U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – GROUND VEHICLE SYSTEMS CENTER

HEAVY-DUTY DIESEL PISTON THERMAL ANALYSIS: HIGH-TEMPERATURE ALLOYS

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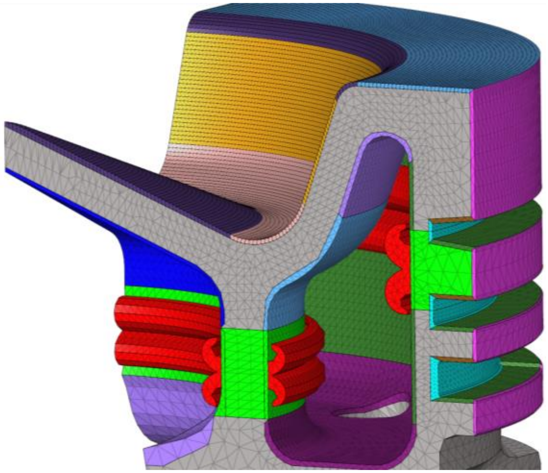
OBJECTIVE AND METHODS

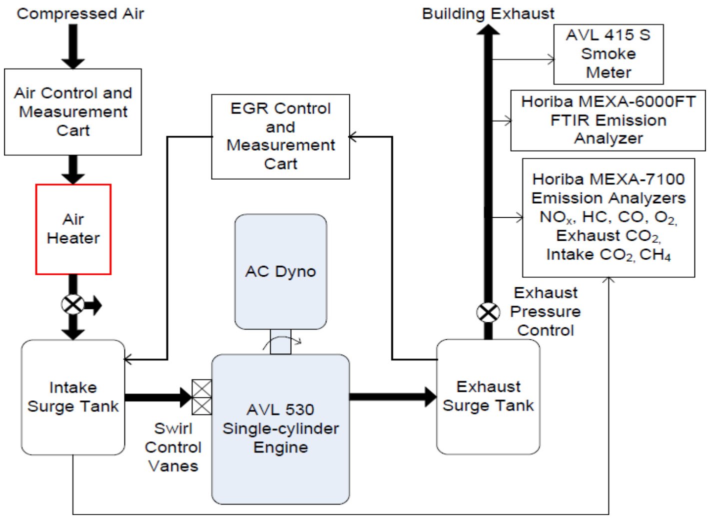
- Objective: Support a research program investigating the use of commercial and developmental high-temperature alloys in a heavy-duty diesel piston application
- Methods:
  - Perform a Steady-State Thermal-Stress Analysis to predict the piston temperature profile
    1. Given experimental measurements of piston surface heat flux (p.3) and subsurface temperature (p.4) for microalloyed steel (MAS) piston, calibrate the under-crown heat transfer coefficients (p.5) in the model
    2. Given experimental surface heat flux and calibrated heat transfer coefficients from previous step, model the piston temperature profiles (p.7) when changing to conductivity of high-temperature commercial alloys A286 (UNS S66286), 422 (S42200), DH31-EX (Daido Steel), and H10 (T20810)
  - Perform a fatigue analysis (not shown in this presentation)
- Finite element (FE) model details:
  - FEA / Fatigue Solver: Abaqus Standard / Fe-Safe
  - Procedure: Coupled Temperature-Displacement
  - Element Type: Solid (C3D4T) thermally coupled tetrahedron elements
  - Piston details: Federal Mogul design X6146F04,122 mm bore size

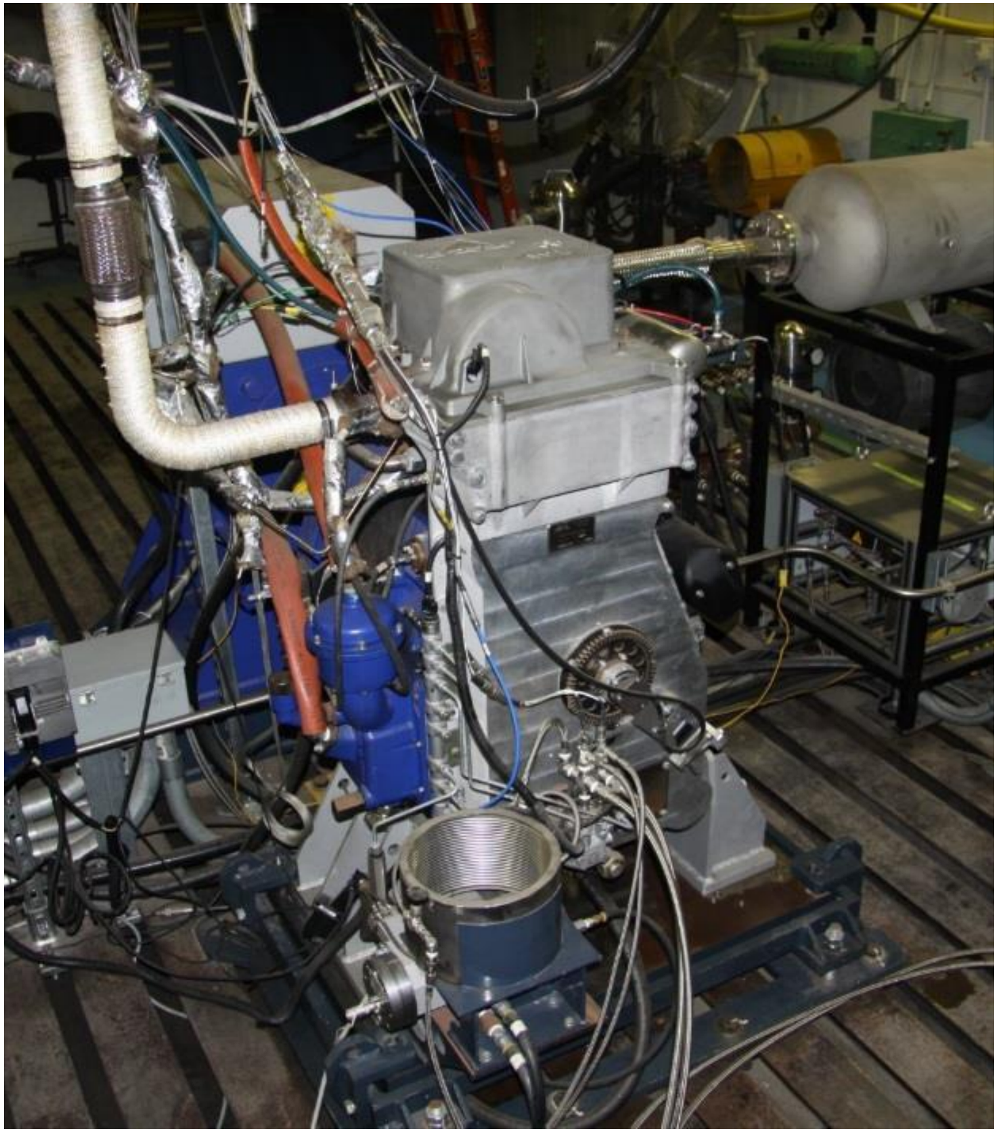


SINGLE-CYLINDER RESEARCH ENGINE

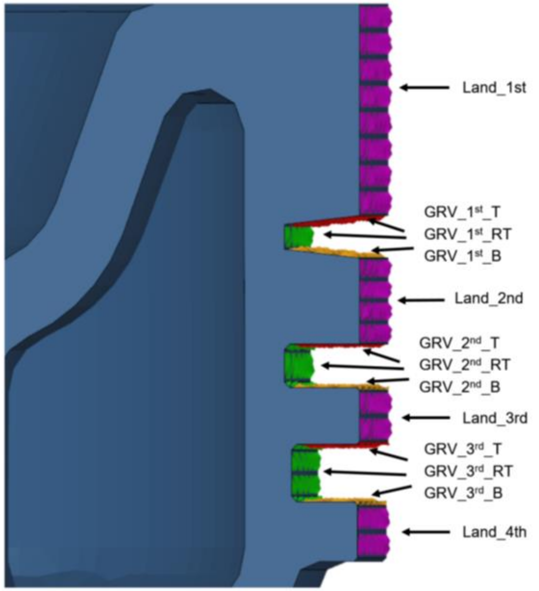
Four-stroke diesel engine specifications:

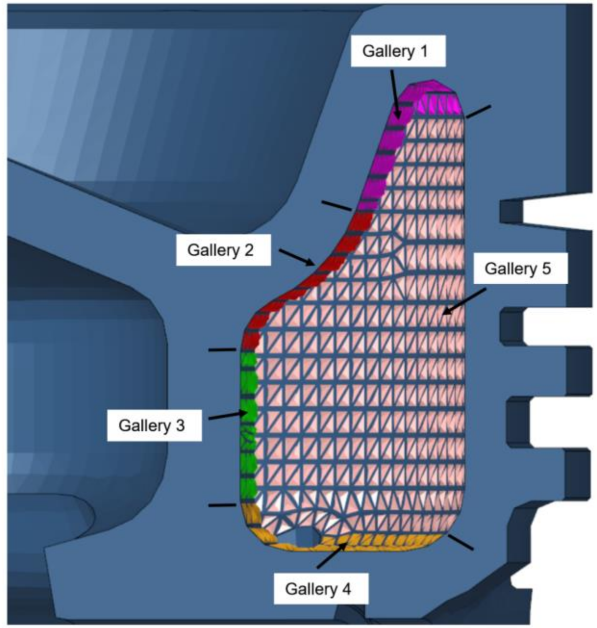
Displacement (l)	1.49
Bore (mm)	122
Stroke (mm)	128
Number of Valves	4
Compression Ratio	14.5
Swirl Ratio (variable)	0-3.5
Peak Firing Pressure (bar)	250
Max. Injection Pressure (bar)	2000
Injector Nozzle Geometry (mm)	8 hole x 0.167 (baseline)

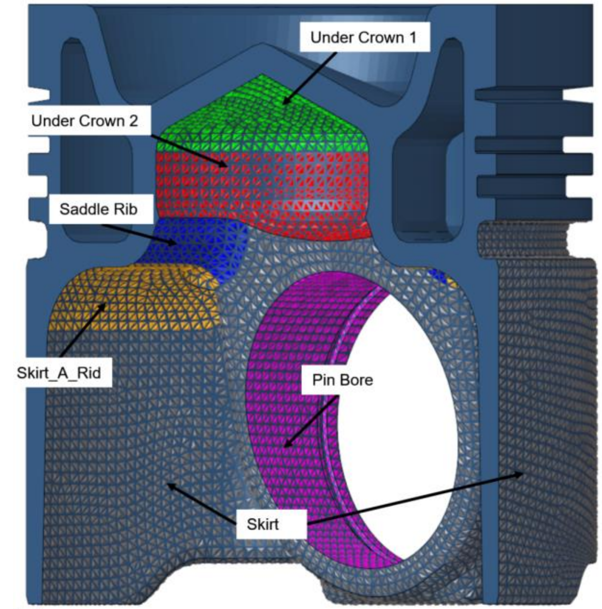




FEA MODEL: INITIAL TEMPERATURE & HEAT TRANSFER COEFFICIENTS







Group	Initial Temp C	Heat Transfer Coefficient W/ (m^2 * K)
Land_1st	300	200
Grv_1st_T	210	3000
Grv_1st_RT	160	1000
Grv_1st_B	150	3500
Land_2nd	140	2500
Grv_2nd_T	180	1550
Grv_2nd_RT	180	620
Grv_2nd_B	180	1550
Land_3rd	165	527
Grv_3rd_T	155	930
Grv_3rd_RT	155	620
Grv_3rd_B	155	930
Land_4th	150	527

Group	Initial Temp C	Heat Transfer Coefficient W/ (m^2 * K)
Gallery1	120	2200
Gallery2	120	2200
Gallery3	120	2000
Gallery4	125	1000
Gallery5	120	2000

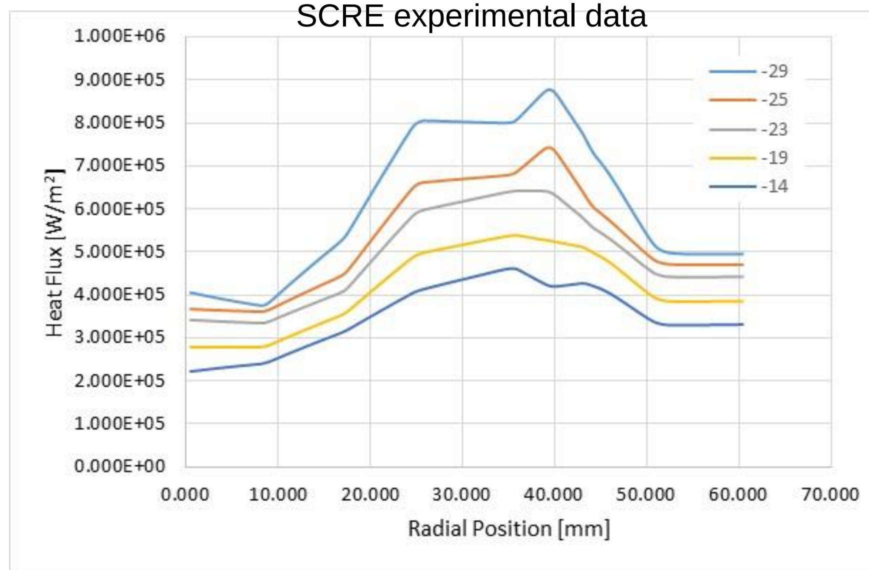
Group	Initial Temp C	Heat Transfer Coefficient W/ (m^2 * K)
Saddle_Rib	140	570
Under_Crown1	170	1000
Under_Crown2	140	750
Pin_Bore	180	1800
Skirt_a_rid	140	570
Skirt	140	570
Pin	150	100,000

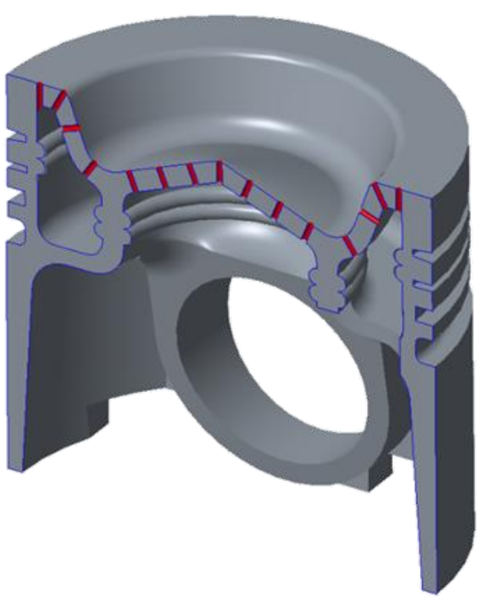
*Skirt_a_rid and Saddle_Rib missing HTC and Temperature properties, copied the properties from Skirt Group.

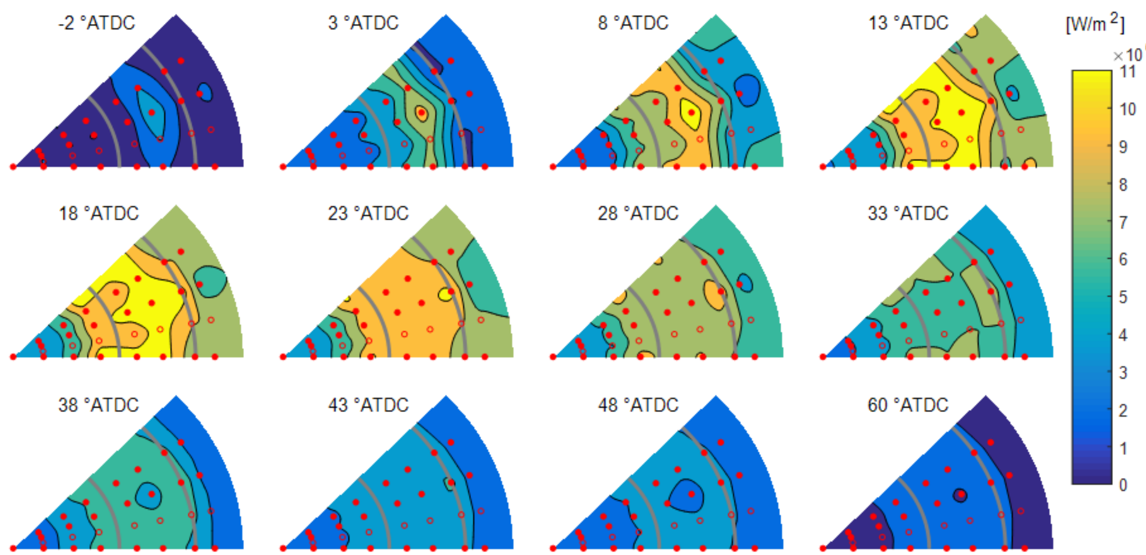
Reference:
Federal Mogul Report RDS 2011-0174, "Structural Analysis of AVL TARDEC X6147F02_FEA1," 2011.

PISTON CROWN HEAT FLUX BOUNDARY CONDITION

- Model rated power operating condition
  - 2500 rpm, $IMEP_g$= 20.3 bar
  - Start of injection command (SOIC) -25˚ aTDC
- Assume heat flux only a function of radius (constant in azimuthal direction)
- Heat flux generated from surface fast-response thermocouple measurements in a single-cylinder research engine (SCRE)
  - Gingrich, Eric, *High-output Diesel Engine Heat Transfer*. PhD dissertation, University of Wisconsin - Madison, 2020.



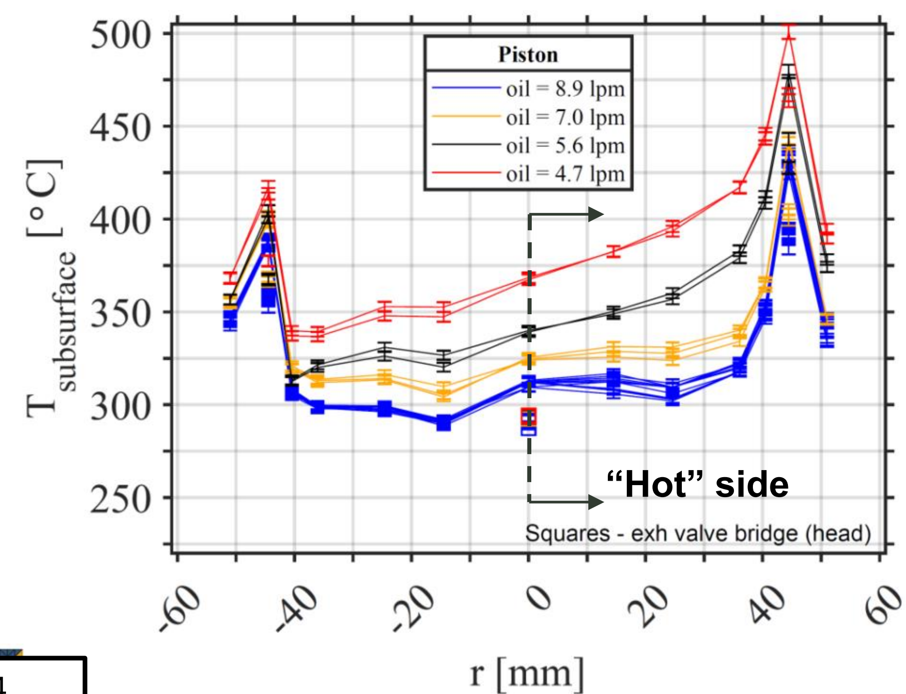


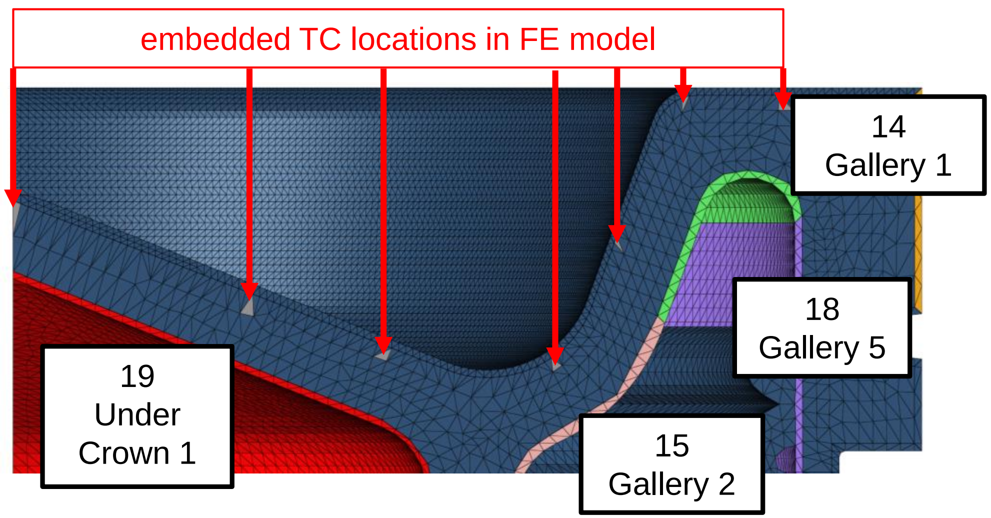


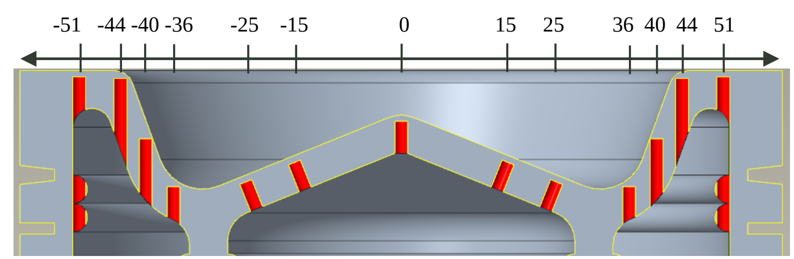
PISTON OIL GALLERY BOUNDARY CONDITION

- Model rated power operating condition
  - 2500 rpm, $IMEP_g$= 20.3 bar
  - SOIC -25˚ aTDC
- Calibrate the FE model heat transfer coefficients on the under-crown surfaces to match embedded (subsurface) thermocouple (TC) measurements of an MAS piston in SCRE
  - Unpublished data set
  - Use data from "Hot" side of piston (SCRE utilizes a single piston cooling nozzle)

SCRE experimental data



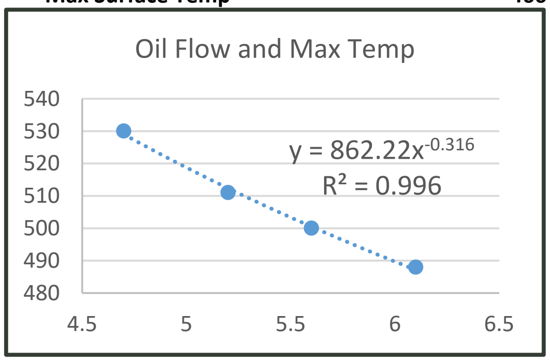


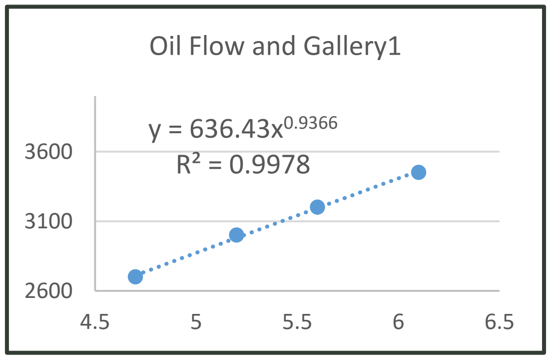


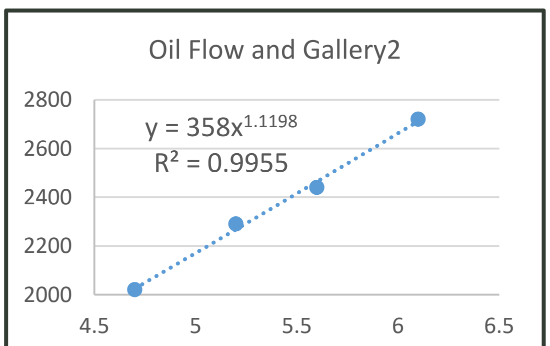
Embedded TC radial locations in SCRE
(all TCs nominally 1 mm below surface)

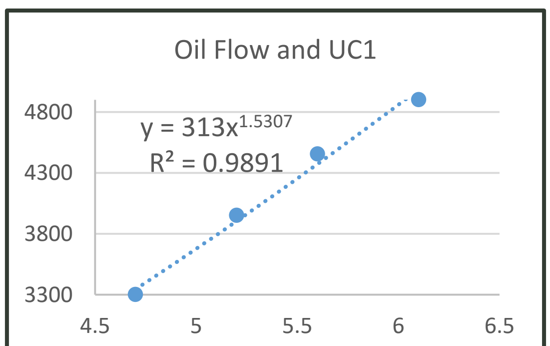
FE MODEL HTC CALIBRATION – BOTTOM HTC
MAX SURFACE TEMP 550 AND 600 C

Operating Condition (Rated Power, 2500rpm, 20.3bar IMEPg)										
Average Temperature* (1mm Subsurface) for prescribed surface Heat Flux										
Parametric Study of bottom HTCs										
Oil Flow Rate (lpm)	**8.9**		**6.1**		**5.6**		**5.2**		**4.7**	
HTC W/ (m^2 *K)	**Gallery 1**	**3950**	**Gallery 1**	**3450**	**Gallery 1**	**3200**	**Gallery 1**	**3000**	**Gallery 1**	**2700**
	Gallery 2	**3350**	**Gallery 2**	**2720**	**Gallery 2**	**2440**	**Gallery 2**	**2290**	**Gallery 2**	**2020**
	Under Crown 1	**6380**	**Under Crown 1**	**4900**	**Under Crown 1**	**4455**	**Under Crown 1**	**3950**	**Under Crown 1**	**3300**
Thermocouples	Test [C]	FEA [C]	Test [C]	FEA [C]	Test [C]	FEA [C]	Test [C]	FEA [C]	Test [C]	FEA [C]
1	362	399	366	416	376	425	383	434	392	448
2 / 7	449 / 408	448	465 / 424	470	477 / 435	482	486 / 449	493	501 / 465	511
3	369	370	394	394	410	409	424	420	445	442
4	329	309	365	332	381	345	396	355	417	375
5	312	321	346	343	358	354	373	365	395	386
6	314	311	340	336	350	347	363	361	383	386
8	314	327	332	353	340	365	351	380	368	406
Max Surface Temp		**466**		**488**		**500**		**511**		**530**



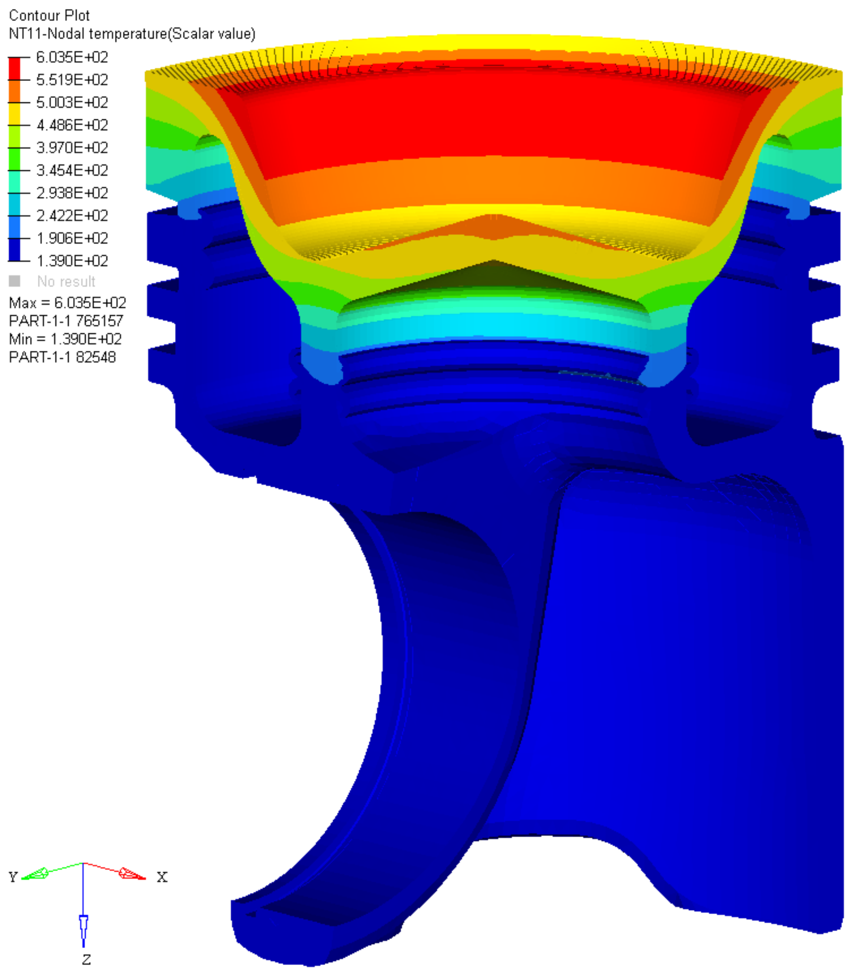






Oil Flow Rate	**4.15**	**3.15**
Gallery 1	**2410**	**1860**
Gallery 2	**1760**	**1295**
Under Crown 1	**2760**	**1810**
Thermocouples	FEA [C]	FEA [C]
1	465	505
2 / 7	532	584
3	466	529
4	398	457
5	410	476
6	414	496
8	436	525
Max Surf Temp	**551.0**	**603.5**

STEADY STATE TEMPERATURE-MATERIAL- MAS, 3.15 LPM OIL FLOW

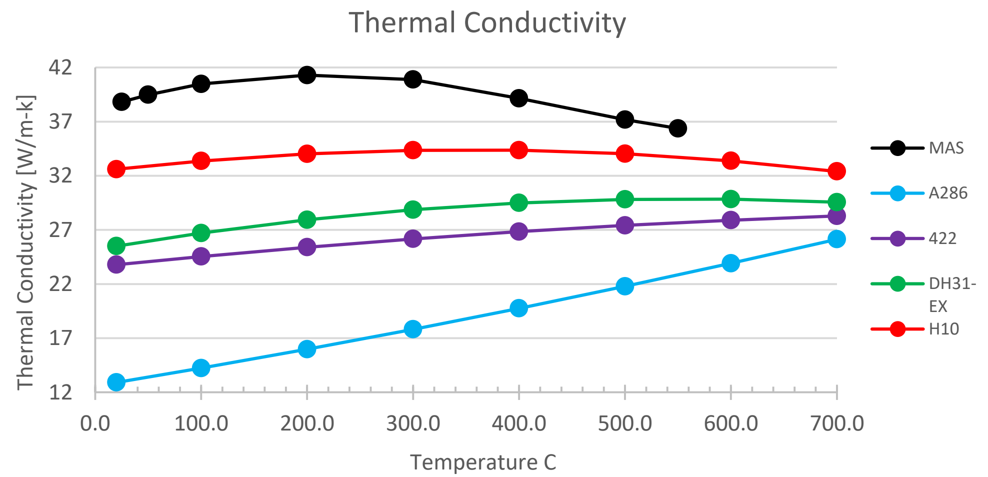


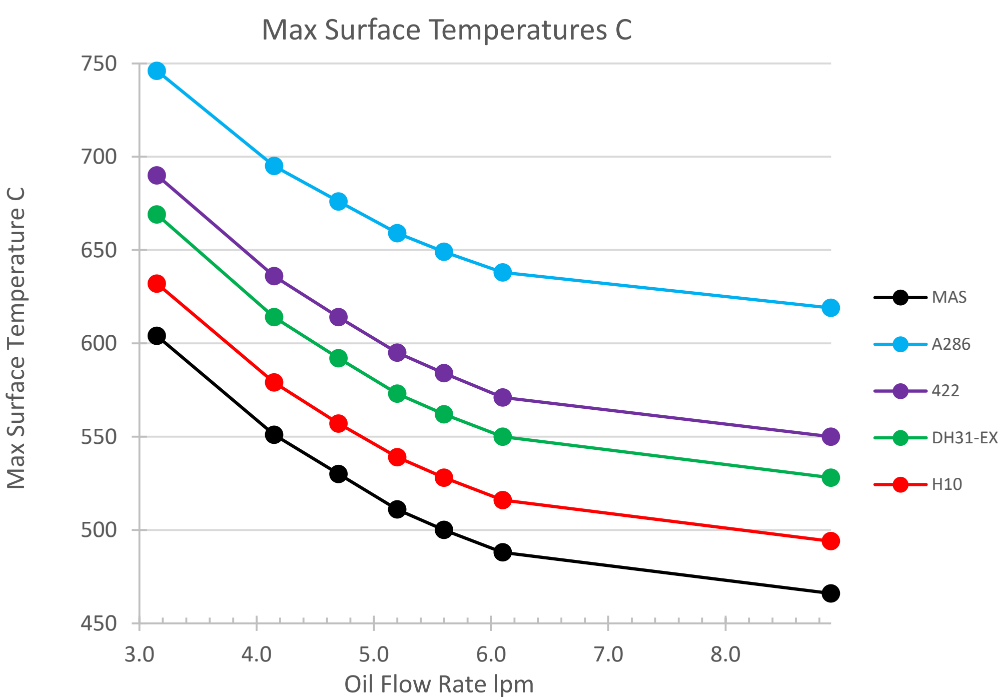
Group	Group Name	Surface Temperatures C
1	Bowl Apex	535.3
2	Bowl Bot	517.6
3	Bowl Wall	600.4
4	**Bowl Rim**	**603.5**
5	Bowl Top	589.6
6	Grv 1st RT	246.5
7	Grv 2nd RT	161.2
8	Grv 3rd RT	148.6
9	Gallery 1	491.5
10	Gallery 2	447.1
11	Gallery 3	253.4
12	Gallery 4	164.2
13	Gallery 5	349.5
14	Pin Bore	152.4
15	Saddle Rib	170.8
17	Skirt A Rid	142.6
18	Under Crown 1	475.7

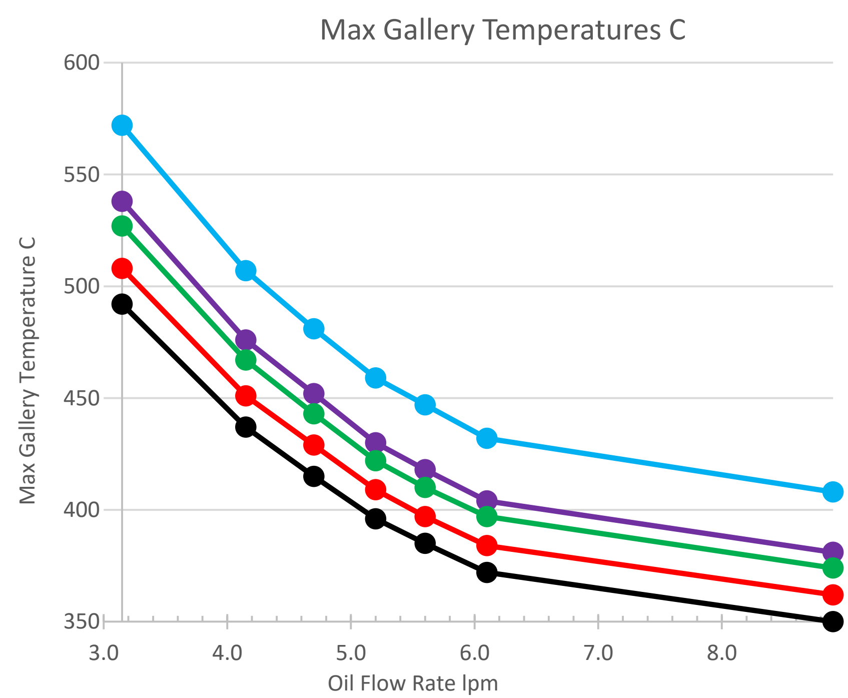
THERMAL CONDUCTIVITY EFFECT: FOUR CANDIDATE HIGH-TEMPERATURE ALLOYS

Temperature	Conductivity [W/m-K]			
[C]	A286	422	DH31-EX	H10
20	12.91	23.79	25.50	32.60
100	14.24	24.54	26.70	33.36
200	15.98	25.40	27.94	34.03
300	17.81	26.17	28.86	34.36
400	19.75	26.84	29.49	34.36
500	21.78	27.41	29.81	34.04
600	23.91	27.90	29.84	33.38
700	26.14	28.29	29.55	32.40

Conductivity data compiled by Dean Pierce, Oak Ridge National Laboratory

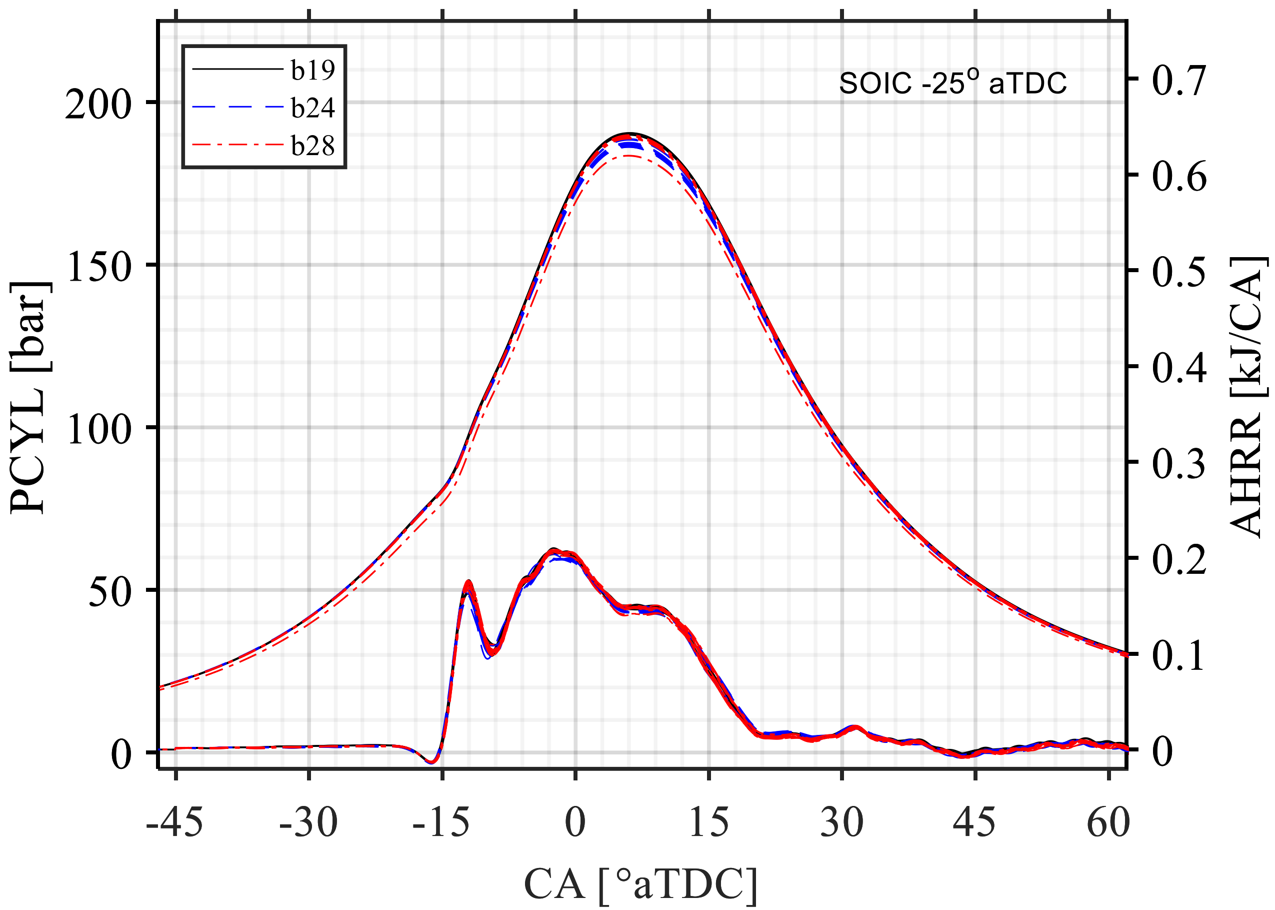






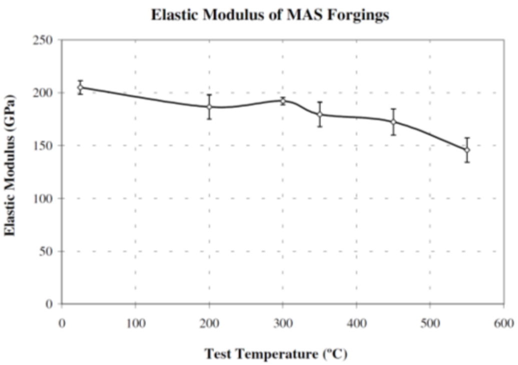
BACK-UP SLIDES

CYLINDER PRESSURE (PCYL) AND APPARENT HEAT RELEASE RATE (AHRR)

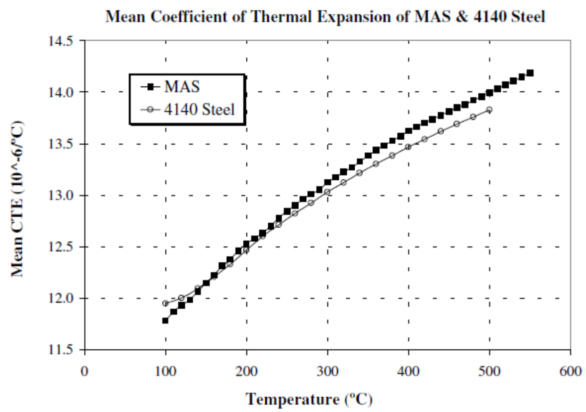


- Operating condition of interest for FE modeling: 2500 rev/min, 20.3 bar gross indicated mean effective pressure (IMEPg) at injection timing SOIC -25˚ aTDC
- For piston abuse testing, cylinder pressure is less than 200 bar for safety

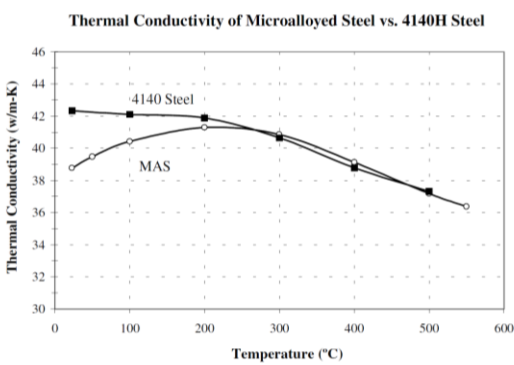
FEA MODEL INPUTS



Elastic Modulus Pa (N/m^2)	Temperature C
2.05E+11	25
1.86E+11	200
1.91E+11	300
1.79E+11	350
1.73E+11	450
1.46E+11	550



Thermal Expansion 10e-6 m/m*K	Temperature C
11.78	100
11.87	110
11.93	120
11.98	130
12.06	140
12.15	150
12.22	160
12.31	170
12.38	180
12.46	190
12.52	200
12.57	210
12.63	220
12.70	230
12.77	240
12.84	250
12.90	260
12.97	270
13.01	280
13.05	290
13.13	300
13.17	310
13.23	320
13.27	330
13.32	340
13.39	350
13.44	360
13.48	370
13.53	380
13.58	390
13.63	400
13.66	410
13.70	420
13.73	430
13.78	440
13.81	450
13.85	460
13.88	470
13.93	480
13.96	490
14.00	500
14.03	510
14.07	520
14.11	530
14.15	540
14.19	550



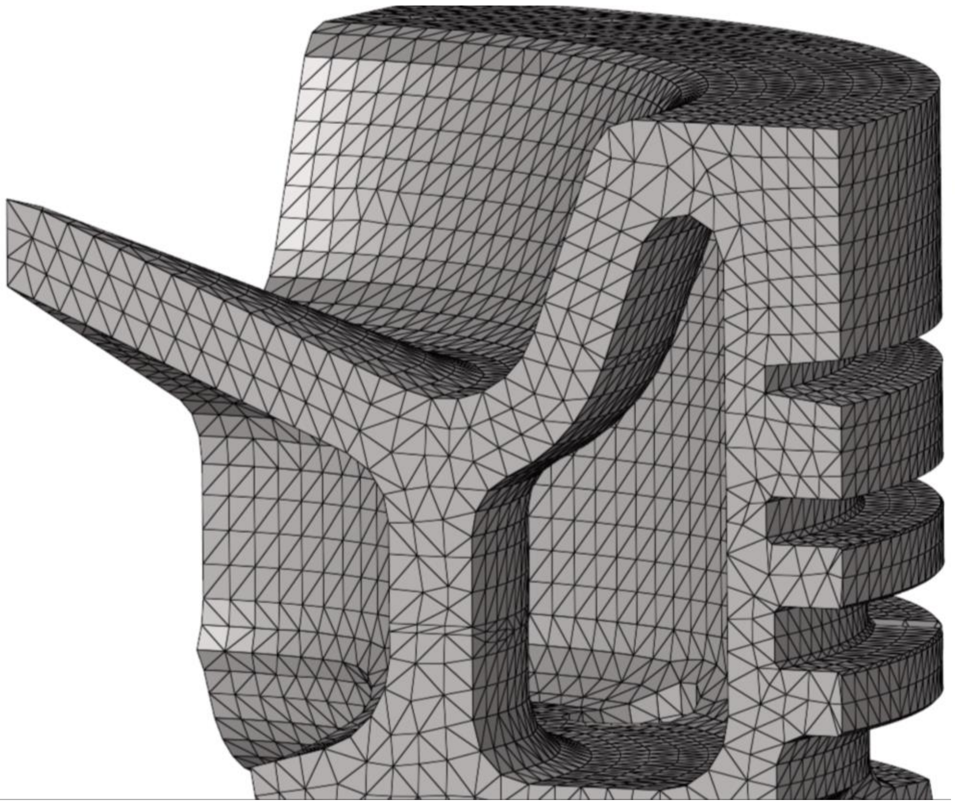
Conductivity W / (m*K)	Temperature C
38.815	25
39.481	50
40.481	100
41.296	200
40.889	300
39.148	400
37.185	500
36.370	550

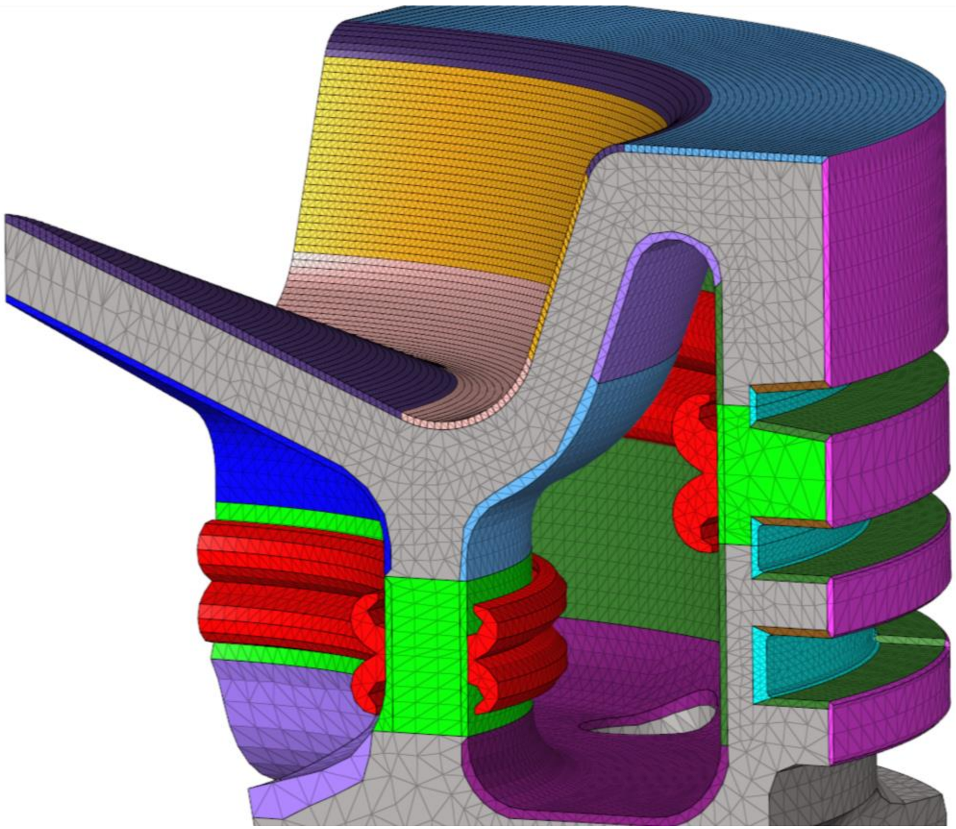
Reference:

Chen and Worden, SAE 2000-01-1232, “Evaluation of Microalloyed Steel for Articulated Piston Applications in Heavy Duty Diesel Engines,” 2000.

MESH REFINEMENT

- Finer mesh at the critical areas.
- Included the friction weld.





- Created separate mesh regions to easily modify the HTC for different materials to match the thermocouple temperature test data.

SOI SURFACE HEAT FLUX
AVERAGE OF BEST FIT

Best Fit for each SOI

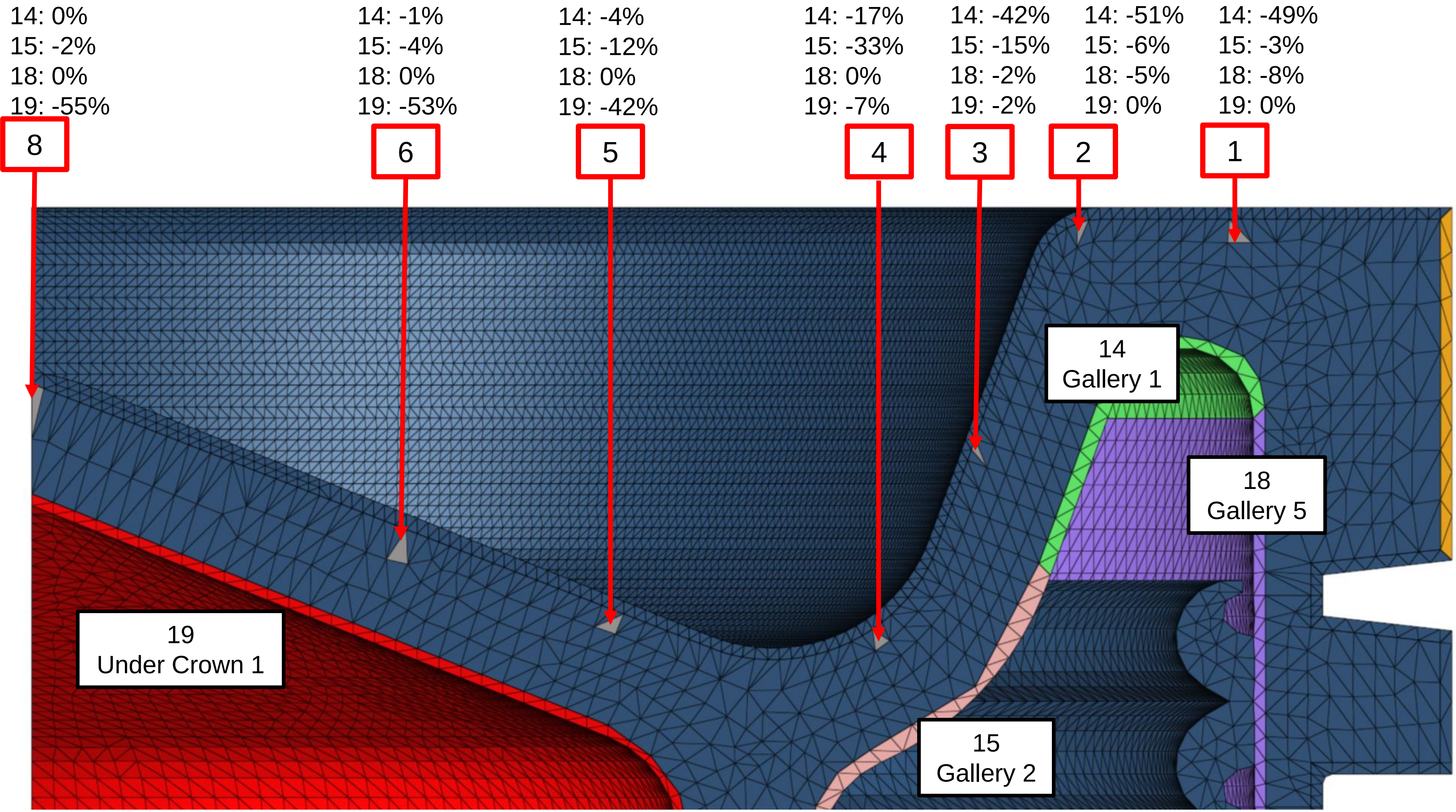
Operating Condition 3 (Rated Power, 2500rpm, 20.3bar IMEPg)										
Average Temperature* (1mm Subsurface) for each Heat Flux										
Parametric Study of Surface Heat Flux										
SOI [˚ATDC] / Heat Flux (W)	-29	9910	-25	8557	-23	7787	-19	6654	-14	5590
Radius / Peak Heat Flux (W/m^2)	39.529	877412	39.360	742659	36.259	642406	35.881	538573	35.481	461834
HTC W/ (m^2 *K)	Gallery 1	5600	Gallery 1	4160	Gallery 1	3360	Gallery 1	2540	Gallery 1	1900
	Gallery 2	2525	Gallery 2	2970	Gallery 2	3040	Gallery 2	3090	Gallery 2	3500
	Under Crown 1	6730	Under Crown 1	6465	Under Crown 1	6140	Under Crown 1	5455	Under Crown 1	4800
	[C]		[C]		[C]		[C]		[C]	
1	374	394	362	394	360	394	350	385	341	367
2 / 7	461 / 426	456	449 / 408	443	443 / 404	439	430 / 391	427	409 / 376	402
3	380	381	369	369	363	363	350	352	331	332
4	339	343	329	314	323	305	312	287	296	265
5	329	353	312	322	306	311	294	293	283	276
6	333	332	314	311	306	302	294	290	284	280
8	335	340	314	327	307	318	296	302	287	290
Max Surface Temp		478		461		455		441		414

Avg
3512
3025
5918

Avg HTC from Best Fit for each SOI

Operating Condition 3 (Rated Power, 2500rpm, 20.3bar IMEPg)										
Average Temperature* (1mm Subsurface) for each Heat Flux										
Parametric Study of Surface Heat Flux										
SOI [˚ATDC] / Heat Flux (W)	-29	9910	-25	8557	-23	7787	-19	6654	-14	5590
Radius / Peak Heat Flux (W/m^2)	39.529	877412	39.360	742659	36.259	642406	35.881	538573	35.481	461834
HTC W/ (m^2 *K)	Gallery 1	3510	Gallery 1	3510	Gallery 1	3510	Gallery 1	3510	Gallery 1	3510
	Gallery 2	3025	Gallery 2	3025	Gallery 2	3025	Gallery 2	3025	Gallery 2	3025
	Under Crown 1	5920	Under Crown 1	5920	Under Crown 1	5920	Under Crown 1	5920	Under Crown 1	5920
	[C]		[C]		[C]		[C]		[C]	
1	374	448	362	412	360	390	350	357	341	323
2 / 7	461 / 426	521	449 / 408	465	443 / 404	434	430 / 391	393	409 / 376	351
3	380	433	369	387	363	359	350	323	331	289
4	339	355	329	321	323	304	312	276	296	253
5	329	363	312	328	306	313	294	288	283	267
6	333	344	314	318	306	305	294	284	284	267
8	335	353	314	334	307	321	296	296	287	277
Max Surface Temp		544		483		450		407		362

HTC CALIBRATION – HTC EFFECT ON SUBSURFACE TEMPERATURE THERMOCOUPLES



- Gallery 1 HTC has the most effect on Thermocouples 1-3.
- UnderCrown1 HTC has the most effect on Thermocouples 5-8.
- Gallery 2 HTC has significant effect on Thermocouples 3-5.
- Gallery 5 showed less than other HTCs and was excluded in the Parametric study.