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16. Abstract

Typically, NASA unmanned satellite projects have three main cost areas (exclusive of launch vehicle costs) the spacecraft platform (SCP), the payload or experiments, and the postlaunch ground equipment and operations. The SCP normally accounts for over half the total project cost. Therefore, accurate estimates of project SCP costs early in project planning are required as a basis for formulating total project budget requirements. Because of this need, it was decided to investigate single formula SCP CER's that could be developed from readily available data by statistical linear regression analysis and used with the degree of detail available at the end of early project planning. In its formulation, the model for single formula CER's has had the advantage of requiring less historic cost and parameter data interpretation than models that go to the subsystem level.

Much of the work that went into the SCP CER equations presented in this document was accomplished while the author was employed at Goddard Space Flight Center and was in part an outgrowth from earlier cost modeling accomplished at that center by the Cost Experience Group.

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CONTENTS

# INTRODUCTION

The Cost Estimating Relationship (CER) equations presented in this document are useful for early planning of unmanned spacecraft projects. Specifically, the CER equations are designed to provide an estimate of spacecraft platform costs to include an indication of recurring and nonrecurring costs. The intention of this report is to provide a working understanding of how these spacecraft platform CER's were derived and how they may be used. It is also the intention of this report to explain a CER concept that can be comparatively easily updated (1) as more spacecraft projects are completed or are near completion, (2) as other cost drives become better understood, and (3) as the effect of such state-of-the-art changes as large scale integrated circuits become measurable.

## Background

Typically, NASA unmanned satellite projects have three main cost areas (exclusive of launch vehicle costs) the spacecraft platform (SCP), the payload or experiments, and the postlaunch ground equipment and operations. The SCP normally accounts for over half the total project cost. Therefore, accurate estimates of project SCP costs early in project planning are required as a basis for formulating total project budget requirements. Because of this need, it was decided to investigate single formula SCP CER's that could be developed from readily available data by statistical linear regression analysis and used with the degree of detail available at the end of early project planning. In its formulation, the model for single formula CER's has had the advantage of requiring less historic cost and parameter data interpretation than models that go to the subsystem level.

Much of the work that went into the SCP CER'equations presented in this document was accomplished while the author was employed at Goddard Space Flight Center and was in part an outgrowth from earlier cost modeling accomplished at that center by the Cost Experience Group. The center, through its Cost Experience Group, has contributed to the cost modeling art by development of total project cost estimating models as well as subsystem CER's.

## Summary

To arrive at acceptable cost estimating equations, the highest correlation and best fit between historic project SCP cost and combinations of related parametric data was sought by using statistical curvilinear regression analysis. The selection of independent variables was limited to generally available parametric data, some of which had been found to have a high cost correlation in past modeling experiences at GSFC. The historic data from 17 projects were used as the statistical data base for the CER formulations.

Two facts must be considered when using CER's: (1) CER output reflects the project input used in formulating the models, and (2) they reflect current and past technology and aerospace experience.

In regard to the first fact for example, the data base for the CER's does not include data from such projects as the TOS/ITOS or USAF large quantity satellite projects, and, therefore, the CER's are not effective in directly estimating the costs of such projects.

An example of the second factor is their reflection of aerospace experience and new technology as an influence in decreasing future spacecraft costs per pound; an influence that is very difficult to measure at this time. Some experienced space engineers and project managers believe that past aerospace experience, as well as technological advances such as large scale integrated circuits, may serve to reduce future costs per pound for R&D projects. Initial experience with these CER's, however, indicates that reduction of these cost and weight relationships, because of aerospace learning, may not generally occur, at least not in the immediate future. In fact, although technological advances over the last decade have increased the capability per pound, the average cost per pound after adjustment for inflation has remained relatively stable.

The CER equations presented in this paper have been used in estimating the SCP costs of such new projects as ATS F and G, SMS, Mariner 1973, Pioneers F and G, and Viking Orbiter, as well as completed projects not used in the model statistics. Experience to date in such applications has demonstrated the usefulness and reliability of the equations when properly applied.

## Approach

After historical project cost and parametric data had been collected and normalized, a multiple regression program (revised August 22, 1969) from the Health Science Computer Facility, UCLA, was used with logarithms to derive exponential CER formulas. Such statistics as the standard error of the estimate (SE), coefficient of determination, F value, and T value were determined. A description of these values is given in Appendix A. The basic curvilinear regression formula provided by this program was as follows:

$$Y = a(X_1)^{b1} \quad (X_2)^{b2} \quad (X_3)^{b3} \; . \; . \; . \; (X_n)^{bn}$$

Y = Dependent variable: The cost of spacecraft platform and related costs
X = Independent variables: The SCP parameters and unit quantities
a = Constant derived by program
b = Exponent constant derived by program
n = Number of independent variables

The paremeters found to be the most significant with respect to cost were:

(1) SCP dry weight
(2) Equivalent units of design development and flight SCP effort
(3) Communication and data handling weight
(4) Average spacecraft power required in watts
(5) The number of experiments carried

Combinations of variables were selected as follows: A series of simple scatter diagrams plotting weight and cost variables provided a first cut at the degree of association. A large number of different combinations, including ratios of the independent variables mentioned above, were tested using the regression program.

The equations given in this document were selected based on (1) the statistical best fit in terms of lowest standard error determined for log y, highest coefficient of determination value, F value, and reasonable T values (see appendix A for description of these statistical measures); and (2) the reasonableness of the r esulting combinations of variables, their exponents, and the cost sensitivity of the relationship.

A detailed listing of all project variable values used in deriving the CER equations is found in table I, and described in the following section.

Historical data used in deriving the equations include GSFC scientific and applications spacecraft, USAF communications satellites and Jet Propulsion Laboratory Mariner Planetary Spacecraft. These data were obtained from

| | Data Source |
|---|---|
| GSFC-NASA | Program Obligation Plans, Program Development Plans, monthly (MICS) reports, and project personnel discussions. |
| JPL-NASA | PRC 1970 JPL Cost Prediction Model for Unmanned Space Exploration Missions and the JPL cost estimating staff. |
| USAF | SAMSO Unmanned Spacecraft Cost Model, the cost modeling staff, and background data. |
| Intelsat (4) | Hughes Aircraft Co. proposal documents. |

The majority of present data point used in these models are from GSFC history where the normal mode of operation is an R&D funded prime SCP contractor monitored by Research and Program Management (R&PM) funded in-house staff. To bring all costs to this base, adjustments were made to projects that were built in-house at GSFC. To the R&D costs of GSFC in-house projects (RAE,SSS) were added the direct and indirect costs for in-house engineering and manufacturing man-years paid from R&PM funds minus normal project monitoring staff man-years. Adjustments were also made of JPL project costs, which included the R&D funded in-house monitoring staff. The JPL man-year burdened costs, which are associated with monitoring of JPL in-house Mariner effort paid out of R&D funds, were deducted from total JPL project costs.

All actual project SCP costs were adjusted to 1970 dollar values to account for the effects of inflation. The midpoint year of the expenditures stream

TABLE I

HISTORICAL DATA USED IN CER FORMULATIONS

| Project | SCP 1970 $M | SCP Dry Weight[a] | Equivalent Units | Communications and Data Handling Weight[a] | Average Power Required, Watts | Experiment Quantity |
|---|---|---|---|---|---|---|
| 1 | 177.0 | 887 | 14.3 | 175 | 200 | 20 |
| 2 | 56.5 | 352 | 11.5 | 50 | 30 | 9 |
| 3 | 33.3 | 104 | 10.7 | 15 | 40 | 7 |
| 4 | 14.1 | 112 | 4.0 | 25 | 35 | 7 |
| 5 | 20.7 | 314 | 4.0 | 49 | 32 | 4 |
| 6 | 13.0 | 83 | 3.9 | 25 | 20 | 7 |
| 7 | 15.7 | 216 | 3.6 | 45 | 27 | 6 |
| 8 | 99.0 | 611 | 12.4 | 115 | 150 | 6 |
| 9 | 112.3 | 700 | 9.3 | 134 | 220 | 3 |
| 10 | 90.0 | 1003 | 7.0 | 181 | 245 | 6 |
| 11 | 16.2 | 84 | 7.0 | 26 | 13 | 1 |
| 12 | 70.0 | 880 | 6.1 | 250 | 350 | 1 |
| 13 | 25.7 | 104 | 8.0 | 39 | 34 | 1 |
| 14 | 33.0 | 244 | 6.0 | 81 | 94 | 1 |
| 15 | 79.6 | 516 | 9.5 | 103 | 180 | 4 |
| 16 | 23.5 | 488 | 3.0 | 103 | 180 | 4 |
| 17 | 104.0 | 707 | 10.4 | 153 | 350 | 4 |

a/ These weights are the average of the units flown in each project.

TABLE II

ADJUSTED PROJECT SCP COSTS
(Millions of dollars)

| Project | Midpoint of Expenditures for Inflation Adjustment | Actual or Current Estimate Total Cost | Inflation Adjusted | GSFC In-House Prime Effort | JPL Project Monitoring Staff | Adjusted Project SCP Costs |
|---|---|---|---|---|---|---|
| 1 | 1965 | 141.4 | 177.0 | | | 177.0 |
| 2 | 1965 | 45.0 | 56.5 | | | 56.5 |
| 3 | 1965 | 14.1 | 17.0 | +16.3 | | 33.3 |
| 4 | 1967 | 7.7 | 9.0 | +5.1 | | 14.1 |
| 5 | 1966 | 9.0 | 10.9 | +9.8 | | 20.7 |
| 6 | 1968 | 4.7 | 5.3 | +7.7 | | 13.0 |
| 7 | 1970 | 15.7 | 15.7 | | | 15.7 |
| 8 | 1967 | 84.7 a/ | 99.0 | | | 99.0 |
| 9 | 1965 | 89.6 | 112.3 | | | 112.3 |
| 10 | 1967 | 74.5 | 88.0 | | | 88.0 |
| 11 | 1969 | 13.1 | 16.2 | | | 16.2 |
| 12 | 1969 b/ | 24.0 c/ | 25.7 | | | 25.7 |
| 13 | 1969 b/ | 30.8 c/ | 33.0 | | | 33.0 |
| 14 | 1969 | 65.0 | 70.0 | | | 70.0 |
| 15 | 1970 d/ | 89.0 | 89.0 | | -9.4 | 79.6 |
| 16 | 1970 d/ | 26.6 | 26.6 | | -3.1 | 23.5 |
| 17 | 1970 d/ | 117.5 | 117.5 | | -13.5 | 104.0 |

a/ This figure includes cost of all communications type experiments and cost of gravity gradient boom experiments.

b/ These figures were taken from SAMSO Unmanned Spacecraft Cost Model input data which had been adjusted to 1969 dollars using annual inflation rates very close to those used on the other project costs.

c/ These dollars represent the SAMSO model input data of nonrecurring plus recurring costs for only three flight SCP's per project. They do not represent actual total project cost. A 10% estimated USAF in-house support cost was added.

d/ These figures were taken from PRC/JPL Cost Prediction Model for Unmanned Space Exploration Missions in which dollars had been adjusted to 1970 price levels using annual inflation rates very close to those used on the other project costs.

TABLE III

DERIVATION OF GSFC IN-HOUSE PRIME EFFORT AND JPL IN-HOUSE PROJECT MONITORING STAFF ADJUSTMENT $\Delta$

| Project | Actual or Estimated Project Man Year Total | In-House Monitoring Man Year Estimate from GSFC Man Year Model | Difference | Burdened Man Year, Thous. of $ | Product Mill. of $ | $\Delta$ SCP | Experiments |
|---|---|---|---|---|---|---|---|
| GSFC In-house Prime Effort: | | | | | | | |
| 3 | 577 | 131 | 446 | 44 a/ | $19.6 | 16.3 | 3.3 |
| 4 | 196 | 53 | 143 | 44 a/ | 6.3 | 5.1 | 1.2 |
| 5 | 314 | 75 | 239 | 44 a/ | 10.5 | 9.8 | .7 |
| 6 | 250 | 50 | 200 | 44 a/ | 8.8 | 7.7 | 1.1 |
| JPL Project Monitoring Staff: | | | | | | | |
| 15 | | 293 | | 35 b/ | 10.3 | -9.1 | 1.0 |
| 16 | | 100 | | 35 b/ | 3.5 | -3.1 | .4 |
| 17 | | 427 | | 35 b/ | 15.0 | -13.5 | 1.5 |

a/ This is the average salary for GSFC Technology and Projects Directorate staffs with an average aerospace industry burden rate of 147% applied.

b/ This is the average salary for GSFC Technology Projects and Systems Reliability Directorates with an average aerospace nonpersonnel services burden rate of 1.05%.

was used as a point from which to adjust total SCP costs to 1970 dollars.

Because it was not possible to find documented statistical data on price increases in the aerospace industry, the inflation rate used was an average of data gained from several sources, including the Bureau of Labor Statistics and the Federal Reserve Bank. The following are the inflation factors used between years:

| Years | % Rate of Change |
|---|---|
| 1965 to 1966 | 3.0 |
| 1966 to 1967 | 3.5 |
| 1967 to 1968 | 4.0 |
| 1968 to 1969 | 6.0 |
| 1969 to 1970 | 7.0 |

See tables II and III for adjusted project costs.

## DESCRIPTION OF VARIABLES USED IN REGRESSION ANALYSIS

### Spacecraft Platform Costs

The total project SCP historical costs reflect those accrued through a prime contractor mode of operations and include the special institutional in-house support costs. However, normal NASA or USAF project institutional in-house monitoring staff costs were not included. The SCP costs include design, development, fabrication, and test of all SCP test and flight units.

This included such things as mission analysis program management, and administration, quality control, software studies, necessary test equipment, the integration and test of the spacecraft and experiments, final environmental testing of the integrated satellites, and project-borne launch support costs. It does not include experiment or other payload costs. An exception is that all elements of communications satellite costs were included. Communications satellites were not considered to be payload carriers in the sense of scientific experiments or sensor payloads. In this vein, all communications experiments were considered part of the communications and data handling subsystem and, therefore, part of the spacecraft platform costs. All historical change order and change of scope costs are included.

The included GSFC institutional support costs, mentioned above, in excess of prime contractor dollars were for such things as quality control, computer usage, test and evaluation taxes, special studies, or software and other peripheral R&D project expenses and averaged about 12% of total SCP cost. At the same time, the included Air Force systems engineering and technical direction costs are an additional approximately 10% of their prime contractor costs.

## Spacecraft Platform Weight

This includes all satellite weight except for the experiments (payload) and inordinately heavy but inexpensive items. The latter items not included are solid fuel apogee motors and their shells, adaptors, fuels, parachutes, and any heavy shields or balance weights. Items that may be unusually expensive per pound, such as entry probe pressure spheres and shields, should also be subtracted when using the CER equations. The SCP items deleted are assigned a cost value either from other applicable CER's or analogously. In the case of communications type satellites, the total satellite weight, less the inordinately heavy but relatively inexpensive items mentioned above, should be used.

## Equivalent Units

The system of equivalent units (EU's) provides an approximate means of measuring total project SCP nonrecurring activity in relation to an EU of effort; that is, the effort and cost that go into one unit recurring flight SCP. The unit recurring or EU cost is further defined as the cost of fabricating, testing, and providing launch support for one flight spacecraft after initial development and design or redevelopment and redesign between flights has been completed. Essentially the total number of EU's in a project SCP activity is derived by dividing the total project SCP activity cost by the approximate unit recurring (i.e., one EU) cost.

The following OGO example will illustrate the primary method used for determining the EU values necessary for model derivation. The first step is to determine the total EU value for the project. In the OGO example, project and contractor proposal documents indicated the value of one EU to be about \$12.4M in 1970 dollars. The \$12.4M was then divided into the \$177M total (1970 value) project SCP activity cost to provide a quotient of 14.3 which is the total number of EU's of effort expended in the project. Next, the OGO nonrecurring (NR) development hardware/test and recurring (R) flight hardware/test were analyzed and assigned values in terms of an EU as follows:

| Test Units (NR) | EU value assigned, based on project documents, discussions with project personnel, and other analysis |
|---|---|
| Thermal/mechanical unit | 0.1 |
| Engineering unit | .5 |
| Prototype unit | 1.7 |
| **Flight Units (R)** | |
| Six flights | 6.0 |
| Spares | 1.0 |
| Total | 9.3 |

The EU values assigned to NR and R hardware and related test effort totaled 9.3. The 5.0 EU difference between the 9.3 EU's of hardware effort and the total project effort of 14.3 EU's is considered to be the nonrecurring design, development, mission analysis, and aerospace ground equipment (AGE) effort cost. It was in turn judged from OGO history that of the 5.0 EU's of design and development, approximately two units of effort were initial NR effort and the remaining three were expended in downstream NR redesign, redevelopment, test, new AGE, and mission analysis between each of the seven flights. This then provided the breakdown of EU effort shown for OGO in Table IV. In this technique, all NR and R EU's of effort share the project management, administration, sustaining engineering, and overall quality control costs.

In most scientific satellites the redesign effort is considerable. The redesign and redevelopment effort has normally resulted from previous flight problems, the need to change the subsystem to conform to changing experiment interface requirements, and the propensity to "improve" each follow-on flight. On the other hand, in the case of the JPL Mariner projects, the delay between launches was so short (1 or 2 months) that there was no time for redesign between launches.

When determining the initial nonrecurring design and development EU value for the projects used in model derivation, the design inheritance from previous like or similar programs was considered. Specifically, the IMC series, Syncom, IDCSP/A, Mariner Venus '67 and Intelsat VI benefitted by inheriting from previous like designs. The particular period when the SCP's were built, the contractor, and situation were also considered. For example, the fact that very little, if any, of the present strict GSFC quality control, reporting, and documentation requirements were placed on the early satellites such as the first OSO's is indicated by a low initial design and development EU value for that program.

As should be noted from the foregoing, the EU values and relationships are approximations. They do provide a flexible means for estimating the cost for varied design and development requirements. For this reason tables IV and V should be studied and used as guides for determining the EU values to be used in the CER's shown in Table VI. In general, Appendix B, "Data Collection and CER Application Guidelines" and particularly the "Initial Design, Development, and Inheritance" form given should be used as a guide to formulate EU values. The EU technique also provides a means of breaking down costs into approximate nonrecurring and recurring categories. (See Appendix C.)

## Average Watts

This is the average regulated power (av. watts) required for engineering, housekeeping, communications, data handling, attitude control, guidance, experiments, regulators/converters, and miscellaneous. This is usually the same as the assigned satellite power. In terms of the Earth orbiting satellites, it is the spacecraft power requirement for normal mode of operation. For the planetary satellites like the Mariners and Pioneers F and G, it is the average power required during encounter with a planet. For Pioneer F and G,

TABLE IV

EQUIVALENT UNIT SUMMARY

| Category | OGO A-C | OGO D-F | OSO A-C | OSO D-C | Explorer (IMP) A-C | Explorer (IMP) D&E | Explorer (IMP) F&G | RAE A | SAS A&B | SSS A | ATS | Nimbus 1-3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nonrecurring: | | | | | | | | | | | | |
| Initial design & development d/ | 2.0 | 0.5d/ | 0.4 | 0.7d/ | 1.0d/ | 0.4d/ | 0.4d/ | 1.5 | 0.6 | 1.5 | 2.0a/ | 1.5b/ |
| Thermal/mechanical unit | .1 | | | | .1 | .1 | .1 | .1 | .1 | .1 | .2 | .2 |
| Engineer unit | .5 | | | | | | | | | | .7 | 1.0 |
| Other test units | | | | | .1 | .1 | .1 | | | | .2 | .2 |
| Prototype units | 1.7 | .2 | | .2 | 1.4 | 1.4 | | | | | 1.5 | 1.5 |
| Protoflight units | | | 1.4 | | | | 1.7 | 1.8 | 2.5c/ | 1.8 | | |
| Total Initial NR | 4.3 | .7 | 1.8 | .9 | 2.6 | 2.0 | 2.3 | 3.4 | 3.2 | 3.4 | 4.6 | 4.4 |
| Follow-on Flight redesign | | | | | | | | | | | | |
| Prototype | | | | | | | | | | | 1.3 | 1.4 |
| Redesign total | 1.4 | .9 | .6 | .9 | .2 | .1 | .2 | | .3 | | 1.2a/ | .6 |
| Redesign average bet. flights | (.7) | (.4) | (.3) | (.3) | (.1) | (.1) | (.2) | | (.3) | | (.3) | (.6) |
| Total Nonrecurring | 4.7 | 1.6 | 2.4 | 1.8 | 2.8 | 2.1 | 2.5 | 3.4 | 3.5 | 3.4 | 7.1 | 6.4 |
| Recurring | | | | | | | | | | | | |
| Flight Units | 3.0 | 3.0 | 3.0 | 4.0 | 3.0 | 2.0 | 1.0 | | | | 5.0 | 2.0 |
| Spares | .5 | .5 | .3 | | .4 | .4 | .5 | .6 | .1 | .5 | .3 | .9 |
| Total | 9.2 | 5.1 | 5.7 | 5.8 | 6.2 | 4.5 | 4.0 | 4.0 | 3.6 | 3.9 | 12.4 | 9.3 |
| | 14.3 | | 11.5 | | | | | | | | | |

Table IV cont.

| Category | Nimbus B&D | Syncom A-C | IDCSP | IDCSP/A | Intelsat VI | MM'64 | MV'67 | MM'69 |
|---|---|---|---|---|---|---|---|---|
| Nonrecurring: | | | | | | | | |
| Initial design & development d/ | 1.2 b/ d/ | 1.0 d/ | 1.4 | 1.0 d/ | 0.5 d/ | 3.0 | 0.5 d/ | 2.9 |
| Thermal/mechanical unit | .2 | | .1 | | | | | |
| Engineer unit | .7 | .3 | 1.0 | | | | | |
| Other test units | .4 | 1.0 | .5 | | | 2.0 | | 3.0 |
| Prototype unit | 1.0 | 1.4 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| Protoflight units | | | | | | | | |
| Total Initial NR | 3.5 | 3.7 | 4.5 | 2.5 | 2.0 | 6.5 | 2.0 | 7.4 |
| Follow-on Flight redesign | | | | | | | | |
| Prototype | | | | | | | | |
| Redesign total | .5 | | | | | | | |
| Redesign average bet. flights | (.5) | | | | | | | |
| Total Nonrecurring | 4.0 | 3.7 | 4.5 | 2.5 | 2.0 | 6.5 | 2.0 | 7.4 |
| Recurring: | | | | | | | | |
| Flight units | 2.0 | 3.0 | 3.0 | 3.0 | 4.0 | 2.0 | 1.0 | 2.0 |
| Spares | 1.0 | .3 | .5 | .5 | .3 | 1.0 | | 1.0 |
| Total | 7.0 | 7.0 | 8.0 | 6.0 | 6.3 | 9.5 | 3.0 | 10.4 |

a/ Includes design and development effort for gravity gradiant stabilization system.
b/ Includes design and development effort for HDRESS tape recorder.
c/ The value is for two protoflight units.
d/ Reflects the savings realized from design inheritance.

TABLE V

EQUIVALENT UNIT VALUE RANGE

| Category | Range |
|---|---|
| Nonrecurring Effort: | |
| Design and development effort without inheritance: | |
| Average GSFC project | 1.5 to 2.0 |
| JPL Mariner project | 3.0 |
| Thermal/Mechanical test unit | .1 |
| Engineering unit | .3 to .5 |
| Prototype unit | 1.5 to 1.8 a/ |
| Redesign between each flight | .0 to .7 |
| Recurring effort: | |
| Flight units | Actual count |
| Spares | Project staff estimate |
| Total EU used as CER input | |

a/ Normal prototype effort is worth 1.5 EU's whereas a protoflight is assigned a value of 1.8 on the average.

and Explorer 33 and 35 type planetary missions, where experiments are in operation on a more continuous basis, it is similar to Earth orbiting satellites and the normal cruise mode power requirement is most appropriate.

## The Communication and Data Handling System Weight

The weight of this system (C&DH wt) consists of all onboard equipment necessary for (1) receiving, decoding, and processing commands, (2) formating payload and engineering data, (3) data storage, (4) tracking, and (5) data automation. This includes data relay devices and an average of 5 pounds of dipole-type antennas, but not the weight of larger and heavier dish-type antennas or mechanisms. It also includes the JPL Mariner Command and Control Sequences.

## Experiment Quantity

This value is the average number of primary experiments to be flown on each flight spacecraft and is designated as Exp Qty in this report.

# THE DERIVED COST ESTIMATING RELATIONSHIPS

Table VI presents the CER equations with a list of the projects included in their derivation and a comparison of actual input costs with the model calculated costs. All CER output costs are in millions of constant 1970 dollars. They include (1) the contract dollars, (2) the average additional institutional 12% support costs, and (3) expected change order costs (from historical experience). In addition it needs to be understood that these CER's, as derived, are designed for estimating the cost of scientific (Earth orbiter and planetary) and application-type projects. The economies of quantity application satellite production are not provided for in these models. For the users benefit, an example of the use of an SCP CER to derive a project SCP activity cost estimate is provided in Appendix D. Finally, particular caution should be used when estimating proposals who's physical/performance characteristics significantly exceed those of the historic inputs to CER derivation.

Table VI

UNIVERSAL DATA POINT CER'S

CER NO. 1

$$SCP = 0.186(SCPwt)^{0.61581} (EU)^{0.96837} \text{ in 1970 \$M}$$

Coefficient of determination = 0.9772
SE determined for log Y = 0.05952, antilog 1.14
F value = 301

T value (10% level of significance = 1.77):
SCP wt 15.17
EU 21.91

| Projects Included in Derivation | Budget or Actual Cost, 1970 $M | Model Calculations, 1970 $M | Calculations Over (Under) Budget or Actual |
|---|---|---|---|
| 1 | 177.0 | 160.0 | (17.0) |
| 2 | 56.0 | 73.2 | 17.2 |
| 3 | 15.7 | 17.6 | 1.9 |
| 4 | 33.3 | 32.3 | (1.0) |
| 5 | 14.1 | 13.0 | (1.1) |
| 6 | 20.7 | 24.5 | 3.8 |
| 7 | 13.0 | 10.6 | (2.4) |
| 8 | 99.0 | 110.0 | 11.0 |
| 9 | 109.8 | 91.1 | (18.7) |
| 10 | 90.0 | 86.3 | (3.7) |
| 11 | 79.6 | 77.0 | 2.6 |
| 12 | 23.5 | 24.4 | .9 |
| 13 | 104.0 | 102.0 | (2.0) |
| 14 | 16.2 | 18.7 | 2.5 |
| 15 | 25.7 | 24.3 | (1.4) |
| 16 | 33.0 | 31.1 | (1.9) |
| 17 | 70.0 | 69.7 | (.3) |

## CER NO. 2

$$SCP = 0.260(SCP\ wt)^{0.42971}\ (EU)^{0.95632}\ (Av\ watts)^{0.17339}\ \text{in 1970 \$M}$$

Coefficient of determination = 0.9878
SE determined for log Y = 0.04516, antilog 1.11
F value = 351

Degrees of freedom = 13
T value (10% level of significance = 1.77):

| | |
|---|---|
| SCP wt | 6.78 |
| EU | 16.77 |
| Av watts | 3.36 |

| Projects Included in Derivation | Budget or Actual Cost, 1970 $M | Model Calculations 1970 $M | Câlculations Over (Under) Budget or Actual |
|---|---|---|---|
| 1 | 177.0 | 153.3 | (23.7) |
| 2 | 56.0 | 60.2 | 4.2 |
| 3 | 15.7 | 15.8 | .1 |
| 4 | 33.3 | 35.0 | 1.7 |
| 5 | 14.1 | 13.8 | (.3) |
| 6 | 20.7 | 21.1 | .4 |
| 7 | 13.0 | 10.7 | (2.3) |
| 8 | 99.0 | 108.4 | 9.4 |
| 9 | 109.8 | 93.3 | (16.5) |
| 10 | 90.0 | 84.5 | (5.5) |
| 11 | 79.6 | 80.7 | 1.1 |
| 12 | 23.5 | 26.2 | 2.7 |
| 13 | 104.0 | 113.0 | 9.0 |
| 14 | 16.2 | 17.5 | 1.3 |
| 15 | 25.7 | 25.8 | .1 |
| 16 | 33.0 | 33.7 | .7 |
| 17 | 70.0 | 74.5 | 4.5 |

CER NO. 3

SCP = 0.214(SCP wt)$^{0.44989}$ (EU)$^{0.98582}$ (C&DH wt)$^{0.18432}$ in 1970 $M

Coefficient of determination = 0.9806
SE determined for log Y = 0.05709, antilog 1.14
F value = 219

Degrees of freedom = 13
T value (10% level of significance = 1.77):

| | |
|---|---|
| SCP wt | 3.80 |
| EU | 13.52 |
| C&DH wt | 1.48 |

| Projects Included in Derivation | Budget or Actual Cost, 1970 $M | Model Calculations 1970 $M | Calculations Over (Under) Budget of Actual |
|---|---|---|---|
| 1 | 177.0 | 161.9 | (15.1) |
| 2 | 56.0 | 68.4 | 12.4 |
| 3 | 15.7 | 17.1 | 1.4 |
| 4 | 33.3 | 29.5 | (3.8) |
| 5 | 14.1 | 12.7 | (1.4) |
| 6 | 20.7 | 22.9 | 2.2 |
| 7 | 13.0 | 10.8 | (2.2) |
| 8 | 99.0 | 11.0 | 11.1 |
| 9 | 109.8 | 90.6 | (19.2) |
| 10 | 90.0 | 85.1 | (4.9) |
| 11 | 79.6 | 76.9 | (2.7) |
| 12 | 23.5 | 24.1 | .6 |
| 13 | 104.0 | 104.2 | .2 |
| 14 | 16.2 | 19.5 | 3.3 |
| 15 | 25.7 | 26.3 | .6 |
| 16 | 33.0 | 33.4 | .4 |
| 17 | 70.0 | 74.4 | 4.4 |

## CER NO. 4

$$SCP = 0.306(SCP\ wt)^{0.21619}\ (EU)^{0.95778}\ (C\&DH\ wt)^{0.23191}\ (Av\ watts)^{0.16527}$$

$$(Exp\ Qty)^{0.08674}\ \text{in 1970 \$M}$$

Coefficient of determination = 0.992
SE determined for log Y = 0.374, antilog 1.09
F value = 272

Degrees of freedom = 11
T value (10% level of significance = 1.80):

| | |
|---|---|
| SCP wt | 1.86 |
| EU | 18.59 |
| C&DH wt | 1.82 |
| Av watts | 3.22 |
| Exp Qty | 2.34 |

| Projects Included in Derivations | Budget or Actual Cost, 1970 $M | Model Calculations 1970 $M | Calculations Over (Under) Budget or Actual |
|---|---|---|---|
| 1 | 177.0 | 174.7 | (2.3) |
| 2 | 56.0 | 59.2 | 3.2 |
| 3 | 15.7 | 16.2 | .5 |
| 4 | 33.3 | 33.0 | (.3) |
| 5 | 14.1 | 14.4 | .3 |
| 6 | 20.7 | 19.7 | (1.0) |
| 7 | 13.0 | 12.0 | (1.0) |
| 8 | 99.0 | 109.6 | 10.6 |
| 9 | 109.0 | 90.3 | (19.3) |
| 10 | 90.0 | 85.0 | (5.0) |
| 11 | 79.6 | 79.4 | (.2) |
| 12 | 23.5 | 26.0 | 2.5 |
| 13 | 104.0 | 113.4 | 9.4 |
| 14 | 16.2 | 16.7 | .5 |
| 15 | 25.7 | 25.6 | (.1) |
| 16 | 33.0 | 32.8 | (.2) |
| 17 | 70.0 | 70.9 | .9 |

## STATISTICAL NOTE

It should be noted that, statistically, a high degree of correlation between independent variables in a multiple regression equation may provide a much larger standard error than is indicated by the program results. Several of the equations (see Table VI: CER nos.2, 3, and 4) presented in this report contain independent variables that are interdependent. Therefore, to test for sensitivity the equations were derived twice, once with 10 data points and once with 17 data points, to determine the difference between the exponents for the same variable when the number of data points is varied. A difference that exceeds the value of one standard error for the exponents indicates that the standard error value for the CER equation may be larger than that derived in this report. The reader is referred to table VII which provides detailed comparison of the program-derived CER exponents with their standard error. Determining the actual standard error for equations with several independent variables when interdependence is present is very difficult and was not attempted in this statistical analysis. It should be noted that in CER #1 (table VI) the two independent variables have no correlation and therefore the standard error value given for it does not suffer from the possible inaccuracy described above.

TABLE VII

COMPARISON OF CER EXPONENTS
DERIVED WITH 17 AND 10 DATA POINTS

| CER No. | Variable | 17 Data Points | SE for Exponents | 10 Data Points |
|---|---|---|---|---|
| 1 | A | 0.186 | | |
| | SCP wt | 0.616 | 0.041 | 0.598 |
| | EU | 0.968 | 0.075 | 0.968 |
| 2 | A | 0.260 | | |
| | SCP wt | 0.430 | 0.063 | 0.372 |
| | EU | 0.956 | 0.057 | 0.870 |
| | Av watts | 0.173 | 0.052 | 0.276 |
| 3 | A | 0.214 | | |
| | SCP wt | 0.450 | 0.118 | 0.032 |
| | EU | 0.986 | 0.073 | 1.076 |
| | C&DH | 0.184 | 0.124 | 0.573 |
| 4 | A | 0.306 | | |
| | SCP wt | 0.216 | 0.116 | 0.115 |
| | EU | 0.958 | 0.052 | 0.946 |
| | C&DH | 0.232 | 0.127 | 0.309 |
| | Av watts | 0.165 | 0.051 | 0.217 |
| | Exp Qty | 0.087 | 0.037 | 0.008 |

## FUNCTIONAL APPLICATION SATELLITE EXPERIENCE

The TOS, ITOS application weather satellite series was not used in formulating the CER's because they are significantly lower in cost per pound than are scientific spacecraft. These weather satellites are functional applications satellites that take advantage of existing state-of-the-art black box and subsystem designs and a great deal of design inheritance from series to series. These TOS and ITOS satellites by group are very close to being assembly line products that, for instance, involve fewer expensive engineering labor hours than tailored scientific spacecraft. The satellites have all been built by one contractor, RCA, which has gained a good deal of experience in evolving and producing this particular group of application satellites.

Those U.S. Air Force satellite application programs, which involve large quantities of the same satellite and are essentially production line operations like the weather satellites, are also significantly overestimated by these CER's. The CER's in this report overestimate such production application type spacecraft by about 30%.

## CONCLUSION

It is intended that these CER's will be updated as more data become available. The CER formulas contained herein (Table VI), when used intelligently with valid parametric data and sound assumptions, are a means of obtaining an indication of the total SCP cost range for most new satellite project proposals.

APPENDICES

# APPENDIX A

## STATISTICAL MEASURES

This appendix defines and gives the mathematical formulas for the statistical neasures used in selecting appropriate equations from those derived with the curvilinear program.

### DEFINITIONS

#### The Standard Error of Estimate

For a multiple regression equation, the standard error of estimate (SE) measures the closeness with which the estimated values agree with the original values. It is the average of the deviations about the line of regression.

The size of the SE is a measure of the degree of association between series. The larger the SE value, the greater the scatter about the line of regression, and the poorer the CER. One SE about the regression line indicates that the error in this estimate should be within these limits in about 68% of the cases, within two SE about 95% of the cases, and within three about 99.7% of the cases.

Because the value of the exponent of each independent variable is determined by the use of logarithms, there is a significant difference between the interpretation of the SE in the exponential case and in the conventional linear method. To set upper and lower bounds on the estimate within "n" standard deviations using the exponential approach, the following equations should be used.1/ 2/

1/ A detailed discussion of the calculation of regression equations and SE's for the relationship between log Y and X can be found in "Statistics with Applications in Management and Economics" by Earl K. Bowen, Richard D. Irwin, Inc., Homewood, Ill., 1960.

2/ M. F. Brunner, "Use of Standard Error of the Estimate in Exponential Equations," Memo for the Record, Goddard Space Flight Center, December 1970.

A) Upper bound = (Estimate) $(\text{Anti-log of the SE})^n$ of the estimate where

$$1 = n = 3$$

B) Lower bound = $\dfrac{(\text{Estimate})}{(\text{Anti-log of the SE})^n \text{ of the estimate}}$ where

$$1 = n = 3$$

Example: Estimate = \$100,000
Log of the Standard Error = .097
Anti-log of the standard error = 1.25

A) 1 standard deviation
Upper bound = \$100,000 (1.25) = \$125,000
Lower bound = $\dfrac{\$100,000}{1.25}$ = \$ 80,000

B) 2 standard deviation
Upper bound = \$100,000 $(1.25)^2$ = \$156,250
Lower bound = $\dfrac{\$100,000}{(1.25)^2}$ = \$ 64,000

C) 3 standard deviation
Upper bound = \$100,000 $(1.25)^3$ = \$195,312 2/
Lower bound = $\dfrac{\$100,000}{(1.25)^3}$ = \$ 51,200

The Coefficient of Determination

The coefficient of determination shows the proportion of total variance accounted for by the estimating relationship. When all observed points in the sample are on the least-square line, the coefficient of determination equals 1 and there is no unexplained or residual variance. As the proportion of total variance that remains unexplained increases, the coefficient of determination approaches zero.3/

The F Test

The F value found in this test is the ratio of the explained to the unexplained variance.3/

3/ C. A. Batchelder et al., "An Introduction to Equipment Cost Estimating," RM-6103-SA, the Rand Corp., December 1969.

## T Ratios

These ratios test the significance of the relationship between X and Y. In multiple regression, T ratios indicate not only the significance of each of the independent variables, but also the presence of an unacceptable strong relationship between these variables. In these CER equations, a T ratio equal to or higher than a 10% level of significance value was sought.

## Degrees of Freedom

This is the difference between the number of data points used in deriving the formula and the number of variables in the formula.

## MATHEMATICAL FORMULAS

### Standard Error

$$SE = \sqrt{\frac{\Sigma(Y_i - \hat{Y}_i)^2}{DF}}$$

where $Y_i$ = Actual value of Y.

$\hat{Y}_i$ = Estimated value of Y.

and

DF = Degrees of freedom.

### Coefficient of Determination

$$r^2 = \frac{\Sigma(\hat{Y}_i - \bar{Y})^2}{\Sigma(Y_i - \bar{Y})^2}$$

where $\bar{Y}$ = Mean value of Y.

### F Test

$$F = \frac{\Sigma(\hat{Y}_i - \bar{Y})^2/n}{\Sigma(Y_i - \hat{Y}_i)^2/DF}$$

### T Test

$$t_{\hat{b}} = \frac{\hat{b}}{S_{\hat{b}}}$$

where $\hat{b}$ = Estimated coefficient

and

$S_{\hat{b}}$ = Standard error of the estimated coefficient.

APPENDIX B

DATA COLLECTION AND CER APPLICATION GUIDELINES

This form is designed to be used with the basic SCP cost estimating model document.

Key Project Planning Contacts
(Name) (Phone)

PROJECT ______________________ 1. ______________________
2. ______________________
DATE ______________________ 3. ______________________

GENERAL INFORMATION AND GUIDELINES (to provide insight into proposal)

Spacecraft design concept (TOS, OSO, Mariner, ATS, etc.) ______________________

______________________

Management mode (in-house prime effort, contractor prime, combination)

______________________

Launch dates ______________________

Possible contractor proposers ______________________

______________________

Type stabilization (spin, 3 axis, gravity gradient) ______________________

______________________

Pointing accuracy: Max ______________________ Normal ______________________

Telemetry bit rate ______________________

Data storage, core or tape ______________________

Other cost affecting design factors ______________________

Major development articles or subsystems ______________________

Unusual redundancy ______________________

Proposal planning completed to date, phase A or B ______________________

Dollars or man months spent on studies and planning to date ______________________

(This provides some indication of the firmness of proposal data provided)

CER DIRECT INPUT DATA

1. Weight in pounds from proposal weight statement (subtract inordinately heavy but relatively inexpensive items) (Item weights subtracted to be estimated by other means.)

| | | |
|---|---|---|
| Total gross satellite wt | ________ | lbs. |
| Fuel | ________ | |
| Other (inordinately heavy or expensive items | ________ | |
| Dry satellite weight | ________ | |
| Experiments | ________ | |
| Spacecraft platform wt | ________ | |

Weight relationship indicators

| Subsystem | Model Data Points Average % of Net Satellite Weight | | Proposal % of Net Satellite Weight |
|---|---|---|---|
| C&DH: | | | |
| Scientific spacecraft | 14 | | |
| Communications spacecraft | 33 | | |
| Mariners | 18 | 19 | |
| Experiments | | | |
| Earth orbiting spacecraft | 28 | | |
| Planetary spacecraft | 12 | 23 | |
| Structure and thermal | | 20 | |
| Power supply | | 23 | |
| Attitude control | | | |
| 3 axis | 18 | | |
| Gravity gradient | 14 | | |
| Spin | 07 | 12 | |
| Other | | 03 | |
| Total | | 100% | 100% |

2. Power average load (from proposal power allocation statement) example

| | | |
|---|---|---|
| Converter loss | ________ | watts |
| Engineer | ________ | watts |
| Experiments | ________ | watts |
| Communication | ________ | watts |
| Other | | watts |
| Total average load | ________ | |

(Max array output ________) Max load ________

3. Equivalent unit value assignment

Nonrecurring effort

| | |
|---|---|
| D/D effort | ________ |
| Thermal mechanical unit | ________ |
| Engineer unit | ________ |
| Other test units | ________ |
| Prototype or protoflight | ________ |
| Redesign between flights (including that to accommodate new experiments) | ________ |

Recurring effort

| | |
|---|---|
| Number of flight units | ________ |
| Spares | ________ |
| Total Proposal EU's | ________ |

COMPUTATIONS

| CER number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Summary of input data: | | | | |
| SCP | ____ | ____ | ____ | ____ |
| EU | ____ | ____ | ____ | ____ |
| Av watts | ____ | ____ | ____ | ____ |
| C&DH wt | ____ | ____ | ____ | ____ |
| Exp Qty | ____ | ____ | ____ | ____ |
| CER estimates | ____ | ____ | ____ | ____ |

| | |
|---|---|
| Estimate adjustments as required: | ____ |
| Aerospace learning (use with discretion) | |
| Tiros, TOS, ITOS techniques (determine from subsystem D/D data sheet) to 25% | - ____ |
| Industrial technological learning to 10% | - ____ |
| Difference, if any | ____ |
| Power (RTG adjustment or excess power required) | + or - |
| Shields and spheres | + ____ |
| Other heavy items | + ____ |
| Apogee motor | + ____ |

If JPL proposal, add monitoring man years (GSFC in-house man year CER) X \$35K + ____

If GSFC in-house prime effort, subtract the results of the following: GSFC in-house man years CER results X 3.5 = ____________ X \$44K = - ____

SCP total estimate: ____

In-house support costs, 12% - ____

Contract costs

Experiments: $\frac{\text{Exp wt}}{\text{SCSCP wt}} = \frac{\text{Exp \$}}{\text{SCP \$}}$ (use only for very) ( rough estimate )

____

Ground operation equipment:

Control center ____________

Unique equipment ____________

Special operations ____________

Total ____

Shroud modifications or new project design cost ____

Other ____________

Total satellite projects, 1970 \$M ____

## INITIAL DESIGN, DEVELOPMENT, AND INHERITANCE FORM INSTRUCTIONS

By interviewing the project planning staff determine the following information for each subsystem and enter on the form:

Design Inheritance Satellite: The project and satellite from which design inheritance is expected to be gained, if any.

% Inheritances: The percent of expected design inheritance, if any. Note: This step needs to be taken with care. Even when existing designs are intended to be used for most components of a spacecraft, provision should be made in the estimated % inheritance for altering the existing design because of (1) integration of updated electrical piece parts, (2) new electrical and mechanical interface characteristics dictated by the overall spacecraft design, and (3) the consequent need to also repackage the inherited designs.

Subsystem % Cost Driver: Estimated percent that each subsystem is expected to be of total SCP subsystem costs. The sum of the subsystem percentages in this column should be 100%.

Weighted Inheritance: Multiply the % inheritance by the subsystem % cost driver and enter product. Sum the subsystem lines and subtract from 100. Multiply the result by the design and development (D/D) without inheritance figures selected from between the 1.5 to 3.5 to obtain the D/D with inheritance.

Test and Spare Units Columns: Under each column and by subsystems, list the number of each test unit or spare expected to be built. Analyze all lines and enter at bottom of each column the decimal value relation to "one" equivalent production flight spacecraft.

INITIAL DESIGN, DEVELOPMENT, AND INHERITANCE

Project ________________
Date ________________

| Subsystem | Design Inheritance Satellite | % Inheritance | Subsystem % Cost Driver | Weighted Inheritance % | Mechanical Thermal Unit | Engineer Unit, Describe | Other | Spares |
|---|---|---|---|---|---|---|---|---|
| Structure and Thermal | | | | | | | | |
| Mechanical Devices | | | | | | | | |
| Communications | | | | | | | | |
| Date Handling | | | | | | | | |
| Attitude Control | | | | | | | | |
| Electrical Power | | | | | | | | |

Total 100% 100% - ______ % (Sum) . _____ EU . _____ EU . _____ EU . _____ EU

= ________ X 1.5 to 3.5 (D/D without inheritance =

________ D/D with inheritance

## APPENDIX C

## NONRECURRING AND RECURRING COST BREAKDOWN

Approximate nonrecurring and unit recurring costs can be determined as described in the following example of an estimate derived using the CER:

| Project equivalent unit (EU) values assigned: | Example |
|---|---|
| Nonrecurring EU's: | |
| Initial design and development | 2.0 |
| Thermal/Mechanical test unit | .1 |
| Engineer test unit | .5 |
| Prototype | 1.5 |
| Follow-on redesign and development | .6 |
| Nonrecurring EU total | 4.7 |
| Recurring EU's: | |
| Number of flight units (actual count) | 3.0 |
| Spares | .4 |
| Total | 3.4 |
| EU value total | 8.1 |

If we assume, for example, that the SCP weight, the average watts value, and the 8.1 EU total, when entered into the CER equation, provided an SCP CER estimate of \$81M (1970 \$) then to determine unit recurring cost we simply divide the estimate by total EU's: \$81M ÷ 8.1 EU's = \$10M

To determine total design and development effort cost through prototype we multiply the nonrecurring EU total times the unit recurring value: 4.7 x 10 = \$47M

The above provides the following estimated SCP cost breakdown for the example estimate:

| | |
|---|---|
| Nonrecurring (\$10M x 4.7) | \$47M |
| Recurring (\$10M x 3) | 30M |
| Spares (\$10M x 0.4) | 4M |
| Project SCP total | \$81M |

## APPENDIX D

## ERTS SCP ESTIMATE DERIVATION USING CER NO. 2

| | | |
|---|---|---|
| EU* | Design and development | 0.5 |
| | Structure dynamics model | .1 |
| | Thermal test model | .1 |
| | Antenna test model | .1 |
| | Bench integration and test | .3 |
| | Flight A (protoflight) | 1.5 |
| | Flight B | 1.0 |
| | Spares | .3 |
| | Total | 3.7 |
| SCP wt | (Lbs.) | |
| | Total SC wt | 1564 |
| | Experiments | -273 |
| | Attitude control system fuel | -23 |
| | Orbit adjust system fuel | -11 |
| | Total | 1257 |
| Av watts | 450 | |

Estimates $\$56.2M = 0.260(1257)^{0.42971}(3.7)^{0.95632}(450)^{0.17339}$

* these EU values reflect the design/hardware inheritance that was expected from the NIMBUS project as shown on the following form.

# INITIAL DESIGN, DEVELOPMENT, AND INHERITANCE - -

PROJECT ERTS A & B

DATE 11/71

| SUBSYSTEM | DESIGN INHERITANCE SATELLITE | % INHERITANCE X | SUBSYSTEM % COST DRIVER = | WEIGHTED INHERITANCE % | MECHANICAL THERMAL UNIT | ENGINEER UNIT DESCRIBE | OTHER DESCRIBE | SPARES |
|---|---|---|---|---|---|---|---|---|
| STRUCTURE AND THERMAL | NIMBUS II & III | 80% | 21% | 16 | 2 | | | |
| ORBIT ADJUST | | 0% | 0% | | | | | |
| COMMUNICATIONS AND DATE HANDLING INCLUDING: JPL COMMAND, CENTRAL COMPUTER & SEQUENCER COMMAND SYS. | NIMBUS D | 20% | 24% | 05 | | BENCH INTEGRATION 1 | | |
| ATTITUDE CONTROL | NIMBUS E & F | 90% | 30% | 27 | | 1 | | |
| ELECTRICAL POWER | NIMBUS III & D | 80% | 24% | 20 | | 1 | | |
| | | | TOTAL 100% | SUM 100% - 68% | .1 EU | .3 EU | . EU | .3 EU |

= .32 X 1.5 to 3.5 (D/D w/o Inheritance) = $\boxed{.5}$ D/D with Inheritance

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