Nammo
SECURING THE FUTURE

LEROS ACE-25 ADVANCED INJECTORS EXECUTIVE SUMMARY

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Nammo (U.K.) Ltd
Building 47, Westcott Venture Park,
Westcott, Aylesbury,
Bucks.
HP18 0XB.

Compiled by:

Rob Westcott
Senior Propulsion Engineer

Approved by:

Andy Godber
Programme Manager

Authorised by: I Coxhill approval by email - see 1016-2263

Ian Coxhill
Chief Engineer

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1016-2263	1	14/12/2020	New Document

INTRODUCTION

This presentation forms the Executive Summary for ESA De-Risk Program 'LEROS ACE-25 Engine Development' as per contract No. 4000129626/19/NL/BJ/ig

Previous documentation relevant to this program includes:

Baseline Design Review (BDR) presentation - 'ESA Submission - 110N Engine Development Presentation'

Test Readiness Review (TRR) presentation - 'ACE-25_ESA_Version'

LEROS ACE-25 ESA De-Risk Final Report – '506464-5154'

This Executive Summary presentation provides an overview of the complete project and the results from the project.
A path forward/development plan for future work is provided in LEROS ACE-25 ESA De-Risk Final Report – '506464-5154'

1 – INTRODUCTION
KEY REQUIREMENTS

The LEROS ACE-25 is a 110N Hydrazine/MON engine being developed for a large US prime who are looking to reduce the critical failure mode of using a single ~450N apogee engine by replacing it with 4-6 ~110N smaller engines.
The critical requirements of this 110N smaller engine are:

1. Engine must be immediately ready to fire and usable throughout the entire ~16 year life of the spacecraft

2. Engine must be capable of operating with a large Mixture Ratio (MR) range of 0.63 to 1.07

3. Engine must be capable of operating with a large Inlet Temperature range of 5°C to 60°C

4. Engine must be qualified for a total burn duration of 80,000 seconds (22.2 hours)

5. The engine must produce a nominal Isp of ≥320 seconds

6. Engine must have the ability to accommodate changing MR and sporadic pulsing firing during tank depletion

1 – INTRODUCTION
INJECTOR DESIGN APPROACH

The full injector (and complete engine) design philosophy and design approach are discussed in deliverable D1 'ESA Submission - 110N Engine Development Presentation'.
Identified below are some of the key advantages of the advanced injector design selected.

- The requirements and the associated design challenges lead the design/configuration of the injector away from the conventional LEROS 1c style injector towards an advanced injector design.

- Big advantages of the advanced injector configuration as compared to a conventional LEROS 1c injector configuration include:

    - Reduced/No sensitivity of Net Momentum Angle to MR
    - Reduced 'free' oxidiser and potential for 'free' oxidiser to reach the combustion chamber walls.
    - Faster/Shorter mixing and combustion times/lengths
    - Secondary mixing

- The scope of this ESA De-Risk project was to design, manufacture and test 2 advanced injector concepts to determine the potential capabilities of this type of injector design in an engine of this size.

- Ultimately, Nammo tested 6 advanced injector/engine configurations with excellent and promising results.

2 – ADDITIONAL HARDWARE DESCRIPTION

In order to test the advanced injector designs the following additional hardware a bolt-up engine assembly capable of firing in the Medium Altitude Test Facility (MATFA) was required:

Engine Assembly – As per bolt-up Medium Altitude Test Facility (MATFa) engine assembly drawing 66632.

This bolt-up configuration allows multiple injector and chamber configurations to be tested.

3 –TEST FACILITY

The advanced injectors/engine configurations were tested in the Medium Altitude Test Facility (MATFa). During firing the vacuum cell pressure will be maintained at <75 mbar providing an excellent thermally representative environment.

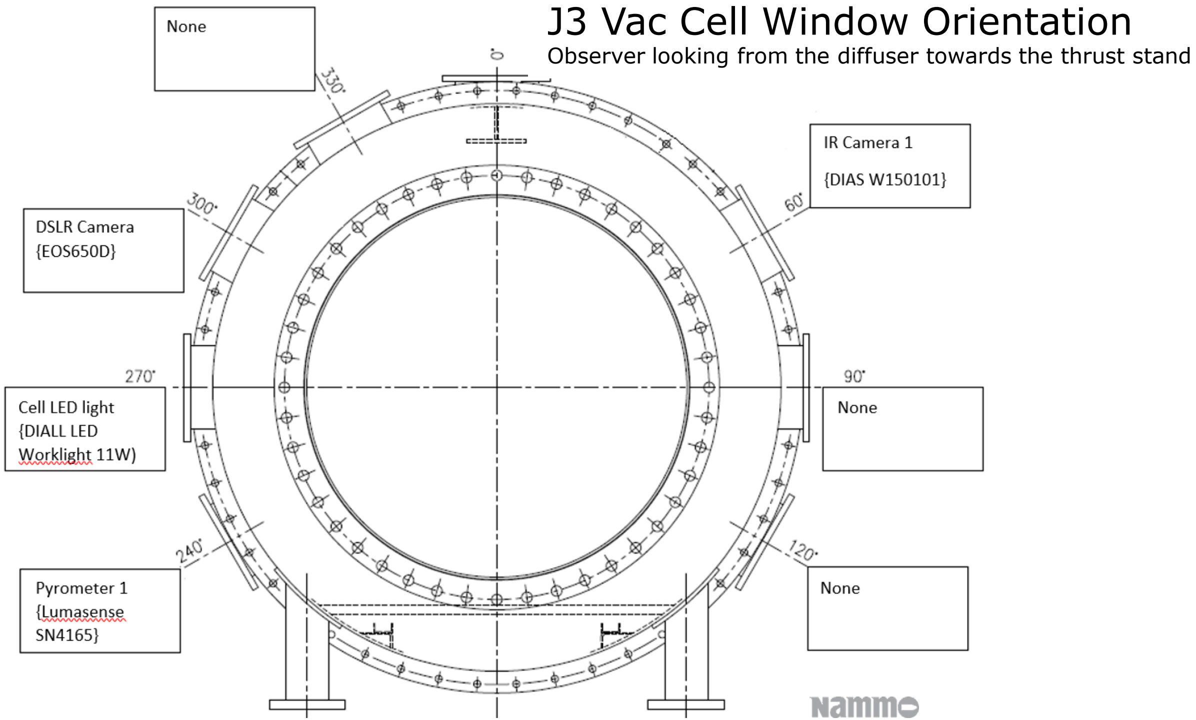
The major modifications to the test facility that were made to allow testing of the ACE-25 are as follows:

1) Master and Slave load cells were replaced with 300N Novatech load cells and the hydraulic actuators used for calibration were changed specifically for the 300N range.

2) A specific diffuser was designed and built for hotfire testing of the ACE-25 engine

3 –TEST FACILITY

The diagram below shows the locations of IR cameras and the optical camera located around the vacuum chamber



INTRODUCTION

The following slides provide firing results for a number of the advanced injector/engine configurations:

- These injectors/engine configurations are:

  I681/1 – 66591/1 in the 41mm Ch
  FFC% = 26.3%
  NMA = NA
  FFC Swirl Angle = 0° (Alternate 16 large straight, 16 small straight)

  I681/3 – 66591/3 in the 51mm Ch
  FFC% = 42.17%
  NMA = NA
  FFC Swirl Angle = Alternate 16 large straight, 16 small straight

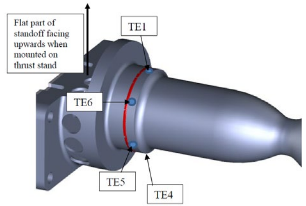
  I691/3 – 66646/3 in the 66mm Ch
  FFC% = 41.8%
  NMA = NA
  FFC Swirl Angle = 30°

  I693/2 – 66646/2 in the 66mm Ch. This config also used a distribution ring
  FFC% = 32.07%
  NMA = NA
  FFC Swirl Angle = 30°

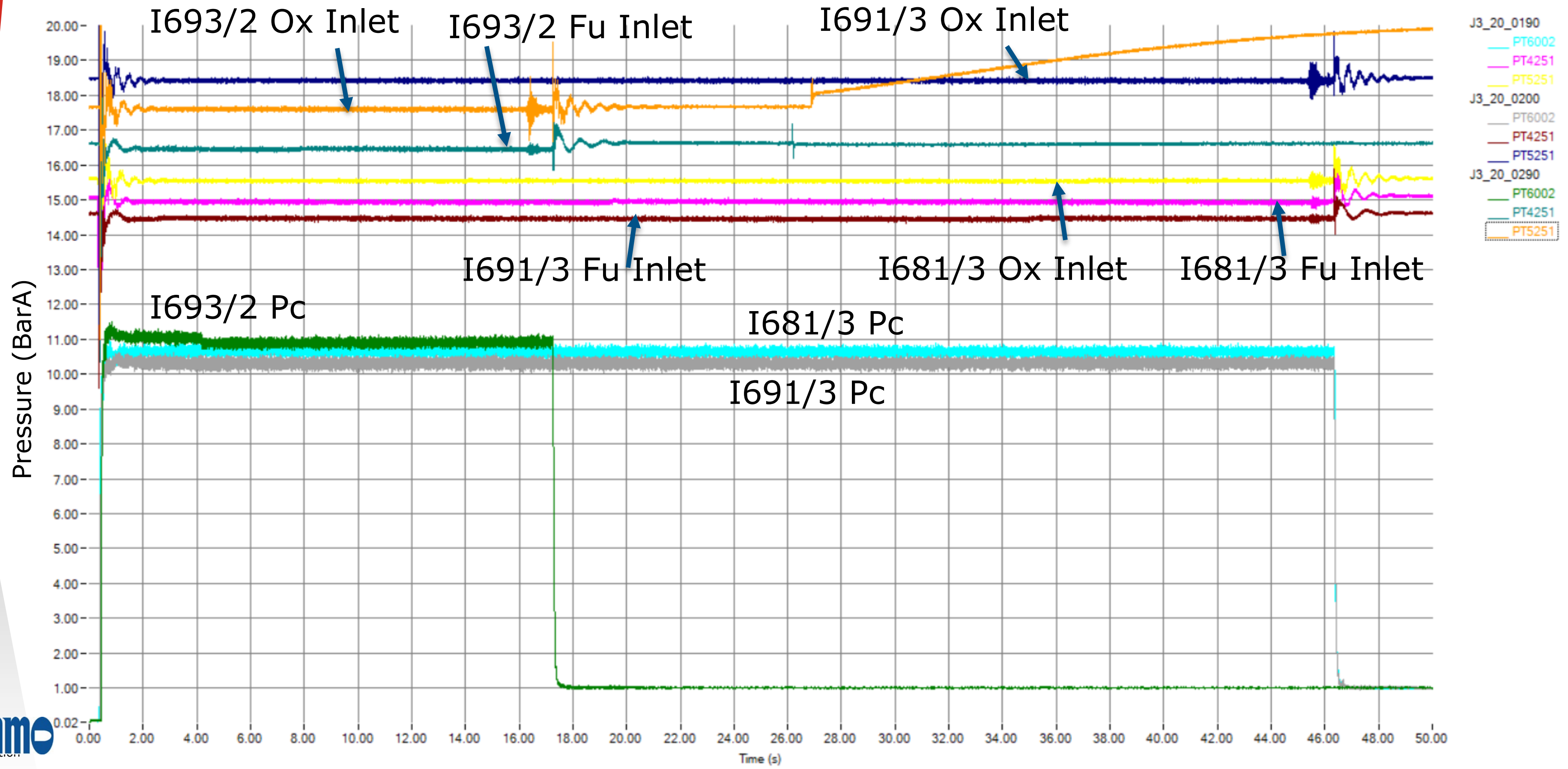
ADVANCED INJECTORS

Matrix Number	Injector SN	FFC%	FFC Swirl	Chamber Length (mm)	Fuel Inlet Bara	Fuel Inlet Psia	Ox Inlet Bara	Ox Inlet Psia	MR	Vac Pred Thrust (N)	Vac Pred Thrust (lbf)	Vac Pred Isp (seconds)	Pc Roughness (%)	Burn Duration (seconds)	Predicted Chamber Temp (degC)	Average ToC Temps measured at end of firing (degC)
	I681/1	26.3	Alt	41	15.6	226.8	11.9	172.7	0.61	95.38	21.4	315.3	2.36	45.0	1369.00	368
	I681/3	42.17	Alt	51	13.9	201.0	11.9	173.3	0.61	92.61	20.8	302.3	2.33	46.0	<600	175
	I691/3	41.8	30	66	13.7	198.5	16.1	233.9	0.71	97.65	22.0	306.3	2.61	46.0	1342.40	125
2	I693/2	32.07	30	66	14.9	216.7	13.0	188.1	0.55	92.32	20.8	307.9	1.94	46.0	1437.50	200
	I681/1	26.3	Alt	41	13.0	188.8	14.6	211.5	1.16	96.69	21.7	316.4	1.89	10.4		424
	I681/3	42.17	Alt	51	11.9	171.9	14.8	214.5	1.05	90.50	20.3	298.3	4.40	24.2		193
	I691/3	41.8	30	66												
4	I693/2	32.07	30	66												
	I681/1	26.3	Alt	41	17.0	245.9	15.5	224.7	0.84	110.73	24.9	322.3	1.92	13.7	1470.00	~800
	I681/3	42.17	Alt	51	14.9	216.3	15.5	225.4	0.86	108.24	24.3	313.0	2.33	46.0	1389.90	190
	I691/3	41.8	30	66	14.5	209.6	18.4	267.0	0.84	106.02	23.8	308.1	2.41	46.0	1394.50	144
6	I693/2	32.07	30	66	16.5	238.6	17.6	255.2	0.84	112.29	25.2	319.6	1.83	16.9	1525.00	174
	I681/1	26.3	Alt	41	22.1	320.1	16.9	244.9	0.66	125.02	28.1	317.7	2.35	45.1	1458	260
	I681/3	42.17	Alt	51	18.9	274.5	16.7	242.1	0.66	122.89	27.6	313.5	2.99	46.0	1361	184
	I691/3	41.8	30	66												
8	I693/2	32.07	30	66	20.6	298.5	18.5	268.5	0.65	124.84	28.1	318.4	1.95	18.3		188.0
	I681/1	26.3	Alt	41	21.9	318.2	20.1	291.3	0.86	134.10	30.1	320.9	2.17	9.0		234
	I681/3	42.17	Alt	51	19.2	278.5	20.0	290.2	0.86	133.13	29.9	317.8	2.61	46.0	1402	205
	I691/3	41.8	30	66	18.6	269.4	24.6	357.2	0.96	133.63	30.0	308.7	2.50	46.0	1424	177
10	I693/2	32.07	30	66	20.7	299.8	22.7	329.5	0.86	134.67	30.3	321.4	1.92	6.1		155
	I681/1	26.3	Alt	41	18.5	267.6	20.0	289.9	1.07	125.46	28.2	320.1	2.73	9.7		393
	I681/3	42.17	Alt	51												
	I691/3	41.8	30	66												
12	I693/2	32.07	30	66	17.5	253.2	22.9	332.8	1.09	123.09	27.7	310.1	1.60	5.8		148

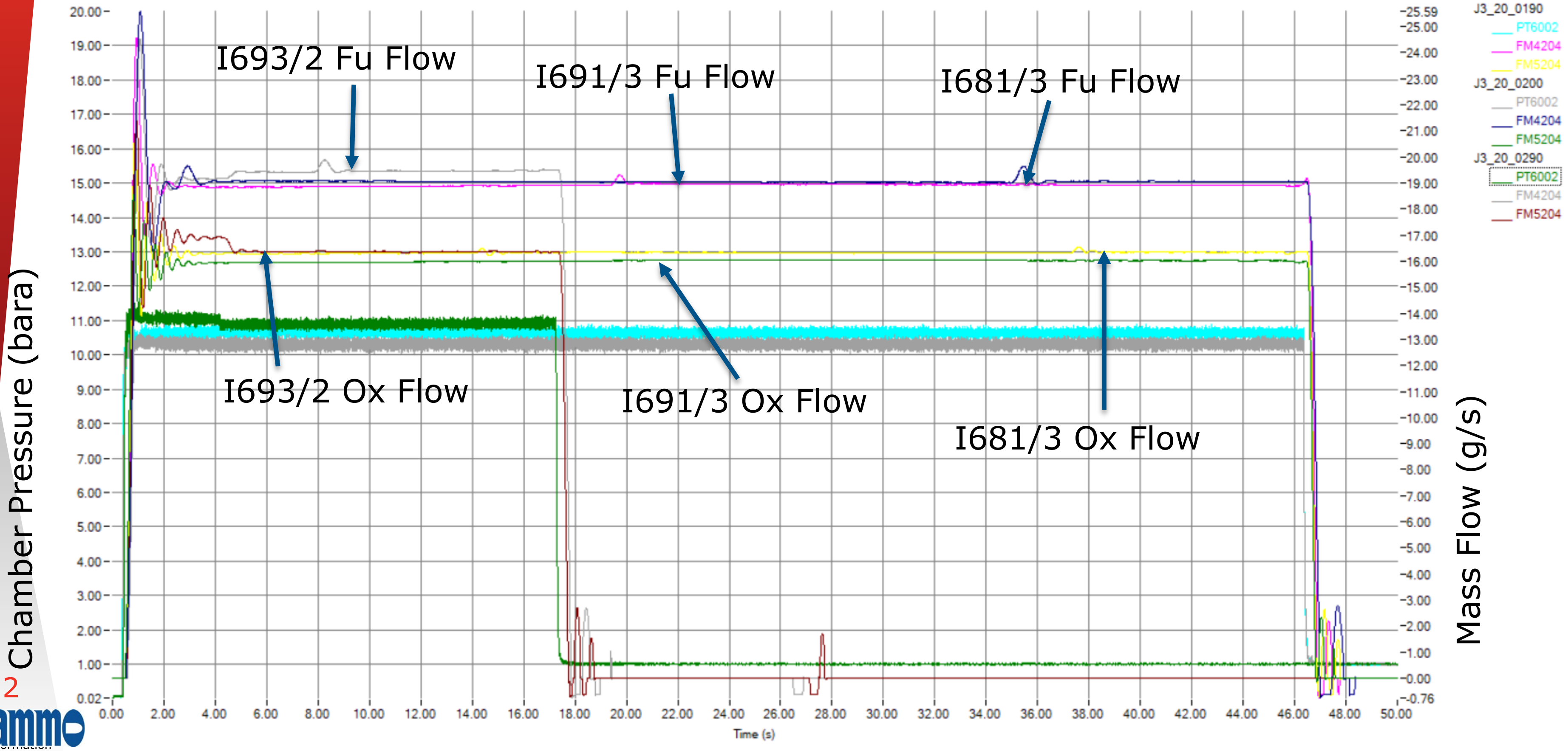
Top of Chamber (ToC) temperature measurement locations



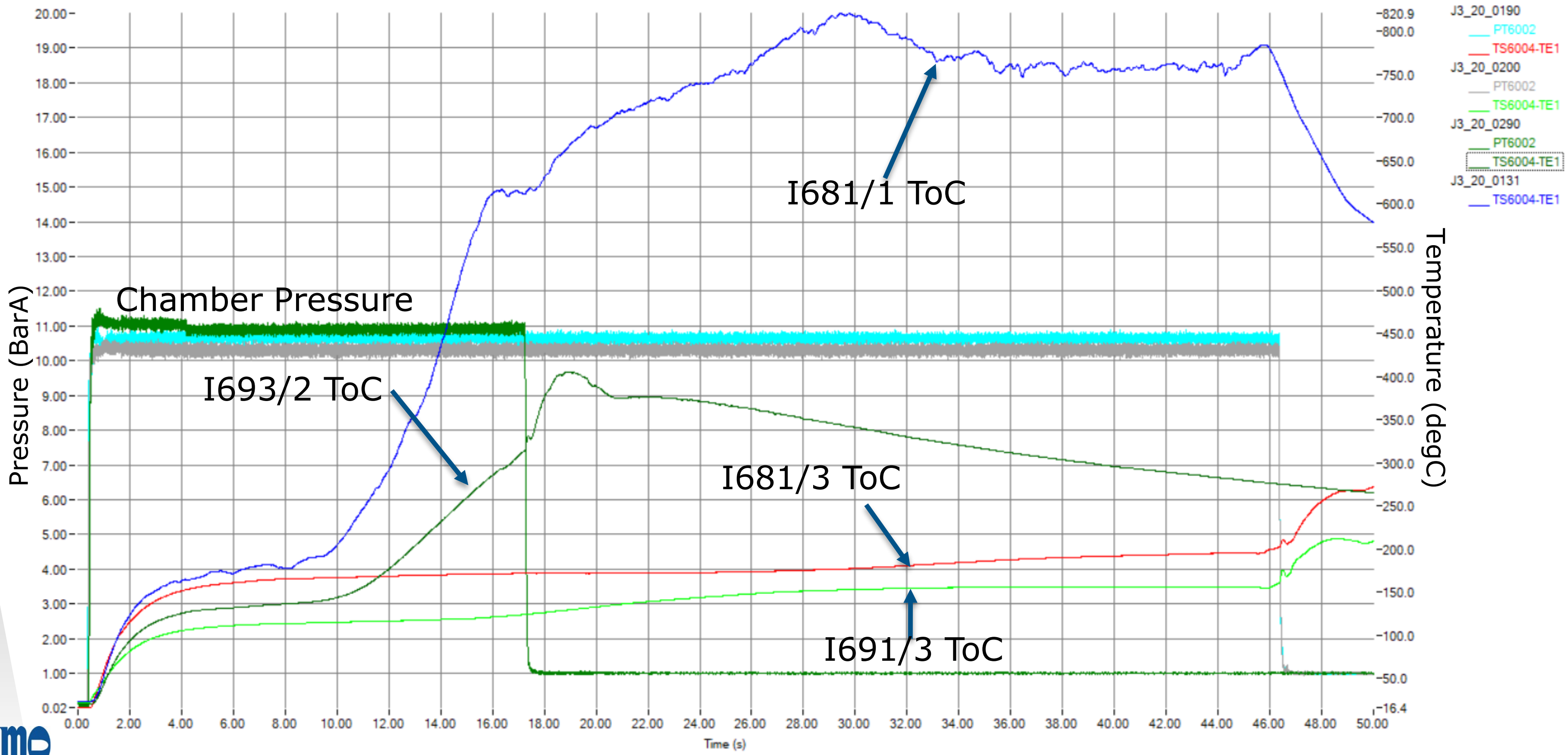
ADVANCED INJECTORS NOMINAL POINT



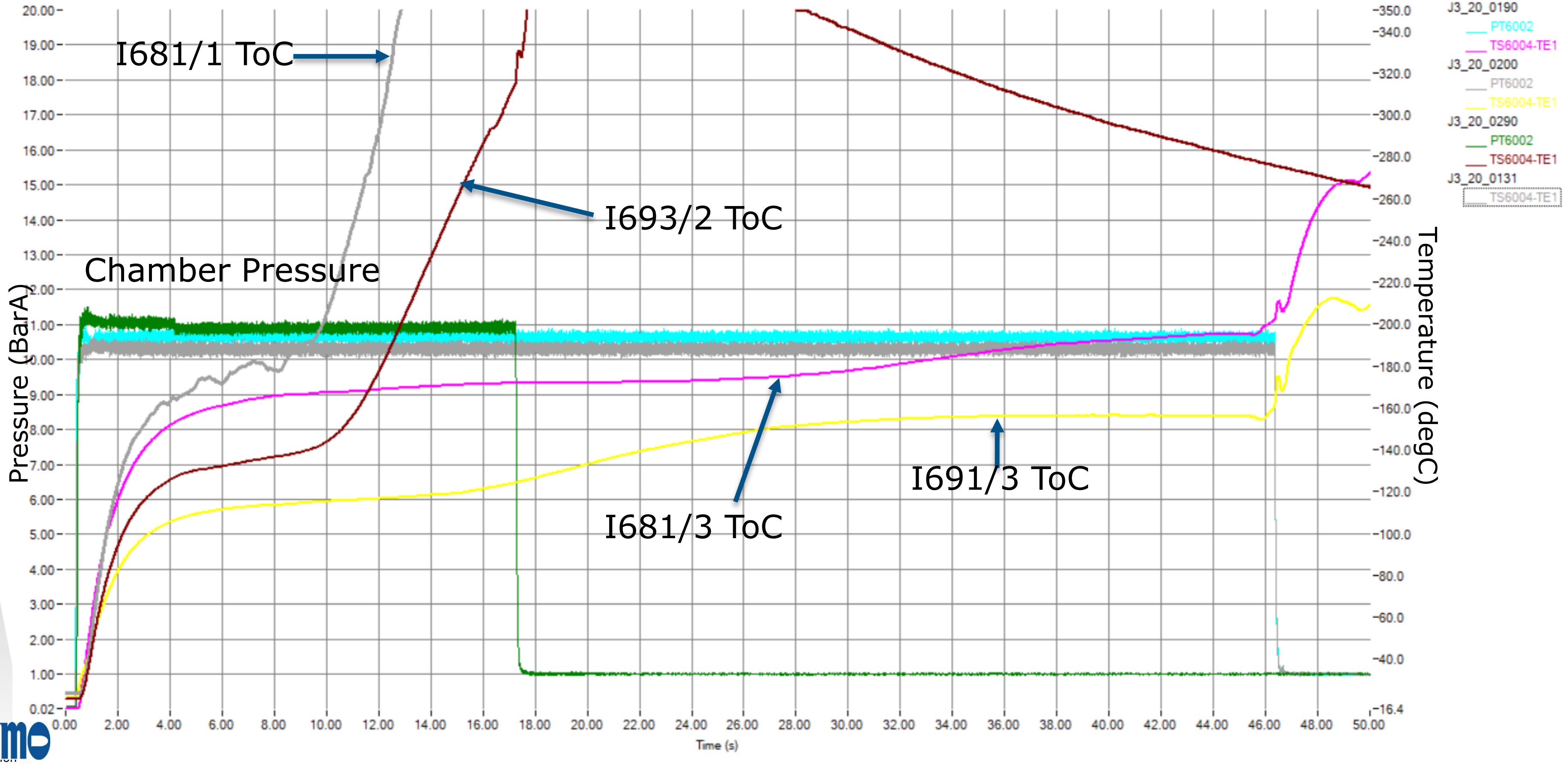
ADVANCED INJECTORS NOMINAL POINT



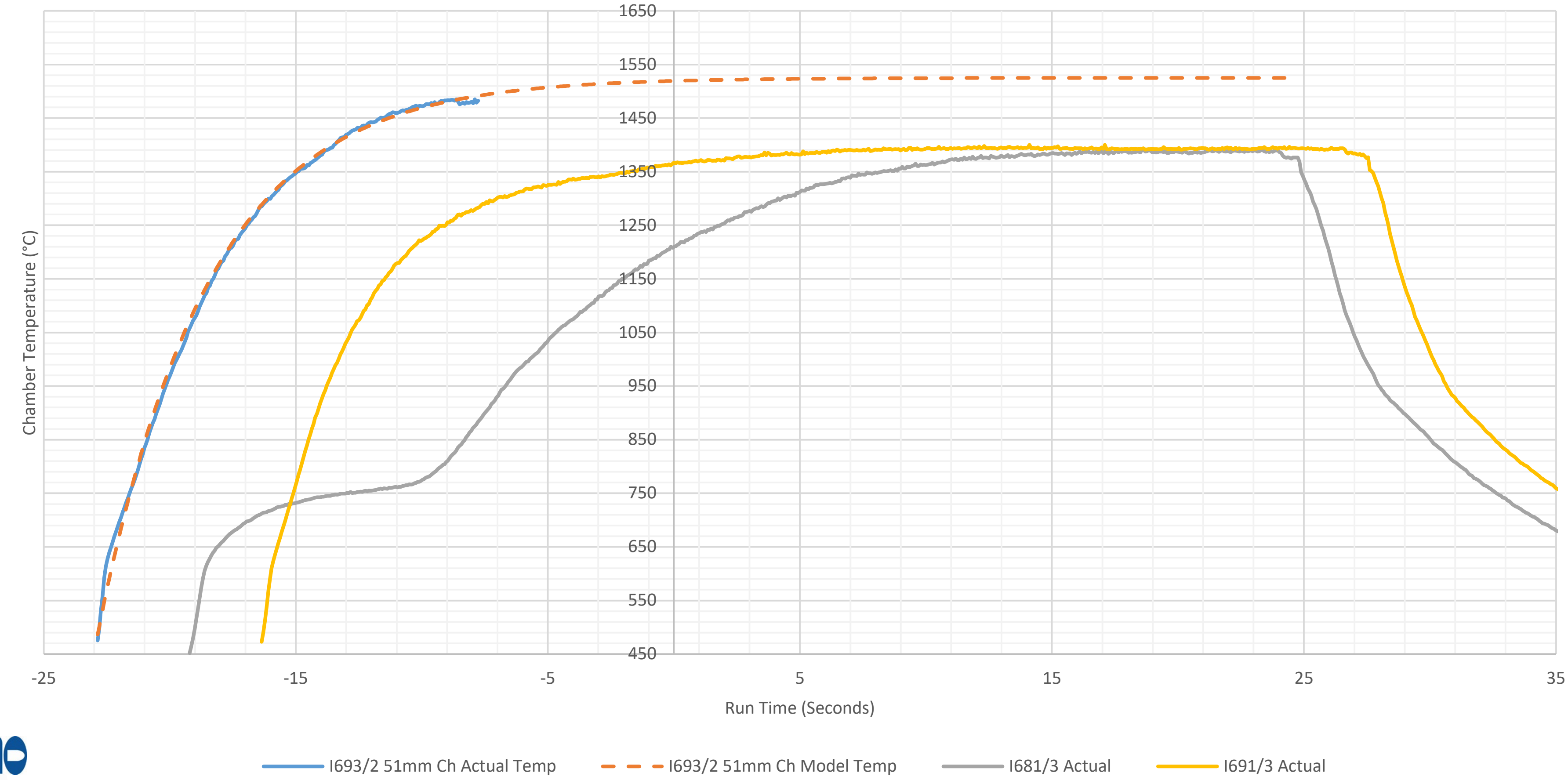
ADVANCED INJECTORS NOMINAL POINT



ADVANCED INJECTORS NOMINAL POINT



ADVANCED INJECTORS NOMINAL POINT



ADVANCED INJECTORS NOMINAL POINT

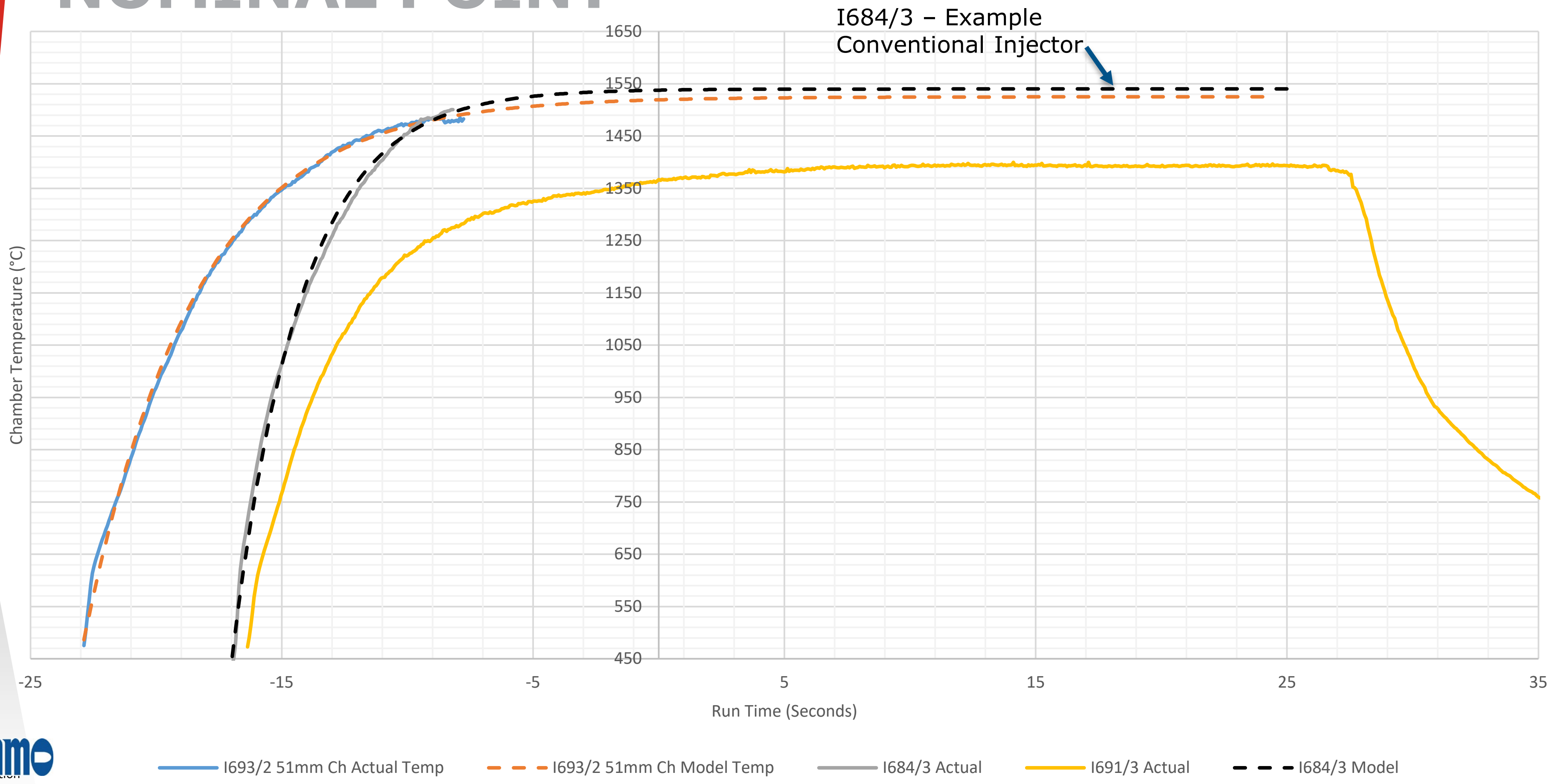
The model used for predicting estimated chamber temperature at equilibrium (ETE) uses the following equation:

$$ETE = t_{amb} + t_{\max\_delta} \times \left(1 - e^{-\frac{T - T_{offset}}{T_c}}\right)$$

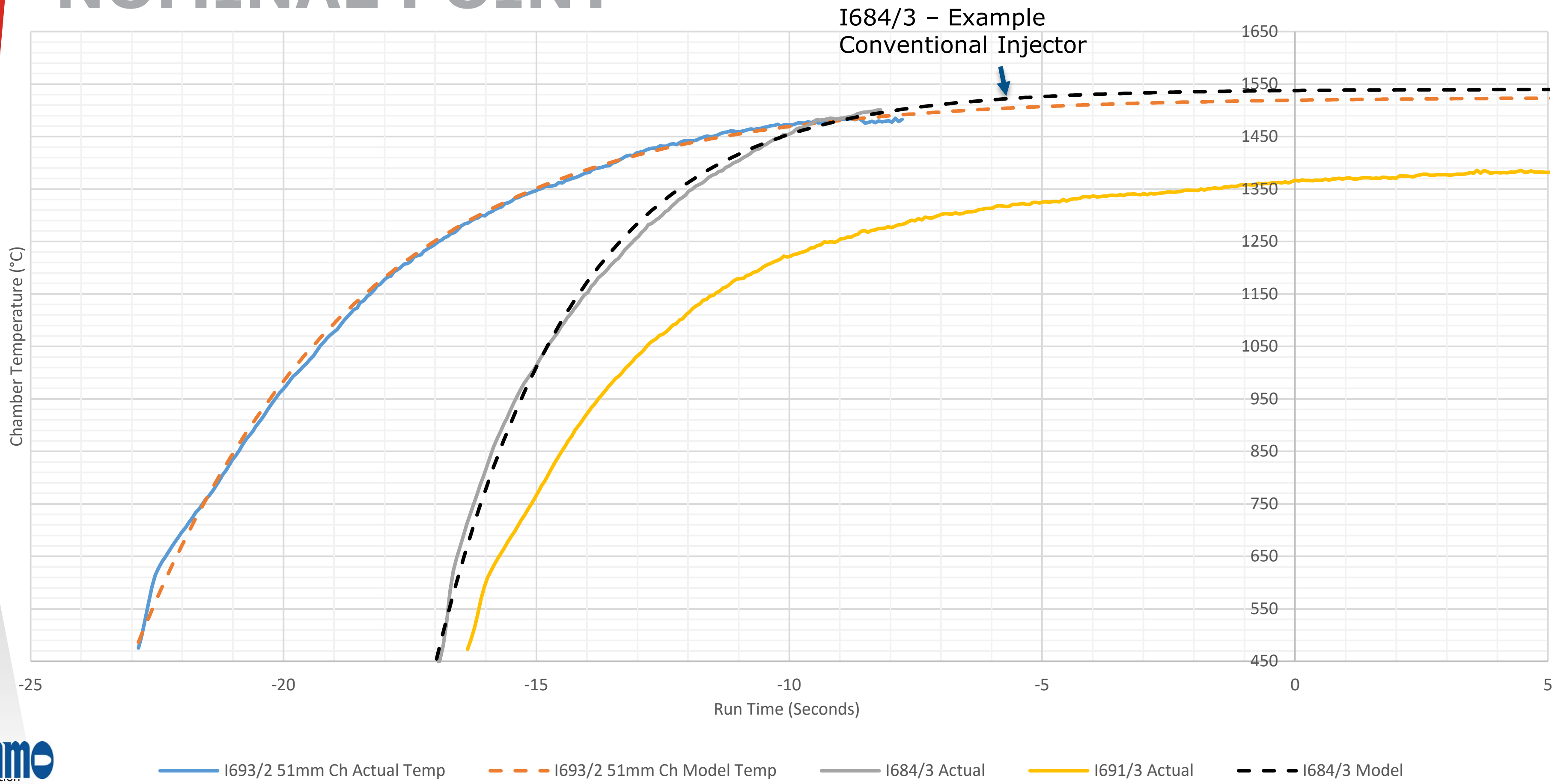
Where:
t_{amb} is the ambient temperature of the chamber at the start of firing (20°
$t_{\max\_delta}$ is the increase in chamber temperature
T is the time into the run or run duration
T_{offset} is the time offset between the model and the actual test data
T_c is the time constant

The model is generated by comparing the actual firing data with the model predicted data. The above parameters are then adjusted until the sum of the errors between the actual temperature results and the model predicted results are minimized. The model predicted results can then be extrapolated out to a time value where the chamber temperature has reached equilibrium:

ADVANCED INJECTORS NOMINAL POINT

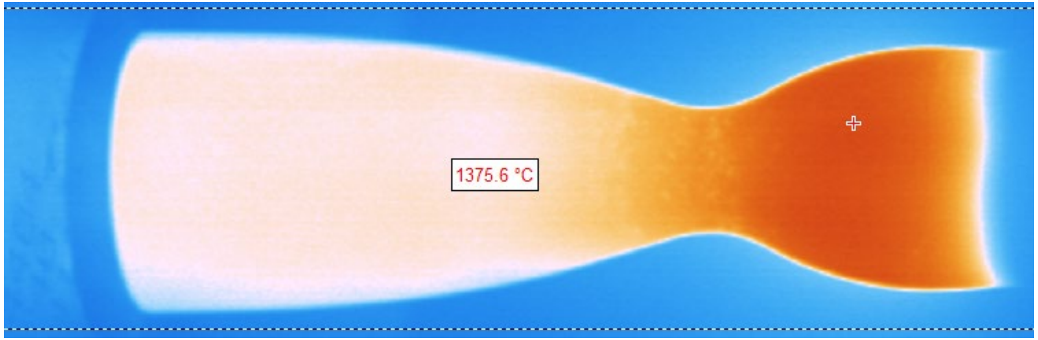


ADVANCED INJECTORS NOMINAL POINT



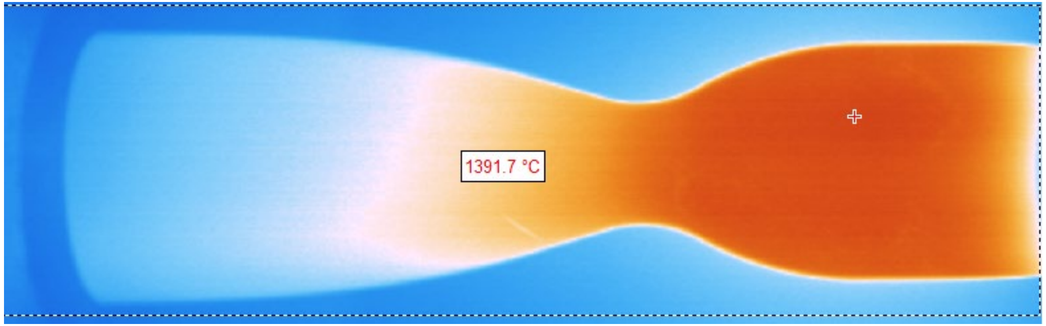
ADVANCED INJECTORS NOMINAL POINT

I681/3 51mm Ch



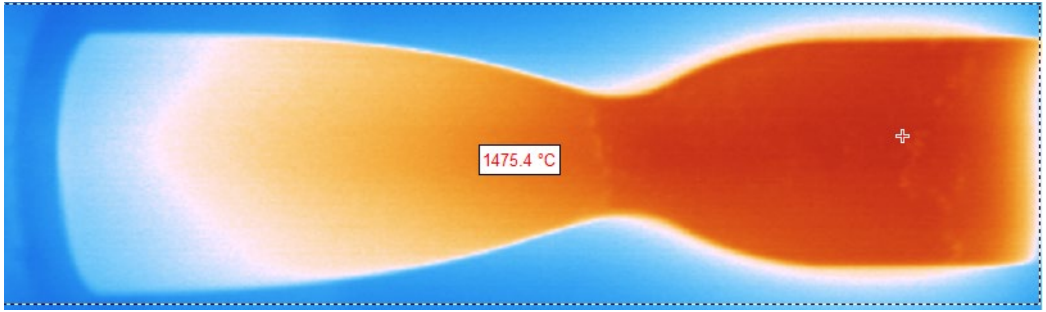
44 seconds into a 45 second run

I691/3 66mm Ch



44 seconds into a 45 second run

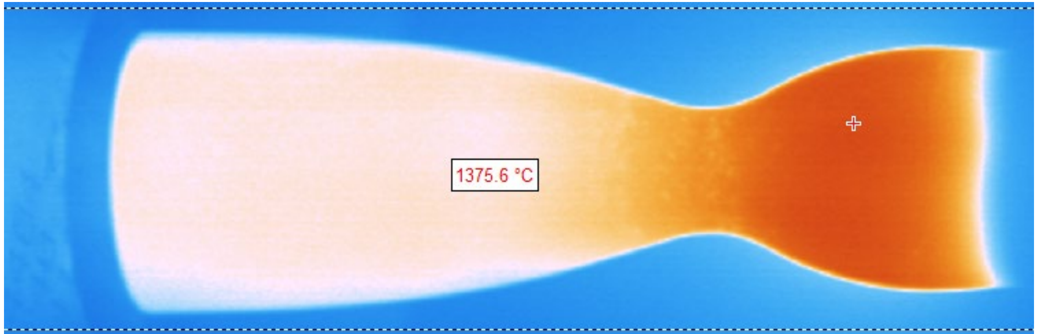
I693/2 66mm Ch



16 seconds into a 17 second run

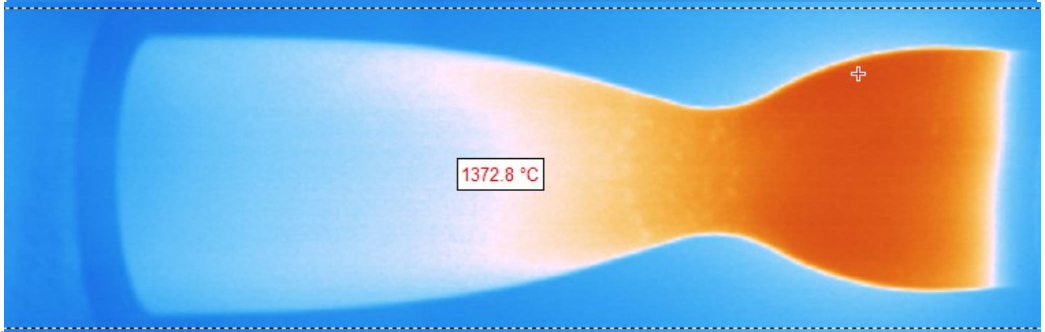
ADVANCED INJECTORS NOMINAL POINT

I681/3 51mm Ch



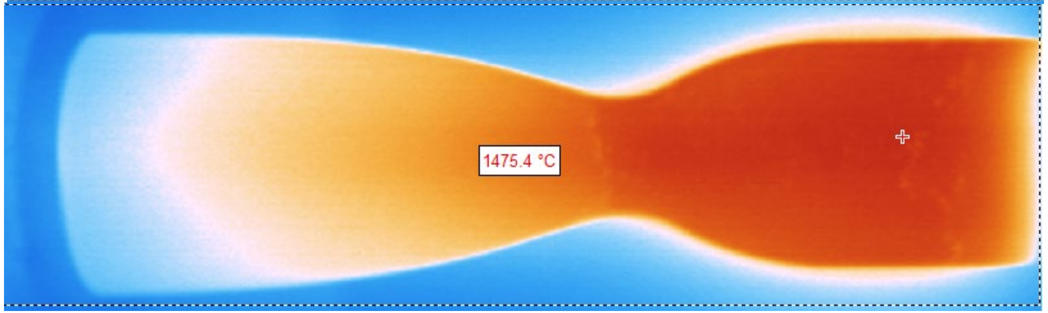
44 seconds into a 45 second run

I691/3 51mm Ch



44 seconds into a 45 second run

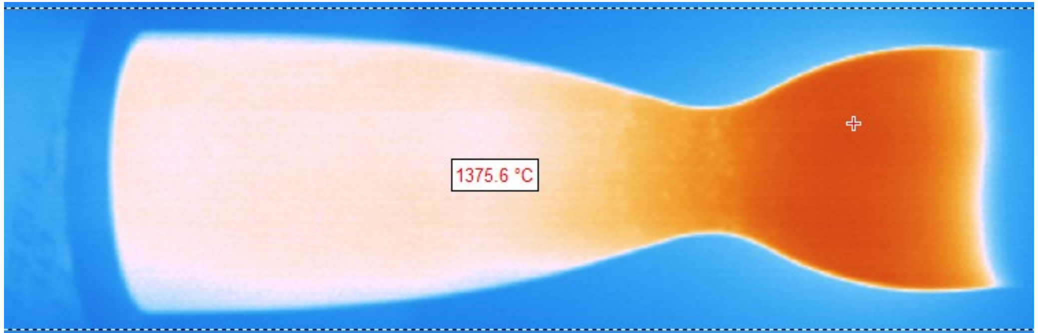
I693/2 66mm Ch



16 seconds into a 17 second run

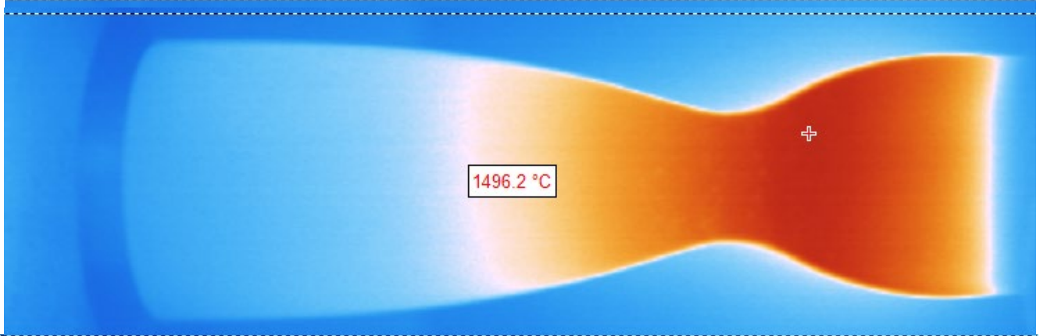
ADVANCED INJECTORS NOMINAL POINT

I681/3 51mm Ch



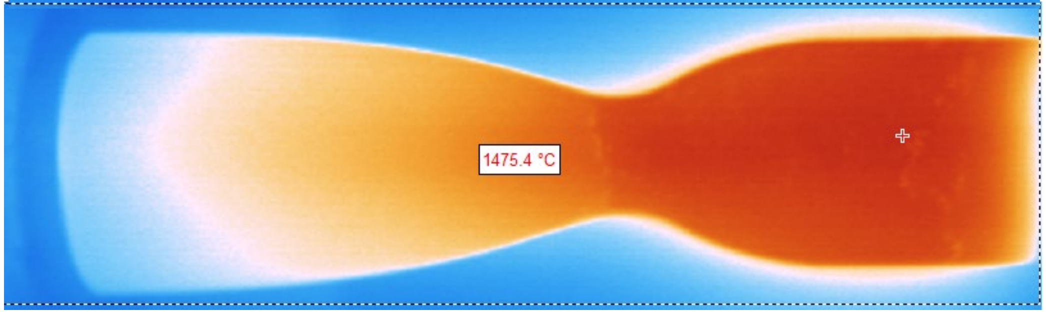
44 seconds into a 45 second run

I684/3 51mm Ch
Conventional Inj



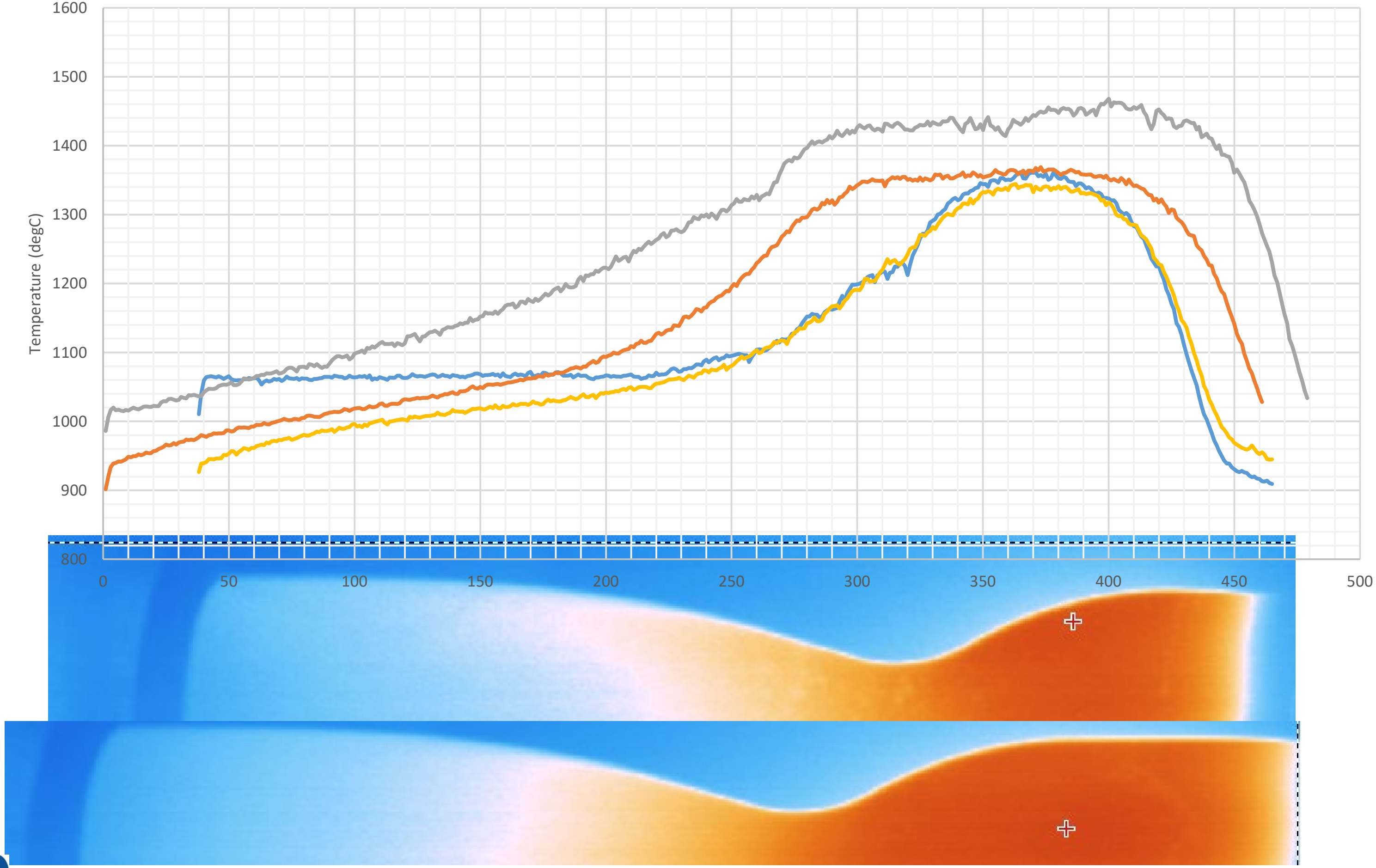
9 seconds into a 10 second run

I693/2 66mm Ch



16 seconds into a 17 second run

ADVANCED INJECTORS NOMINAL POINT

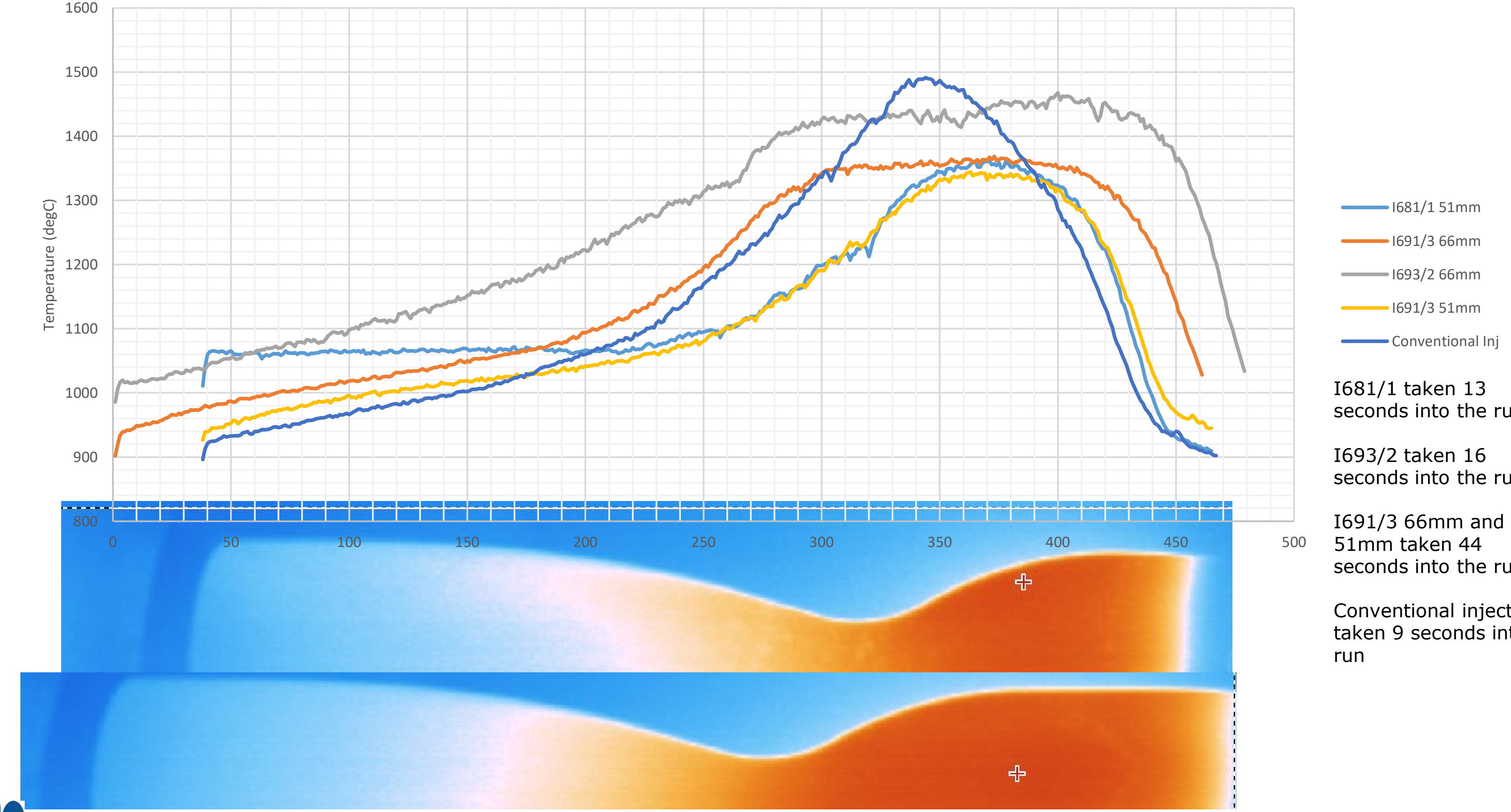


I681/1 taken 13 seconds into the run

I693/2 taken 16 seconds into the run

I691/3 66mm and 51mm taken 44 seconds into the run

ADVANCED INJECTORS NOMINAL POINT



I681/1 taken 13 seconds into the run

I693/2 taken 16 seconds into the run

I691/3 66mm and 51mm taken 44 seconds into the run

Conventional injector taken 9 seconds into run

ADVANCED INJECTOR ASSESSMENT SUMMARY

Based on the results presented in the this presentation and the wider data set of recorded results, the following conclusions are drawn regarding advanced injectors:

1. 30 degrees swirl FFC maintains the Top of Chamber (ToC) temperatures at a lower point than no swirl or the alternate Big and Small FFC jets.

2. 30 degrees swirl FFC does not appear to result in higher peak chamber temperatures

3. Increasing the FFC% **has** a significant impact on ToC temperatures

4. Increasing the FFC% **has** a significant impact in reducing the peak chamber temperature

5. Increasing the FFC% **has a fairly significant negative** impact on Isp performance. This is probably due to the fact that an increase in FFC% has no positive impact on the NMA (unlike the conventional injectors where increasing the FFC% increases the NMA)

CHAMBER LENGTH ASSESSMENT FOR THE ADVANCED INJECTOR

Based on the results from testing I691/3 (which has FFC% = 41.8% NMA = NA FFC Swirl Angle = 30°) in the 41mm chamber, the 51mm chamber and the 66mm chamber the following observations have been made;

- As was the case when testing the '/1' variants (with their lower FFC%) of the advanced injector the longest chamber did not give the highest Isp performance. The 51mm chamber gave the highest Isp performance. There is a balance point with the advanced injectors between chamber length and FFC%

- When the chamber length was long enough to get the engine running in the 'hotter' state (i.e. >600°C which was not the case for the 41mm chamber), the peak chamber temperatures for the different chamber lengths were comparable.

- All chamber lengths seemed to result in similar and satisfactory chamber pressure roughness. For the conventional injectors, shorter chambers produced rougher/increased chamber pressure roughness

- When the chamber length was long enough to get the engine running in the 'hotter' state (i.e. >600°C which was not the case for the 41mm chamber), the Top of Chamber temperatures were generally lower with the longer chamber.

ADVANCED INJECTOR CONCLUSIONS

The testing of the advanced injector designs has been **VERY** successful especially given that no development of the injector core has been performed in the scope of this program.

Interestingly, the data suggests that the injector design is optimized around the nominal operating point i.e. the best performance seems to occur at around the nominal MR and thrust.

All injectors have run with good stability across the wide operating box.

The advanced injectors give excellent 'value for money' in as much as their Isp performance Vs their peak chamber temperatures are excellent and much better than the conventional injector designs.

ADVANCED INJECTOR CONCLUSIONS

The testing of advanced injector I681/1 with it's low peak chamber temperature and therefore allowing run durations to go for the full 45 seconds, really highlighted the key issue of excessively hot Top of Chamber (ToC) temperatures

For both the advanced injectors and conventional injectors this has been a key design challenge.

For the advanced injectors it is this design challenge that has resulted in the 30 degrees swirl FFC and higher FFC% being preferred.

The increase in FFC% has had a fairly significant impact on Isp performance, more so than with the conventional injectors where pushing up the FFC% does also result in an increase in Net Momentum Angle (NMA) which helps recover some of the lost Isp. This is not the case for the advanced injectors.

As the ToC temperatures are such a significant design/performance driver it is important to consider the fact that we are using a bolt-up engine assembly

ADVANCED INJECTOR PATH FORWARD

Based on the hotfire testing of advanced injector designs across the Phase 1a and Phase 1b test campaigns, Nammo would like to progress the following advanced injector designs forward to bolt-up altitude hotfire testing. All predicted data assumes the injector is fired in a chamber of length 56mm. This chamber length has been driven by the needs of conventional injectors:

Advanced Injector Follow On 1:

FFC% = 36.0%
NMA = NA
FFC Swirl Angle = 30°

Based on extrapolation of the test data from all the advanced injector designs tested it is felt this advanced injector configuration would give at the nominal operating point an Isp of **>318** seconds, a chamber temperature of **1477°C** and maintain top of chamber temperatures within acceptable limits.
This advanced injector variant would be made by modifying existing injector I693/2 and drilling out the FFC holes

This follow on advanced injector design is considered a fairly conservative, low risk, risk reduction option as we already have a good amount of hotfire test data that brackets this injector design

ADVANCED INJECTOR PATH FORWARD

Advanced Injector Follow On 2:

FFC% = 22%
NMA = NA
FFC Swirl Angle = 60°

Testing of all the advanced injector designs have shown that peak chamber temperature is not the primary design driver especially given the capabilities of the baselined Rhenium/Iridium chambers.
As mentioned previously, the Top of Chamber (ToC) temperatures are really the key thermal design driver and have led to FFC% being pushed up at the expense of Isp performance.

This second follow on advanced injector design looks to address this ToC thermal challenge with the novel thermal management strategy of concentrating all the Fuel Film Cooling very much at the top of the chamber. This strategy is based on the positive results seen on ToC temperatures when using 30 degrees swirl FFC. Concentrating the FFC at the top of the chamber would allow the FFC% to be reduced and therefore result an increase in Isp performance. The swirl angle of 60° has been chosen very much as an initial estimate and a number of factors would need to be considered before settling on the exact swirl angle include manufacturing feasibility considerations.

This strategy may result in an increase in peak chamber temperature but as noted previously, there is margin with regards to peak chamber temperature

ADVANCED INJECTOR PATH FORWARD

Advanced Injector Follow On 2 Continued:

FFC% = 22%
NMA = NA
FFC Swirl Angle = 60°

It is calculated that this injector design would result in the following performance figures:

Predicted Isp = 325 seconds
Predicted Chamber Temperature = 1660°C

These are of course predicted performance figures based on extrapolation of results from existing designs and the big question regarding this advanced injector follow on design is whether the Top of Chamber (ToC) temperatures are maintained within acceptable levels.

With this injector, there would be the option to drill out FFC holes to increase the FFC% should it be deemed necessary in order to control ToC temperatures or perhaps peak chamber temperatures. Any increase in FFC% would of course have an impact on Isp performance.

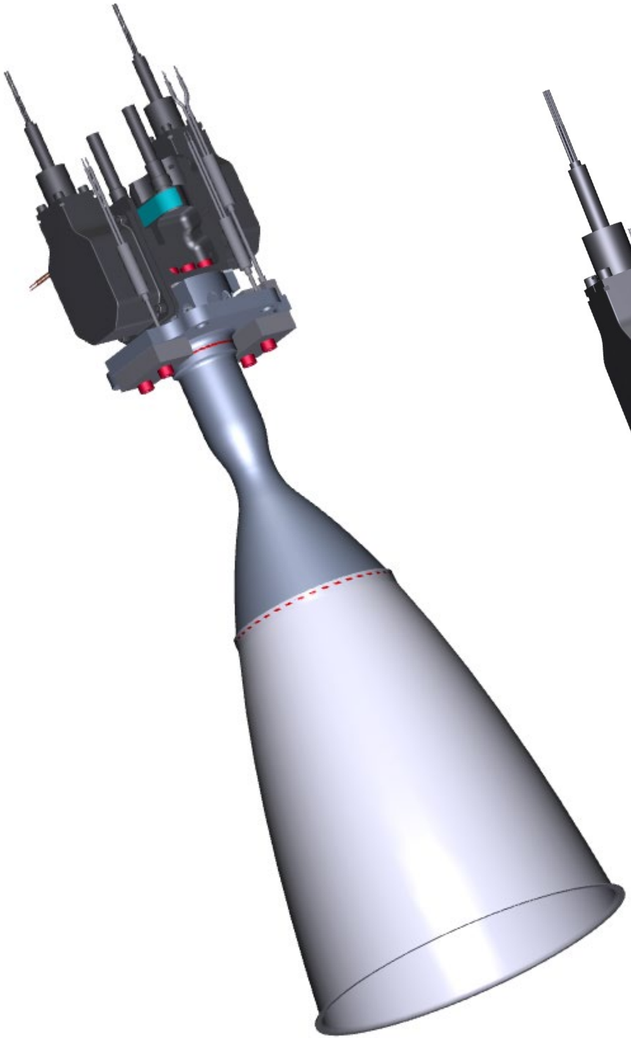
ESA DE-RISK PROJECT CONCLUSIONS

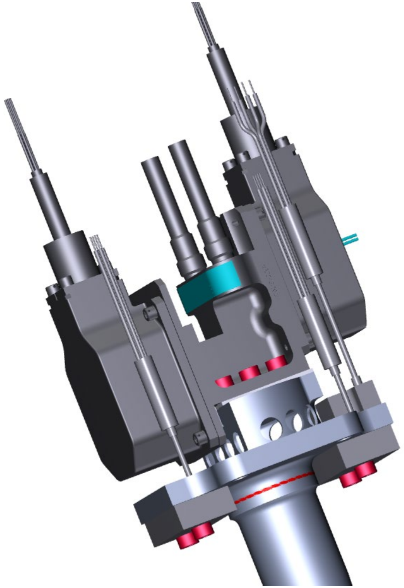
Nammo consider this ESA De-Risk project into the potential performance of this type of advanced injector a great success.

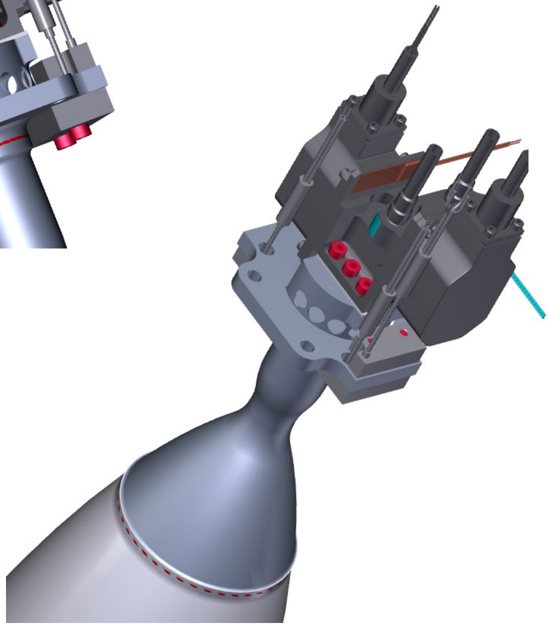
With very little optimization the advanced injector design has demonstrated excellent Isp performance for the resulting chamber temperature.

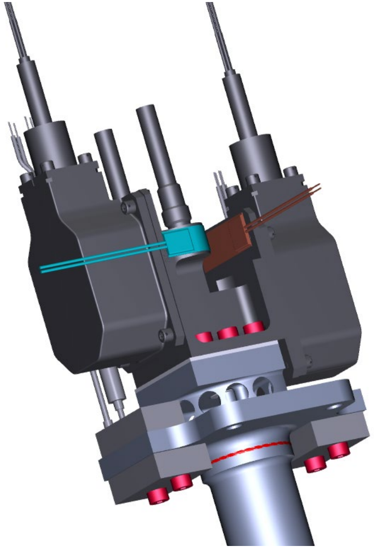
This ratio of Isp to chamber temperature for the advanced injector designs are significantly better than with conventional injector designs. This really shows the potential of this type of advanced injector.

It is felt with a further round of design optimization and testing, the advanced injector concept could produce world beating Isp performance within the capabilities of existing and available combustion chamber materials.







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Thank you.