# Rocket Propulsion HW 4: NASA CEA

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# 1 Objective

In this assignment, you will use NASA's Chemical Equilibrium with Applications (CEA) program to model the performance of an existing rocket engine. You will base your analysis on known data for thrust, nozzle expansion ratio, propellant type, and oxidizer-to-fuel (O/F) ratio, assuming an infinite-area combustor (IAC) configuration. The provided CEA Example 8 (rocket IAC case) will serve as a reference for formatting your input file and interpreting the output. Your task is to select a real rocket, gather its relevant performance and design data, and replicate its behavior using CEA.

# 2 Assignment Details

## 2.1 1. Select a Rocket Engine

- Choose an existing rocket engine that uses either a liquid propellant or hybrid solid-liquid propellant system. Examples include the SpaceX Merlin 1D (liquid: RP-1/LOX), the Rocketdyne F-1 (liquid: RP-1/LOX), or a hybrid system like SpaceShipOne's rocket motor (solid HTPB/liquid $N_2O$).
- Additionally, consider exploring newer technologies and smaller systems. For example, Dawn Aerospace offers a novel $N_2O$ Ethane-based 3D printed bipropellant satellite thruster for in-space applications ([4]).
- For the very ambitious, you could create your own speculative propellant combinations. Consider exploring options such as HAN/Ionic liquids, $N_2O$ monopropellants, or Dinitramide-based compounds. Aerojet is developing new thrusters using these technologies ([5], [6]).
- **Custom Propellant Implementation:**
  - While standard CEA species are sufficient, extra credit is available for custom propellants:
  - *Method 1: Case-specific definition*

    ```
    fuel=Par        t,k=298    h,kj/mol=-630
     elements C 28 H 58
    ```

  - *Method 2: Permanent addition to thermo.inp*

    ```
    name=CustomFuel   fuel   wt=1.0   t,k=298.15
    h,cal/g=-500.0    e C 2 H 5 N 1 O 2
    ```

  - Required parameters for full implementation:
    - NASA polynomial coefficients (7-9 coefficients)
    - Specific heat capacity ($C_p$) data
    - Reference for thermodynamic properties
- Research and document the following parameters from credible sources (e.g., NASA, SpaceX, or published literature):
  - Propellant combination (fuel and oxidizer)

- Oxidizer-to-fuel (O/F) mass ratio
- Chamber pressure (in bars or convert to bars)
- Nozzle exit area ratio ($A_e/A_t$) or sufficient data to calculate it (e.g., exit pressure or thrust)
- Thrust output (in kN or lbf, to validate your CEA results)
- Optional: Initial propellant temperatures (if available; otherwise, use standard cryogenic or ambient values)

## 2.2 2. Reference CEA Example 8

- The attached Example 8 from [1] models a liquid $H_2/LO_2$ rocket with an infinite-area combustor (IAC). Key features include:
  - Fuel: $H_2$(L) at 20.27 K
  - Oxidizer: $O_2$(L) at 90.17 K
  - O/F ratio: 5.55157
  - Chamber pressure: 53.3172 bars
  - Equilibrium chemistry
  - Exit conditions: Pressure ratios ($p_i/p = 10, 100, 1000$), subsonic area ratio ($A_e/A_t = 1.58$), and supersonic area ratios ($A_e/A_t = 25, 50, 75$)
- Use this as a template to structure your CEA input file, adapting it to your chosen rocket's parameters.

## 2.3 3. Create Your CEA Input File

- Write a CEA input file for your selected rocket engine. Assume an infinite-area combustor (IAC) as in Example 8.
- Specify:
  - Propellant types (e.g., RP-1(L), LOX(L), HTPB(S), $N_2O$(L)) and their initial temperatures (use thermo.lib defaults if unknown)
  - O/F ratio based on your rocket's data
  - Chamber pressure ($p$, bar)
  - At least three nozzle exit conditions:
    * One subsonic area ratio (subar)
    * Two supersonic area ratios (supar) based on your rocket's nozzle design or estimated from thrust data
  - Use equilibrium chemistry (`equilibrium` keyword)
  - Output in SI units (`output siunits`)
- Follow formatting guidelines demonstrated in [3]
- Example format (based on Example 8): See attached CEA .inp file

## 2.4 4. Run CEA and Analyze Results

- Run your input file in CEA in MS/DOS (via a local installation).
- Extract key performance parameters from the output, including:
  - Specific impulse ($I_{sp}$) at the nozzle exit
  - Thrust coefficient ($C_f$)
  - Exhaust velocity ($V_e$)
  - Exit pressure and temperature for each area ratio
- Compare your calculated thrust ($F = \dot{m} \cdot V_e$, where $\dot{m}$ is mass flow rate) to the real rocket's reported thrust. Estimate $\dot{m}$ if not provided, using $I_{sp}$ and total impulse or burn time if available.
- Alternatively, determine the nozzle throat area and calculate the mass flow rate through the nozzle using the choked flow relation:

$$\dot{m} = A^* \sqrt{\gamma \rho_0 P_0 \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

  where $A^*$ is the throat area, $P_0$ is the stagnation pressure, $\rho_0$ is the stagnation density, and $\gamma$ is the ratio of specific heats. These parameters can be extracted from your CEA output for the mixture conditions at the throat.

## 2.5 5. Deliverables

- Submit a report (2-3 pages) including:
  - **Engineering Presentation Standards:**
    - Prioritize data visualization over text: use tables, charts, and graphs
    - Include properly labeled axes, units, and error bars where applicable
    - Follow engineering precision standards in all numerical presentations
    - Remember: a well-designed figure is worth 1000 words of explanation
  - A brief description of your chosen rocket engine with key parameters presented in a table format (with sources cited)
  - Your CEA input files (both .inp and .out) with clear formatting and comments
  - Key results visualized through:
    - Comparative tables of $I_{sp}$, $C_f$, $V_e$, and thrust values
    - Plots showing parameter relationships (e.g., O/F ratio vs. performance)
    - Jupyter notebooks or similar tools for data processing (if used)
  - A quantitative comparison of CEA-predicted thrust to actual thrust, with:
    - Percentage differences clearly calculated
    - Error analysis with potential sources identified
    - Visual representation of discrepancies
  - Analysis of the following (using data visualization where possible):

1. O/F ratio effects on performance (show with plots)
2. Optimum O/F ratio determination (with supporting data)
3. Propellant combination effects on:
   * Flame temperature
   * Molecular weight of combustion products
   * Specific impulse
4. Key assumptions and quantified impact on accuracy
5. Three factors CEA ignores that affect actual engine performance:
   * Finite-rate chemistry
   * Nozzle boundary layers
   * Heat transfer losses
6. Propellant handling safety concerns and storage tank design implications
7. Additional relevant considerations for this rocket type

- **Note:** This is an engineering analysis, not a creative writing exercise. Prioritize:
  - Concise, precise technical communication
  - Quantitative data over qualitative descriptions
  - Professional-quality visualizations
  - "Less is more" - focus on clarity and precision

### 2.6 6. Tips

- If exact data (e.g., O/F or $A_e/A_t$) is unavailable, make reasonable estimates based on similar engines and justify them in your report.
- Use standard propellant temperatures from thermo.lib (e.g., LOX at 90 K, RP-1 at 298 K) if specific values aren't provided.
- For hybrid rockets, treat the solid and liquid phases appropriately in the `reactant` section.

## 3 Due Date

Submit your report by April 2, 2025 via MCV.

## 4 Grading Criteria

- Completeness and accuracy of rocket data (20%)
- Correct CEA input file formatting and relevance to the chosen rocket (30%)
- Analysis of CEA output and thrust comparison (30%)
- Quality of discussion and responses to questions (20%)

# 5 References

## References


[1] NASA CEA Example Cases, https://www.mycourseville.com/?q=courseville/course/61217/view_content_node_1596557_material

[2] NASA CEA Program Documentation, https://www.mycourseville.com/?q=courseville/course/61217/view_content_node_1604116_material

[3] Rocket Propulsion Lecture 7: CEA Analysis (2024), https://mycourseville-default.s3.ap-southeast-1.amazonaws.com/useruploaded_course_files/2024_2/61217/materials/Lecture_7-1259550-17416739115435.pdf

[4] Dawn Aerospace Green Propulsion Systems, https://www.dawnaerospace.com/green-propulsion#thrusters

[5] Petersen E.L. et al. (2023) *Review of Alternative Sustainable Fuels for Hybrid Rocket Propulsion*, Aerospace, 10(7), 643. https://www.mdpi.com/2226-4310/10/7/643

[6] Chiaverini M.J. et al. (2021) *Review of Hybrid Rocket Propulsion Technologies*, Aerospace, 8(1), 20. https://www.mdpi.com/2226-4310/8/1/20

[7] Masse R. et al. (2021) *Review of State-of-the-Art Green Monopropellants: For Propulsion Systems Analysts and Designers*, Aerospace, 8(1), 20. https://www.mdpi.com/2226-4310/8/1/20