



**da Vinci**

PROJECT



**Canada's PRIZE Contender**

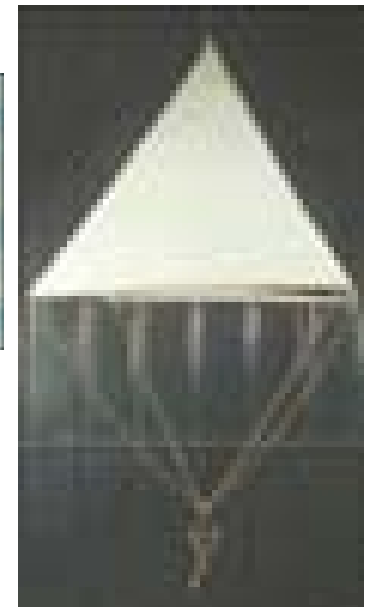
# AERO-HEATING ANALYSIS FOR DAVINCI SPACE PROJECT ROCKET BALLUTE

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<http://www.davinciproject.com>

**Prepared for NASA Thermo-Fluids Workshop  
Huntsville, Alabama, Sept 10-14, 2001**



**X-Project:** objective is to fly a spacecraft with the three astronauts, to elevation >100 km and to do it TWICE during the two week period. No government funding is allowed. Award: 10 million \$\$\$, 20 teams are now registered



**DaVinci Project:** to meet this objective using “off-the shelf” commercial technologies. Utilize helium balloon for delivery to 80,000 ft, rocket on the tether, commercial multi-use engines. Rocket is returned using pressurized ballute to be deployed during the re-entry.

Follows Leonardo da Vinci parachute idea (see first title slide)

Rocket



**Ballute 1:**  
Peak  
temperatures

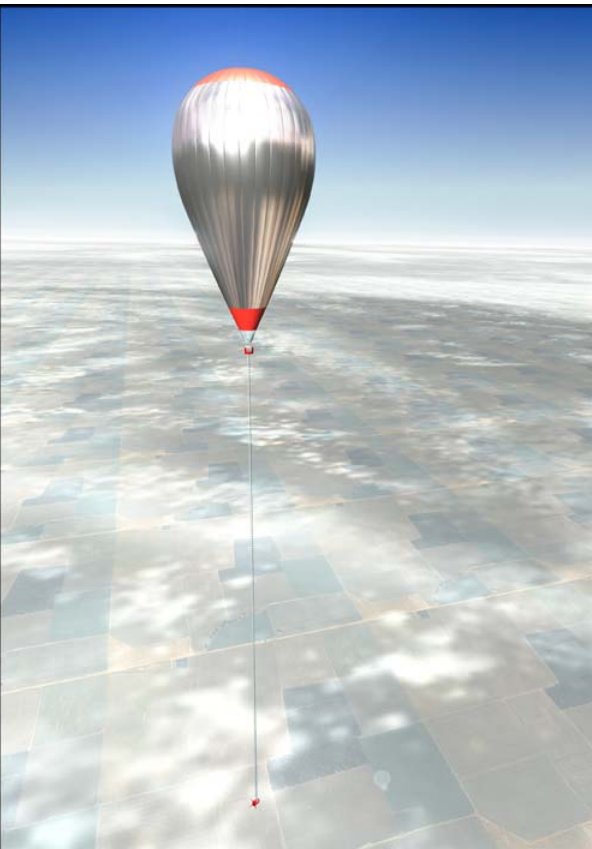
**Ballute 2:**  
High to medium  
Temperatures

Example: Shock wave visualization



**Bow shock wave is formed in front of the vehicle, internally pressurized ballutes assume thermal and pressure loads and protect the rocket and astronauts (rear) from excessive heat during re-entry.**

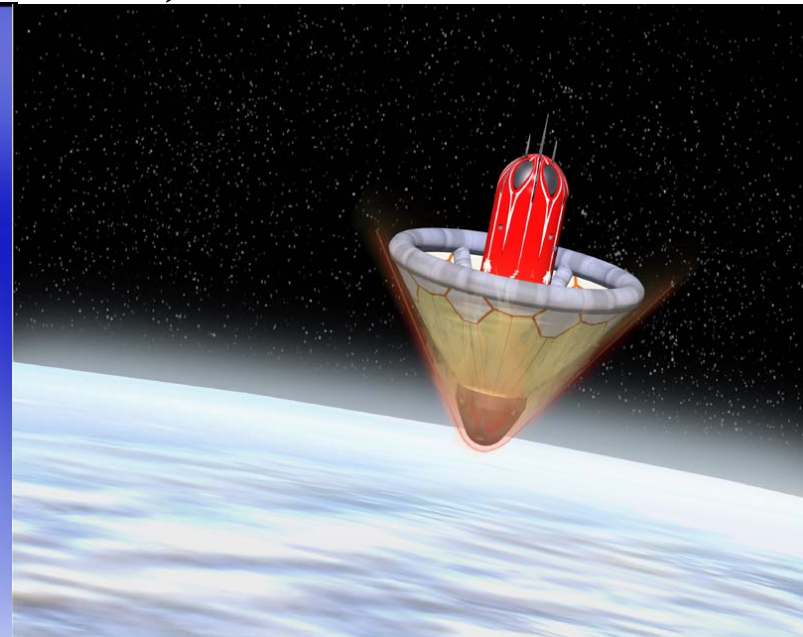
a)



b)



c)



- a) Vehicle tethered below the balloon
- b) Close-up view of Vehicle
- c) Vehicle re-entry with ballute deployed



**Brian Feeney -  
Project Director**



**Full scale prototype**



**daVinci Team**



**In the exhibit hall**



**First conceptual  
prototype**



**Assembled ballutes**

- A) CFD REQUIRED ADDITIONAL DATASETS THAT DESIGNERS DID NOT HAVE INITIALLY, OR HAVE NOT CONSIDERED INITIALLY (ballute thickness, configuration, velocity estimations)**
- B) CFD ANSWERED SOME QUESTIONS THAT DESIGNERS HAD RAIZED (Cd, Pressure)**
- C) CFD RAIZED SET OF NEW QUESTIONS FOR DESIGNERS TO THINK ABOUT (STABILITY, LOADS, OVERHEATING)**
- D) CFD REQUIRED NEW AND MORE ACCURATE DATA (TRAJECTORY, GEOMETRY), ELEVATED DESIGN PROCESS TO A NEW LEVEL**

**MAJOR “PRACTICAL” CFD DILLEMA → CHOICE OF CFD SOFTWARE and MODELS  
ULTIMATELY WE USED WHAT WE COULD AFFORD AND WHAT WE KNEW.**

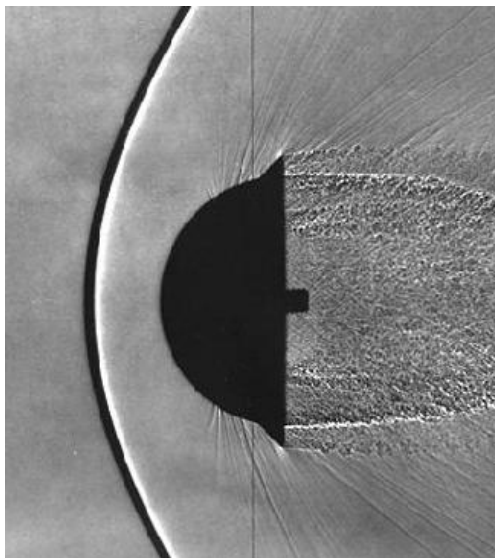
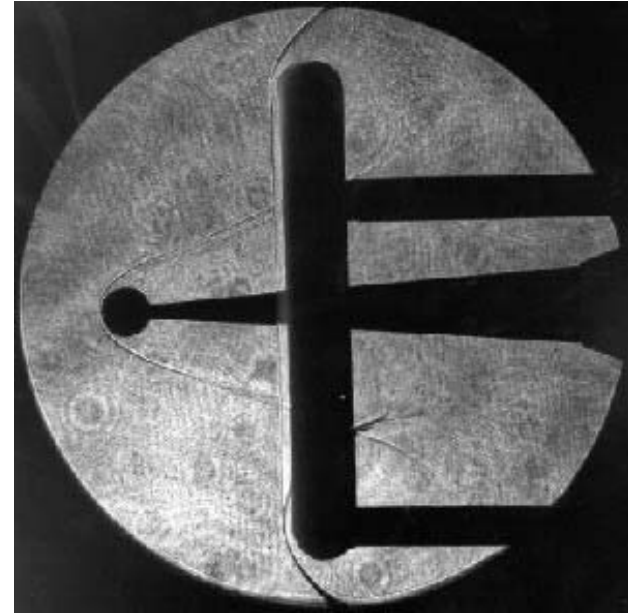
**CFD-ACE+ software package was utilized during the phase of conceptual design.**

**According to software developer (CFDRC) it can predict supersonic flows up to Mach =4.**

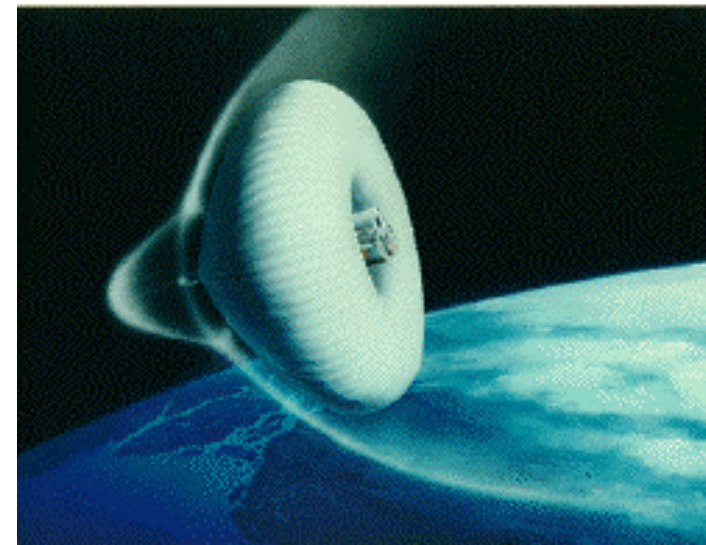
**We estimated air and flow conditions, temperature distributions, pressure field and drag coefficient Cd. These data helped to further modify the trajectory and to make new apogee and altitude estimations for the overall mission. These changes allowed us to minimize external thermal loads and to meet and exceed ballute material limitations.**

**At this point minor changes in ballute shape are no longer mission critical due to safety factor on material properties. Pressure forces on ballute were also estimated and weight requirements for helium gas were established.**

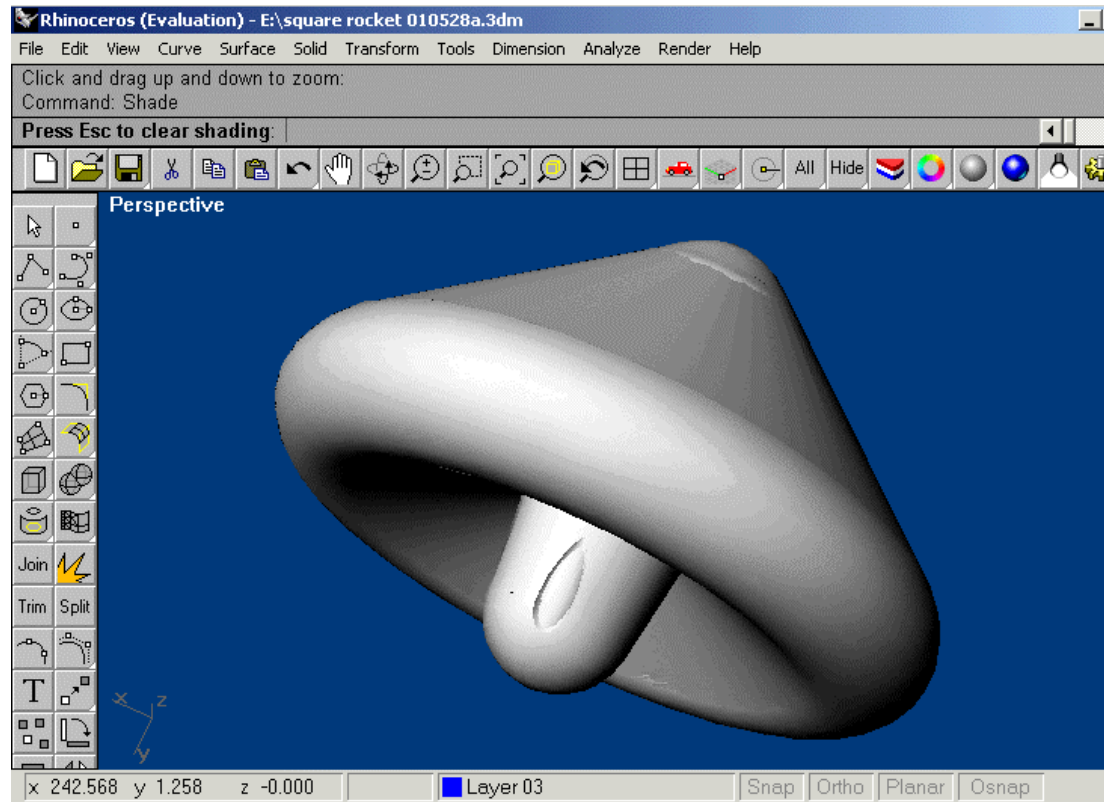
**MODE OF OPERATION: DESIGNERS PROVIDE INPUT ---> CFD ---> DISCUSSIONS ---> NEW INPUT --> more CFD**



**Bow shock  
visualization**

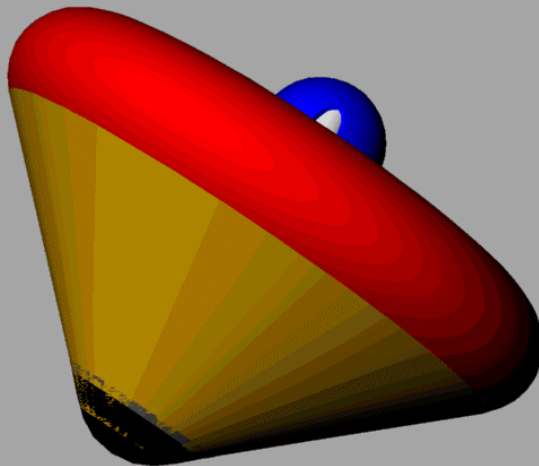
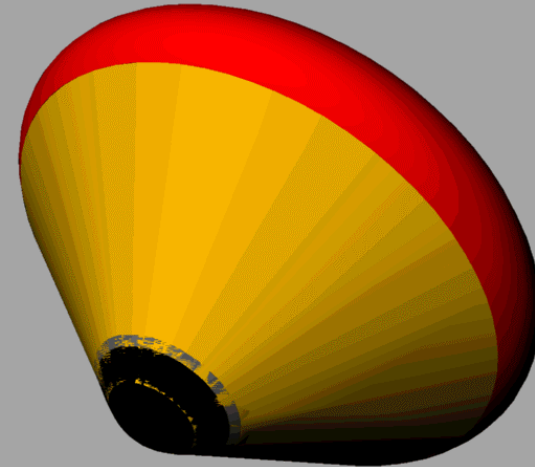
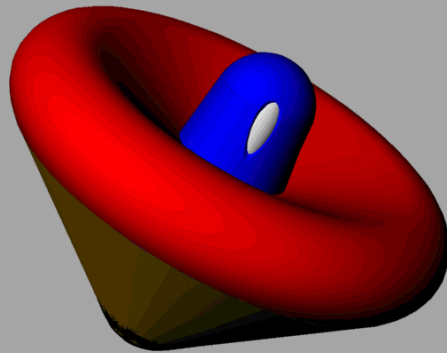


# Rocket Ballute - Present Design



**New Conceptual Configuration evolved as a result of engineering evaluation that followed CFD studies -- SECOND ITERATION OF CONCEPTUAL DESIGN**

# Rocket Ballute-Present Design

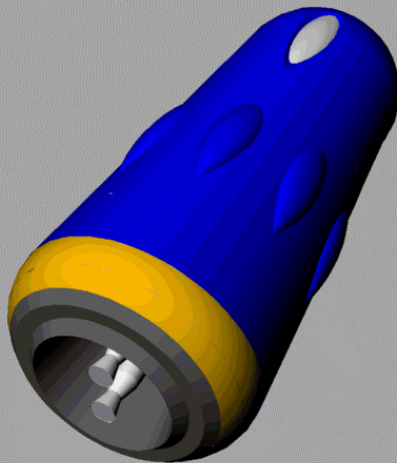
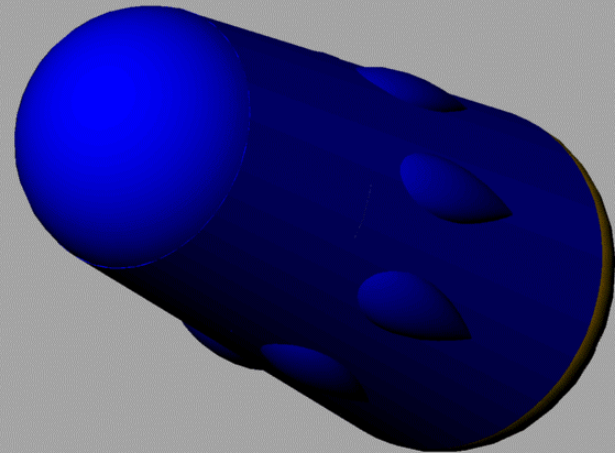
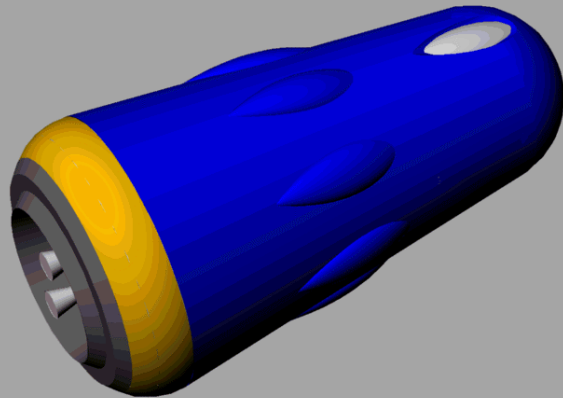


## CHANGES:

- larger OD for ballute
- larger filled volume (front)
- longer to avoid “wake closure” on capsule
- longer to move center of pressure away from center of mass

<<CONFIGURATION IS FINALIZED>>

# Rocket --- Present Design



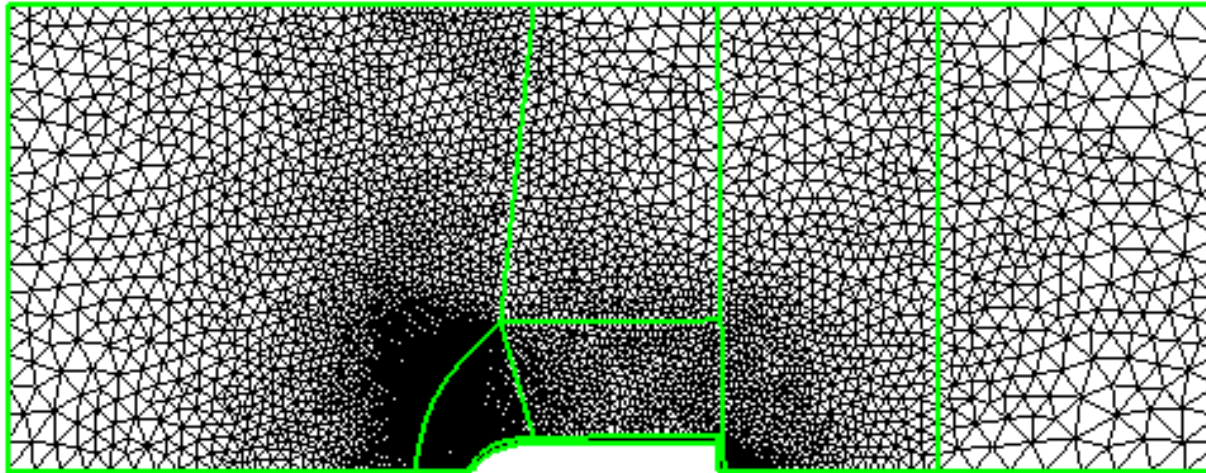
## CHANGES:

-larger OD for rocket "base"

-larger front nose diameter and angle

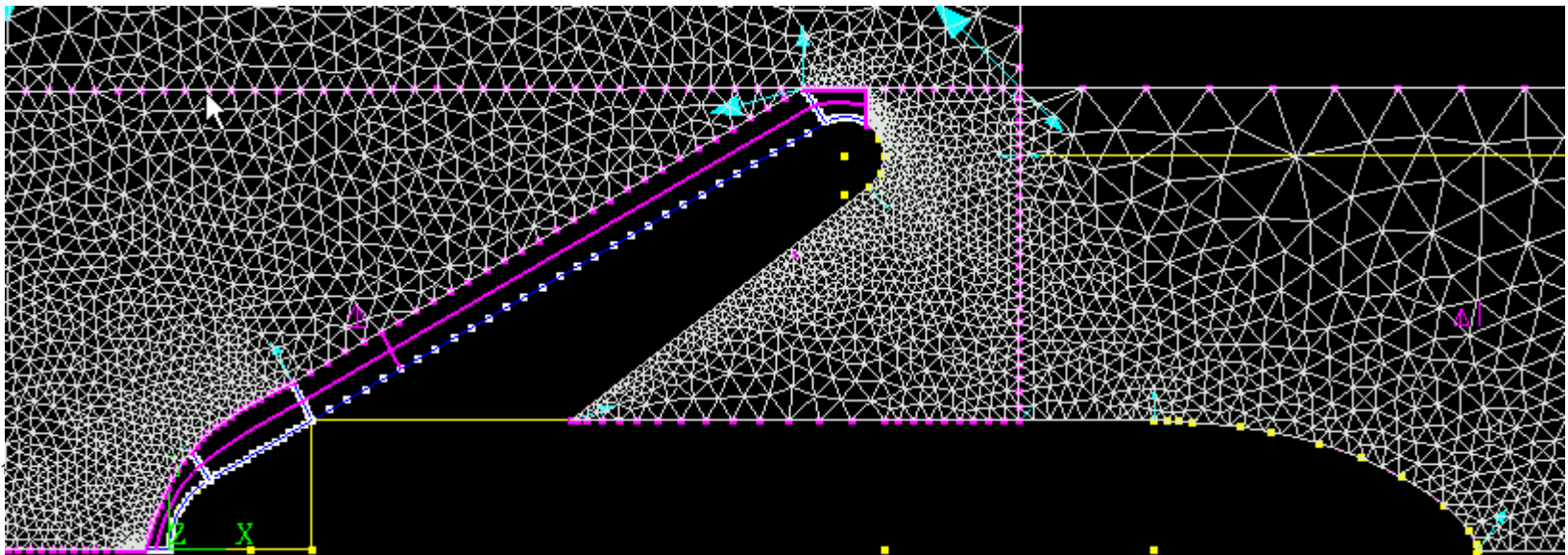
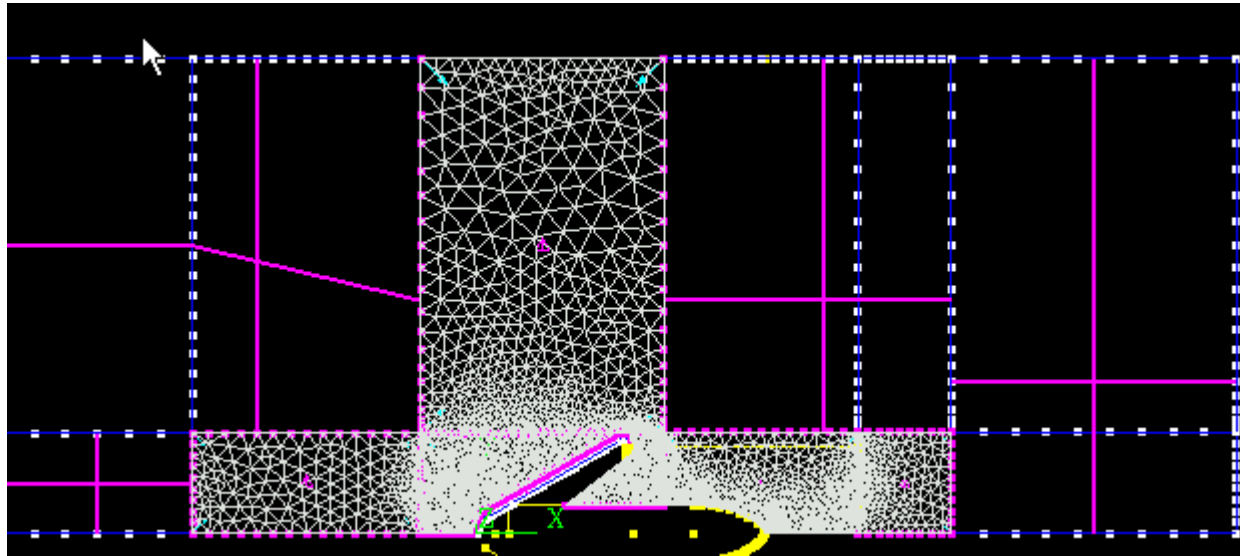
**SUBJECT TO SUBSEQUENT EVALUATION**

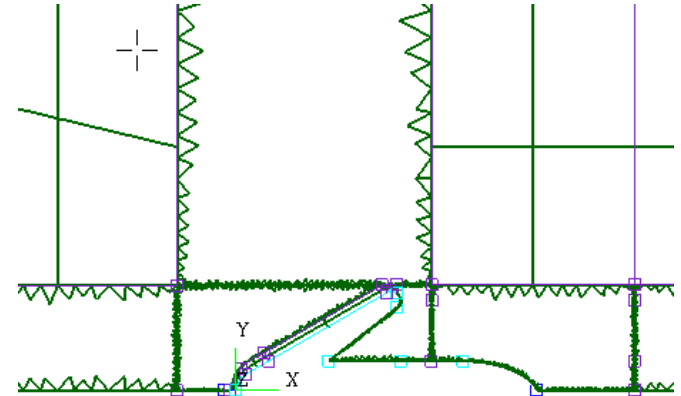
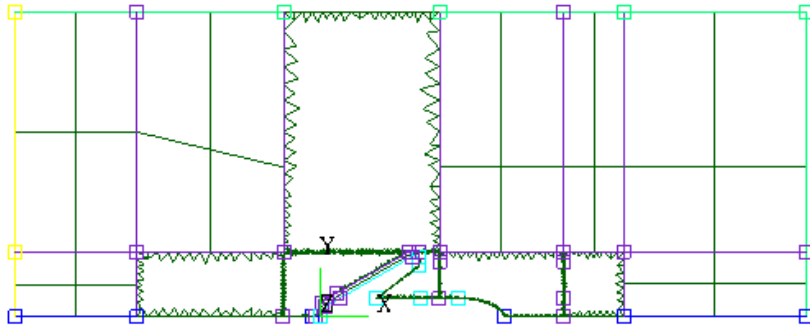
# Computational Setup



Rocket

# Hybrid S-U Gridding





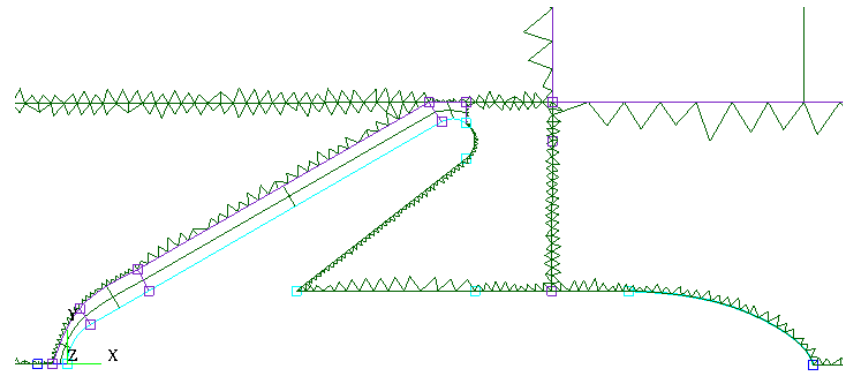
Output

Pressure Forces

Name	Key	Type	X-axis	Y-axis	
4	b1	464	Wall	1.722654E+04	-1.191149E+04
7	b1	471	Wall	1.861155E+04	-3.223037E+04
9	b2	491	Wall	2.857052E+05	-4.947670E+05
11	b3	492	Wall	5.738700E+03	-1.255066E+04
62	rb	583	Wall	-4.191336E-12	9.547799E+03
64	rbrear	585	Wall	3.005454E+03	1.291571E+04
75	rb	542	Wall	0.000000E+00	2.260614E+04
76	rb	543	Wall	-4.279382E-12	9.828310E+03
77	b4	598	Wall	1.397867E+04	6.904508E+02
78	b5s	599	Wall	3.215643E+04	-4.123918E+04

Shear Forces

Name	Key	Type	X-axis	Y-axis	
4	b1	464	Wall	2.884109E+01	2.981358E+01
7	b1	471	Wall	1.435156E+02	8.290480E+01
9	b2	491	Wall	1.887833E+03	1.088571E+03
11	b3	492	Wall	1.684699E+02	2.881604E+01
62	rb	583	Wall	-3.849444E+00	3.784508E-01
64	rbrear	585	Wall	-2.980826E+00	3.375424E-01
75	rb	542	Wall	-2.468475E+00	8.473813E-02
76	rb	543	Wall	-3.492539E+00	-2.613778E-02
77	b4	598	Wall	1.106551E+01	-6.542686E+00
78	b5s	599	Wall	2.188292E+00	1.945553E+00



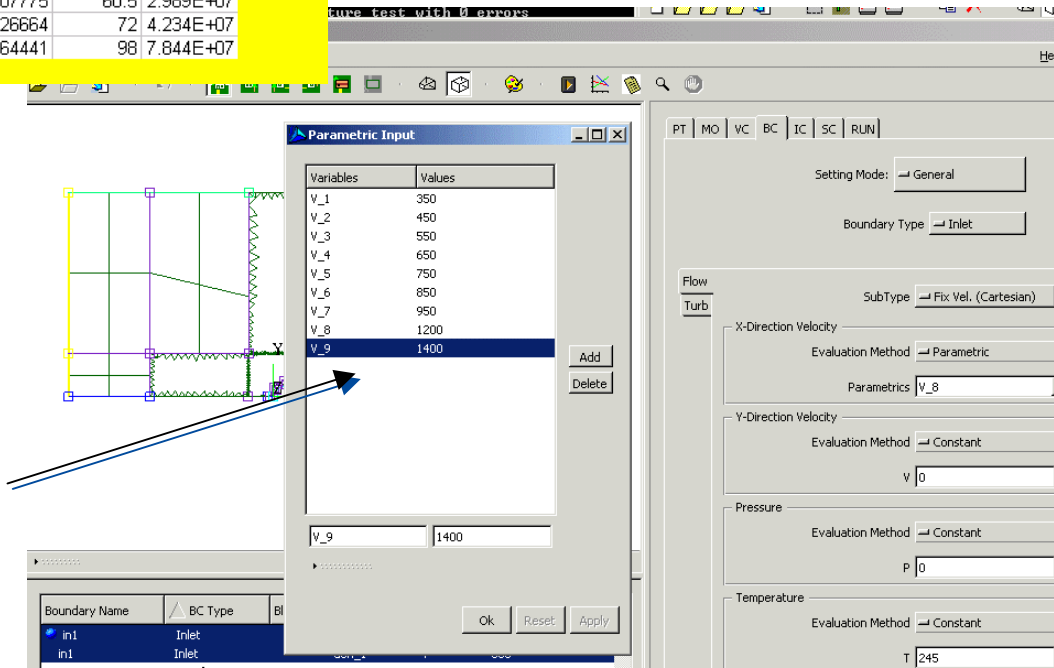
**K-eps RNG Turbulence Model, with the following inlet conditions: example P=20E3 Pa, T=245 (low altitude)**

P, Pa	T, K	mu	RHO	Beta	Tu_free	Velocity	M	K	D
20,000	245	1.56885E-05	0.284732	0.2	0.01	350	1.11611	6.125	3.064E+05
20,000	245	1.56885E-05	0.284732	0.2	0.01	450	1.434999	10.125	8.373E+05
20,000	245	1.56885E-05	0.284732	0.2	0.01	550	1.753888	15.125	1.868E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	650	2.072776	21.125	3.645E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	750	2.391665	28.125	6.460E+06
20,000	245	1.56885E-05	0.284732	0.2	0.01	850	2.710554	36.125	1.066E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	950	3.029442	45.125	1.663E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1000	3.188887	50	2.042E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1100	3.507775	60.5	2.989E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1200	3.826664	72	4.234E+07
20,000	245	1.56885E-05	0.284732	0.2	0.01	1400	4.464441	98	7.844E+07

## Inlet velocity conditions:

we start computations with lower flow (V=350..450 m/s) and then use converged solutions from lower velocity case as start-up for higher velocity case.

For a given altitude (pressure, Temperature) we run range of velocity conditions between 350...1400 m/s



The screenshot shows the CFD software interface. A 'Parametric Input' window is open, displaying a table of variables and values:

Variables	Values
V_1	350
V_2	450
V_3	550
V_4	650
V_5	750
V_6	850
V_7	950
V_8	1200
V_9	1400

Below the table, the variable 'V\_9' is selected with a value of 1400. The 'Boundary Name' list shows 'in1' with 'Inlet' as the BC Type. The 'Boundary Type' is set to 'Inlet', and the 'SubType' is 'Fix. Vel. (Cartesian)'. The 'X-Direction Velocity' is set to 'Parametric' with 'V\_8' as the parameter. The 'Y-Direction Velocity' is set to 'Constant' with a value of 0. The 'Pressure' is set to 'Constant' with a value of 0. The 'Temperature' is set to 'Constant' with a value of 245.

Computational Domain:  
approximately 12K  
nodes

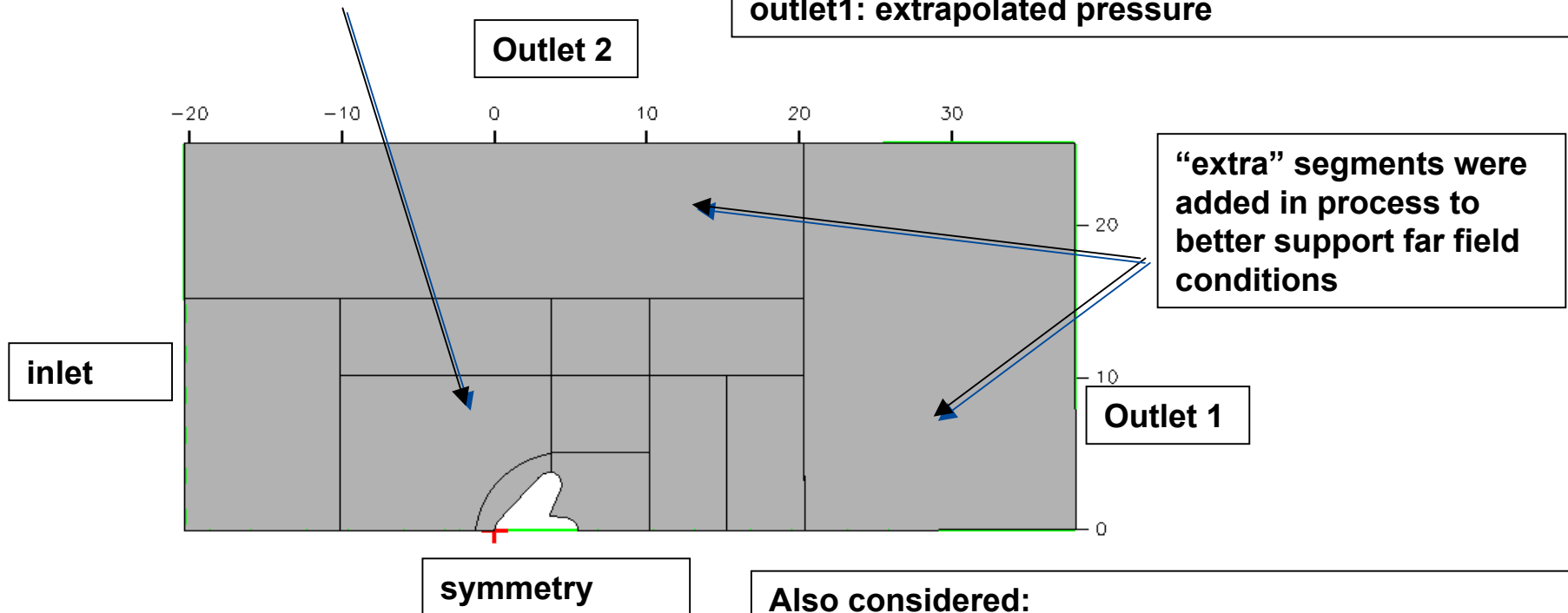
**Most Robust model:**

IC: previous solution for all fields

inlet: fixed inlet velocity  $V_{free}$

outlet2: fixed far field velocity  $V_{free}$

outlet1: extrapolated pressure



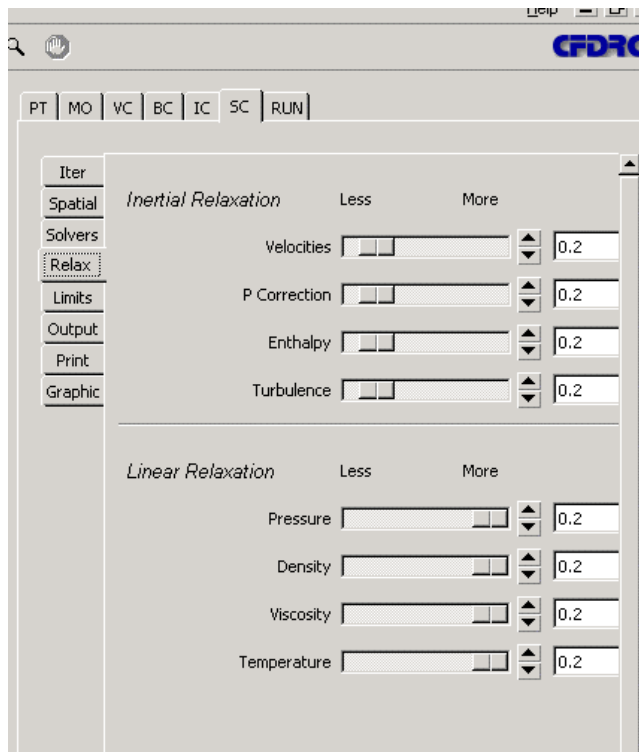
**“extra” segments were added in process to better support far field conditions**

**Also considered:**

outlet2: fixed pressure,  $P=0$ , or extrapolated pressure

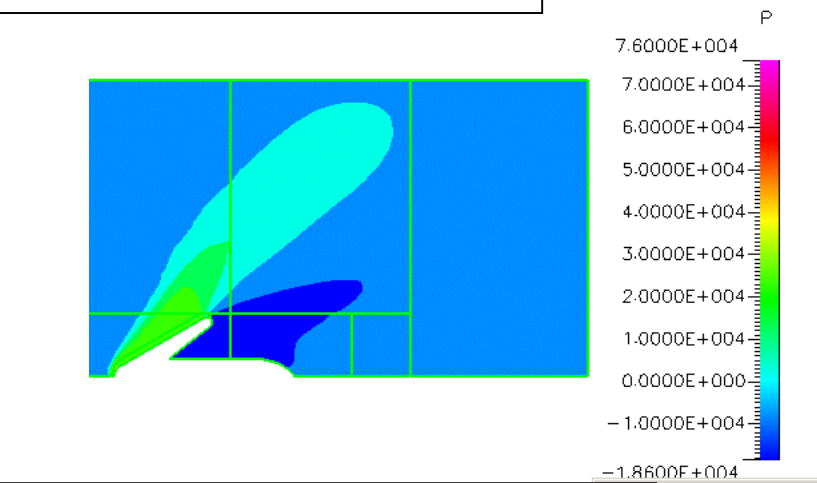
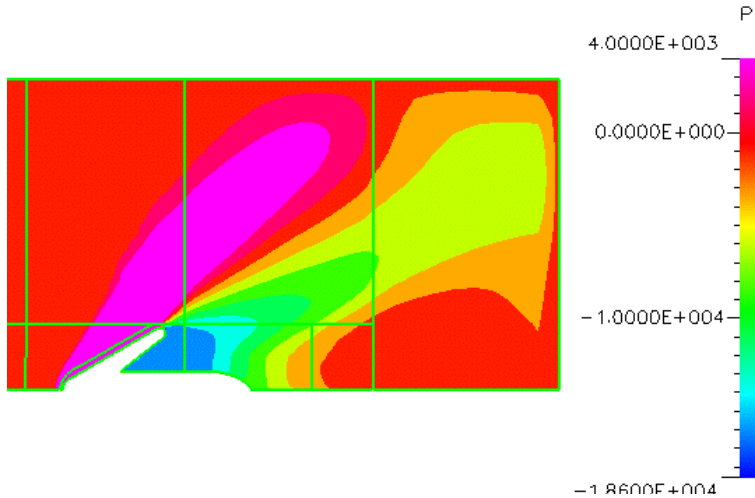
outlet1: fixed pressure,  $P=0$

If any node at the outlet has velocity  $<M$ , extrapolated condition will lead to divergence

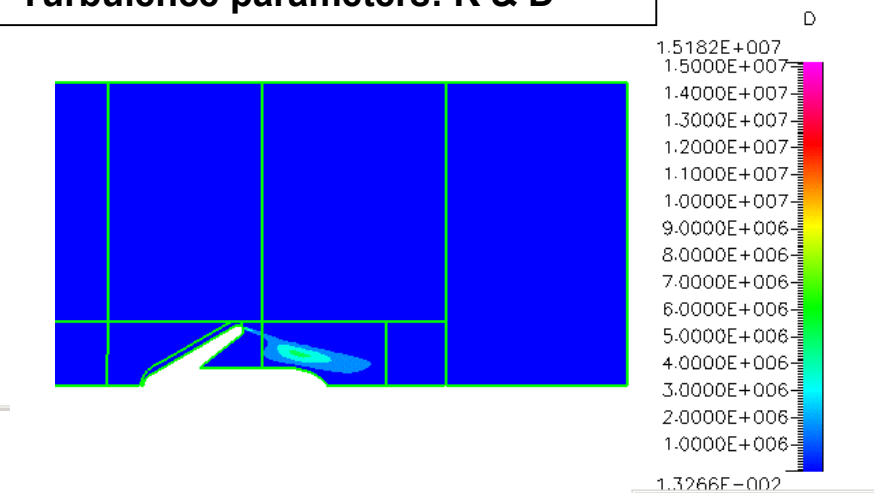
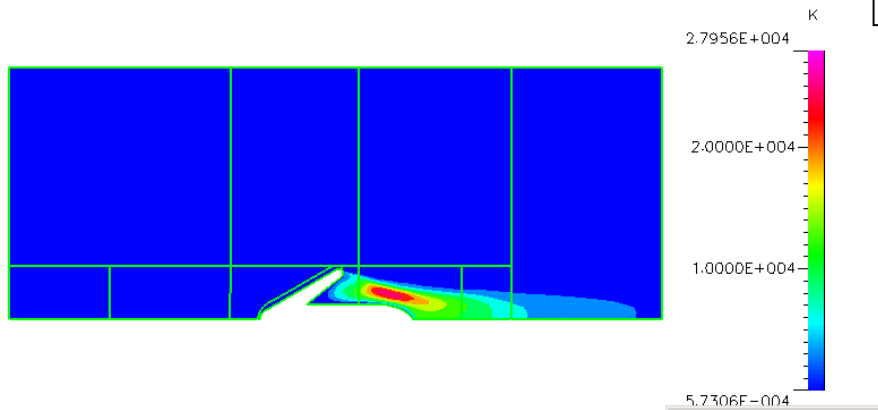


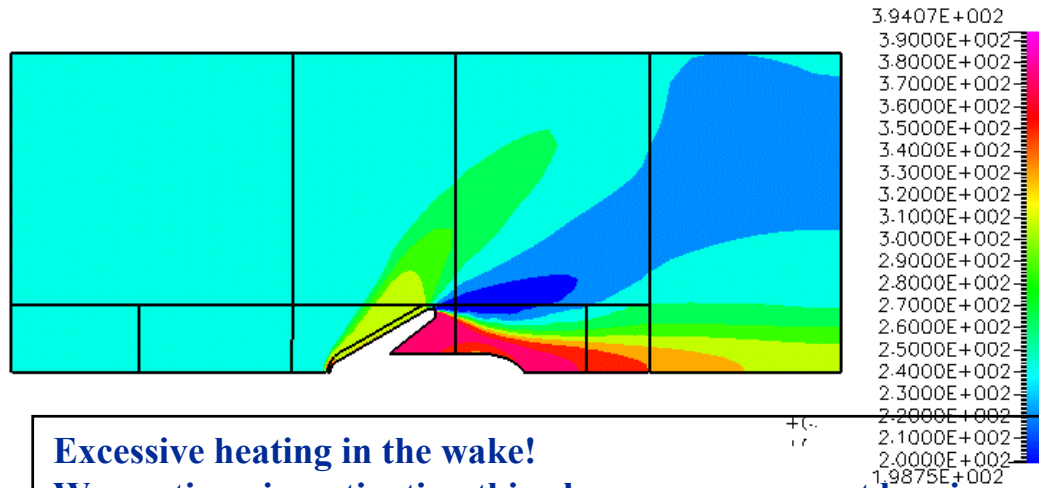
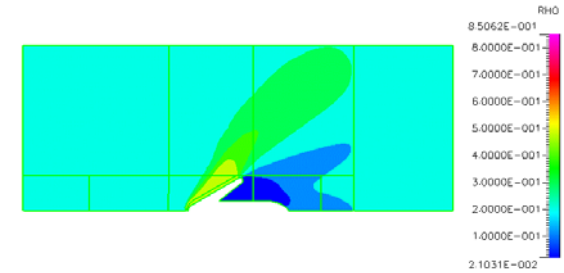
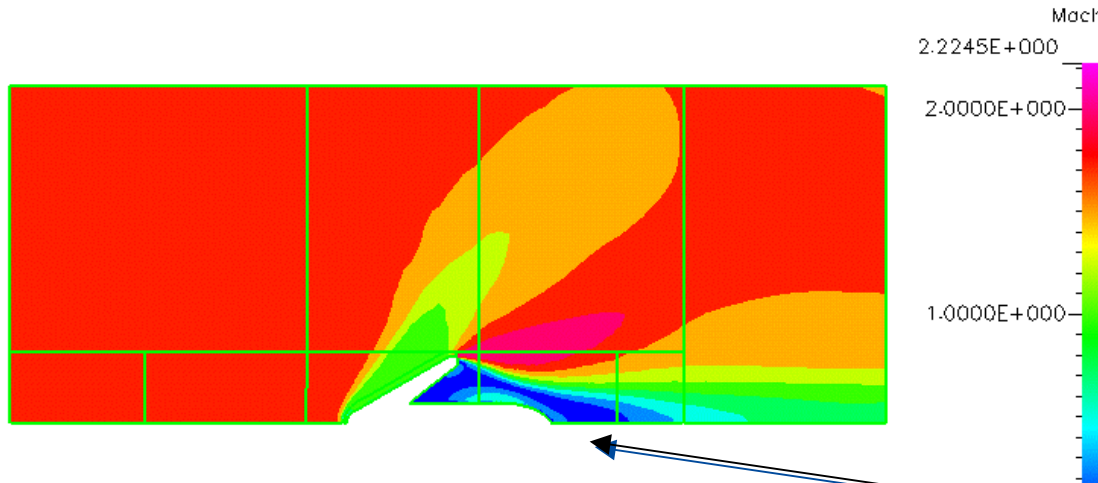
**-OUTLET BOUNDARY CONDITIONS and CONVERGENCE at different velocities**  
**-startup solution with 100 m/s ramp**  
**-linear relaxation for pressure, density, viscosity and temperature in the range 0.7...0.2**  
**[note that we use pressure based code in this study]**

## Pressure fields



## Turbulence parameters: K & D

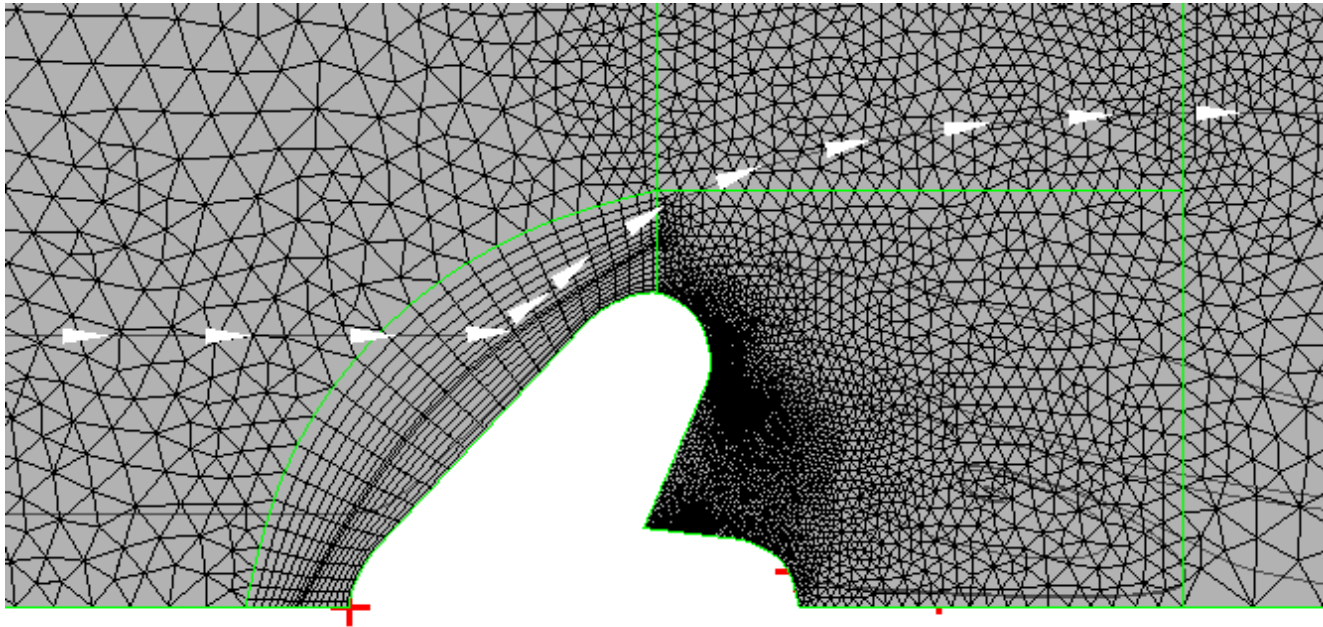




**Recirculation Zone --flow impingement on the capsule. Consequently this finding lead to rocket ballute re-design.**

**Excessive heating in the wake!  
We continue investigating this phenomena , suspect bug in software or in our model setup.**

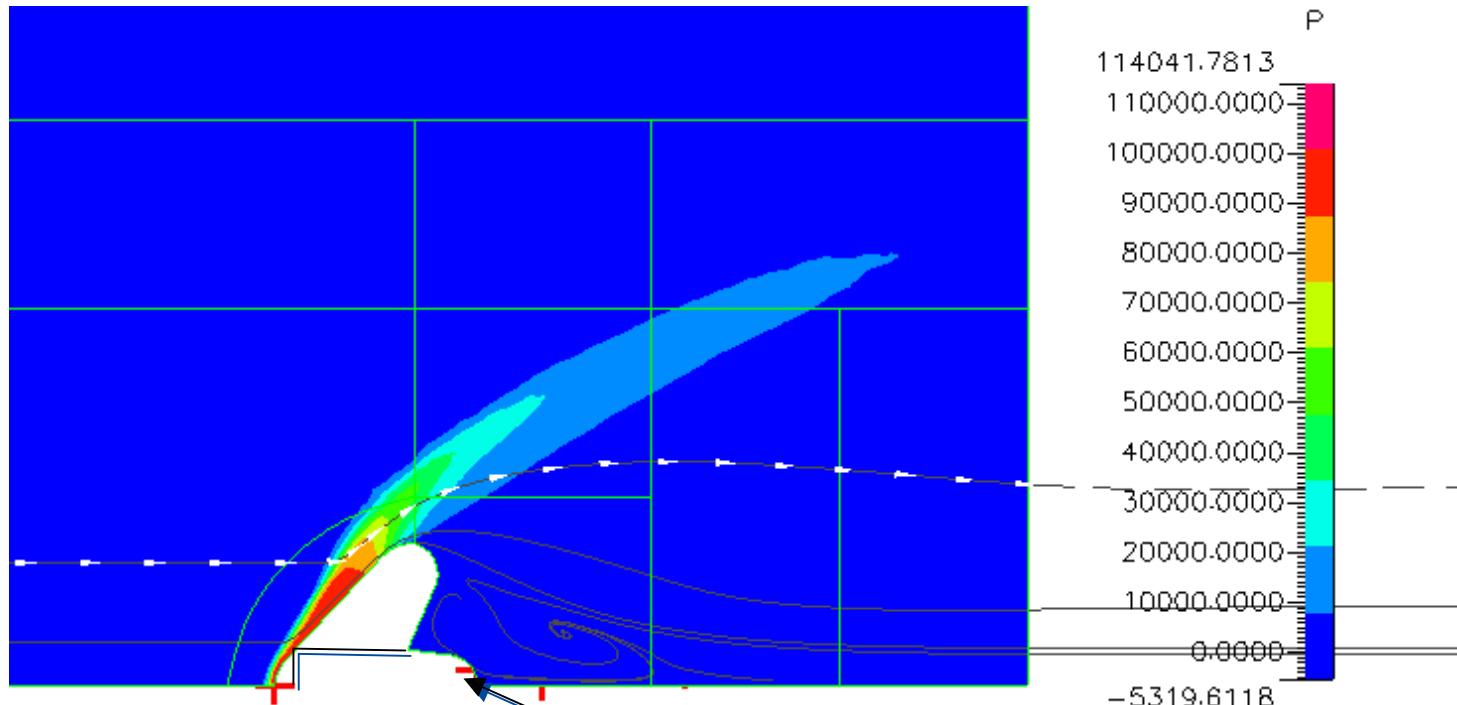
## Second Design Iteration, $R_{ballute}=1.5$ meters



Hybrid structured-unstructured  
grid near ballute

Worst case scenario considered: M=4.5 at H=35 km

Max pressure is close to 15 psi: defines requirements for ballute pressurization, helium mass for on-board storage

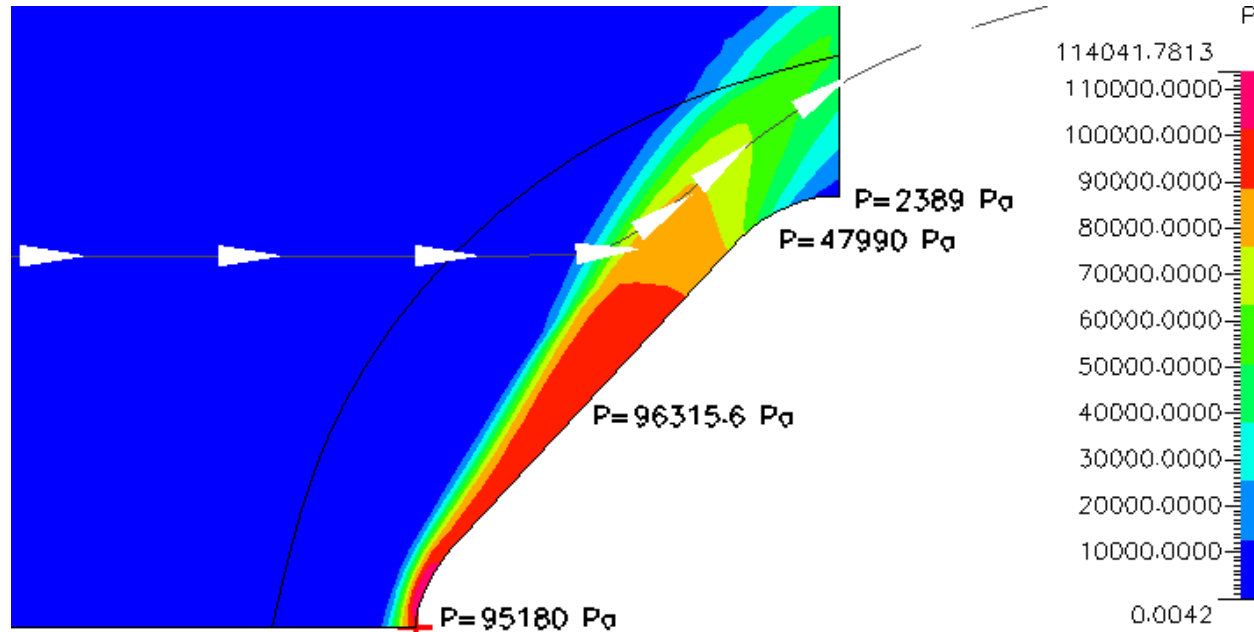


Flight Conditions: H=35.000 m P=5787 Pa, V=1400 m/s, M=4.51

capsule

Note much shorter rocket body and larger aspect ratio. Correspondingly wake is now much larger and covers entire capsule with astronauts.

Worst case scenario considered:  $M=4.5$  at  $H=35$  km



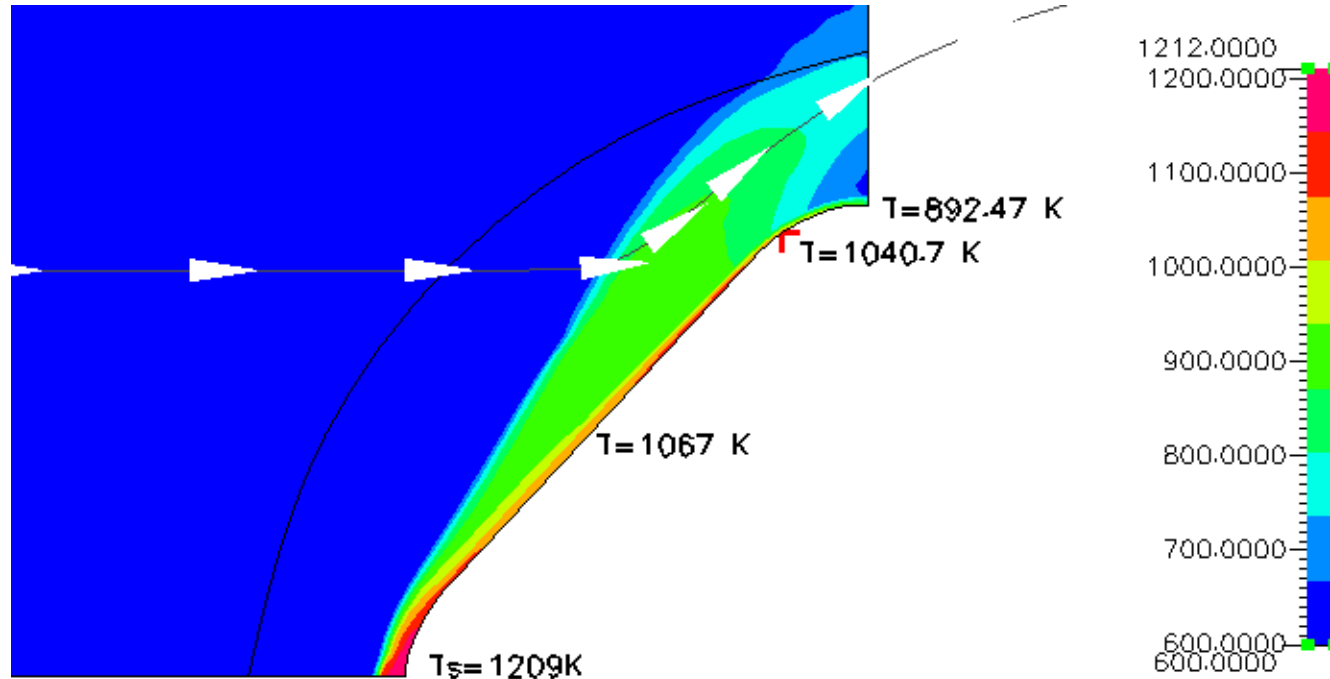
Flight Conditions:  $H=35.000$  m ,  $P=5787$  Pa,  $V=1400$  m/s,  $M=4.51$   
 $R_{max}=1.5$  m,  $Area=7.38$ ,  $F_{tot}=6.14E5$ ,  $Cd(calc)=1.009$

FIRST ITERATION: maximum load conditions



# Forebody Heating - Ballute

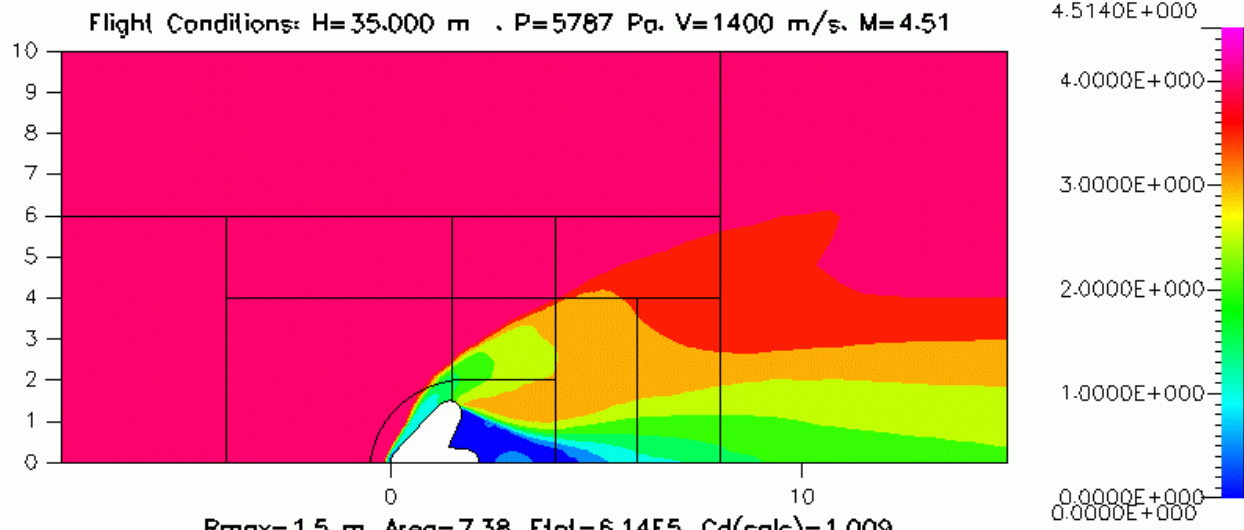
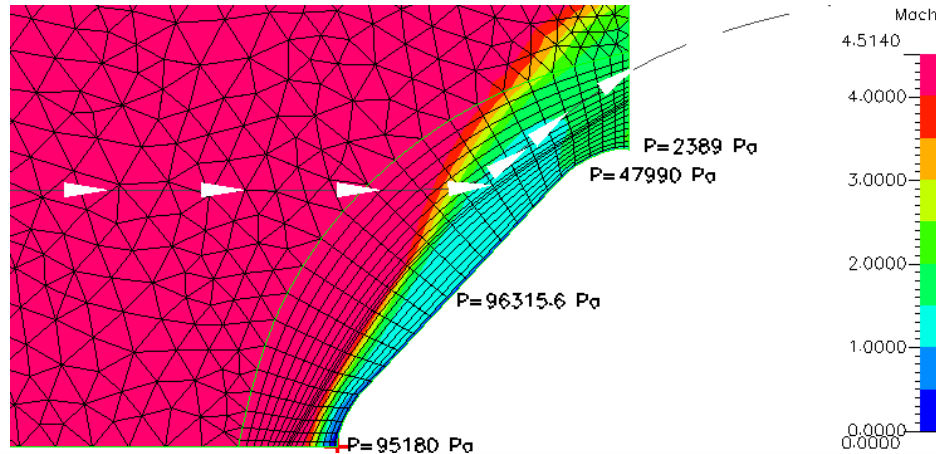
Worst case scenario considered:  $M=4.5$  at  $H=35$  km



Flight Conditions:  $H=35.000$  m ,  $P=5787$  Pa,  $V=1400$  m/s,  $M=4.51$   
 $R_{max}=1.5$  m,  $Area=7.38$ ,  $F_{tot}=6.14E5$ ,  $Cd(calc)=1.009$

FIRST ITERATION: maximum load conditions

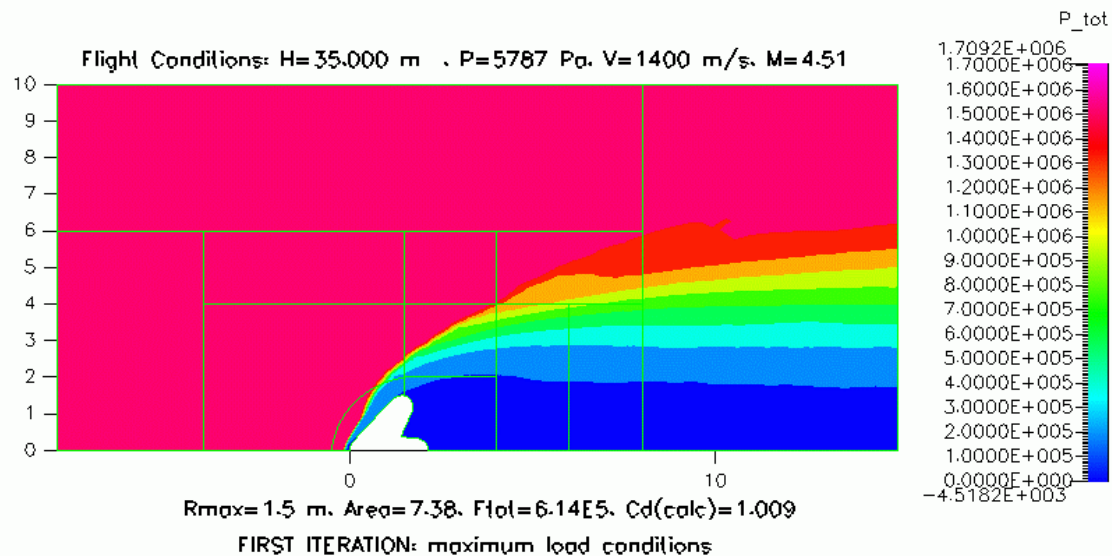
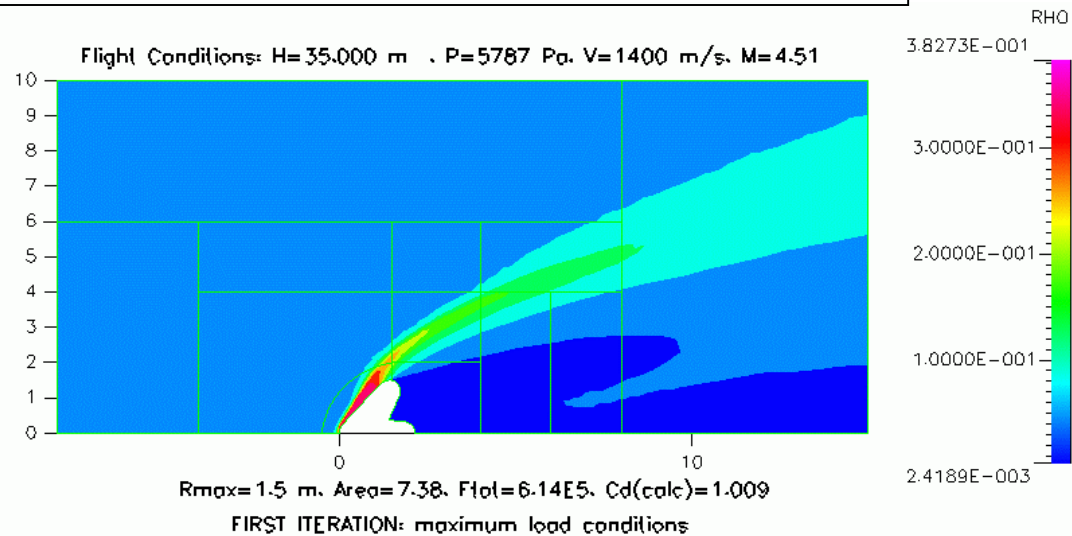
# Mach Number



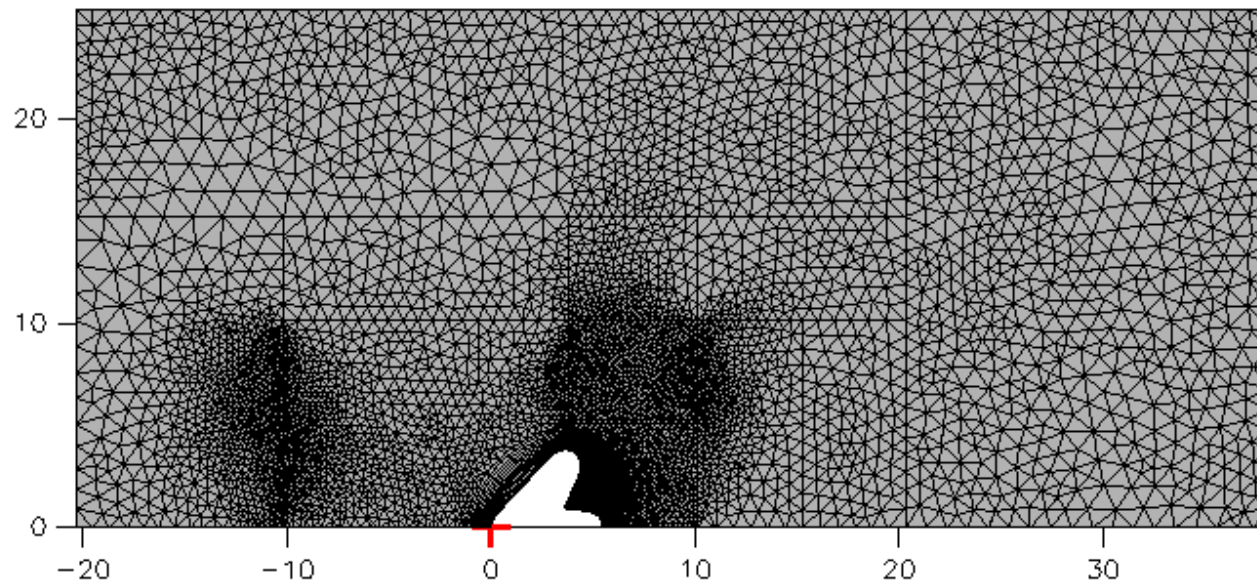
FIRST ITERATION: maximum load conditions

**Worst case scenario considered: M=4.5 at H=35 km**

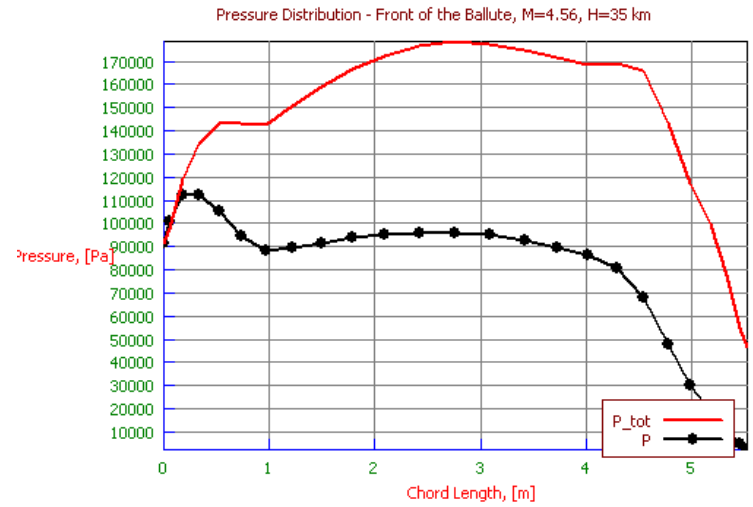
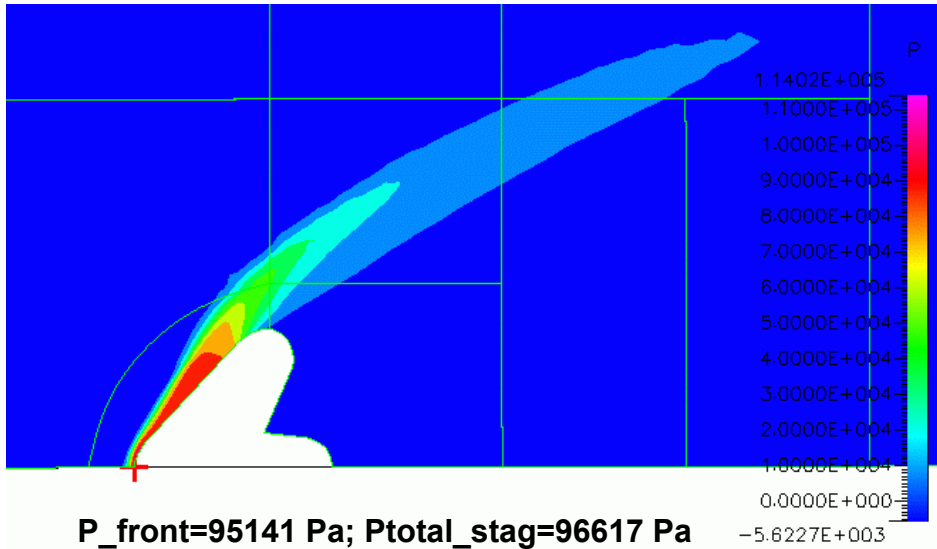
**Worst case scenario considered: M=4.5 at H=35 km**

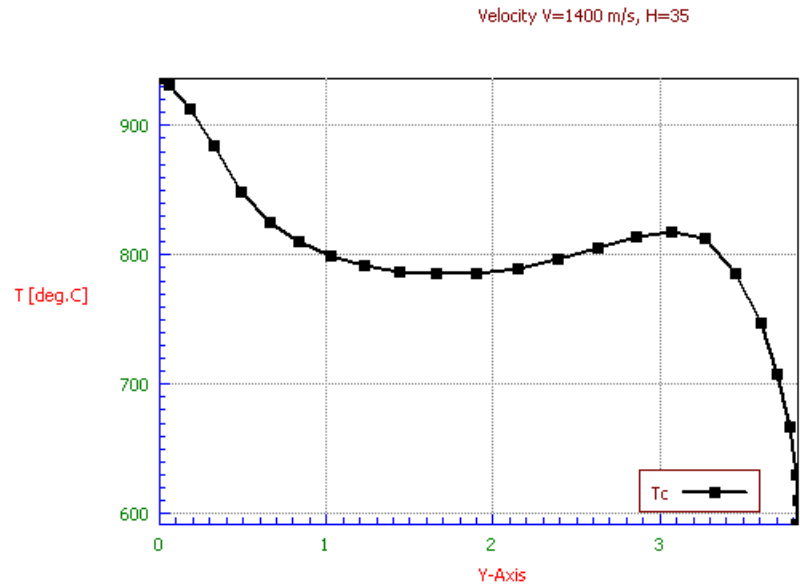
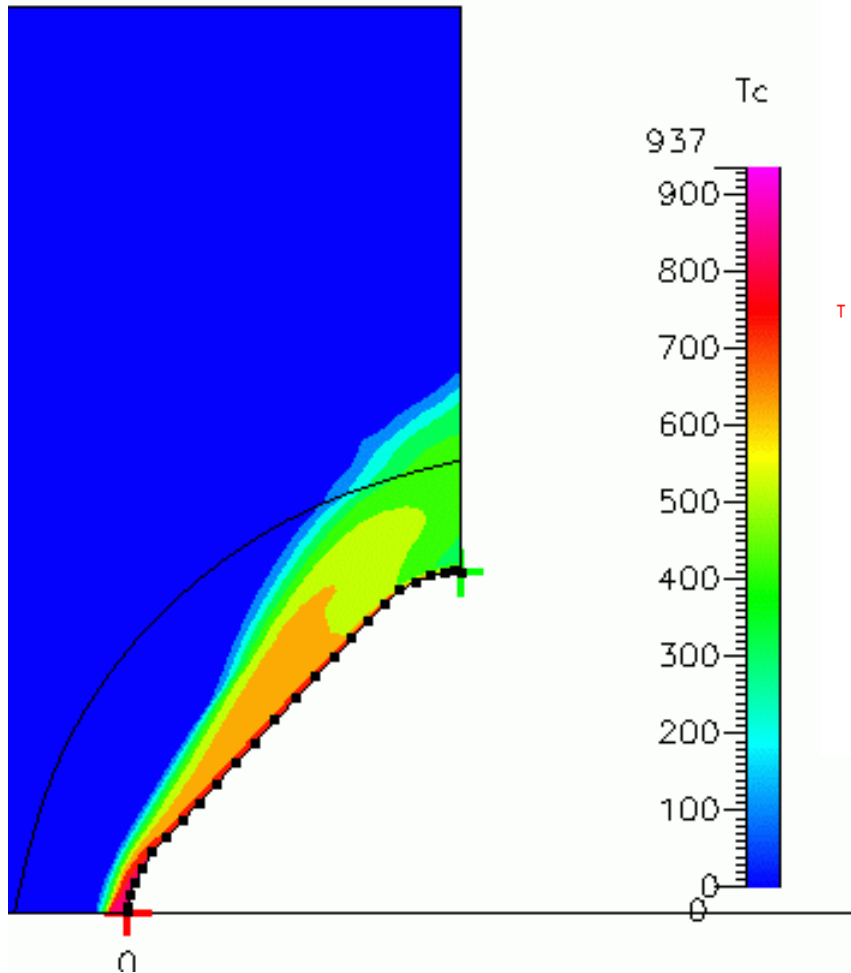


## Third Iteration: Increased Ballute Outer Radius $R_{max}=3.78$ meters



**Worst case scenario considered:  $M=4.5$  at  $H=35$  km**

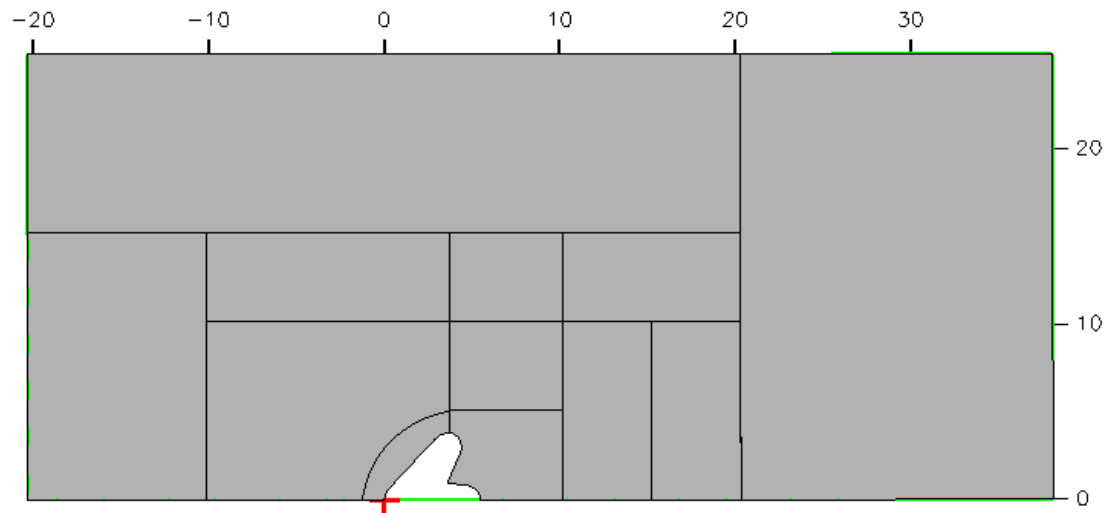




**$T_{max}=1209K$ ,  $T_{max}=936.2$  C;**

**Peak loads shown in previous section are on the limit of available resources and material properties.**

**Here we present results for three different trajectories: with apogees of 110, 120 and 130 km. According to preliminary ballistic analyses this corresponds with maximum velocities of 925 , 110 and 1091 m/s at approximate altitude of 47 km.**

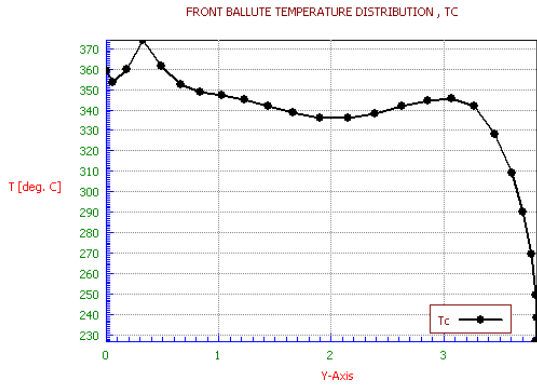


**Ballistic analyses utilized  $C_d=1$ , estimated from previous CFD studies for rocket ballute. For considered trajectories maximum velocities were reached at 43..48 km range. For the “first cut” we assumed that velocities of 925 m/s, 1010 m/s and 1095 m/s were all reached at 47 km altitude. Standard Atmosphere table for this altitude shows pressure of 1207 Pa and temperature  $T=274K$**

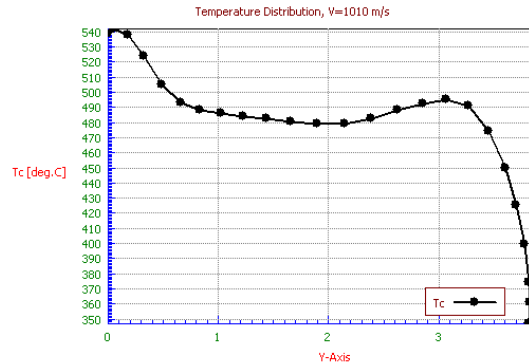
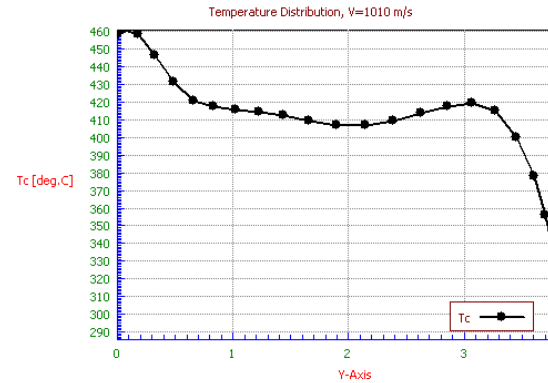
**We performed external flow CFD simulations for on-design max.velocities. These velocities are 925 m/s for 110 km trajectory, 1010 m/s for 120 km trajectory and 1091 m/s for 130 km trajectory.**

**In order to perform analysis using ACE+ at high supersonic speeds lower velocity supersonic solution must be obtained first (for example at  $U_{freestream}=500$  m/s), and then used as “initial field” for conditions with higher velocities. We used intermediate solutions at 500, 650, 700 and 850 m/s.**

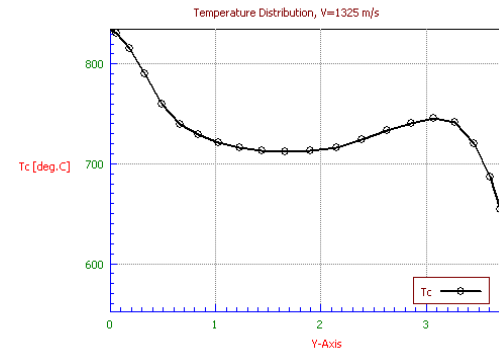
**110 km apogee: T peak=373 C**



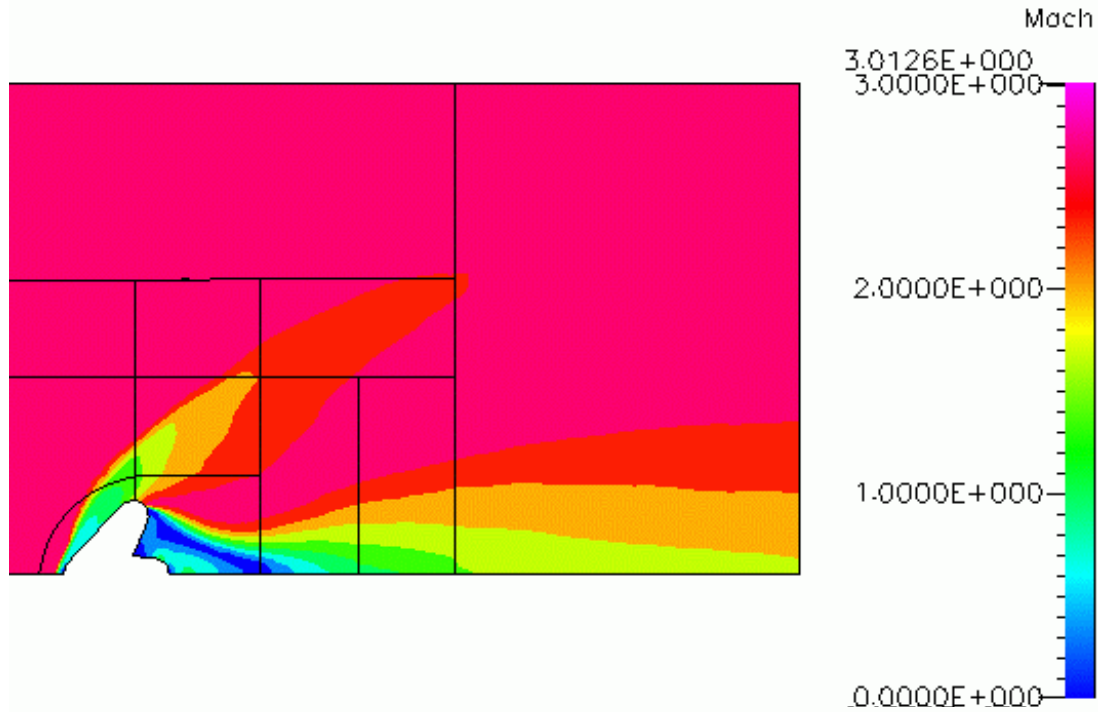
**120 km apogee: T peak=461 C**



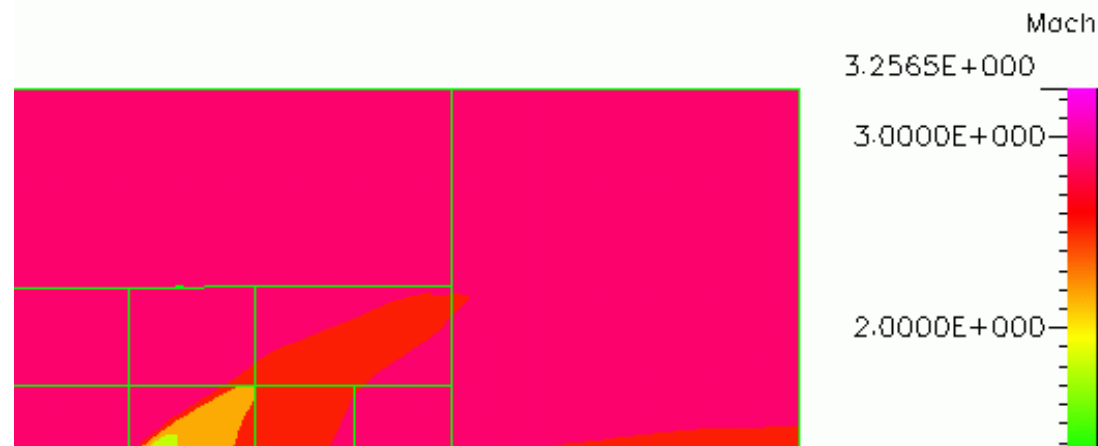
**130 km apogee: T peak=543C**



**Vmax=1325 m/s; T peak=834C**



110 km apogee, V=925 m/s



120 km apogee, V=1010 m/s

Comparison of aero-heating (air temperature in front of the ballute) shows significant reduction of thermal loads down to  $T_{max}=372$  C for the trajectory with 110 km apogee. This trajectory meets X-Prize requirements. Trajectory with 120 apogee is also meeting X-prize requirements and material limitations for ballute. Our main design objective will be to achieve velocities below 1000 m/s at altitudes below 45 km. Our preliminary analysis show that we can meet this objective.

- we utilized CFD-ACE+ to analyze several consecutive iterations for the design of daVinci rocket ballute;
- using CFD we were able to “zero-in” on a conceptual configuration, flight scenario and trajectory requirements that will meet X-prize objectives and also minimize thermal loads;
- estimated thermal loads ( $T_{max}<500$ C) can be met with commercially available materials used by ballute manufacturers

## CFD Heads-up:

- coupled flow, heating shell simulation
- density-based gas flow and heating simulations
- wake heating issues
- transient mission profile simulations
- capsule transient heating analysis
- ballute and air heating analysis
- coupled flow --ballute fluid-structure interaction