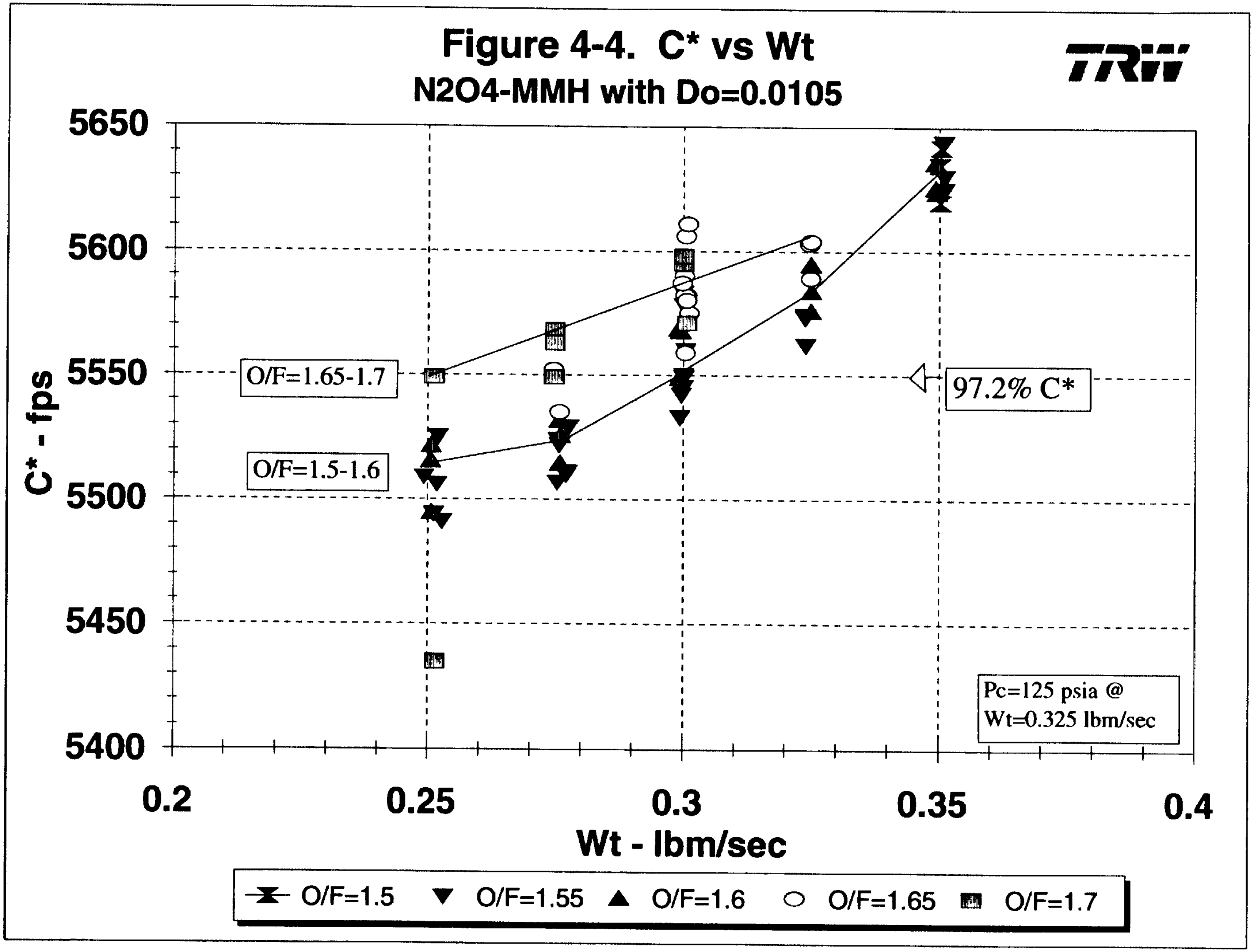


Figure 4-4. C* vs Wt
N2O4-MMH with Do=0.0105
TRW
C* - fps
5650
5600
5550
5500
5450
5400
0.2
0.25
0.3
0.35
0.4
Wt - lbm/sec
O/F=1.65-1.7
O/F=1.5-1.6
97.2% C*
Pc=125 psia @
Wt=0.325 lbm/sec
O/F=1.5
O/F=1.55
O/F=1.6
O/F=1.65
O/F=1.7

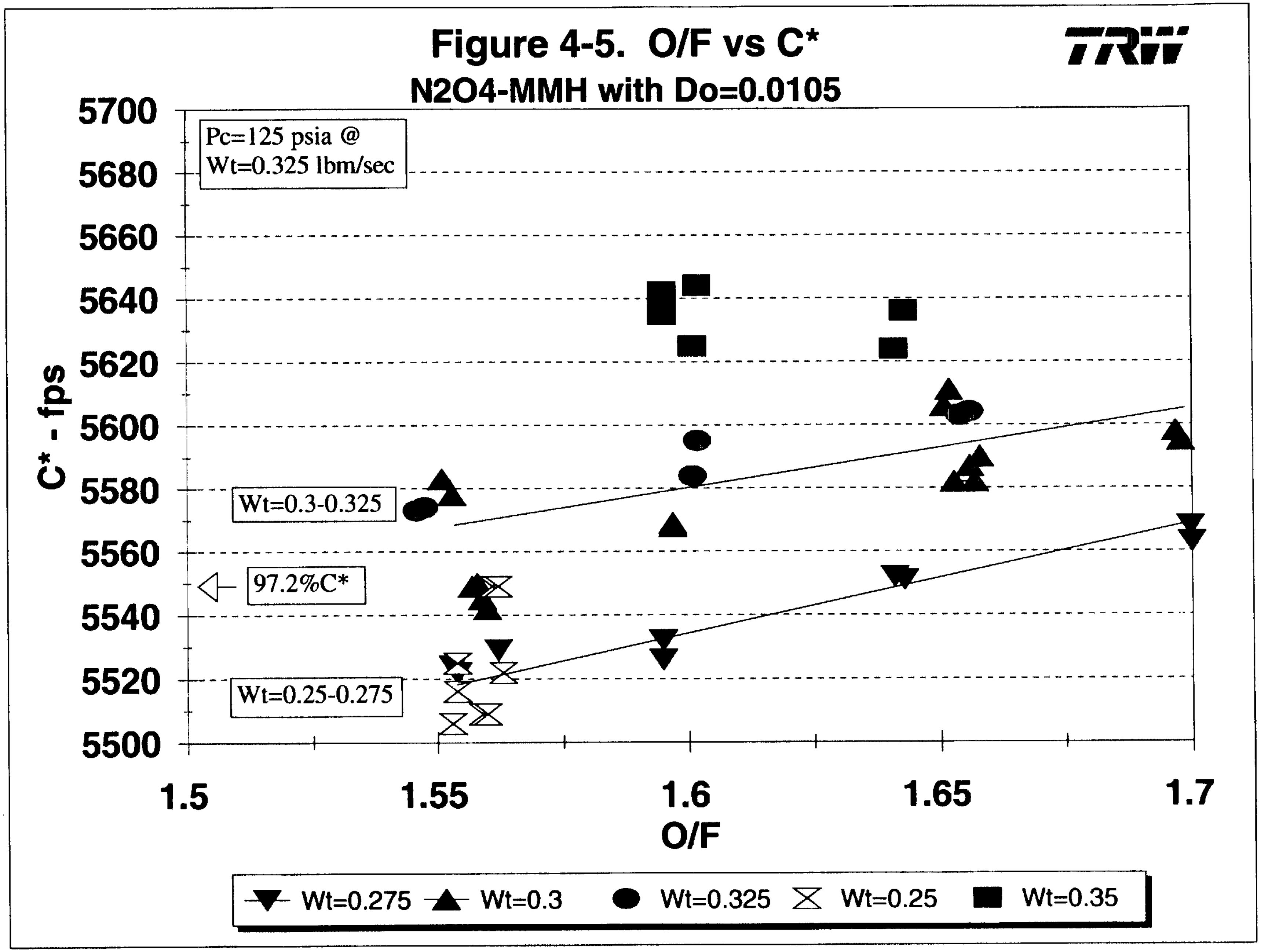


Figure 4-5. O/F vs C*
N2O4-MMH with Do=0.0105
5700
5680
5660
5640
5620
5600
5580
5560
5540
5520
5500
C* - fps
1.5
1.55
1.6
1.65
1.7
O/F
Pc=125 psia @
Wt=0.325 lbm/sec
Wt=0.3-0.325
97.2%C*
Wt=0.25-0.275
Wt=0.275
Wt=0.3
Wt=0.325
Wt=0.25
Wt=0.35

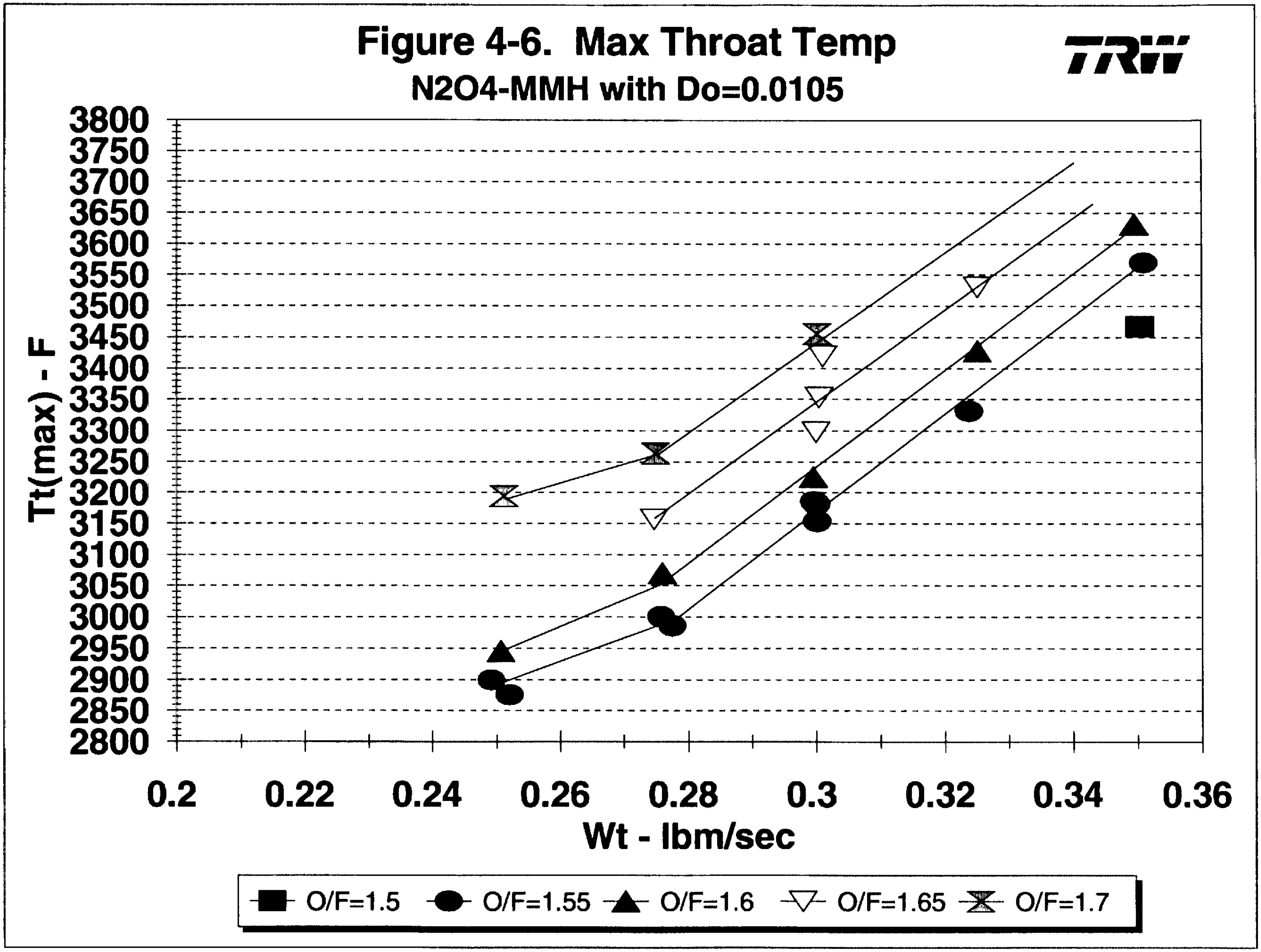


Figure 4-6. Max Throat Temp
N2O4-MMH with Do=0.0105
TRW
Tt(max) - F
3800
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
3200
3150
3100
3050
3000
2950
2900
2850
2800
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
Wt - lbm/sec
O/F=1.5
O/F=1.55
O/F=1.6
O/F=1.65
O/F=1.7

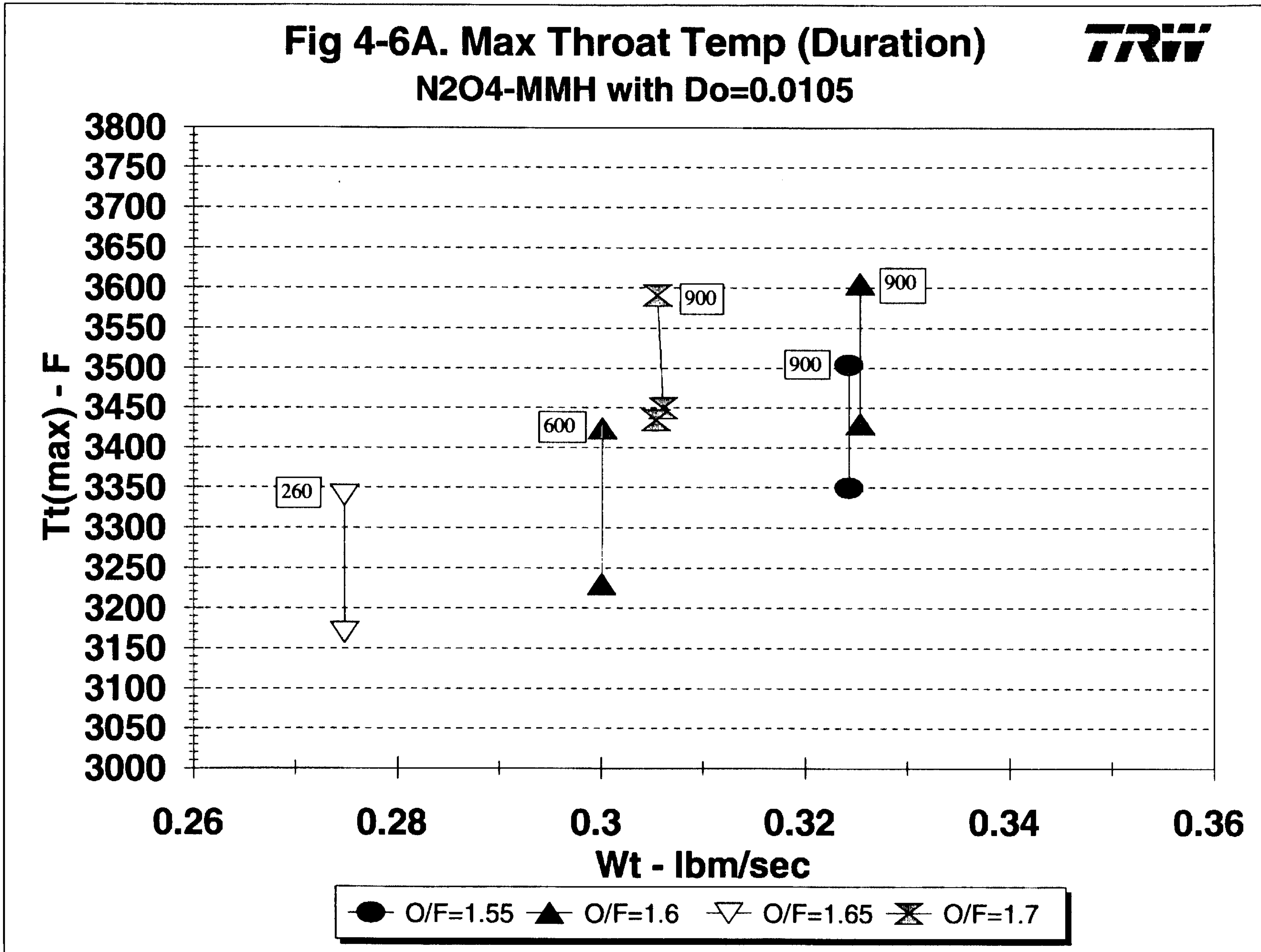


Fig 4-6A. Max Throat Temp (Duration)
N2O4-MMH with Do=0.0105
TRW
Tt(max) - F
3800
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
3200
3150
3100
3050
3000
0.26
0.28
0.3
0.32
0.34
0.36
Wt - lbm/sec
260
600
900
900
900
O/F=1.55
O/F=1.6
O/F=1.65
O/F=1.7

Figure 4-7. Oxidizer Pinlet vs Wox

N2O4-MMH with Do=0.0105

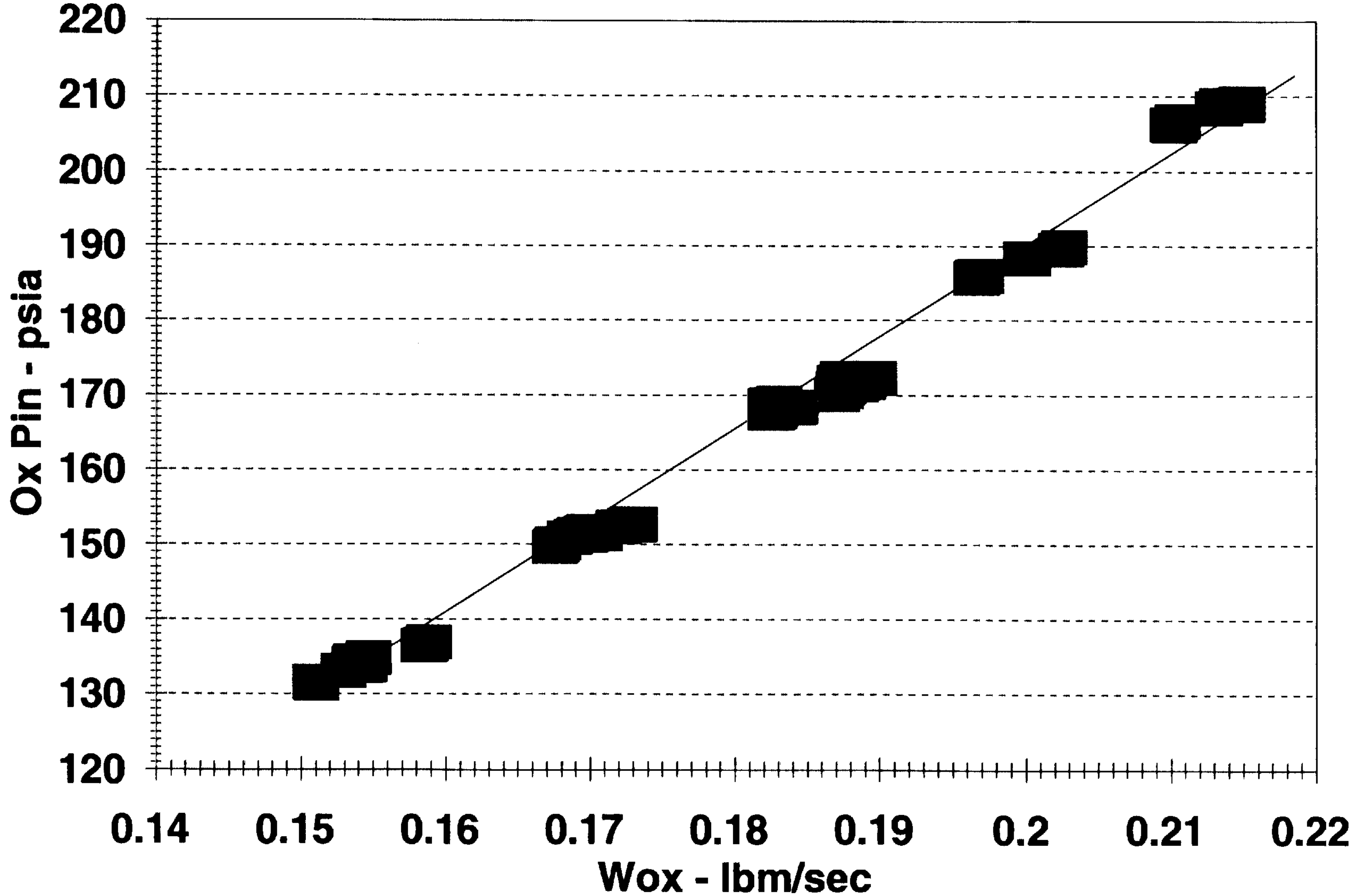
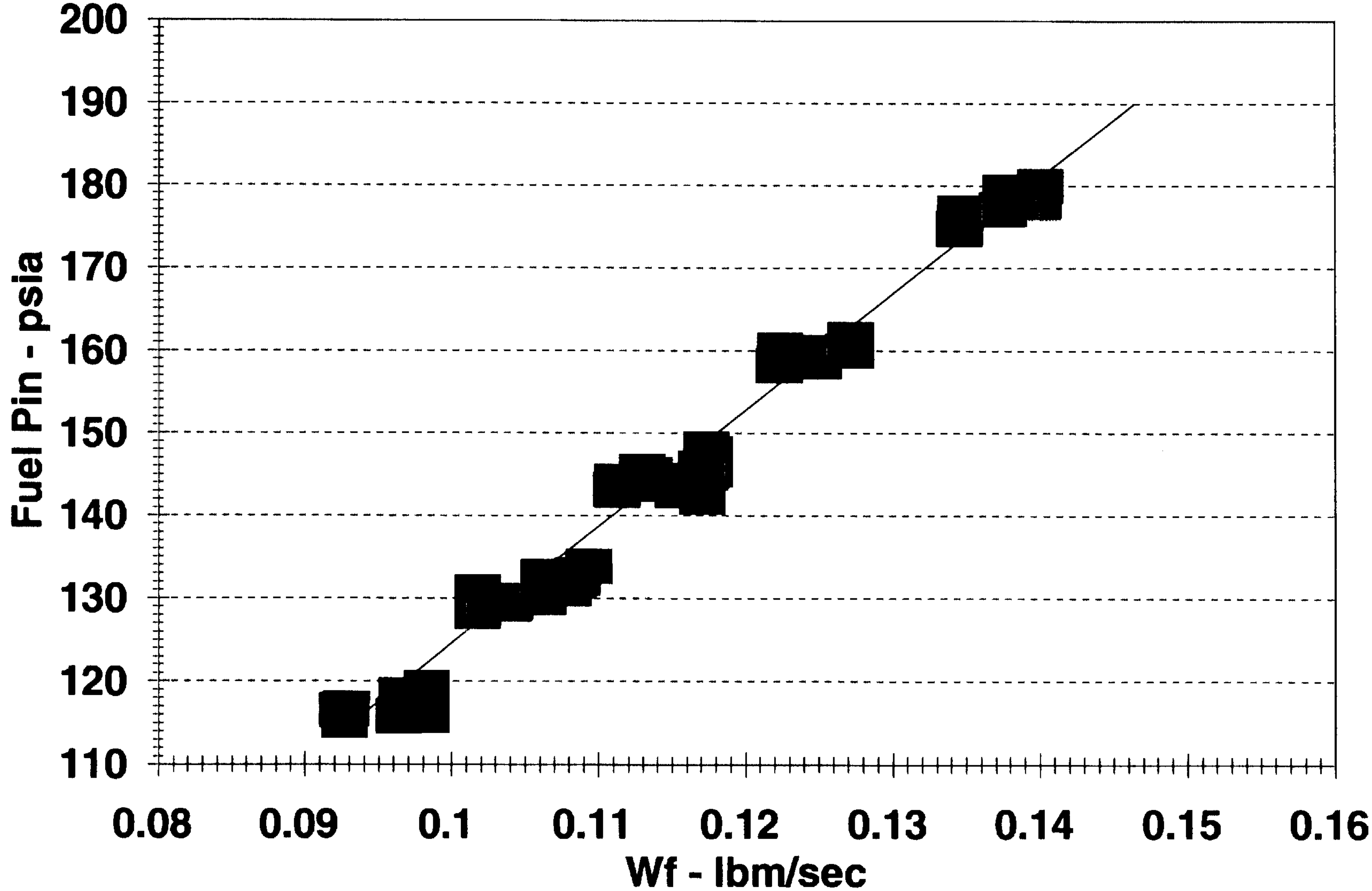


Figure 4-8. Fuel Inlet Pressure vs Wf

N2O4-MMH with Do=0.0105



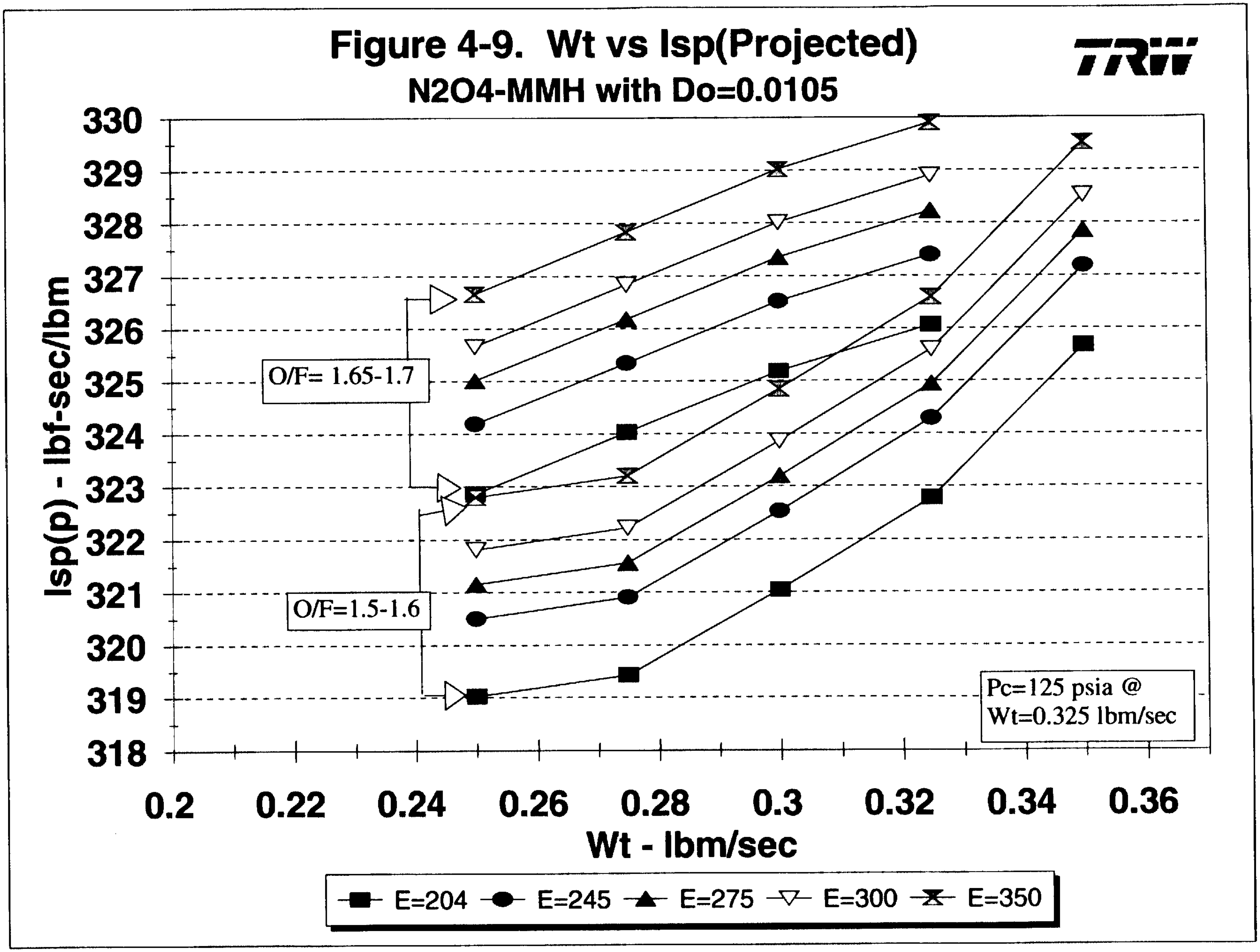


Figure 4-9. Wt vs Isp(Projected)
N2O4-MMH with Do=0.0105
TRW
Isp(p) - lbf-sec/lbm
330
329
328
327
326
325
324
323
322
321
320
319
318
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
Wt - lbm/sec
O/F= 1.65-1.7
O/F=1.5-1.6
Pc=125 psia @
Wt=0.325 lbm/sec
E=204
E=245
E=275
E=300
E=350

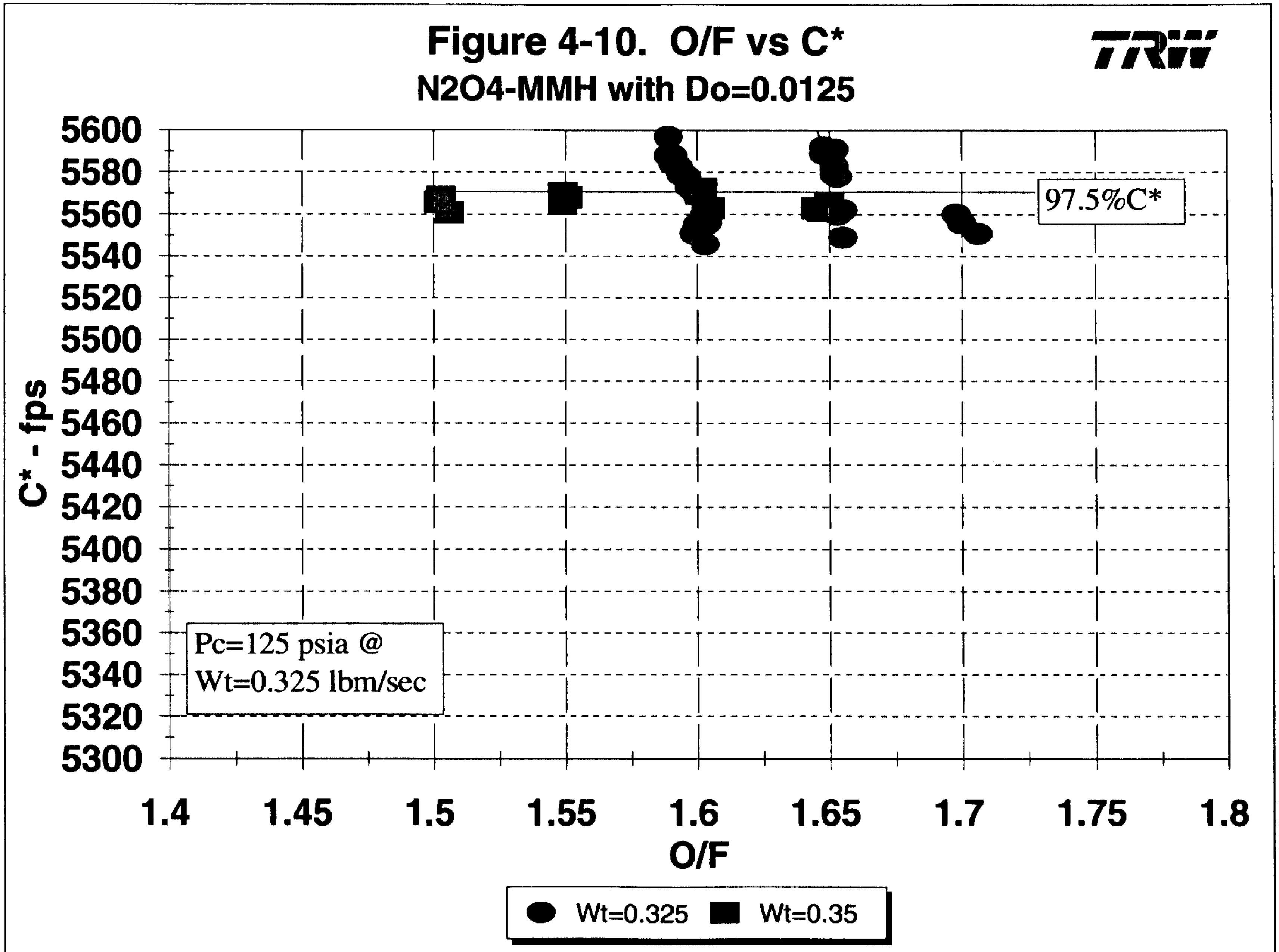


Figure 4-10. O/F vs C*
N2O4-MMH with Do=0.0125
C* - fps
5600
5580
5560
5540
5520
5500
5480
5460
5440
5420
5400
5380
5360
5340
5320
5300
1.4
1.45
1.5
1.55
1.6
1.65
1.7
1.75
1.8
O/F
97.5%C*
Pc=125 psia @
Wt=0.325 lbm/sec
Wt=0.325
Wt=0.35

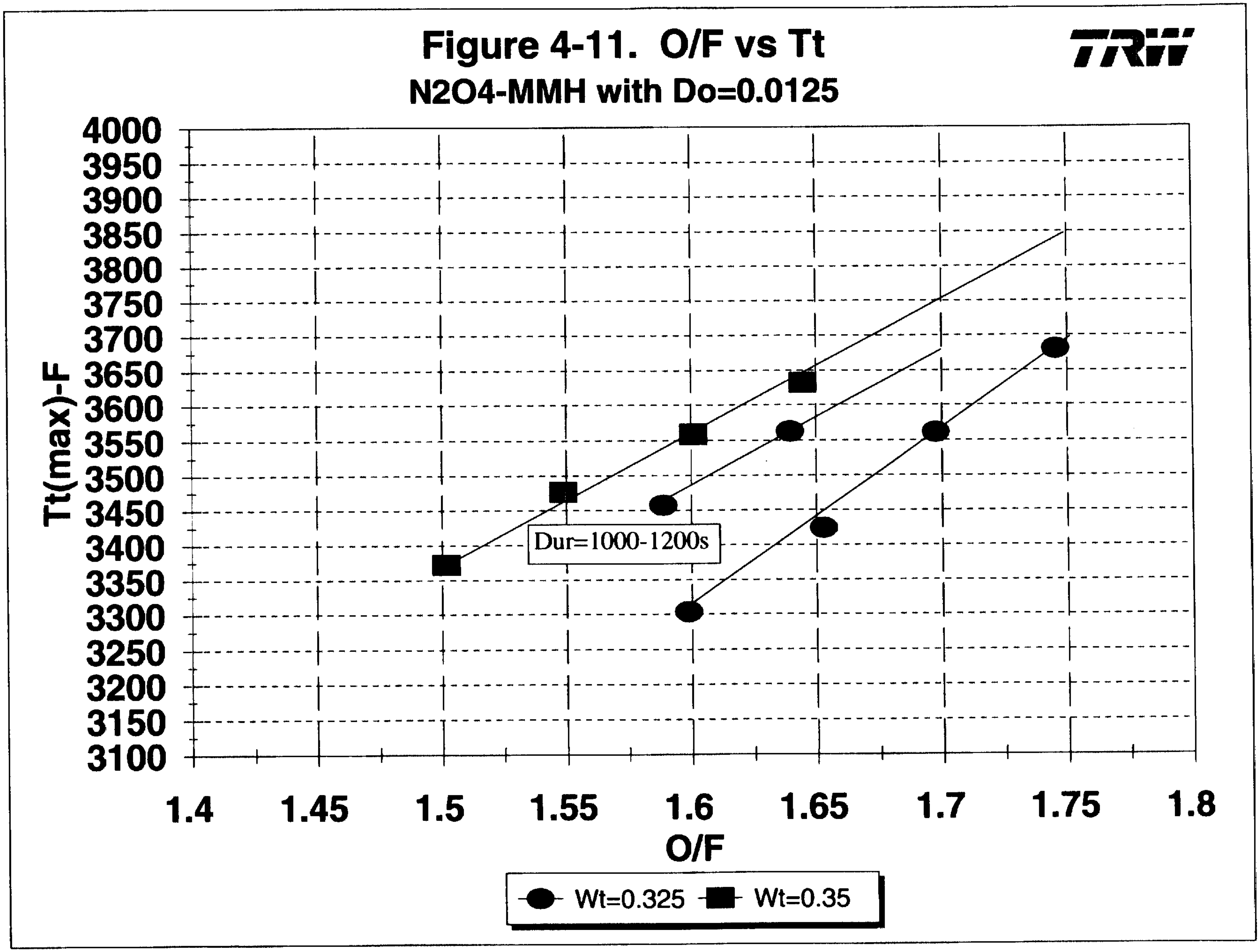


Figure 4-11. O/F vs Tt
N2O4-MMH with Do=0.0125
Tt(max)-F
4000
3950
3900
3850
3800
3750
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
3200
3150
3100
1.4
1.45
1.5
1.55
1.6
1.65
1.7
1.75
1.8
O/F
Dur=1000-1200s
Wt=0.325
Wt=0.35

Figure 4-12. Oxidizer Pinlet vs Wox

N2O4-MMH with Do=0.0125

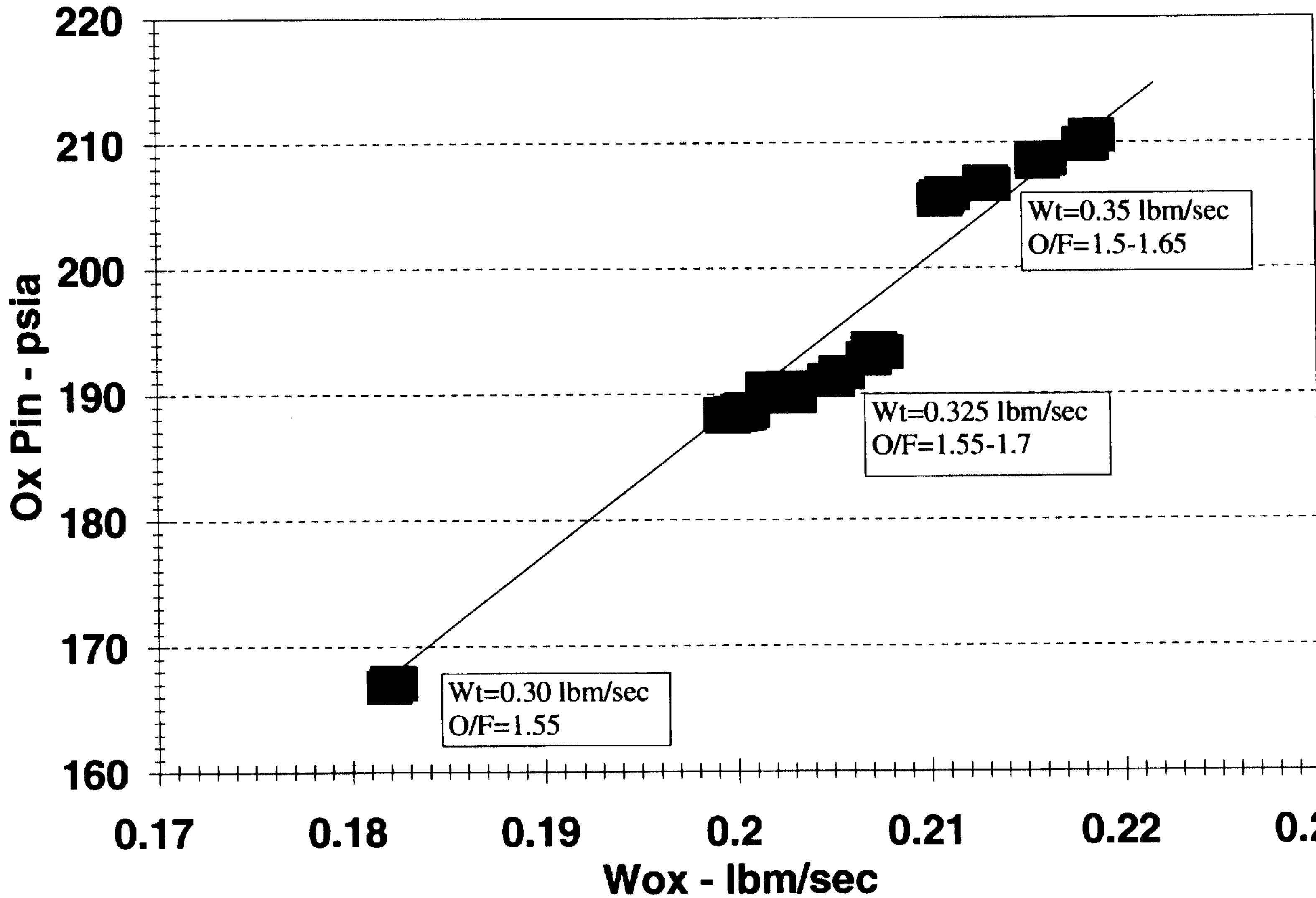
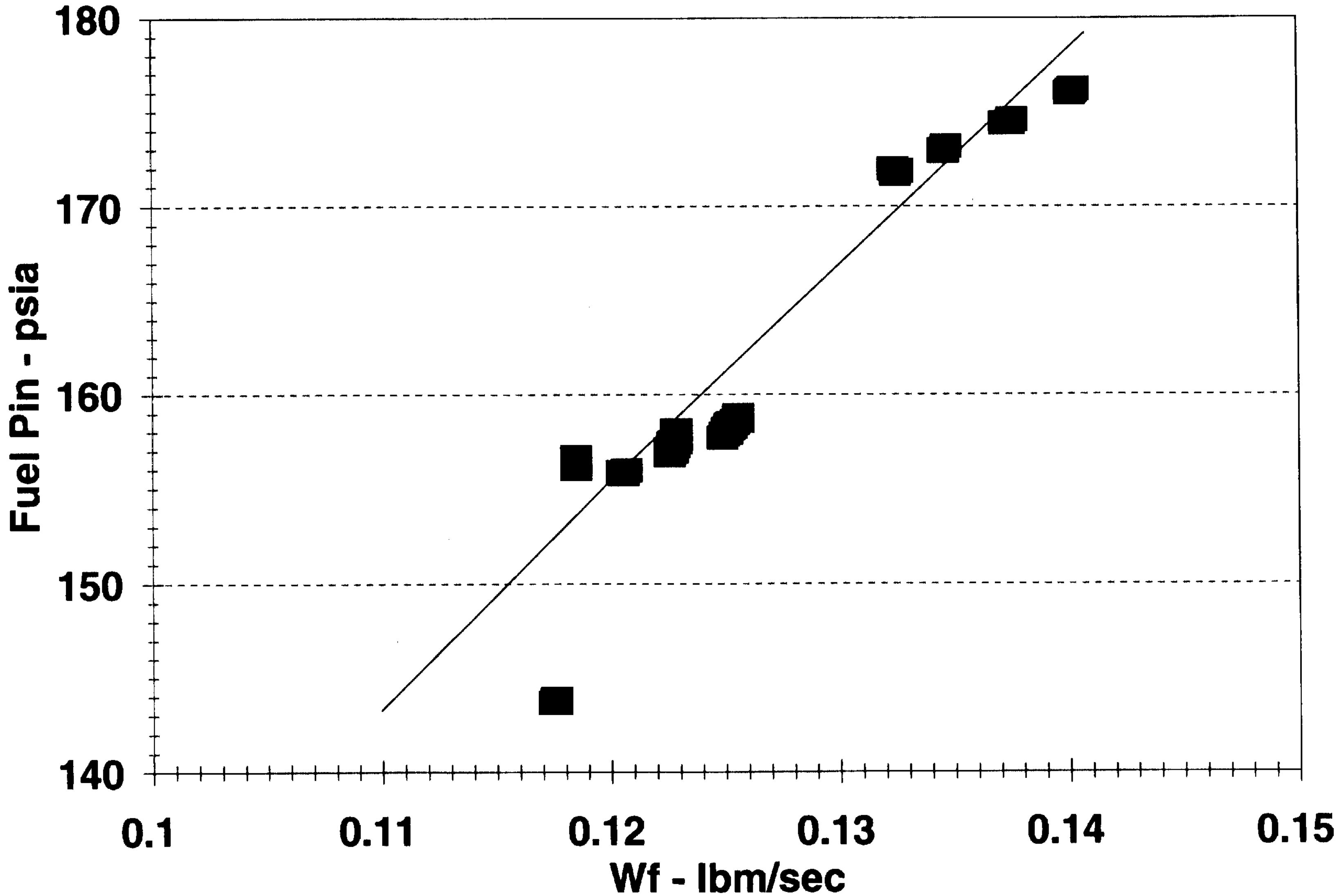


Figure 4-13. Fuel Pin vs Wf

N2O4-MMH with Do=0.0125



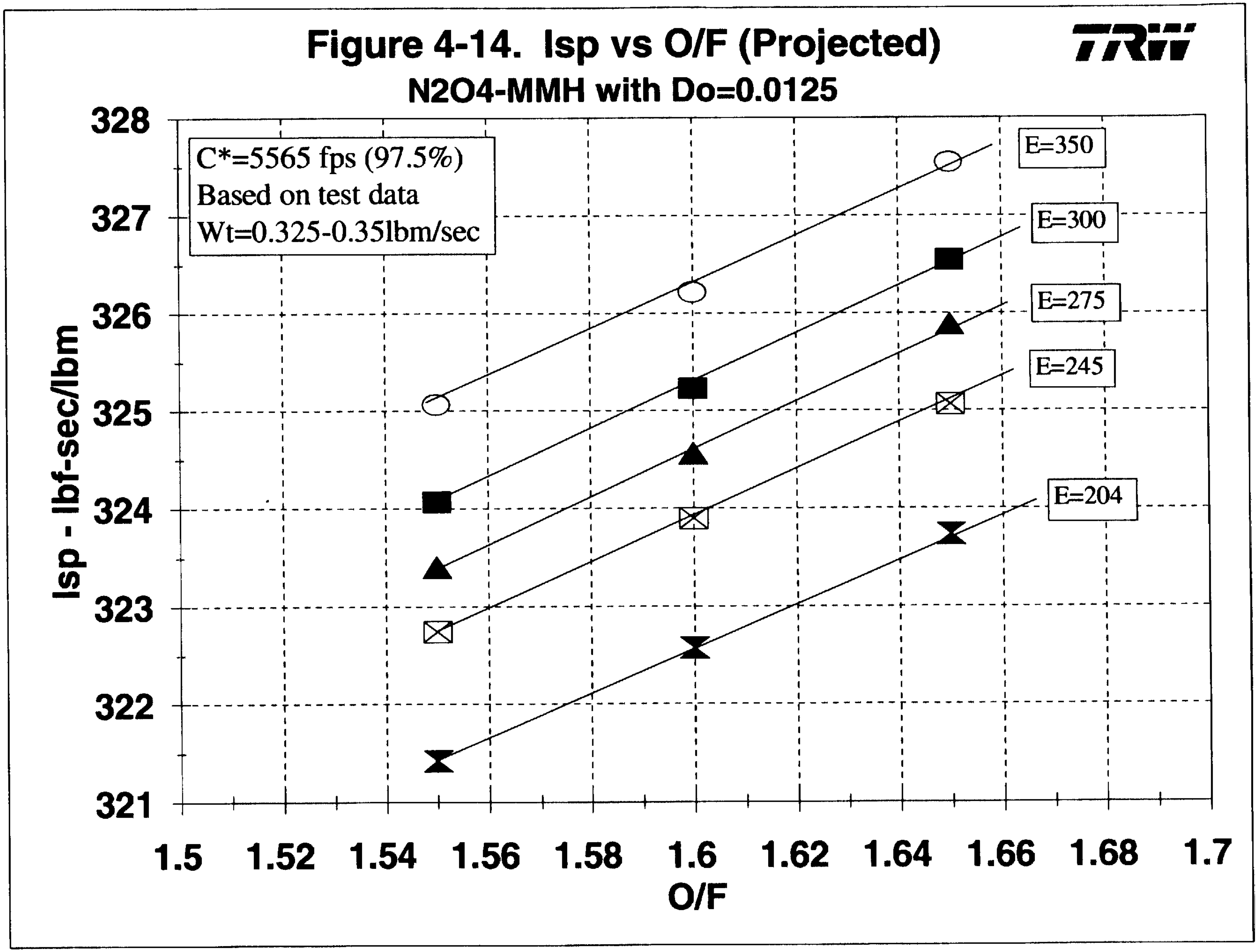


Figure 4-14. Isp vs O/F (Projected)
N2O4-MMH with Do=0.0125
C*=5565 fps (97.5%)
Based on test data
Wt=0.325-0.35lbm/sec
E=350
E=300
E=275
E=245
E=204
Isp - lbf-sec/lbm
328
327
326
325
324
323
322
321
1.5
1.52
1.54
1.56
1.58
1.6
1.62
1.64
1.66
1.68
1.7
O/F

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Under the High Pressure Earth Storable Rocket Technology (HIPES) Program, TRW successfully completed testing of two 100 lbf thrust class rhenium chambers using N_2O_4-MMH. The first chamber was successfully fired for 4789 seconds of operating time with a maximum duration of 700 seconds. This chamber had been previously fired for 5230 seconds with N_2O_4-N_2H_4. The second chamber was successfully fired for 8085 seconds with a maximum firing duration of 1200 seconds. The Isp for both chambers ranged from 323 lbf-sec/lbm to 330 lbf-sec/lbm.

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