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A FUNCTION-BASED EXPLORATION OF JPL'S PROBLEM /FAILURE REPORTING DATABASE

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ABSTRACT

This paper presents the exploration of a failure database derived from a Problem and Failure Reporting (P/FR) database for NASA space missions. The overall goal is to analyze an existing database of problems and anomalies recorded at the Jet Propulsion Laboratory (JPL) for multiple missions, and classify a subset of them into distinct failure modes from a predetermined set of failure modes. Results are presented to describe the failure modes and functional descriptions derived from the PF/R database, using observed in-flight failure reports for six unmanned space missions. The challenges and issues in mining this information are presented, as well as comments on the adequacy of the existing failure mode and function taxonomies to describe the subset of observed failures reported in the PF/R database, and on the utility of such large databases.

KEYWORDS

Failure mode identification; Functional modeling; Failure mode taxonomy; Function-failure knowledge base.

INTRODUCTION

A product has an understood performance and lifecycle defined by the designer, manufacturer and customer. During a product's lifecycle, the product must perform its function safely and efficiently [2-4]. Designers typically use previous designs or experience to perform a failure analysis on new products. This is highly dependent on the experience of the designer and may not capture all possible failure modes. There are structured methods that provide techniques for failure modes analysis, such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Failure Modes and Effects Critical Analysis (FMECA). These methods require a substantial amount of experience to be implemented. In this work, we aim to facilitate the use of knowledge from historical failures and anomalies to identify potential failures during a project's conceptual design phase.

The function-failure method was developed to draw from similarities between different components/systems by exploring the correlation between the functions these systems were designed to perform, and the failure modes that they were historically subject to [5]. The feasibility of the approach was demonstrated using historical data from rotorcraft accident reports [6]. An analysis of a subset of failures was performed on NTSB reports of the Bell 206 helicopter, and the components of the engine and power train system were broken

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down into functionality. A formalized methodology was presented in Stock et al. [7] to demonstrate the utility of the function-based analysis approach in conceptual design. The function-failure design method requires a function-failure knowledge base, which currently is populated using the rotorcraft function and failure data. The focus of the current research is to extend the failure modes and functionality knowledge base into the critical domain of space missions.

The development of a common (standardized) vocabulary to describe failure modes at their most elemental level has been a critical part of our approach. The initial set of mechanical failure modes developed by Collins [1] was extended significantly after mapping the rotorcraft failures to the failure mode taxonomy [6-8]. A preliminary set of requirements for a comprehensive failure mode taxonomy was presented in Tumer et al. [9]. These studies led to a clear need to extend the function-failure mode knowledge base to include failures and functions specific to space missions. As a result, this paper presents a study of larger failure databases derived from a problem and failure reporting database for space missions, with the following two purposes: 1) building on the existing function-failure knowledge base by adding more failure modes encountered during development and operations in space missions; 2) testing the current functional taxonomy to determine its applicability to space missions. The overall goal is to analyze an existing database of problems and anomalies recorded at Jet Propulsion Laboratory (JPL) for multiple missions, and classify them into failure modes from a predetermined set of failure modes that were generated from previous work by the authors and others [6, 8-11]. The components that experienced the failure modes in the anomaly reports and databases were broken down into an abstract form of function flows derived from a predetermined set of functions and flows, generated in previous work by Stone et al. [12-14]. An attempt was made to functionally model the subsystems of the unmanned spacecraft. In-flight anomalies from the Viking I and II, Voyager I and II, Galileo, and Magellan were analyzed. The results from this analysis are presented in the form of charts and matrices in the following sections.

BACKGROUND

One of the main goals in this paper is to build upon the function-failure knowledge base using spacecraft/mission failures and anomaly data. The function-failure knowledge base is an essential component of our approach to failure analysis during conceptual design [5-6, 8, 15]. The general procedure to derive the function-failure knowledge base (EF matrix) is outlined in Figure 1, by performing a matrix multiplication of a function-component matrix (EC) and a component-failure matrix (CF). This approach has been discussed in great detail in previous work, and hence only a brief description is provided in this paper: First, the failures from historical accident, maintenance, and anomaly reports are analyzed thoroughly and placed in vector form after mapping the descriptions onto a standardized failure mode taxonomy [5, 7, 15]. Next, the components affected by these failures are determined and their functionality modeled using a functional modeling approach and a function-flow taxonomy. The set of function and flow descriptions for the complete taxonomy are included in prior publication and hence will not be repeated here. Using this information, two initial matrices are formed by the designer in order to compute the function-failure matrix, namely, the elemental function-component matrix (EC) and the component failure matrix (CF). The dimension of the function-component matrix is determined by the component vector (obtained from the bill of materials) and the function vector (obtained from the bill of materials and the functional model). Similarly, the dimension of the component-failure matrix is obtained from the component vector and the failure vector. The function-failure matrix is obtained from the matrix multiplication of the two matrices.

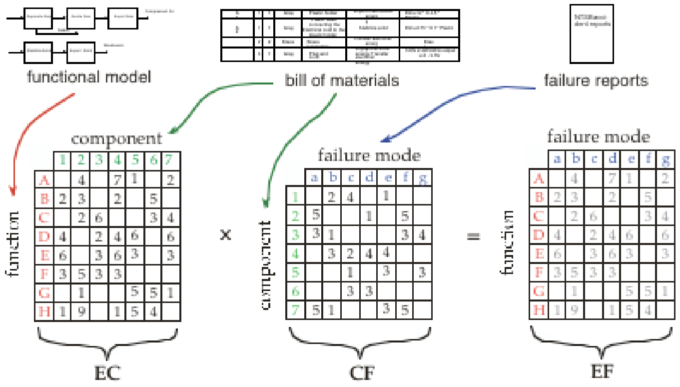

Figure 1. The general procedure of formulating a function-failure knowledge base.

Failure Mode Taxonomy

Past research has looked into consumer products [8] and rotorcraft components and failures from accident reports [6]. Current work is looking into expanding the failure mode database to provide a comprehensive coverage for failures due to spacecraft design and development process [9]. This paper specifically explores a subset of space mission failure reports to determine the types of failures and functions that can accurately represent the function-failure domain for NASA's unmanned space missions. The results from this work will help in the development of a failure identification tool that can be used during conceptual design [7].

Function-Flow Taxonomy

To describe component functionality, a taxonomy known as the functional basis is used. The functional basis was formulated to address the need for a clear vocabulary to describe product and component function and has emerged as a standardized design language [16]. It was formulated in concert with NIST to unify two similar, independent research efforts [5]. The functional basis consists of two sets of terminology: one containing verbs to describe function, and a second containing nouns to describe flow. The functional basis spans all engineering domains while retaining independence of terms. Taken together in function-flow format, the terms combine to describe the function(s) of a component or product.

JPL's Problem and Failure Reporting Database

Data were taken from the Jet Propulsion Laboratory's (JPL) Problem/Failure Reporting (P/FR) system in an effort to expand the component failure matrix to include actual failure data on unmanned spacecraft. The JPL P/FR database is very large, containing development and operations anomaly and failure data on more than 300 missions. The primary purpose of the P/FR database is to record failures and to ensure that proper corrective action is taken in each case. Resolution of failures down to their root cause, is secondary in importance to properly resolving each failure, and in the case of in-flight failures, is often impossible. This increases the difficulty of using the P/FR database for our purposes. It was decided to concentrate on in-flight anomaly data on a subset of six JPL Class A missions because extensive work had already been done [10,11] in analyzing and summarizing these failures, making the root causes easier to determine.

APPROACH

Analysis of Unmanned Spacecraft Missions

Six unmanned JPL spacecraft missions were examined in this work. Specifically, in-flight anomalies from the Viking I & II, Voyager I & II, Galileo, and Magellan missions were analyzed to derive the corresponding failure modes and functions. The target database was the Problem/Failure Reporting Database (P/FR) at NASA JPL. To narrow the scope of the research, a summarized version of the in-flight anomalies from this database was used for the above listed missions. The subset of anomalies were extracted from the JPL database and analyzed by Quinn [11] and Brown [10]. The database of failures and reports were first analyzed thoroughly to derive a mapping of the reported failures onto a standardized set of failure modes, and then dissected to determine the components that were impacted and their corresponding functional descriptions.

Mapping onto the Failure Mode Taxonomy

The list of failure modes developed by Collins [1] was used in this work as a starting point to determine whether that set of failure modes would be sufficient to capture the failures encountered during space missions. An attempt was made to build a failure mode vector space using new failure data from JPL reports [10,11], while at the same time, reducing the overlap within this vector space. A few additional mechanical failure modes (e.g., debonding) were identified and added to the original mechanical failure mode list. Table 1 contains the revised elemental failure modes and their description.

The process used to map the failure and anomaly reports to identify the actual failure modes that occurred was straightforward. The first step involved looking at the primary identifiers, presented in Table 1, to define the failure environment. Questions were asked regarding the types of failures described in the PF/R reports (e.g., was there a corrosive or abrasive material present, was the component exposed to high temperatures or high radiation, was the component under an impact load or cyclic loading, and was the loading condition rapidly changed?) Answering these questions narrows down the choice of failure modes that are applicable to the specific anomaly. The second step involved a study of how the component was affected by the environmental conditions. Questions were asked regarding the mode in which a component failed (e.g., did the component bend, did it fracture, did it deform/change dimensions, did two parts seize together, or did the surface begin to crack?) Once the choices have been narrowed down to a small set of failure modes using the primary identifiers, the set of secondary identifiers was used to pick the most descriptive failure mode.

A large percentage of failures that were represented in the problem and anomaly reports were electrical in nature. As a result, elemental electrical failure modes that may cause electrical failures needed to be represented in the failure mode space. Some electrical failure modes discussed by Lall [17] and Hoa [18] were analyzed and added to the failure mode vector space. The electrical failure modes represent a first attempt to define the elemental electrical failure mode vector space, and are currently being developed further. Table 1 also contains the few electrical failure modes that we were able to develop to represent that part of the vector space. Current work focuses on refining the electrical failure modes to develop a comprehensive set.

Mapping onto the Function-Flow Taxonomy

The hypothesis of the methodology proposed by Tumer and Stone [5, 15] is that there is an inherent correlation between the functionality of the components and subsystems where failure modes occur, and the elemental failure modes at the physical level. A functional model provides an abstract representation of the systems, independent of form and specific design solutions, while providing a good first model of the system being designed. The function and flow pairs used in this work are adapted directly from Stone et al. [12-14], and have been well established and tested across product domains. Therefore, unlike the elemental list of failure modes, the elemental list of function and flows was used as is and represents the components very well.

Determining the functionality proved quite a challenge and required significant experience. However, since designers do have this experience, the functional taxonomy provides a means to standardize the vocabulary used for describing functionality. For the current analysis, the descriptions of the components in the reports were used to determine the functionality of the components. For some of the components (Galileo only), actual drawings were used to examine the geometric shape and the interaction with other components to determine the functionality. Interactions with Mr. Arthur Brown were essential in clarifying some of the component functions due to his expertise and experience with the spacecrafts and anomalies. Additionally, engineering drawings were requested from JPL to understand the specific subsystems where failures occurred and derive their functionality.

Examining the drawings to determine the component functions proved very difficult, mainly due to the large number and complexity of the drawings. More than one drawing would have to be examined in order to get a good idea in determining the functionality of the components and systems. Additional time and effort had to be spent obtaining the drawings, due to export control review necessary to obtain government (public-domain) documents from the space program. In this work, we have developed a preliminary functional model of the subsystems and components that failed, without relying on the drawings. In order to do a complete functional model of the systems, a lot more time and communication is necessary. Many drawings would be needed to break the systems down to their component functionality. In order to model a subsystem of the Galileo, one would probably have to look at least 20-30 drawings for that particular system to model it. More drawings were requested and have been received for further in-depth analysis of the subsystems and components in question.

Using the P/FR Database vs. JPL Reports

The Problem/Failure Reporting (P/FR) database at JPL contains thousands of anomaly reports. In previous work by Brown and Quinn [10,11], in-flight failures on six missions were analyzed and summarized. In these reports, the authors expanded upon the PF/R anomalies (in-flight only) by reading individual reports and interacting with a group of experts at JPL. As a result, it was easier to determine the failed component and the nature of the failure from Brown and Quinn's observations, rather than starting from the P/FR database. For most of the anomalies that were examined, we were able to determine the component and classify the failure mode that occurred with confidence, resulting in 69 out of 86 anomalies (80% of the anomalies) to be added to the function-failure database.

The other source of anomaly data was the P/FR database at JPL. The reported anomalies ranged from simple slow responses in the systems to actual failure or shutdowns in systems on the spacecraft. The database often does not provide a sufficient description of the failure events; as a result root causes were difficult to determine without expertise and substantial background work. Over 1000 reports were examined for the Magellan and Galileo missions; from those anomalies, only eight more entries were added to the EF knowledge base. The reports that were examined were in a sense chosen at random according to how they were received in a search. The objective was to determine what was the most effective way of extracting component-failure mode data from the PF/R database.

RESULTS

Resulting Failure Modes

Table 2 contains the components and their failure modes in matrix form for all the anomalies that were logged in the function-failure database. An entry of one or greater indicates the number of times that the failure occurred for a given component. Several listed failure modes have an "*" before it. These represent questionable "failure modes" in the sense that they are not present in the failure mode taxonomy in Table 1, but are reported in the P/FR database. There was not enough confidence to either classify the failures using the failure mode taxonomy or to create a new failure mode to add to the taxonomy. A visual representation of the component-failure mode matrix is shown in Figure 2. Identifying the failure modes requires experience with the systems and the environments that the components were in at the time of failure.

The subsystems where the failures occurred were also recorded in the database. A pie chart was created to illustrate which subsystems had failures, shown in Figure 3. The chart illustrates the distribution of the failure modes across the subsystems. Table 3 shows the particular failure modes that occurred for the subsystems in matrix form. It also contains the names of the subsystems for reference when looking at Figure 2. A visual representation of Table 3 is shown in Figure 4.

Resulting Functional Descriptions

Table 4 contains the components and their functionality in matrix form. An entry of "1" or greater indicates how many components with the specific function flow failed. In previous work the function–component matrix is binary indicating only the functions the component performs. In this paper the frequency of the component's failure is captured. If the number is "1" or greater, then the component performs the function flow. If the number is greater than "1" then the component failed that many times in the six missions. A visual representation of this matrix is presented in Figure 5. The functionality was determined through component description or through drawings. Using the drawings was a difficult task because many drawings had to be examined to determine the functionality of the component.

Discussion

In general, reliance on the summarized reports by Quinn and Brown was essential in defining the failure modes using the failure reports from the PF/R database. The exploration of the PF/R database with the current set of failure modes showed that the list is not adequate to address common spacecraft failures. We were able to map mechanical failures onto the existing taxonomy, but had a lot of failures that we were either unable to explain (due to lack of sufficient information on the cause of failure), or because electrical and software failures were not considered. Specifically, expert knowledge is a must to be able to describe the failure modes correctly; starting from the reports that already filtered through the original PFR data helped tremendously. Furthermore, electrical failures are the most important category that needs to be explored; a graduate student is currently working closely with JPL experts to generate a comprehensive list. In addition, because many of the components for the missions are electrical components, the function taxonomy was expanded to electrical functions, but the same verb-object pairs were used. The verb-object functionality was interpreted in an electrical domain; this mapping needs to be scrutinized further.

In addition, functions were defined using a combination of failure descriptions, and components, but further insight was acquired using textbook and prior design knowledge; design experience and engineering drawings proved critical in populating the function-failure knowledge base. But once a functional model of the subsystems has been developed and the knowledge base has been built, applying the function-failure design method during conceptual design is straightforward for designers.

When the database was first being developed using the elemental function and failure mode taxonomies, we examined all six missions that were analyzed in Brown's and Quinn's reports: Viking I & II, Voyager I & II, Galileo, and Magellan. Once we started concentrating on the P/FR, we decided to focus on the Galileo and Magellan mission. The P/FR search was narrowed to these two missions to determine how effective and efficiently component-failure mode data can be extracted form the P/FR database. This was done because of the vast amount of data available for each mission and the complexity of the systems of the spacecraft. It is recommended that the next step should be to model the systems of the Galileo spacecraft first, then go through the P/FR database and examine the anomalies. Knowing the systems better will help a great deal in determining the failed components and the way in which they failed. Modeling the systems of the Galileo will not be an easy task. Possibly modeling one subsystem at a time and searching the P/FR database for each subsystem after it has been modeled would be the most effective way of approaching this task.

SUMMARY

This paper explores a subset of JPL's Problem and Failure Reporting (PF/R) database to determine its usability for the function-failure design approach previously proposed by the authors [7,15]. The function-failure design approach requires the development of a function-failure knowledge base derived by mapping observed failures onto a failure-mode taxonomy. The failure modes are then analyzed by exploring similarities with respect to the component/subsystem functionality. To compute the similarities, functional descriptions of the components and subsystems impacted by the observed failures were derived using functional modeling techniques and a functional taxonomy previously developed by Stone et al. [14,16]. A preliminary knowledge base has been developed using rotorcraft accidents by Roberts et al. [6]. In this paper, the goal was to augment the existing function-failure knowledge base to include failures and functions specific to space missions. The approach was presented to describe the process used to map anomaly descriptions onto the standardized failure mode taxonomy, as well as to map components onto a functional taxonomy. The resulting components, failure modes, and functions were presented in the form of tables and charts using the standardized vocabulary proposed in this work. The difficulties and challenges in exploring the anomaly data using the P/FR database were identified and future work identified to address the open issues.

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Table 1. Failure mode taxonomy extension.

Primary Identifier	Secondary Identifier	Failure Mode
(Corrosion) Material deterioration due to chemical or electrochemical interaction with environment	Surface exposed to corrosive media	Direct chemical attack
	Electrochemical corrosion of two dissimilar metals that come in electrical contact	Galvanic corrosion
	Localized in crevices, cracks and joints where stagnant solution is trapped	Crevice corrosion
	Localized development of array of holes or pits	Pitting corrosion
	Grain boundaries of Cu, Cr, Ni, Al, Mg, Zn alloys corrode due to improper heat treated	Intergranular corrosion
	One element of solid alloy is removed	Selective leaching
	Presence of abrasive/ viscid material flow that erodes the material	Erosion corrosion
	Bubbles near pressure vessel walls collapse and cause particles to be expelled form the surface	Cavitation erosion
	Hydrogen blistering, embrittlement, or decarburization	Hydrogen damage
	Food ingestion and waste elimination of living organisms where waste products act as corrosive media	Biological corrosion
	Fluctuating load combined with corrosion action creates stress raisers which accelerate fatigue which in turn exposes new layer to corrosion	Corrosion fatigue
	Applied stresses on a part in a corrosive media	Stress corrosion
(Wear) Undesired change in dimension	Combined adhesive and abrasive wear with the presence of a corrosive medium	Corrosive wear
	High pressure at contact sites Plastic deformation Rupture of junction	Adhesive wear
	Particles removed by harder mating surface or by particles/debris entrapped between mating surfaces	Abrasive wear
	Cyclic shearing stress by rolling or sliding contact Manifests as pitting, cracking, scaling	Surface fatigue wear
	Repeated plastic deformation Severe impact induced	Deformation wear
	Elastic deformation Impact induced Failure occurs by nucleation or crack propagation	Impact wear
(Impact) Impact load of large magnitude	Separation into 2 or more parts	Impact fracture
	Plastic or elastic deformation	Impact deformation
	Mating parts Small lateral displacements Joints not intended to move	Impact fretting
(Fretting) Small amplitude fluctuating loads or deformations at joints not intended to move	Surface discontinuities and micro cracks caused by fretting that propagate under cyclic loads	Fretting fatigue
	Surface degradation	Fretting corrosion
	Change in dimensions	Fretting wear
(Creep) Plastic deformation	Stress and temperature influence Accumulated change in dimensions interfere with part performance	Creep
	Buckling due dimension change	Creep buckling
	Pre-strained or pre-stressed part relaxes Possibly aggravated by high temperature	Thermal/stress relaxation
	Rupture (into two pieces) occurs due to stress-time-temperature conditions Steady-state creep growth period is short	Stress rupture
(Thermal) Fluctuating thermal load	Fluctuating loads or deformations induced	Thermal fatigue
	High temperature Elastic deformation	Temperature induced deformation
	Thermal gradients produce differential thermal strains lead to yielding or fracture	Thermal shock
(Galling & Seizure) Sliding surfaces	Combination of loads, sliding velocities, temperatures, lubricants produce surface destruction	Galling
	Two parts virtually welded together	Seizure
(Radiation) Nuclear radiation	Loss of ductility	Radiation damage

Table 1 continued. Failure mode taxonomy extension.

(Buckling) High and/or point load geometric configuration	Deflection increases greatly for slight increases in load	Buckling
(Fatigue) Fluctuating loads or deformation	Sudden separation into two parts Magnitude of load such that **more** than 10,000 cycles required	High cycle fatigue
	Sudden separation into two parts Magnitude of load such that **less** than 10,000 cycles required	Low cycle fatigue
	Rolling surfaces in contact Pitting, cracking and spalling of contact surfaces	Surface fatigue
	Repetitive impact Failure occurs by nucleation or crack propagation	Impact fatigue
(Ductile deformation) Ductile material	Imposed operational loads produces elastic deformation of part	Force induced elastic deformation
	Plastic deformation	Yielding
	Curved surfaces Local yielding of mating members Static force induced	Brinelling
(Rupture) Separate into two or more parts	Brittle material Elastic deformation exceeded Granular, multifaceted fracture surface	Brittle fracture
	Dull fibrous surface from propagation of internal voids Ductile material	Ductile rupture
	Two parts bonded together by adhesive, weld, etc. separate	Debonding
(Electrical) Charge trapping and interface trap generation	Alters transistor characteristics, increased threshold voltage or substrate current, decreased transduction	Hot carrier effects
Electrical transients	Shorts, opens and higher current in semiconductor junctions resulting in melt down Caused by nuclear radiation, electromagnetic pulses, radar, lightning, and switching transients	Electrical overstress
High passages of current/ current density	Form vacancies or voids in wires causing resistance or open circuits Occurs predominantly in aluminum and silicon	Electromigration
Introduction of Na+	Changes in threshold voltages or conduction short between adjacent devices	Ionic contamination
Excessive electric field across gate oxide	Shorts between transistor gate and drain	Gate oxide breakdown
High voltages 100-200 kV discharged through circuit	Dielectric breakdown Junction short circuits Cracks between isolated regions	Electrostatic discharge

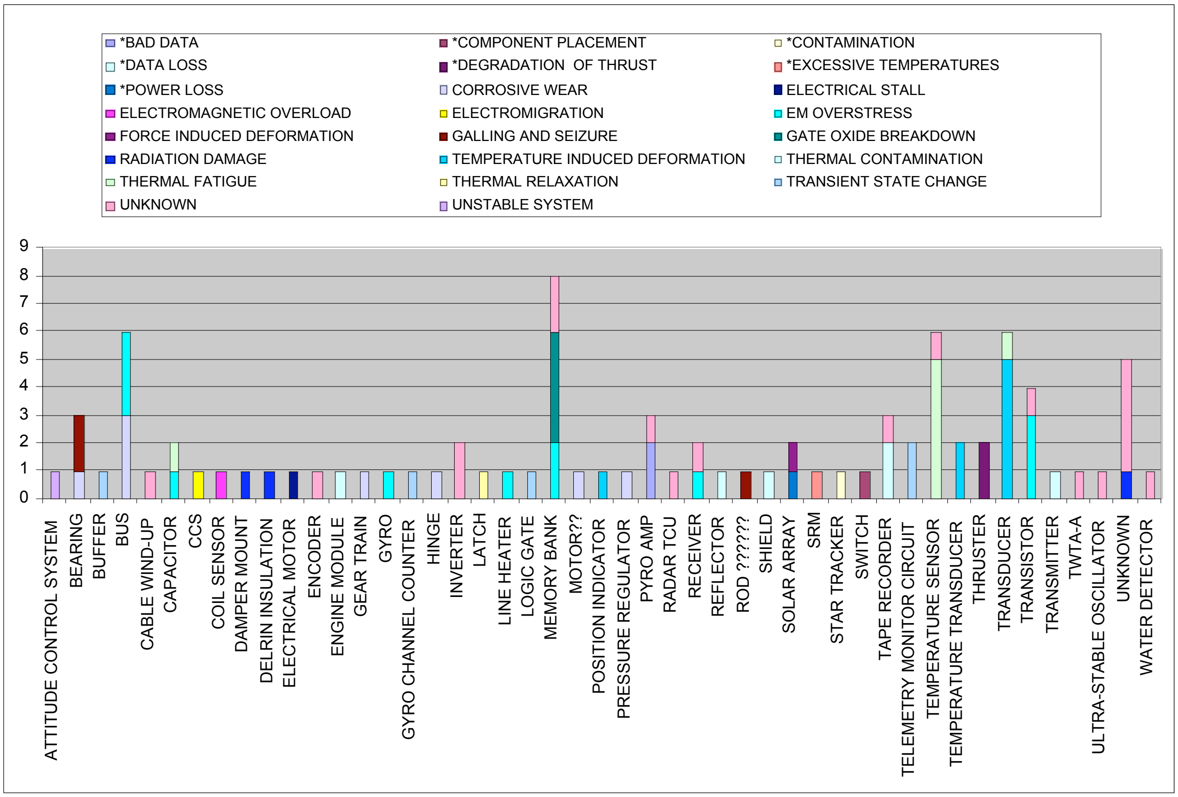

Figure 2. Component-failure chart for six missions.

Table 2. Component-failure mode matrix for six missions.

Component	*BAD DATA	*COMPONENT PLACEMENT	*CONTAMINATION	*DATA LOSS	*DEGRADATION OF THRUST	*EXCESSIVE TEMPERATURES	*POWER LOSS	CORROSIVE WEAR	ELECTRICAL STALL	ELECTROMAGNETIC OVERLOAD	ELECTROMIGRATION	EM OVERSTRESS	FORCE INDUCED DEFORMATION	GALLING AND SEIZURE	GATE OXIDE BREAKDOWN	RADIATION DAMAGE	TEMPERATURE INDUCED DEFORMAT	THERMAL CONTAMINATION	THERMAL FATIGUE	THERMAL RELAXATION	TRANSIENT STATE CHANGE	UNKNOWN	UNSTABLE SYSTEM
ATTITUDE CONTROL SYSTEM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
BEARING	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
BUFFER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
BUS	0	0	0	0	0	0	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
CABLE WIND-UP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
CAPACITOR	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
CCS	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
COIL SENSOR	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
DAMPER MOUNT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
DELRIN INSULATION	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
ELECTRICAL MOTOR	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ENCODER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
ENGINE MODULE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
GEAR TRAIN	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GYRO	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
GYRO CHANNEL COUNTER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
HINGE	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INVERTER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
LATCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
LINE HEATER	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
LOGIC GATE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
MEMORY BANK	0	0	0	0	0	0	0	0	0	0	0	2	0	0	4	0	0	0	0	0	0	2	0
MOTOR??	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
POSITION INDICATOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
PRESSURE REGULATOR	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PYRO AMP	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
RADAR TCU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
RECEIVER	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
REFLECTOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
ROD	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
SHIELD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
SOLAR ARRAY	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
SRM	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STAR TRACKER	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SWITCH	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TAPE RECORDER	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
TELEMETRY MONITOR CIRCUIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
TEMPERATURE SENSOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	1	0
TEMPERATURE TRANSDUCER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
THRUSTER	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRANSDUCER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0
TRANSISTOR	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0
TRANSMITTER	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TWTA-A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
ULTRA-STABLE OSCILLATOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
UNKNOWN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	4	0
WATER DETECTOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Table 3. Subsystems and the failure mode matrix for all six missions.

S/S	Subsystem Name	*BAD DATA	*COMPONENT PLACEMENT	*CONTAMINATION	*DATA LOSS	*DEGRADATION OF THRUST	*EXCESSIVE TEMPERATURES	*POWER LOSS	CORROSIVE WEAR	ELECTRICAL STALL	ELECTROMAGNETIC OVERLOAD	ELECTROMIGRATION	EM OVERSTRESS	FORCE INDUCED DEFORMATION	GALLING AND SEIZURE	GATE OXIDE BREAKDOWN	RADIATION DAMAGE	TEMPERATURE INDUCED DEFORMATION	THERMAL CONTAMINATION	THERMAL FATIGUE	THERMAL RELAXATION	TRANSIENT STATE CHANGE	UNKNOWN	UNSTABLE SYSTEM
AACS	Attitude & Articulation Control Subsystem	0	0	1	0	0	0	0	2	0	0	0	2	1	3	0	1	0	0	0	0	1	3	1
CCS	Computer Command Subsystem	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0
CDS	Command & Data Subsystem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
CRS	Cosmic Ray Instrument	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
DEV	Devices Subsystem	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DMS	Data Memory Subsystem	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
FDS	Flight Data Subsystem	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0	1	2	0
IRIS	Interferometer Spectrometer Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
LECP	Low Energy Charged Particle Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
MAG	Magnetometer Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
NIMS	Near Infrared Mapping Spectrometer Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0
PIPS	Photomultiplier Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
PPSG	Propulsion & Pyrotechnic Subsystem	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0
PROP	Propulsion Subsystem	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PWS	Plasma Wave Instrument	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0
PYRO	Pyrotechnic Subsystem	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
RFS	Radio Frequency Subsystem	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	2	5	0
RPM	Retro Propulsion Module Subsystem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0
SSI	Solid State Imaging Instrument	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
STRU	Structure Subsystem	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	5	0	0	1	0
SXA	S/X Band Antenna Subsystem	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TCU	Telemetry & Command Subsystem	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
THER	Thermal Control Subsystem	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
(blank)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

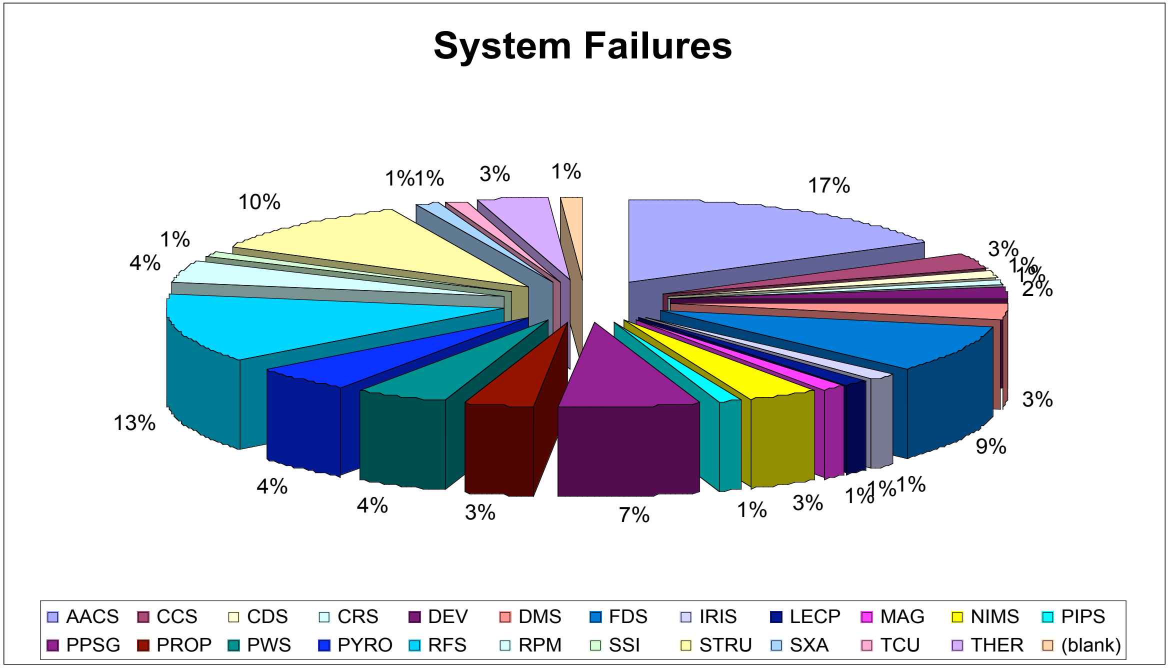

Figure 3. Subsystem failures for all six missions.

Table 4. Function-component matrix, EC.

Function	Flow	ATTITUDE CONTROL SYSTEM	BEARING	BUFFER	BUS	CABLE WIND-UP	CAPACITOR	CCS	COIL SENSOR	DAMPER MOUNT	DELRIN INSULATION	ELECTRICAL MOTOR	ENCODER	ENGINE MODULE	GEAR TRAIN	GYRO	GYRO CHANNEL COUNTER	HINGE	INVERTER	LATCH	LINE HEATER	LOGIC GATE	MEMORY BANK	MOTOR??	POSITION INDICATOR	PRESSURE REGULATOR	PYRO AMP	RADAR TCU	RECEIVER	REFLECTOR	ROD ??????	SHIELD	SOLAR ARRAY	SRM	STAR TRACKER	SWITCH	TAPE RECORDER	TELEMETRY MONITOR CIRCUI	TEMPERATURE SENSOR	TEMPERATURE TRANSDUCER	THRUSTER	TRANSDUCER	TRANSISTOR	TRANSMITTER
ACTUATE	CONTROL	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SOLID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHANGE	EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
	ME	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	PNE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
CONVERT	CHE TO ME	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EE TO ME	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EE TO THE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EME TO EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
	PNE TO ME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
COUPLE	CONTROL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
	EE	0	0	0	6	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
EXPORT	GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
GUIDE	GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
	ME	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
IMPORT	CONTROL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
	GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
INDICATE	STATUS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0
POSITION	ME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PROCESS	STATUS	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
REGULATE	EE	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	ME	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SECURE	SOLID	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SENSE	CONTROL	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LIQUID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	STATUS	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	6	3	0	3	0	0
	THE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
STABILIZE	ME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STOP	EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
	EME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	GAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	RE	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	THE	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STORE	CONTROL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EE	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EME	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
	STATUS	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
SUPPLY	EE	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRANSFER	CONTROL	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
	ME	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	STATUS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
	THE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
(blank)	(blank)	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

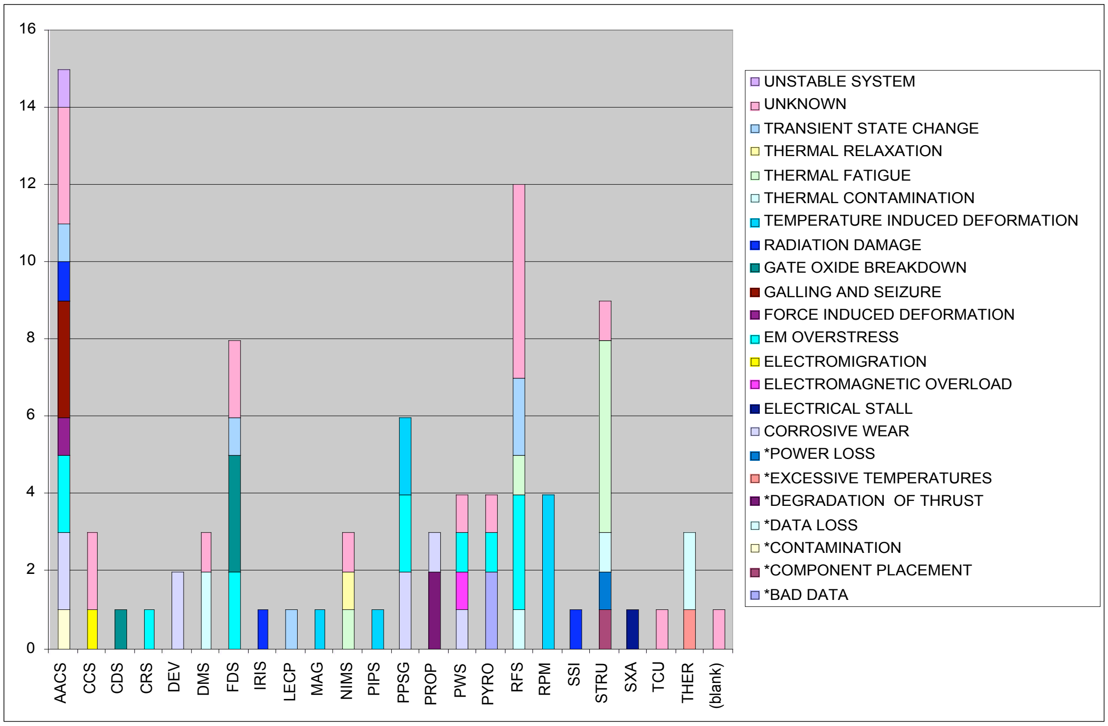

Figure 4. Subsystem-failure mode chart for six missions.

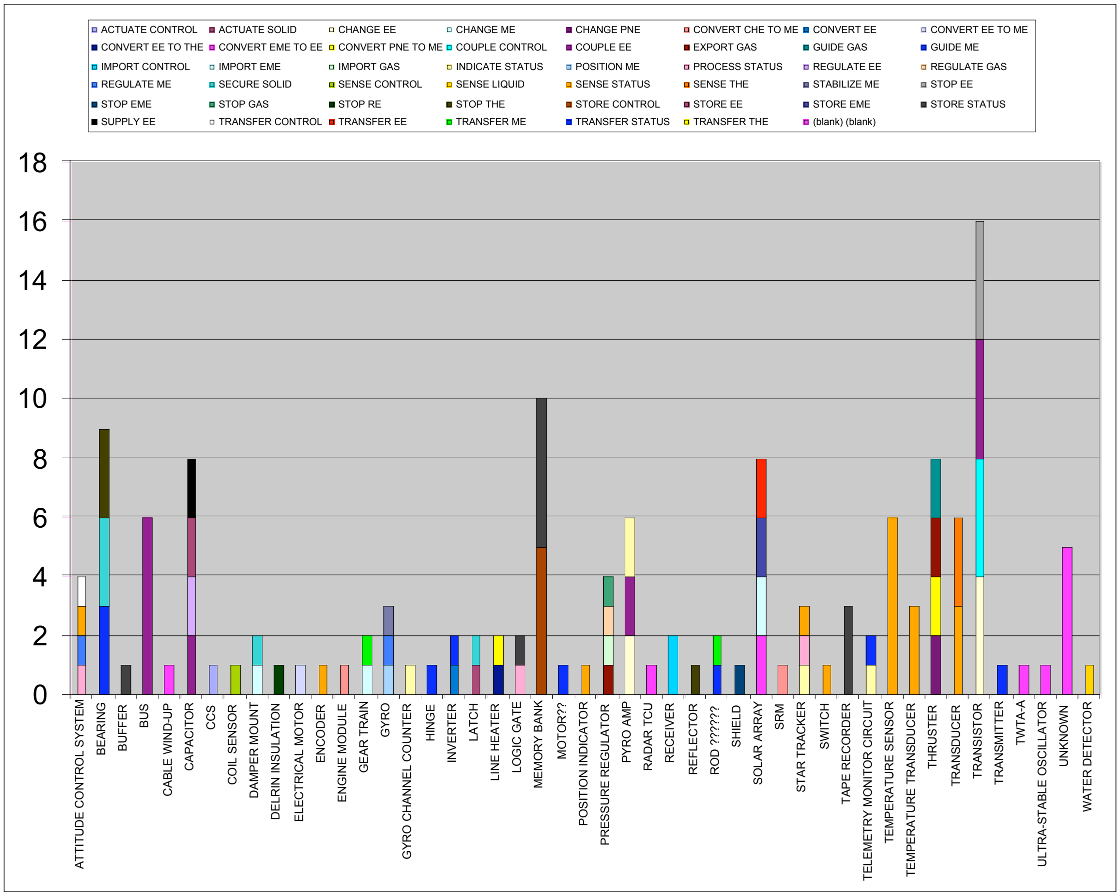

Figure 5. Function-component chart for six missions.