TRADE STUDIES
Finding the best alternative for system performance from available options
Early on, trade studies were based on judgment calls
  - Required experience and intuition
  - Increasing system complexity made this more difficult

The process has been “systemized”
  - Elaborate mathematical decision analyses (and the computers)
  - Are the results better? Debatable
  - For certain, they diffuse responsibility for decisions

Still required:
  - Engineering judgment
  - Good output only comes from good input (gigo)
  - Output must be evaluated by someone with knowledge, experience, understanding
WHAT IS A TRADE STUDY?

• A trade study is a formal tool that supports decision making

• A trade study is an objective comparison of all realistic alternatives
  • Architectures; baselines; design, verification, manufacturing, deployment, training, operations, support, or disposal approaches
  • Performance, cost, schedule, risk, and all other pertinent criteria A trade study documents the requirements, assumptions, criteria and priorities used for a decision. This is useful since new information frequently arises and decisions are re-evaluated

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TRADE STUDIES SUPPORT DECISION MAKING THROUGHOUT DEVELOPMENT

- Requirements development - e.g., to resolve conflicts; to resolve TBDs and TBRs
- System synthesis - e.g., assess the impact of alternative performance or resource allocations
- Investigate alternate technologies for risk or cost reduction
- Assess proposed design changes
- Make/buy decisions (i.e., build the part from a new design or buy from commercial, existing sources)
DECISION DRIVERS

- Safety
  - Rigid constraints
  - No room for compromise
- Performance
  - Little room for compromise
  - Probably a requirement
- Cost
  - Often the decisive factor
THE TRADE STUDY PROCESS (1/2)

1. Define the objectives of the trade study
2. Review inputs, including the constraints and assumptions
3. Choose the evaluation criteria and their relative importance (these can be qualitative)
4. Identify and select the alternatives
5. Assess the performance of each option for each criteria
6. Compare the results and choose an option
7. Document the trade study process and its results
THE TRADE STUDY PROCESS (2/2)

Establish the study problem
- Develop a problem statement
- Identify requirements and constraints
- Establish analysis level of detail

Select and set up methodology
- Choose trade-off methodology
- Develop and quantify criteria, including weights where appropriate

Review inputs
- Check requirements and constraints for completeness and conflicts
- Develop customer-team communication

Identify and select alternatives
- Identify alternatives
- Select viable candidates for study

Analyze results
- Calculate relative value based on chosen methodology
- Evaluate alternatives
- Perform sensitivity analysis
- Select preferred alternative
- Re-evaluate results

Measure performance
- Develop models and measurements of merit
- Develop values for viable candidates

Document process and results
EVALUATION CRITERIA (1/2)

• Criteria for decision making
  • Measures of Effectiveness (MOE) – customer point-of-view
  • Measures of Performance (MOP) – engineer point-of-view
• Measure of Effectiveness – the effectiveness of a solution
  • How well are mission objectives achieved
  • MOEs assess ‘how well’ not ‘how’
• Examples of MOEs
  • Life cycle cost
  • Schedule, e.g., development time, mission duration
  • Technology readiness level (maturity of concept/hardware)
  • Crew capacity
  • Payload Mass
**EVALUATION CRITERIA (2/2)**

- **Measure of Performance (MOP)** – the measure of a particular design
  - A specified quantitative measure
  - Satisfying an MOP helps ensure that an MOE for the system will be satisfied

- **Examples of MOPs**
  - Mass
  - Power consumption
  - Specific impulse
  - Consumables required
  - Propellant type

- MOEs and MOPs are system figures of merit (FOM)
TRADE STUDY CONSIDERATIONS (1/4)

ASSUMPTIONS

- Trade studies are based on assumptions the team makes.
- Examples of driving assumptions:
  - Crew size assumption drives the amount of consumables and the design of the Life Support System
  - Mission duration assumption drives the amount of power required which in turn drives the choice of power subsystem
  - Landing location on the moon drives delta-v requirements which in turn drives orbit selection and propulsion subsystem
- Changing assumptions within the trade study allows the team to perform a 'what-if' analysis
  - Allows the team to understand the integrity of the design alternative selected
  - Shows the importance of that assumption
TRADE STUDY CONSIDERATIONS (2/4)
MISSION ENVIRONMENT

• The trade space for subsystem alternatives is often defined by the space environment for the mission
  • Why use RTGs when the mission is at 1 AU or on the Moon?
    • RTGs for deep space missions where solar intensity is less
    • But, what if the sun isn't visible from deep in a crater?
• Types of thermal control
  • Consider the operating temperature extremes
  • Passive versus active
• Types of rendezvous and ‘landing’ with a Near Earth Object (NEO)
  • Need to understand the orbit, spin, and composition of object, if known
  • What assumptions can you make about its gravity field?
• Lunar missions
  • Is your system operating at one particular location (like Apollo)
  • Or at global sites depending on the particular mission?
• Trade study analysis should only use relevant information
  • Duh
• ‘Materials’ example:
  • Do material characteristics such as tensile strength and Poisson’s ratio really matter in the selection process?
  • Was heritage considered as a design factor, i.e., has this material flown on previous space missions?
    • If not, what is the cost to bring that technology up to flight-ready status?
  • Availability and cost
TRADE STUDY CONSIDERATIONS (4/4)
TRADE SPACE VS VEHICLE DESIGN

• Is a trade study really necessary?
  • Cargo capsule example:
    • Structural design of capsule is not a trade
    • Evaluation criteria are the design characteristics
    • Heritage is reference information for actual design work
  • Mars habitat example:
    • What are the communications requirements for the mission (voice, video, etc.)?
    • Amount of bandwidth to specify for comm subsystem

• Key question to ask: What makes for a successful mission?
  • Answer defines which trades are of most importance
  • Might drive additional trades
    • Maximum surface exploration time => robust power and Life Support System
    • 1-week cargo delivery => launch vehicle availability and mission plan
Four fundamental propulsion choices
- Solid propellant
- Chemical propellant
  - Monopropellant
  - Bipropellant
- Electric

**Solid**
- Pro
  - Simple and reliable
  - Single large impulse
- Con
  - $I_sp$ lower than chemical
  - High acceleration
PROPULSION (2/2)

• **Bipropellant**
  - Higher $I_{sp}$
  - Less prop mass/total impulse

• **Monopropellant**
  - 1/2 to 2/3 Biprop $I_{sp}$
  - Half the valves, lines, and tanks
  - Cooler thrust chamber
  - Simpler system

  Weigh simplicity vs mass vs efficiency vs ...

• **Electric**
  - Very large $I_{sp}$: 2000 – 3000
  - Has very specific applications
  - Requires a considerable (and continuous) source of power
COMMUNICATION SYSTEMS (1/2)

• Basis of trade studies
  • Amount of information to be transmitted
  • Time available for transmission
  • Distance of transmission

• Bottom line
  • Antenna gain
    • More gain = smaller beam width → more pointing accuracy → GNC system
  • Broadcast power
    • More power → more mass → larger solar cells → increased heat dissipation

• Antenna size can be a problem
  • Packaging for launch
  • Folding vs fixed geometry antennas
COMMUNICATION SYSTEMS (2/2)

• Frequency choice
  • X-band, Ka-band, Ku-band
  • Permits larger data rates for a given antenna size & power
  • “Effective gain" is higher at higher frequencies
  • X-band can be attenuated by heavy rain
  • Ka- and Ku-band can be totally obliterated by rain

• Possible trades
  • Reduce amount of data being transmitted
  • Pre-transmission on-board processing and data encoding

• Cost
  • More computational capability; i.e. $$$
  • How to ensure data is not degraded
  • More software is always more expensive
• Typical power sources
  • Solar voltaic cells
  • Batteries (chemical)
  • Fuel cells (chemical)
  • Radioisotope thermoelectric generators (RTG)
  • Nuclear ???

• Chemical – limited to short duration missions
  • Batteries: unfavorable power/mass
  • Fuel cells: more efficient, but more complex. Produce potable water

• Solar
  • Most common power source
  • Distance limits
  • Batteries usually accompany solar cells
• **RTGs**
  - Long duration missions far from Sun
    - Voyager 1 and 2
    - Viking landers
    - Galileo
    - Apollo lunar surface experiments
  - Tend to be heavy
  - Radiation by-product can be trouble for instrumentation/experiments

• **Nuclear**
  - Advantages
    - High power
    - Moderate mass
    - Long life
  - Disadvantages
    - Adds complexity to mission and SC design
    - Political problems – attracts wacko demonstrators
TECHNOLOGY TRADES
NEW VERSUS OLD

Program/Project
On schedule
Within budget
Minimum uncertainty
What you did last time

System Engineer

Engineer
No interest in schedule
No interest in budget
Most recent technology
Why fly “same old thing”

• New technology is desirable
  • Maximize capability
  • Remain competitive
  • Encourage new development

• Can be seductive
  • Over sold
  • Creates uncertainty
  • Cost and schedule risks
• Systems Engineer
  • Must evaluate new technology effect on the complete system
  • Makes technology decision, or
  • Makes recommendation to Program/Project Mgr.

• Questions to ask
  • Will existing technology do the job?
  • What is the additional cost of incorporating the new technology?
    • Existing system?
    • Redesign?
  • Subsystem compatibility? (Is it transparent?)
  • Are new tests required?
  • What is its TRL?
    • Is it actually available?
    • Is it in production?
  • Possible unintended consequences
• May be forced to new technology
  • Older components become increasingly hard to get
    • Very little demand
    • Vendor can no longer make a profit
• Voyager
  • Design utilized many components from Viking landers
  • Vendor was going to shut down the production line
  • Project paid to keep the product line open
  • Cheaper than redesign and maintained schedule
• Systems Engineer assesses the risk of new technology
  • Too conservative: slow to adopt new tech & company falls behind
  • Too optimistic: schedule delays, cost overruns, potential in-flight problems
BACKUP CHARTS
Interplanetary Propulsion
Phase 1

NTR = Nuclear Thermal Rocket

Electric = Solar or Nuclear Electric Propulsion

1988 “Mars Expedition”
1989 “Mars Evolution”
1990 “90-Day Study”
1991 “Synthesis Group”
1993 “DRM 1”
1997 “DRM 3”
1998 “DRM 4”
1999 “Dual Landers”
1989 Zubrin, et.al.
1994-99 Borowski, et.al.
2000 SERT [SSP]
2002 NEP Art. Gravity
2001 DPT/NEP
M1 2005 MSFC MEPT
M2 2005 MSFC NTM MSA
EXAMPLE: EARTH-MOON TRANSIT TRADE OPTION ANALYSES

Key measure of performance: mass

- TLI stages dominate mass composition.
- Ascent/Descent stages for L1 approach are significantly higher than for LO approach (combination of higher ΔV and habitat masses).
- NTR propulsion applied to TLI function results in significant IMLEO benefit due to influence of TLI maneuver.
- Single crew module carried through entire mission has large scaling effect on all propulsive stages.