Beyond Cold Gas Thrusters

- Good - Simple
- Bad - Limited I_{sp}

- How to increase specific impulse of monopropellant?
  – raise T_o

- Where will energy come from?
  – chemical *exothermic decomposition of monopropellant*
  – electrical
  – other heat source (solar, nuclear, …)

Decomposition-Based Monoprop. Thrusters

- How to use energy?
  – increase in T_o
  – also can use to evaporate propellant
  $\Rightarrow$ can store propellant as liquid (less volume)

- Example propellants
  – hydrazine (N_2H_4)
  – hydrogen peroxide (H_2O_2)
  – isopropyl nitrate ($C_3H_7NO_3$)
    - nitric acid propyl ester,…

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Hydrogen Peroxide

- Early use: "monopropellant" to operate turbo-pump on V-2 rocket
  - jet packs
  - also used as oxidizer in some bipropellant combinations (e.g., with kerosene)
  - hypergolic with hydrazine
- Composition
  - hard to find pure H_2O_2, usually has some amount of H_2O
  - commercial grade, only 30% H_2O_2 by mass
  - propellant grade, 85-98% by mass
- Density ~1.4 g/cm^3
- Safety
  - can burn skin
  - contaminated solutions can explode for T>448 K

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Hydrogen Peroxide Decomposition

$$H_2O_2(l) \rightarrow H_2O(g) + 1/2\, O_2(g)$$ Exothermic: 52.24 kJ/mol

- Releases ~50 kJ/mol of H_2O_2 at room temperature
  - part of energy goes to vaporizing liquid
- Rapid reaction either at high temperature – or in the presence of appropriate catalyst
- Less H_2O in solution means
  - more energy release (higher T_o)
  - lower MW of products

- At room temperature (e.g., in storage), conversion is ~1% per year for 95% concentration

H_2O_2 Decomposition Catalysts

- Originally liquid catalysts (injected)
  - potassium permanganate (V-2, K-1 Henschel 293 air-to-surface missile)
  - sodium permanganate
- More common – solid catalyst beds
  - multiple layers of wire screens of silver, platinum, palladium, iron oxide

  - typical size
  - 5 cm long with sufficient cross sectional area can handle 250 kg/m^2·s mass flux

Hydrogen Peroxide Performance

- Temperature
  - $T_{o,max}$ ~ 1250 – 1500 K with catalyst heating
- Possible to operate without active cooling (radiation only) since there are a number of metals sufficiently strong to operate at these temperatures
- Characteristic velocity
  - c^* ~ 1040 m/s (3400 ft/s) for 98% H_2O_2 solution

Hydrazine

- Mostly widely used, storable and high performance
  - attitude control thrusters
  - gas generators
- Composition
  - commercial grade: <1.5% H_2O, < 10 mg particles
  - monoprop. grade: < 1% H_2O, < 0.5% aniline ($C_6H_5NH_2$)
  - high purity: < 0.005% aniline, < 0.003% carbon
    - aniline and impurities can poison catalyst
- Density ~1 g/cm^3, T_{boil}~386 K (235°F)
- Safety
  - toxic and carcinogenic

Hydrazine Decomposition

(R1) $N_2H_4(l) \rightarrow 4/3\,NH_3 + 1/3\,N_2$ Exothermic: ~112 kJ/mol (Vaporization: ~44 kJ/mol)

(R2) $NH_3(g) \rightarrow 1/2\,N_2 + 3/2\,H_2$ Endothermic: ~46 kJ/mol

- Rapid reaction either at high temperature – or in the presence of appropriate catalyst
- After hydrazine decomposes, ammonia can dissociate
  - lowers T_o
  - decreases MW
  - net effect on c^* and I_{sp}?
- Storage tanks typically steel coated with thin protective lining of metal chosen to minimize decomposition, e.g., cadmium, silver, aluminum, nickel, tungsten, tin and tin alloys

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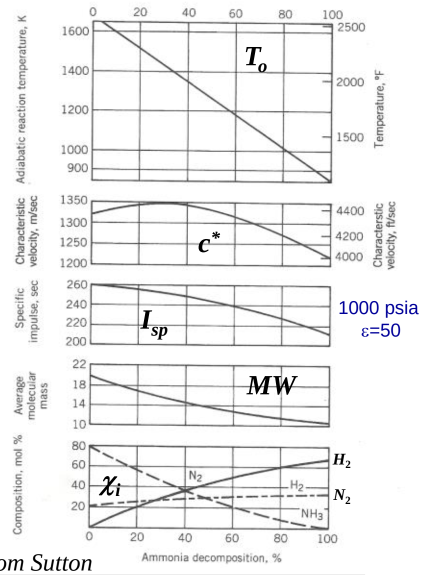
Hydrazine Performance

- From ideal calculations of mixture properties as function of amount of NH_3 decomposition
- T_o: 1600 – 800 K *γ lower w/o decomp. (NH_3)*
- MW: 19 – 11
- c^*: 1350 – 1225 m/s
  - optimum at ~30% decomposition
- I_{sp}: 260 – 210 s
  - max. w/o decomposition (not attainable)
  - overall T_o reduction dominates
- **Best performance requires proper catalyst bed design**



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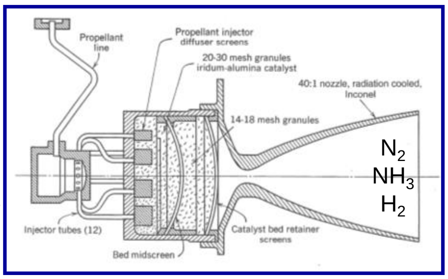
N_2H_4 Decomposition Catalysts



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- Early catalysts (Mariner)
  - N_2O_4 slugs, one per start (so limited #)
- Current catalysts
  - bed of ceramic/alumina pellets coated with iridium (Shell 405 by JPL/Shell 1965 – now Aerojet 405)
  - above 450 K can also use Fe, Ni, Co
  - also approaches using other supports, e.g., carbon nanotubes
  - can achieve ~200 kg/m^2·s mass flux
  - limit bed thickness to limit NH_3 conversion to 30-80% (typical value 55%)

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Hydrazine Thruster: Example

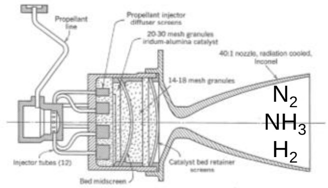
- **Requirement**
  - I_{total}=517 kN s

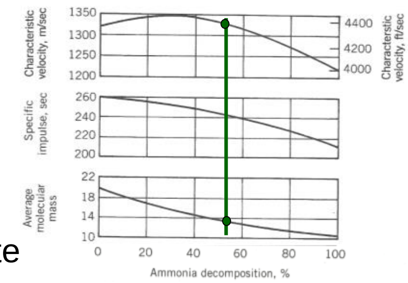
14× cold gas example

- **Design information**
  - catalyst w/ 55% NH_3 conversion
  - ε = 50:1 (20° conical)

c^*=4040 ft/s, 1325 m/s
MW = 13.5
(γ = 1.26)

- **Other design values?**
  - assuming steady-state





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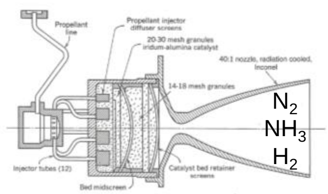
Hydrazine Thruster: Example

- **Solution**



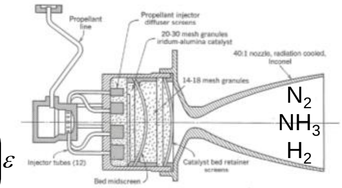
I_{total}=517 kN s
ε = 50:1,20° conical
c^*=4040 ft/s, 1325 m/s
MW = 13.5
(γ = 1.26)

Hydrazine Thruster: Example

- **Solution**
  - c_τ=?

$$c_\tau = \lambda \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\gamma+1/\gamma-1}\left[1-\left(\frac{p_e}{p_o}\right)^{\gamma-1/\gamma}\right]} + \left(\frac{p_e}{p_o}-\frac{p_a}{p_o}\right)\varepsilon$$

$$\lambda_{conical} = \frac{1+\cos\alpha}{2}$$



I_{total}=517 kN s
ε = 50:1,20° conical
c^*=4040 ft/s, 1325 m/s
MW = 13.5
(γ = 1.26)

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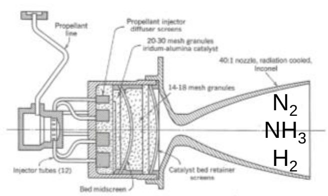
Hydrazine Thruster: Example

- **Solution**
  - minimum storage tank volume



I_{total}=517 kN s
ε = 50:1,20° conical
c^*=4040 ft/s, 1325 m/s
MW = 13.5
(γ = 1.26)
$\boldsymbol{m}_p$=218 kg

- Compared to N_2 thruster example
  - 14× more I_{tot} with only 4× more $\boldsymbol{m}_p$ and 43% of tank volume