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# WEIGHT AND COST FORECASTING FOR ADVANCED MANNED SPACE VEHICLES

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ABSTRACT

The study develops a mass and cost estimating computerized methology for predicting advanced manned space vehicle weights and costs. The user friendly methology designated MERCER (Mass Estimating Relationship/Cost Estimating Relationship) organizes the predictive process according to major vehicle subsystem levels. Design, devlopment, test, evaluation, and flight hardware cost forecasting is treated by the study. This methodology consists of a complete set of mass estimating relationships (MERs) which serve as the control components for the model and cost estimating relationships (CERs) which use MER output as input. To develop this model, numerous MER and CER studies were surveyed and modified where required. Additionally, relationships were regressed from raw data to accomodate the methology. The models and formulations which estimated the cost of historical vehicles to within 20 percent of the actual cost were selected. The result of the research, along with components of the MERCER Program, are reported. On the basis of the analysis, the following conclusions were established: (1) The cost of a spacecraft is best estimated by summing the cost of individual subsystems. (2) No one cost equation can be used for forecasting the cost of all spacecraft. (3) Spacecraft cost is highly correlated with its mass. (4) No study surveyed contained sufficient formulations to autonomously forecast the cost and weight of the entire advanced manned vehicle spacecraft program. (5) No user friendly program was found that linked MERs with CERs to produce spacecraft cost. (6) The group accumulation weight estimation method (summing the estimated weights of the various subsystems) proved to be a useful method for finding total weight and cost of a spacecraft.

## INTRODUCTION

Initial design cost estimates form the premise for budget determination, program approval, and subsequent performance measurement on research spacecraft programs. Unrealistic estimates early in the program are the source of problems for many project managers who are forced to operate within budgets that understate the technical complexity of the job. Cost forecasters consistently report spacecraft cost as a function of the mass; however, the determination of the mass in the initial stage of development still remains a challenge.

The purpose of this study was (1) to extract from the literature those mass estimating relations (MERs) that determine the total mass of a spacecraft by summing the mass of its individual subsystems; (2) to survey cost estimating relationships (CERs) as a function of mass; (3) to normalize and create MER and CER equations in order (4) to develop a computer program that uses MER output as input into CERs producing the cost of a spacecraft as final output.

## MASS ESTIMATING RELATIONSHIPS (MERs)

Forecasting mass properties of a spacecraft vehicle is one of the most important considerations in the design process and yet, one of the most inexact engineering endeavors. While the calculation of propulsion and mission performance are based on widely recognized mathematical forecasting techniques, the estimation of weight is based largely on historical data. The attempt to forecast weight has evolved through the years by collection and correlation of component weights of previously-built vehicles. Advanced vehicle weights are predicted on the basis of component weights of past designs. Although the precise weight of a vehicle is a very complex calculation, mathematical equations for combining the components mass properties into total vehicle mass properties are quite concise. Mass determination for the total vehicle is easily determined once the mass of all subsystems is known. The mass of an individual subsystem is largely a function of the spacecraft geometry; e.g., wetted area, planform area, length, width, volume, etc. These parameters are usually available or can be calculated. This study determines the total weight of spacecraft vehicle by summing the weights of all of its subsystems.

## COST ESTIMATING RELATIONSHIPS (CERs)

Historically, early estimates of spacecraft projects cost have been considerably less than the final actual cost. Spacecraft have been very expensive to produce because of stringent weight and performance requirements, heavy emphasis on reliability, and small production quantities. Various parametric cost estimating models have been developed from experience of the past 30 years, and those models reproduce the cost of the traditional spacecraft with acceptable accuracy. Due to the limited data base of manned space vehicles, a spacecraft cost estimating procedure based on historical data often contains errors. Mathematical relationship errors will exist in any estimating procedure which attempts simplification of actual cause and effect by empirical approximation. A good cost model, of course, is one that strives to minimize these inevitable errors. Cost regression equations for spacecraft subsystems are typical of the type

$$Y = AX^b \quad \text{or} \quad Y = A + BX^c$$

Where Y = cost and X = weight or some other subsystem characteristic. Those cost models that were shown to predict the cost of historical vehicles to within 20 percent of the actual cost were selected or developed for this study. The source of these cost models is reported in the next section of this paper.

## LINKING THE MERs AND CERs

The Mass Estimating Relationship/Cost Estimating Relationship (MER/CER) Program is a computer program for sizing subsystems and vehicle weights and costs for advanced planetary manned vehicles and boost rockets. The major components of the program include: (a) MERs taken from (1) The Mass Properties Systems and Formulation of the NASA Langley Research Center and (2) Handbook for Weight Estimating and Forecasting of Manned Space Systems During Conceptual Design for NASA Johnson Space Center (JSC); and (b) CERs extracted from (1) Marshall Space Flight Center (MSFC) Launch Vehicle Cost Model, (2) MSFC Space Station Cost Model, and (3) NASA's Advanced Planning Cost Model (NAPCOM) prepared by MSFC. The output from each MER in every subsystem becomes the input into the appropriate CER to produce a final cost.

Utilization of previous studies and systems was limited primarily to raw data and formulations used or developed in the earlier works. In a few cases, discrepancies were discovered in listings of raw data and in the calculating of the regressions. In these cases, additional data were used from independent sources and new regressions were calculated to resolve the discrepancies.

The JSC Weight Handbook provided regression curves based on early Shuttle studies and proposals. The MERCER Program converted these curves to mathematical relationships suitable for entry in the EXCEL Program. These equations required system-by-system testing with data from the "as built" Shuttle. The greatest numbers of modifications to the original equations resulted from these tests; however, an independent regression of rocket engine weight versus thrust showed the JSC Handbook curve (and equation) to be more easily applied (broader application) to the MERCER Program than the elaborate and (selectively specific) rocket engine MER in the LaRC paper. Yet, the LaRC body mass relationships proved more accurate than those offered by the JSC Weight Handbook. The MERCER Program permits use of alternate MERs and CERs which may be compared or averaged to enhance accuracy and forecasting credibility.

A final evaluation of the MERCER Program utilized a previous system weight and cost study done by the APDO for the Crew Emergency Rescue Vehicle (CERV) Program. In addition, an "as built" vehicle, Lunar Module, was entered as a test article to confirm MERCER system credibility. Again, an 80% accuracy criteria served as the desired result. Comparing the MERCER result with the two test cases showed better than 80% agreement in weight and cost.

## MERCER PROGRAM APPLICATION

The MERCER Program strives to use features resident in EXCEL and the Macintosh system in a user-friendly fashion. Among these features is the "GO TO" instruction. Clicking on "GO TO" opens a listing of every MER and CER subsystem in the entire MERCER Program so that quick access to specific subsystem entry data as well as weight, and cost results is achieved.

The MERCER Program has a fundamental feature: To compute from an initial specification a forecasted weight for each system of an advanced manned space vehicle or booster rocket; to input the forecasted weight into a corresponding cost equation for forecasting cost of each advanced vehicle system; and finally, to calculate the total forecasted cost.

The MERCER Program features facilitate this fundamental operation. Initial input data is entered in ledger fashion in a single column of the EXCEL spreadsheet matrix. The input data consists of both listed constants selected by the user based on primary space vehicle specifications and the MER input variable (volume, wetted area, planform area, thrust, etc.) The MERCER equation is listed adjacent to the entry data column to assist the user. Again, a designated ledger column serves for listing of all MERs and CERs. This column displays subsystem calculated weights and costs.

Total cost includes two categories: non-recurring design development, test, and evaluation (DDTE) cost and recurring flight hardware (FH) cost. Each subsystem has two cost forecasting equations listed on separate MERCER columns: one for design and development (DD) cost, the other flight FH cost. In some cases, DD cost is designated DD&T with the "T" indicating tooling. In some cases FH cost is designated FH&A with the "A" indicating assembly. Regardless of the listing of "T" or "A" with DD and FH, these are regressions of the same overall cost elements as those listed DD or FH and are treated identically.

DD cost and TE cost are treated separately by MERCER. Subsystem DD costs are summed and used to compute a total vehicle test and evaluation (TE) cost. Again, in accounting ledger fashion, subtotals are displayed for summed subsystem total DD cost, total subsystem FH cost, total TE cost, total FH assembly/test/management cost, and total FH cost. In like fashion, subsystems weights are summed in ledger fashion identifying a total vehicle weight.

MERCER provides a Phase A cost forecast of total vehicle DDTE and FH cost using the NAPCOM CERs. Though MERCER is not organized like the NAPCOM spreadsheet, NAPCOM's CERs are resident in MERCER. The NAPCOM CERs are not modified by MERCER other than normalization to 1989 equivalent dollars. Three NAPCOM equations (Manned Module Cost, Booster Cost, and Orbital Transfer Vehicle Cost) are listed in MERCER. The total MERCER vehicle weight serves as the input to the selected NAPCOM CER. The NAPCOM cost forecast may then be compared to the subsystem based cost estimate generated by MERCER.

## SUMMARY AND CONCLUSION

Advanced Manned Spacecraft weight may be adequately estimated and costed for initial feasibility study utilizing regression mathematics within a programmed methology. The Mass Estimating Relationship/Cost Estimating Relationship Program (MER/CER) is such a system developed by this study for the Advanced Projects Definition Office (APDO) of the New Initiatives Office (NIO). Adequate techniques sizing of subsystem and vehicle weights and costs for advanced planetary manned vehicles and boost rockets were accomplished. Content of the methology includes two independent mass property estimating systems, three independent cost estimation systems, and mass and cost estimation relationships developed by the study. Dry weights are expressed in pounds and costs in 1989 million-dollar units.