Contents

Preface ................................................................xivii
Acknowledgments .................................................. xvii
List of figures ......................................................... xx
List of tables .......................................................... xxi

1 Introduction ......................................................... 1
   1.1 Why Back-of-the-Envelope engineering? ................. 1
      1.1.1 Back-of-the-Envelope engineering; an important adap-
            tation and survival skill for students and practicing
            engineers ........................................ 2
      1.1.2 Design of a high school science fair electro-mechanical
            robot ............................................. 2
      1.1.3 Design of a new commercial rocket launch vehicle for a
            senior engineering student’s design project .......... 3
      1.1.4 Preliminary design of a new telescope system by an
            engineer transferred to a new optical project ......... 3
      1.1.5 Examining the principles and ideas behind Back-of-the-
            Envelope estimation ................................ 4
   1.2 What is a Back-of-the-Envelope engineering estimate? .. 4
      1.2.1 Tradeoff between complexity and accuracy ............ 5
      1.2.2 Back-of-the-Envelope reasoning ....................... 6
      1.2.3 Fermi problems ....................................... 7
      1.2.4 An engineering Fermi problem ....................... 8
   1.3 General guidelines for building a good engineering model .. 12
      1.3.1 Step by step towards estimation ....................... 13
      1.3.2 Quick-Fire estimates ................................. 14
3 Estimating Shuttle launch, orbit, and payload magnitudes .......... 77
  3.1 Introduction ................................................................ 77
    3.1.1 Early Space Shuttle goals and the design phase .......... 78
    3.1.2 The Shuttle testing philosophy and the need for modeling 79
    3.1.3 Back-of-the-Envelope analysis of Shuttle launch, orbit, and payload magnitudes ........................................ 80
  3.2 Shuttle launch, orbit, and reentry basics ......................... 80
    3.2.1 The liftoff to orbit sequence .................................. 80
    3.2.2 Reentry ............................................................... 82
  3.3 Inventory of the Shuttle’s mass and thrust as input to the calculation of burnout velocity .............................................. 83
    3.3.1 Burnout velocity ..................................................... 83
    3.3.2 The velocity budget .................................................. 84
    3.3.3 Mass inventory ....................................................... 84
    3.3.4 Thrust and specific impulse inventory ....................... 84
  3.4 Mass fraction rules of thumb ........................................ 87
  3.5 Quick-Fire modeling of the takeoff mass components and takeoff thrust using SMAD rules of thumb .......................... 89
    3.5.1 Quick-Fire problem approach .................................. 89
    3.5.2 Problem definition and sketch .................................. 90
    3.5.3 Mathematical/“Rule of Thumb” empirical models ......... 90
    3.5.4 Physical parameters and data ................................... 92
    3.5.5 Numerical calculation of total takeoff mass, cargo bay mass, and total takeoff thrust ........................................ 95
    3.5.6 Interpretation of the Quick-Fire results ..................... 97
    3.5.7 From Quick-Fire estimates to Shuttle solutions using more accurate inputs ......................................................... 98
  3.6 Ideal velocity change $\Delta v$ for each stage of an ideal rocket system 98
    3.6.1 Propellant mass versus time ................................... 99
    3.6.2 Time varying velocity change .................................. 100
    3.6.3 Effective burnout time and average flow rate ............... 100
    3.6.4 Ideal altitude or height for each rocket stage .............. 101
  3.7 $\Delta v_{\text{ideal}}$ estimate for Shuttle first stage, without gravity loss 102
    3.7.1 Estimate of SSME propellant mass burned during first stage ................................................................. 103
    3.7.2 First stage mass ratio and average effective exhaust velocity ................................................................. 104
    3.7.3 Average specific impulse for the “parallel” (solid + liquid) first stage burn ..................................................... 104
    3.7.4 $\Delta v_{\text{ideal}}$ estimate for Shuttle first stage ............... 106
    3.7.5 $\Delta v_{\text{ideal}}$ and altitude as functions of time, for the Shuttle first stage ......................................................... 106
  3.8 The effect of gravity on velocity during first stage flight ....... 108
    3.8.1 Modeling the effects of gravity for a curved flight trajectory ................................................................. 108
3.14.2 Approximate linearized solution for payload ........ 145
3.14.3 Reduction in useful cargo mass due to increases in OMS propellant mass ......................... 146
3.14.4 OMS models for correcting cargo or payload mass .... 148
3.14.5 Model for rate of change of “useful cargo” with altitude 150
3.14.6 Approximate analytic model for useful cargo ........ 152
3.14.7 Modeling missions to the International Space Station .. 154
3.15 Tabulated summary of Back-of-the-Envelope equations and numerical results ................................ 155
3.16 References .................................... 166

4 Columbia Shuttle accident analysis with Back-of-the-Envelope methods . 169
  4.1 The Columbia accident and Back-of-the-Envelope analysis ...... 169
  4.1.1 BotE modeling goals for the Columbia accident ........ 171
  4.1.2 Quick estimation vs accurate estimation ............. 172
  4.2 Quick-Fire modeling of the impact velocity of a piece of foam striking the Orbiter wing ................. 172
    4.2.1 Interpretation of Quick-Fire results .................. 176
    4.2.2 The bridge to more accurate BotE results .......... 176
  4.3 Modeling the impact velocity of a piece of foam debris relative to the Orbiter wing; estimations beyond the Quick-Fire time results 177
    4.3.1 Looking at the collision from an earth-fixed or moving Shuttle coordinate system .......... 178
    4.3.2 The constant drag approximation .................. 181
    4.3.3 Analytically solving for the impact velocity and mass, given the time to impact .......... 182
    4.3.4 Summary of results for constant acceleration model compared to data ...................... 189
    4.3.5 The non-constant acceleration solution ............. 189
    4.3.6 An estimate of impact velocity and particle mass, taking the time to impact as given (the “inverse” problem) ........ 194
    4.3.7 Comparing Osheroff’s “inverse” calculations to our “direct” estimate results ............... 195
    4.3.8 Concluding thoughts on the impact velocity estimate ........ 197
  4.4 Modeling the impact pressure and load caused by impact of foam debris with an RCC wing panel .......... 197
    4.4.1 The impact load .................................... 197
    4.4.2 Impact overview ................................... 198
    4.4.3 Impact load mathematical modeling ............... 199
    4.4.4 Elastic model for the impact stress ............... 200
    4.4.5 Elastic–plastic impact of a one-dimensional rod against a rigid-wall ....................... 203
5 Estimating the Orbiter reentry trajectory and the associated peak heating rates
5.1 Introduction .................................. 221
5.2 The deorbit and reentry sequence .......... 222
5.3 Using Quick-Fire methods to crudely estimate peak heating rate and total heat loads from the initial Orbiter kinetic energy 223
5.3.1 Quick-Fire problem definition and sketch 224
5.3.2 The Quick-Fire baseline mathematical model, initial results, and interpretation 224
5.4 A look at heat flux prediction levels based on an analytical model for blunt-body heating 231
5.4.1 Numerical estimates of Stanton number using the Sutton–Graves constant 236
5.5 Simple flight trajectory model ............... 237
5.5.1 A simple BotE model for the initial entry period; the entry solution 239
5.5.2 The equilibrium glide model ............... 249
5.6 Calculating heat transfer rates in the peak heating region 263
5.6.1 Selecting the nose radius .................. 265
5.6.2 Comparing the model maximum rate of heat transfer, \( \hat{q}_{\text{wmax}} \), with data 266
5.6.3 Model estimate for nose radiation equilibrium temperature, \( T_{\text{max}} \) 267
5.6.4 Model calculations of \( \hat{q}_{\text{w}} \) as a function of time 268
5.6.5 Model calculations for total heat load at the stagnation point 271
5.7 Appendix: BotE modeling of non-Orbiter entry problems 274
5.8 References .................................... 275
6 Estimating the dimensions and performance of the Hubble Space Telescope ......................................... 277
6.1 The Hubble Space Telescope .......................................................... 277
  6.1.1 HST system requirements .................................................. 277
  6.1.2 HST engineering systems .................................................. 278
  6.1.3 Requirements for fitting the HST into the Orbiter .................. 279
6.2 The HST Optical Telescope design ............................................... 280
  6.2.1 The equivalent system focal length .................................. 281
  6.2.2 How do designers determine the required system focal ratio, $F_{eq}$? ........................................... 284
  6.2.3 Telescope plate scale ..................................................... 288
  6.2.4 Selection of HST's primary mirror focal ratio, $F_{1} = |f_1|/D$ 289
  6.2.5 Calculating the magnification $m$ and exact constructional length $L$ .............................................. 290
  6.2.6 Estimating the secondary mirror diameter ......................... 291
  6.2.7 Estimating the radius of curvature of the HST secondary mirror .................................................. 292
6.3 Modeling the HST length ............................................................ 295
  6.3.1 The light-shield baffle extension ..................................... 296
  6.3.2 Modeling the length of the light shield ............................. 297
  6.3.3 The length of the instrument section ................................ 298
  6.3.4 Calculating the total HST telescope length ......................... 298
6.4 Summary of calculated HST dimensions ....................................... 299
6.5 Estimating HST mass ................................................................. 300
  6.5.1 Primary mirror design .................................................... 300
  6.5.2 Estimating primary mirror mass ....................................... 301
  6.5.3 The estimated total HST system mass and areal density ....... 303
  6.5.4 Some final words on the HST mass estimation exercise ........ 305
  6.5.5 Onward to an estimate of HST's sensitivity ......................... 306
6.6 Back-of-the-Envelope modeling of the HST's sensitivity or signal to noise ratio .................................. 306
  6.6.1 Defining signal to noise ratio ......................................... 307
  6.6.2 Modeling the mean signal, $S$ ........................................... 307
  6.6.3 Modeling the noise .......................................................... 310
  6.6.4 Final equation for signal to noise ratio ........................... 316
  6.6.5 Final thoughts on BotE estimates for HST sensitivity .......... 318
6.7 References ................................................................................. 319

Index .......................................................................................... 321
Aerospace Engineering on the Back of an Envelope
Alber, I.E.
2012, XXII, 326 p., Hardcover
ISBN: 978-3-642-22536-9