MECH 427/527 and AA 284a
Advanced Rocket Propulsion

Lecture 1
Introduction to Rocket Propulsion

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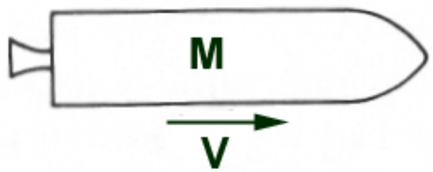
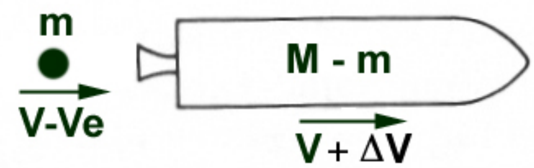
Generation of the Propulsive Force



time t



time t + Δt

- Conservation of momentum (V_e exhaust velocity for a perfectly expanded nozzle)

$$(M-m)\ (V+\Delta V)+m\ (V-V_e)-MV=0$$

$$(M-\dot{m}\Delta t)\ (V+\Delta V)+\dot{m}\Delta t\ (V-V_e)-MV=0$$

$$M\frac{\Delta V}{\Delta t}=\dot{m}V_e$$

$$\lim\ \Delta t \to 0 \qquad M\dot{V}=\dot{m}V_e$$

- Thrust Force: $T=\dot{m}\ V_e$

Rocket Propulsion Fundamentals

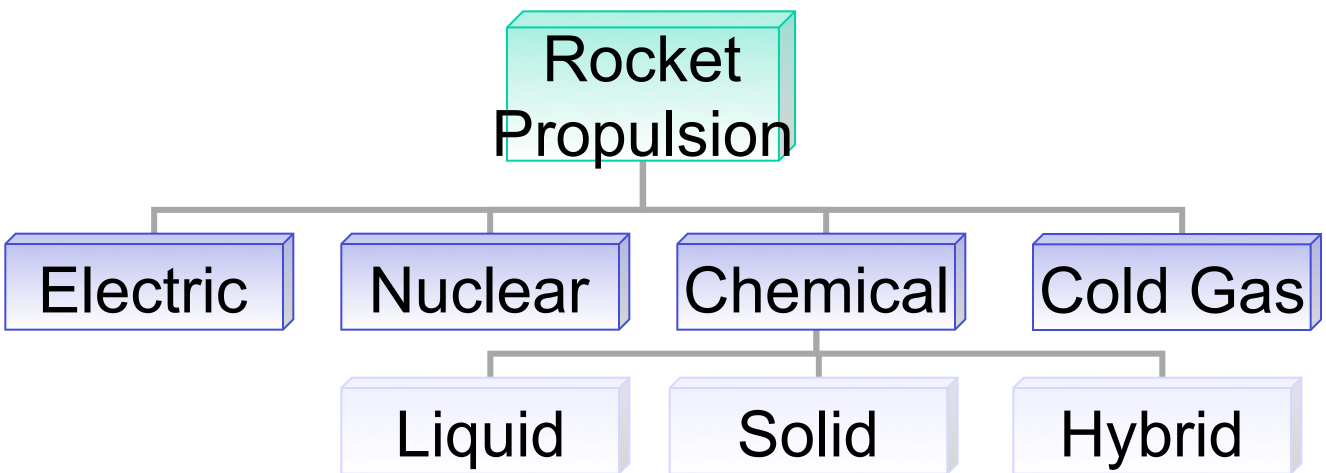
Propulsive Force

=

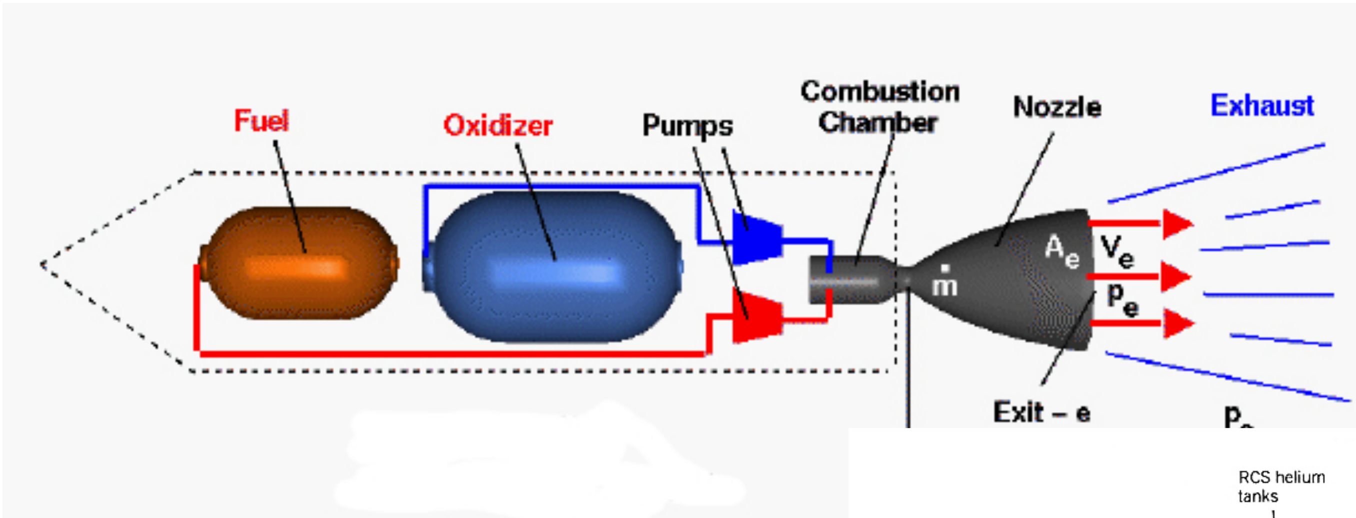
Mass Ejected per Unit Time x Effective Exhaust Velocity

Mass

Energy

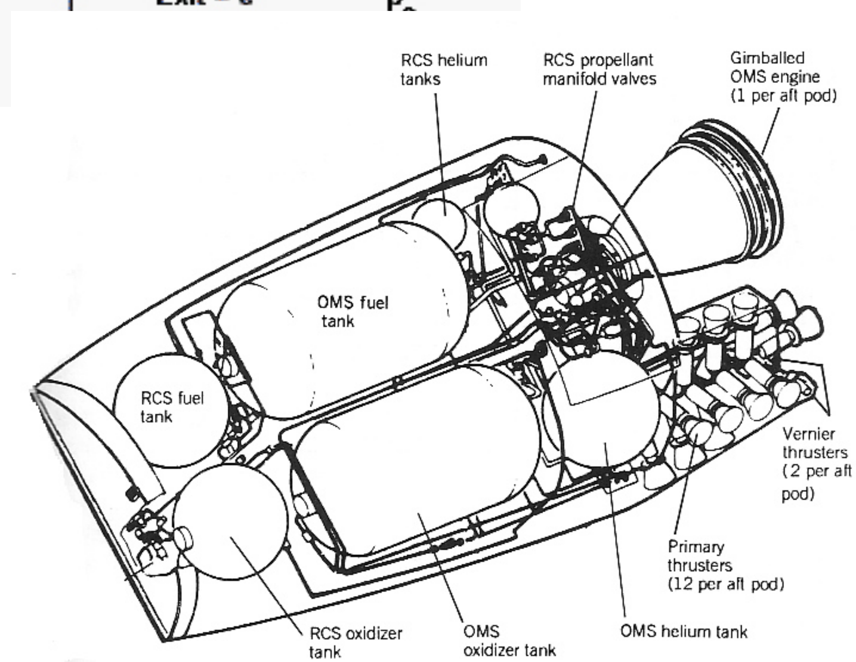


Liquid Rocket Schematic

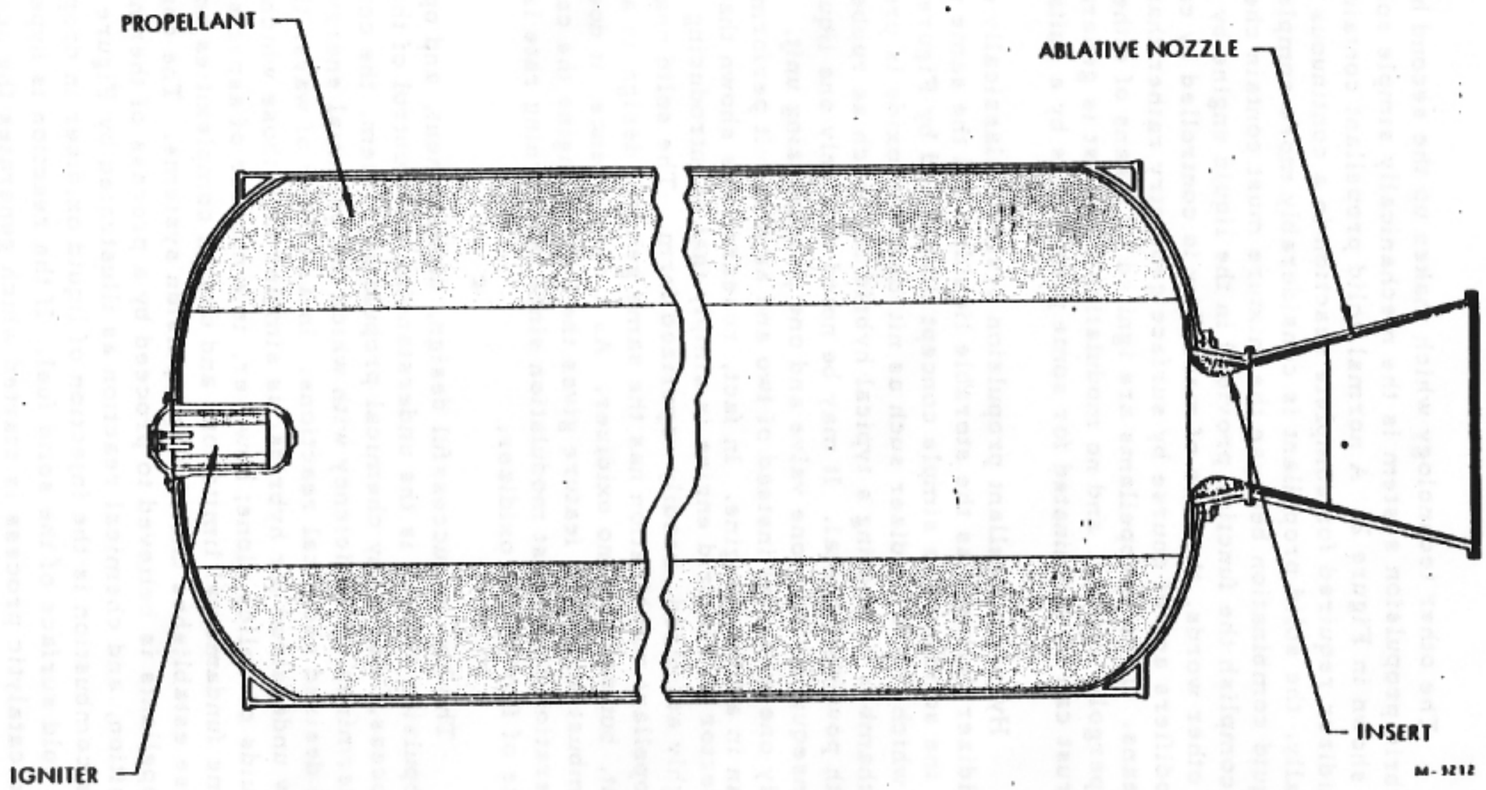


Example Systems:

- Shuttle main engines
- Saturn V all stages
- Delta core
- Shuttle OMS



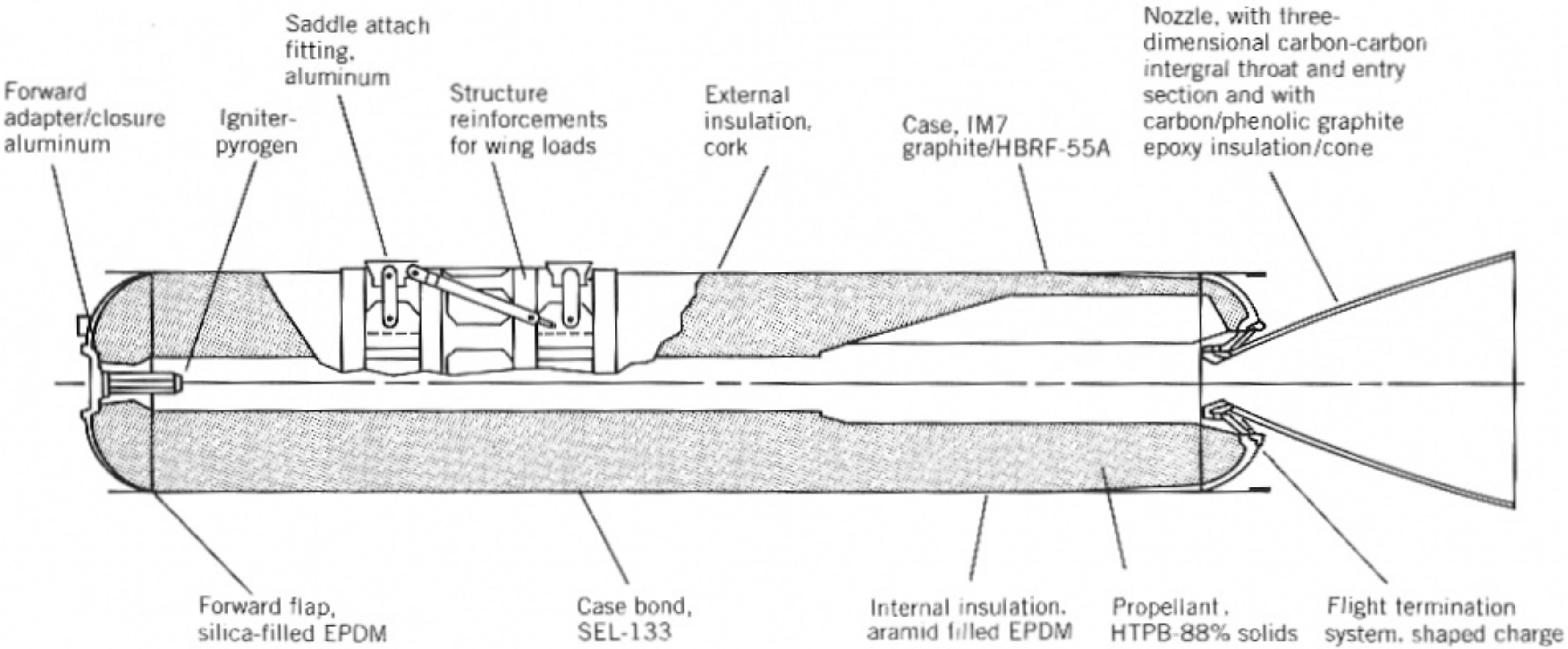
Solid Rocket Schematic



Example Systems:

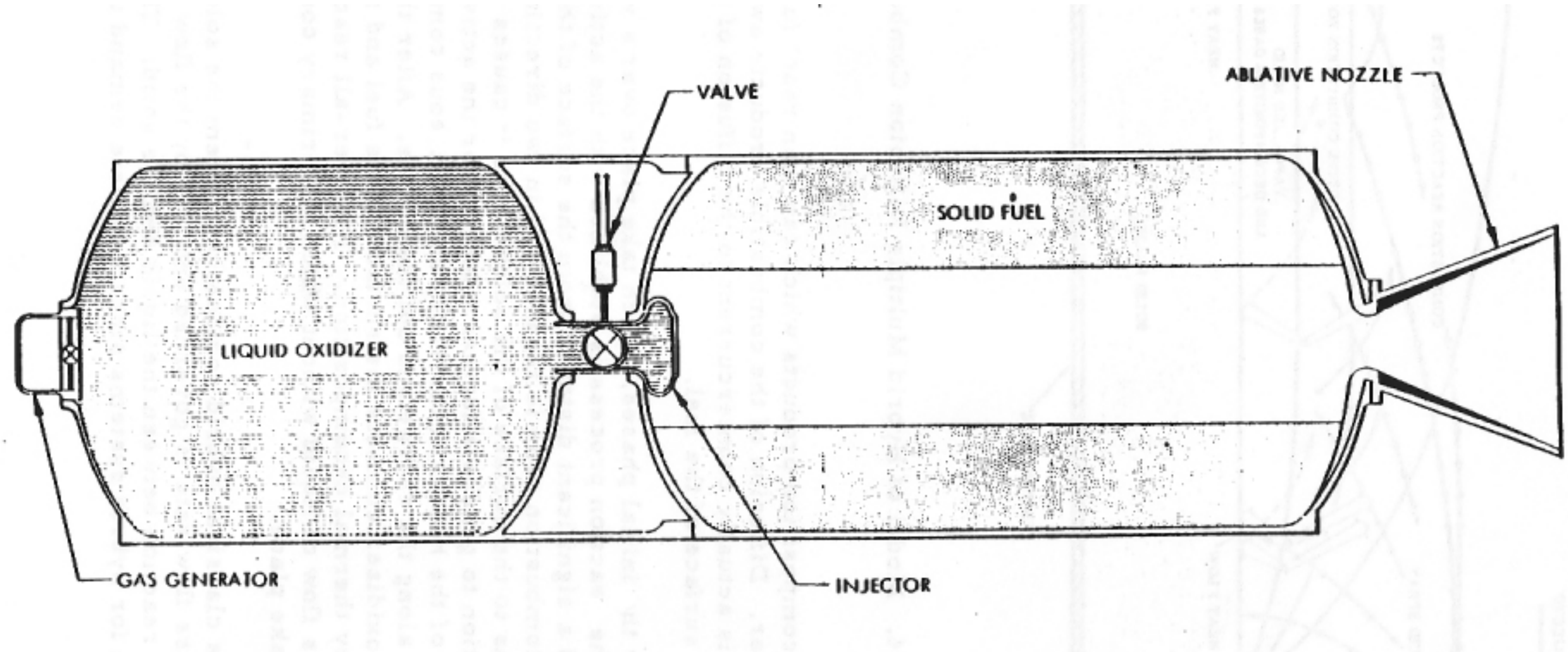
– Shuttle SRM, Ariene V Boosters, Tactical missiles

Solid Rocket System



Pegasus solid rocket motor

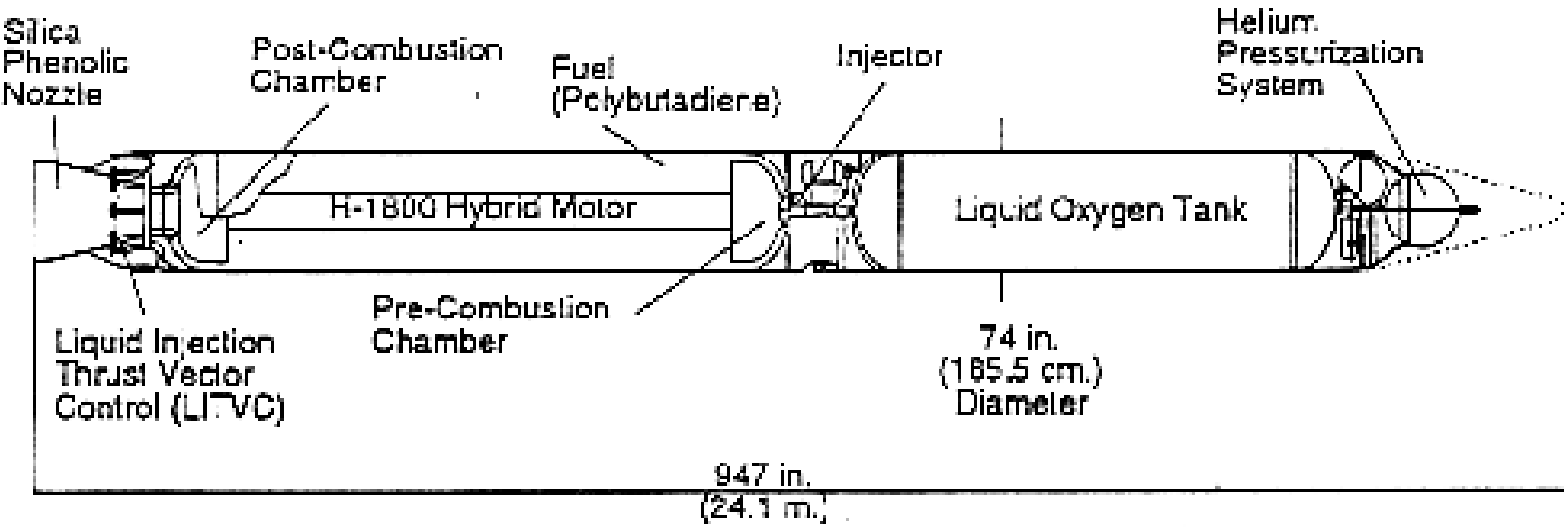
Hybrid Rocket Schematic



Example Systems

– SpaceShipTwo, Target drones, Hobby rockets

Hybrid Rocket System

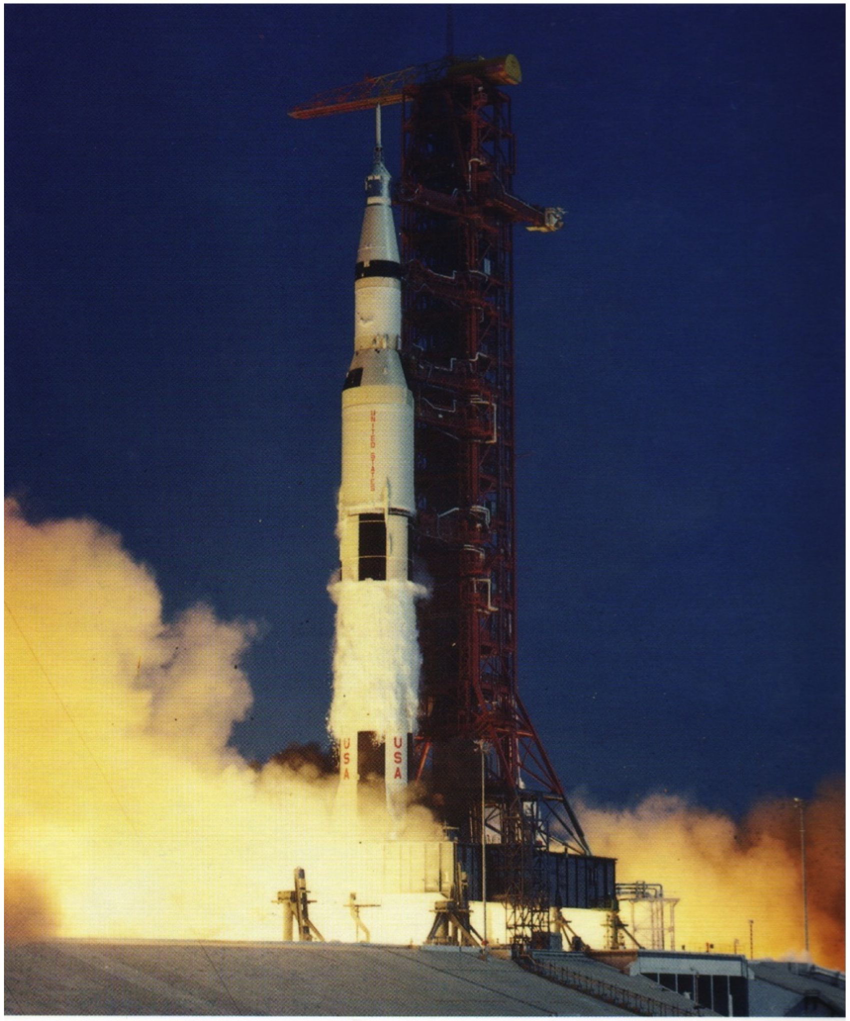


AMROC H1800 Hybrid System

Applications of Rocket Propulsion Systems

- Launch vehicles:
  - Core propulsion, Booster, Upper stage propulsion, Separation rockets
- Civilian sub-orbital applications (other than ballistic missiles)
  - Space tourism, rapid delivery
- Space applications
  - Orbit transfer (GTO to GEO transfer)
  - In space propulsion (main propulsion system, planetary landing, orbit insertion)
  - Attitude control systems
- Military applications
  - Ballistic missiles, Tactical weapon systems, Target drones
- Aircraft thrust augmentation
- Sounding rockets
  - Scientific, Educational, Amateur
- Crew escape systems

Importance of Rocket Propulsion



- Propulsion system constitutes a large fraction of any launch system in terms of
  - Mass
  - Cost
  - Failures
- Propulsion system is an important part of the vehicle (or satellite) for other applications
- Rocket propulsion is **key**
  - to cost effective reliable access to space
  - to achieve the desired mission in space

What Does a Rocket Engineer/Scientist Need to Know ?

- Rocket propulsion is a very interdisciplinary field.
- Some of the important fields are
  - Fluid dynamics/gas dynamics
  - Chemistry, Thermodynamics, Combustion
  - Advanced Physics (Nuclear physics, Electromagnetic theory, Magnetoplasmadynamics, Particle physics)
  - Structures, Material science
  - Thermal protection
  - Flight dynamics, Trajectories
  - Optimization
  - Components (Valves, turbopumps etc)
  - Testing methods, instrumentation
  - Dynamic systems, stability of dynamic systems

Rocket Equation

- Equation of motion in vacuum

$$M\frac{dV}{dt} = T = V_e \dot{m} = -V_e \frac{dM}{dt}$$

- Rearrange in the form

$$dV = -V_e \frac{dM}{M} = -I_{sp} g_o \frac{dM}{M}$$

- Integrate to obtain the "Rocket Equation"

$$\Delta V = I_{sp} g_o \ln\left(\frac{M_i}{M_{bo}}\right)$$

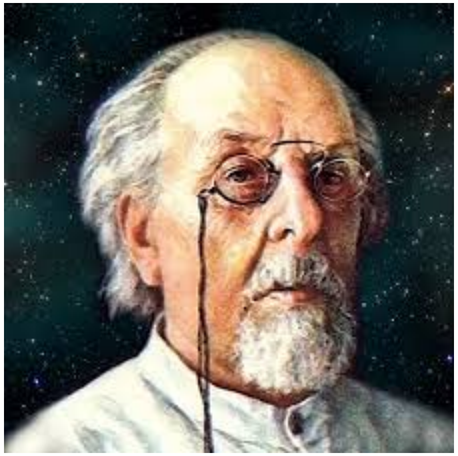
- Single stage to orbit calculation
  - Assume that for a LEO mission $\Delta V = 7{,}500\ m/\sec$ $\quad I_{sp} = 350\ \sec$
  - The rocket equation yields the mass ratio: $M_i / M_{bo} = 8.88$
  - Only **11%** of the vehicle mass is structures/payload

History of Rockets-Early History

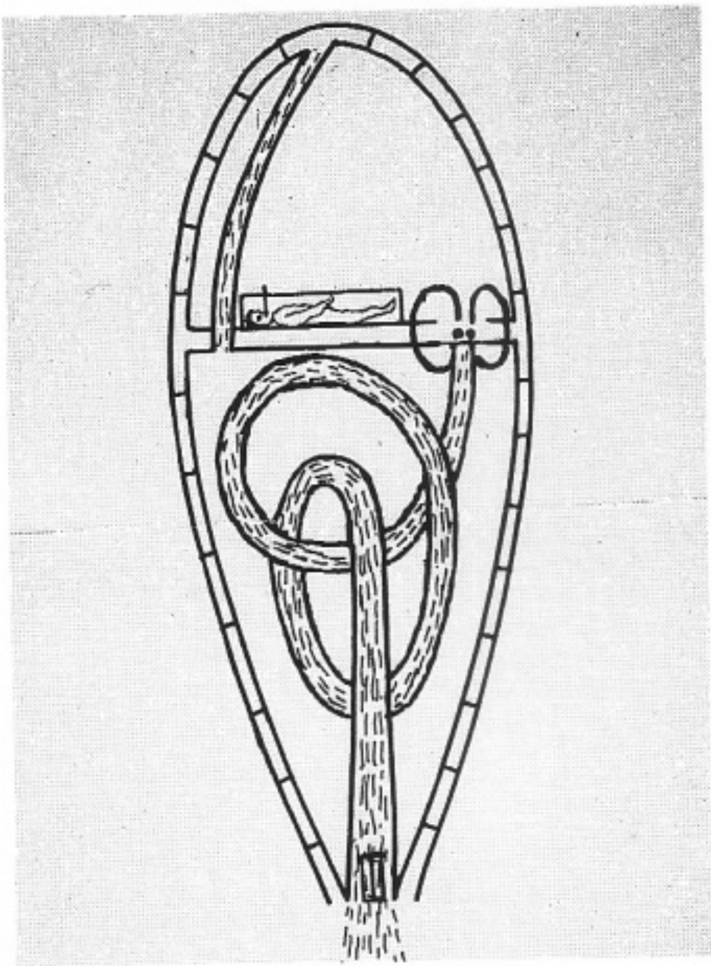
- Hero of Alexandria
  - Credited for inventing the rocket principle
  - Devised many machines using air pressure, steam, water
  - Earliest machines to use the reaction principle-not certain he understood the principles
- China (Feng Jishen) 970 AD
  - Real inventor of rockets
  - Gunpowder in bamboo tubes, a second stick attached for stability
  - Used in ceremonies
- Early Military Use
  - Kublai Khan 1275 (Japanese invasion)
  - Mongolians and Arabs brought the rocket as west as Spain in 1300's
  - Indians (Tipoo Sultan) used rocket against British in 1770's
  - Used in American War of Independence
  - Rockets were **not** used extensively in WW1

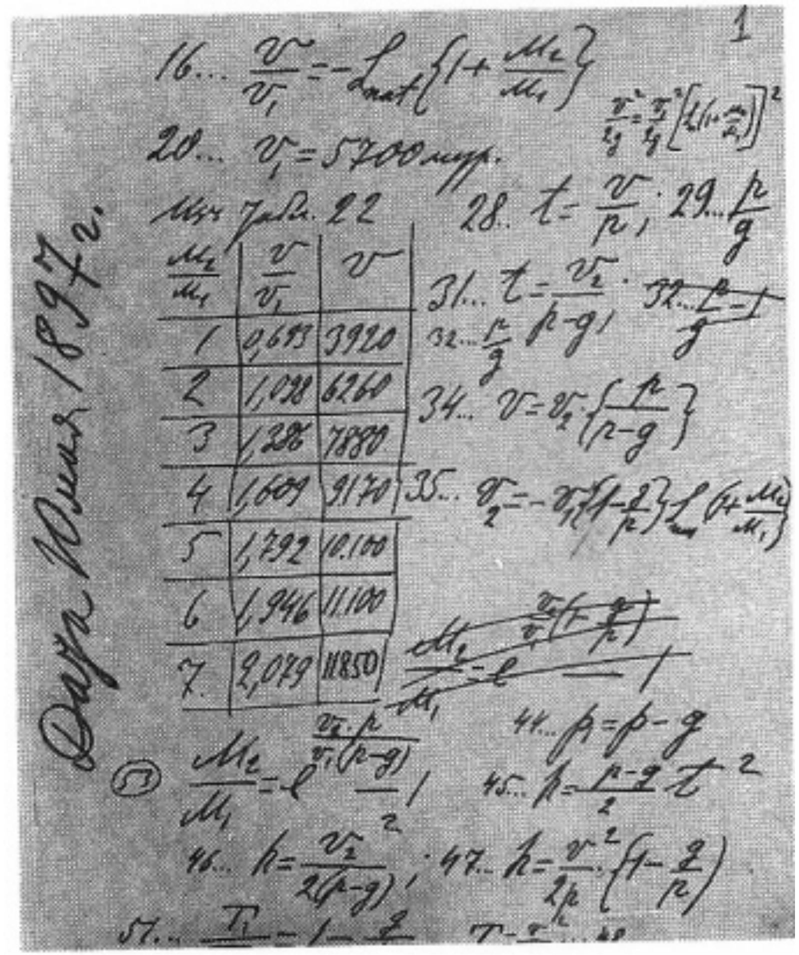
History of Rockets- Birth of Modern Rocketry

- Konstantin Tsiolkovsky (1857-1935) Russian
  - Mathematics teacher, published many papers on the principles of rocketry, all theoretical
  - Here are some of his ideas
    - Space travel (1895)
      - Escape velocity
      - Weightlessness
    - Artificial satellites (1895)
    - Derived the rocket equation (1903)
    - Introduced multi stage rockets (1924)
  - He has laid the mathematical foundation of modern space flight
    - Identified exhaust velocity as an important parameter
      - Understood the importance of high temperature and low molecular weight in obtaining high exhaust velocities
      - Identified liquid oxygen and liquid hydrogen as suitable propellants for space travel



History of Rockets- Birth of Modern Rocketry

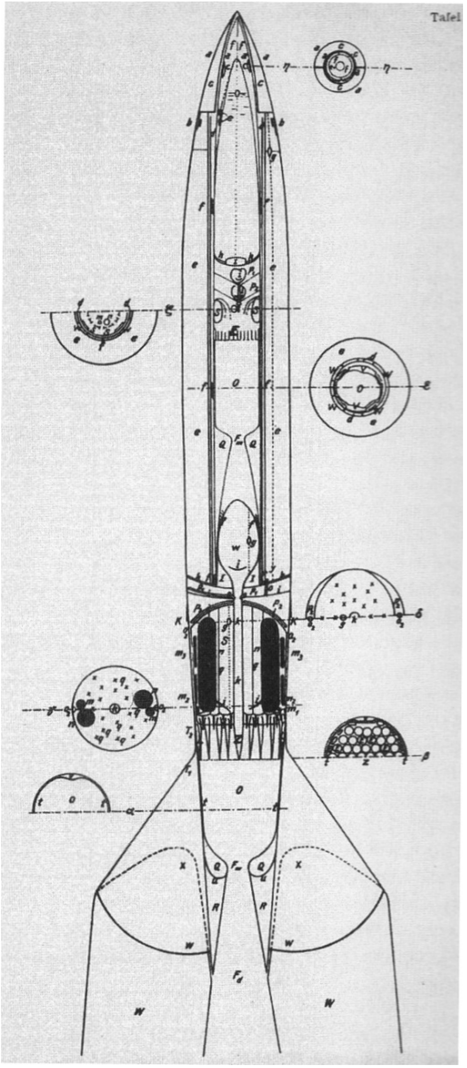




Konstantin Tsiolkovsky’s Rocket Schematic and Calculations

History of Rockets- Birth of Modern Rocketry

- Herman Oberth (1894-1992) German
  - His thesis (which was rejected) on rocket propulsion published in 1923
    - Examined using rockets for space travel
    - Designed of a liquid engine using liquid oxygen and alcohol
  - His work was also mainly theoretical
  - His best seller book generated a huge amateur interest in rocketry in Germany

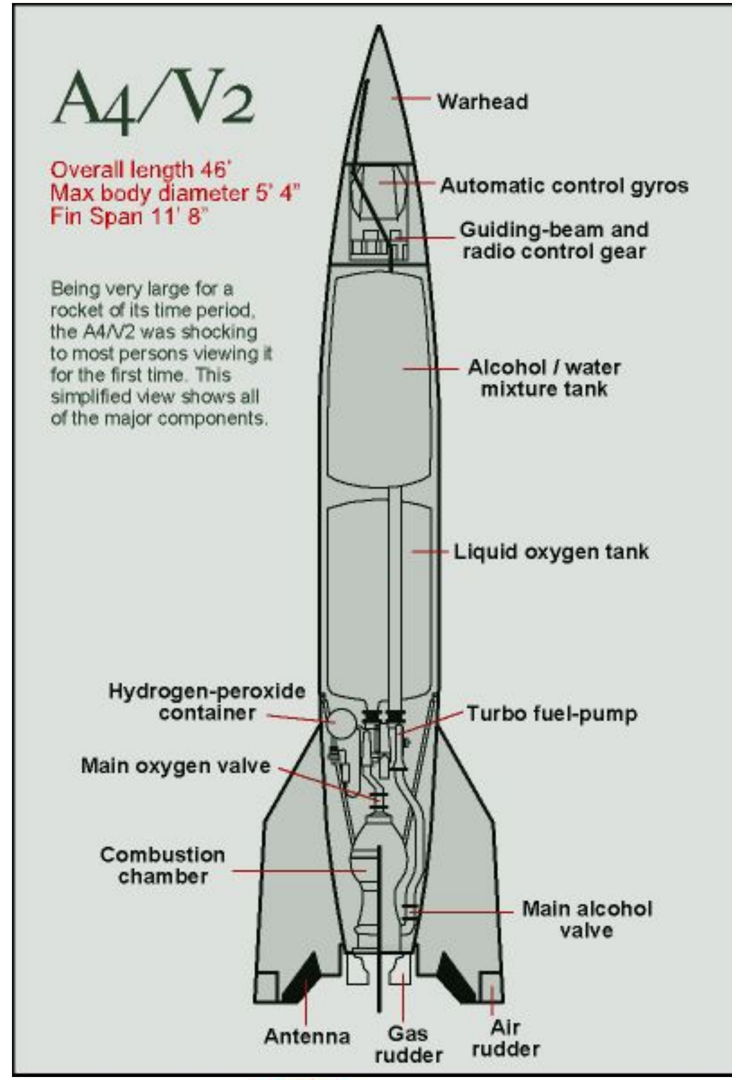


History of Rockets- Birth of Modern Rocketry

- Robert Goddard (1882-1945) American
  - Professor of Physics at Clark University in Massachusetts
  - Published a book "A Method of Reaching Extreme Altitudes"
  - Granted 214 patents on rocket applications
  - Inventions included
    - Gyroscopes for guidance
    - Use of vanes in the plume to steer rocket
    - Use of valve to start and stop
    - Use of liquid oxygen to cool nozzle
    - Use of turbopumps
  - In 1919 published a paper in which he mentioned the possibility of sending a unmanned rocket to the moon. He was ridiculed by the press.
  - Head to New Mexico, continued until 1940.
  - US Government bought his patents for 2 million dollars in 1960.

History of Rockets- Birth of Modern Rocketry

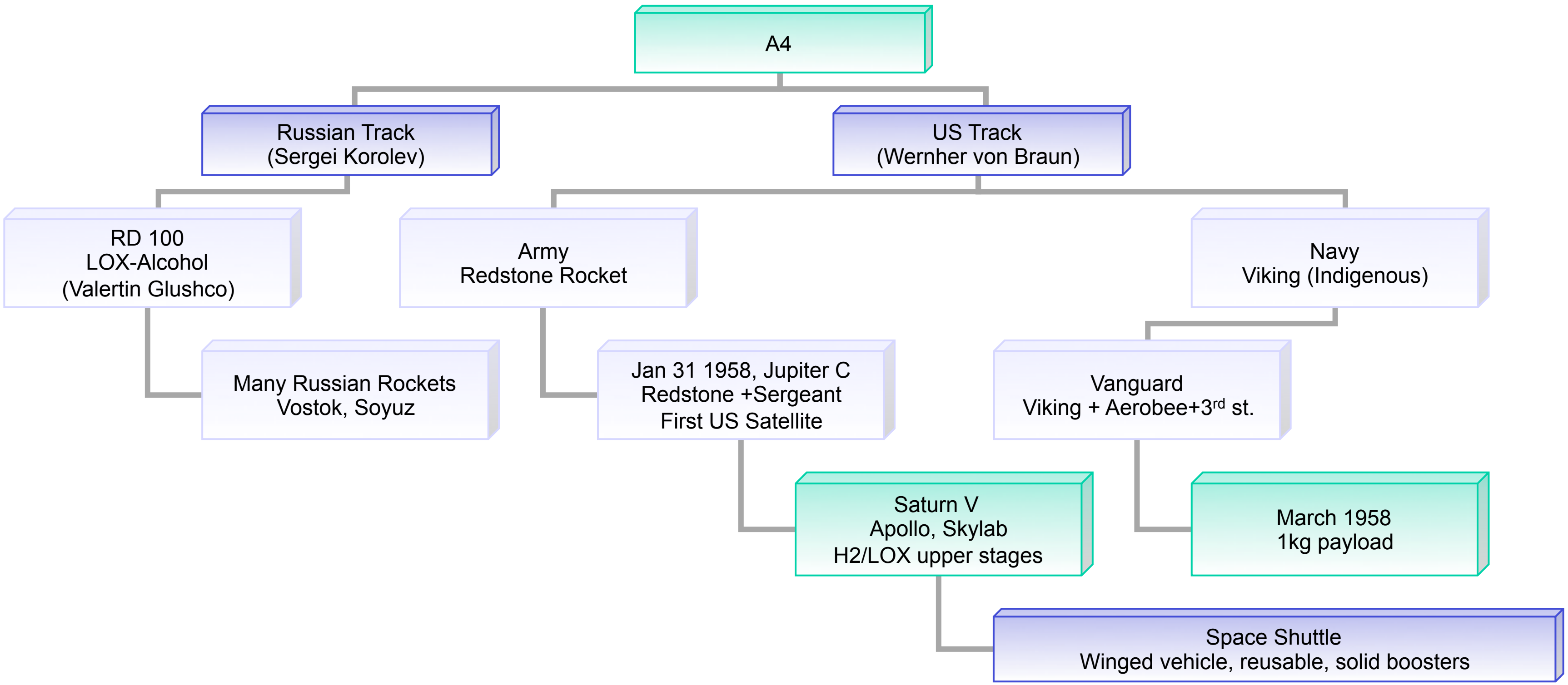
- Wernher von Braun (1912-1977) German/Americ
  - One of the young rocket scientists influenced by Oberth
  - Noticed by the German military in the 1930's, pressured to work for military's interest
  - We was credited as the developer of the A4 (V2) rocket military research station Peenemunde.
  - At the end of WW2
    - Russians took Peenemunde
    - Americans captured Von Braun and his high level technical team.



History of Rockets- Birth of Modern Rocketry

Wernher von Braun and his Rockets

History of Rockets- Birth of Modern Rocketry



History of Rockets- Birth of Modern Rocketry

- For thousands of years rocket technology had
  - Very limited usage (fireworks, limited military weapon)
  - Only propellant gunpowder
- Early in the 20th century pioneers established the foundations of the modern rocket technology
  - Theoretical development
  - Engineering development
  - Development of a vision
- In 1926 Goddard launched the first liquid rocket (apogee: 41 ft)
- In 1942 first successful A4 flight
- In 1950’s scaled up/improved A4 liquid engine technology, developed solid rocket technology
- 1960’s development of segmented solid rocket technology, development of large LOX-kerosene engines, development of large LOX-H2 engines
- 1970’s Shuttle technologies: staged combustion, long lifetime reusable engines
- 1980-2010’s improve the existing technology

Future

“Pragmatism always rests on the efforts of dreamers”

- Wernher von Braun