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Component-Level Electronic-Assembly Repair (CLEAR) Analysis of the Problem Reporting and Corrective Action (PRACA) Database of the International Space Station On-Orbit Electrical Systems

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Summary

The NASA Constellation Program is investigating and developing technologies to support human exploration of the Moon and Mars. The Component-Level Electronic-Assembly Repair (CLEAR) task is part of the Supportability Project managed by the Exploration Technology Development Program. CLEAR is aimed at enabling a flight crew to diagnose and repair electronic circuits in space yet minimize logistics spares, equipment, and crew time and training. For insight into actual space repair needs, in early 2008 the project examined the operational experience of the International Space Station (ISS) program. CLEAR examined the ISS on-orbit Problem Reporting and Corrective Action database for electrical and electronic system problems. The ISS has higher than predicted reliability yet, as expected, it has persistent problems. A goal was to identify which on-orbit electrical problems could be resolved by a component-level replacement. A further goal was to identify problems that could benefit from the additional diagnostic and test capability that a component-level repair capability could provide. The study indicated that many problems stem from a small set of root causes that also represent distinct component problems. The study also determined that there are certain recurring problems where the current telemetry instrumentation and built-in tests are unable to completely resolve the problem. As a result, the root cause is listed as "unknown." Overall, roughly 42 percent of on-orbit electrical problems on ISS could be addressed with a component-level repair. Furthermore, 63 percent of on-orbit electrical problems on ISS could benefit from additional external diagnostic and test capability. These results indicate that in situ component-level repair in combination with diagnostic and test capability can be expected to increase system availability and reduce logistics. The CLEAR approach can increase the flight crew's ability to act decisively to resolve problems while reducing dependency on Earth-supplied logistics for future Constellation Program missions.

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1.0 Introduction

The Component-Level Electronic-Assembly Repair (CLEAR) task was part of the NASA Exploration Technology Development Program (ETDP) Supportability Project from 2006 to 2008. CLEAR's intent was to provide the needed technology to perform in situ repairs of electronic hardware at the component level. Potential in situ repair sites include Earth orbit, the Moon, and even Mars. Because of the ongoing design of Constellation Program (CxP) vehicles and the ongoing maturation of design information in the near term, the CLEAR task chose to examine the design and operational experience of the International Space Station (ISS).

The ISS Problem Reporting and Corrective Action (PRACA) system is used for reporting, processing, and tracking space station hardware problems and their resolutions. This system provides a wealth of historical space system anomalous incidents from all phases of station development and operations, and it is mined by engineers as they design the next generation of exploration spacecraft. This document examines the ISS PRACA system to determine the potential number of problems that could be resolved with a robust on-orbit electronics diagnostic and repair capability, such as that proposed in "Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept" (CLEAR–DOC–007) and "Component-Level Electronic-Assembly Repair (CLEAR) System Architecture" (CLEAR–DOC–008). The appendix defines the acronyms and abbreviations used in this document.

2.0 Documents

The following documents contain supplemental information related to the CLEAR task.

2.1 Reference Documents

Document number	Document title
CLEAR–DOC–006	Component-Level Electronic-Assembly Repair (CLEAR) Assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs
CLEAR–DOC–007	Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept
CLEAR–DOC–008	Component-Level Electronic-Assembly Repair (CLEAR) System Architecture

2.2 Applicable Documents

Document number	Document title
CLEAR–ANA–001	Component-Level Electronic-Assembly Repair (CLEAR) Life-Cycle Cost Impacts of Different Approaches for In Situ Maintenance of Electronics Hardware
CLEAR–ANA–002	Component-Level Electronic-Assembly Repair (CLEAR) Noncontact Coupling Techniques for Performing Signature Analysis
CLEAR–DOC–001	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Exp-1 (CRE–1) Flight System Requirements Document
CLEAR–DOC–002	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Exp-1 (CRE–1) Concept and Hardware Summary
CLEAR–DOC–003	Component-Level Electronic-Assembly Repair (CLEAR) Recommendations for the Design of Electronic Assemblies for NASA's Exploration Program
CLEAR–DOC–004	Component-Level Electronic-Assembly Repair (CLEAR) Trade Study: Current Technologies and Instruments for Electronic Fault Diagnosis and Repair
CLEAR–DOC–006	Component-Level Electronic-Assembly Repair (CLEAR) Assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs
CLEAR–DOC–007	Component-Level Electronic-Assembly Repair (CLEAR) Operational Concept
CLEAR–DOC–008	Component-Level Electronic-Assembly Repair (CLEAR) System Architecture
CLEAR–DOC–009	Component-Level Electronic-Assembly Repair (CLEAR) Recommendations for Enabling Manual Component-Level Electronic Repair for Future Space Missions
CLEAR–RPT–001	Component-Level Electronic-Assembly Repair (CLEAR) Component Repair Experiment 1 (CRE–1) System Requirements Review (SRR) Panel Report
CLEAR–RPT–002	Component-Level Electronic-Assembly Repair (CLEAR) Soldering in Reduced Gravity Experiment (SoRGE) Mission Test Report
CLEAR–RPT–003	Component-Level Electronic-Assembly Repair (CLEAR) Spacecraft Circuit Diagnostics by Analog and Complex Signature Analysis
CLEAR–RPT–004	Component-Level Electronic-Assembly Repair (CLEAR) Synthetic Instrument Capabilities Assessment and Test Report

3.0 Problem Reporting and Corrective Action Database Analysis Scope

"Component-Level Electronic-Assembly Repair (CLEAR) Assessment of Constellation Program In-Space Electronic Diagnostics and Repair Needs" (CLEAR–DOC–006) examines electronic system designs for ISS as an analog for CxP. By accessing design information from the ISS Vehicle Master Database (VMDB), the project determined the nature of the circuits and the equipment needs to diagnose, repair, and test electronics in space. A great deal of circuit drawing documentation was gathered, including information regarding the materials and processes used in fabricating electronics. This design information will allow CLEAR to formulate repair processes.

Design information in the ISS VMDB does not indicate which circuits or components are likely to fail or how often physical repairs are needed. For greater insight into the repair history of ISS, the project studied the ISS PRACA database. The findings relevant to CLEAR diagnostics and repair are described in the following sections.

3.1 International Space Station Electrical Systems

The CLEAR project investigated ISS PRACA documents to determine what problems were occurring on actual flight hardware that were repairable at the component level. Furthermore, the study intended to determine diagnostic and test techniques employed in the repair process. Over 4000 ISS PRACA reports are in the system, and roughly 1900 are electrical and avionics system problems. The following ISS electrical systems were reviewed:

- Electrical Power System (EPS)
- Command and Data Handling (C&DH)
- Communications and Tracking (C&T)
- Guidance, Navigation, and Control (GN&C)
- Extravehicular Robotics (EVR)

The first four systems are considered to be the conventional elements of a space flight power and avionics system. EVR is often considered to be mechanical hardware; however, about two-thirds of its problems are electrical. At the time of the study, 4076 reports were in the ISS PRACA database with 1914 reports (47 percent) attributed to the five systems we identified in Table I.

The PRACA system begins tracking problem reports when hardware goes into the acceptance test phase. Many reports pertain to issues that are not resolved by repairs, such as relaxing specifications or altering documents or procedures. There is much to learn regarding electronic problems reported during preflight tests; however, most of these problems are screened out. The problems that occur in flight tend to be problems that are difficult to detect in ground-screening tests. They may arise because of unusual circumstances that occur in flight or that are operational wear-and-tear problems. Since the objective of the CLEAR Project is to develop in situ diagnostic and repair capability, the project chose to focus on the on-orbit problems.

The ISS has roughly 770 of the PRACA reports addressing on-orbit problems. Electrical problems constitute 328 (42 percent) of these reports. Table I shows the breakdown of the ISS PRACA reports.

TABLE I.—DISTRIBUTION OF INTERNATIONAL SPACE STATION (ISS) ELECTRONICS-RELATED PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

ISS system	All PRACA reports	On-orbit PRACA reports	
		Number	Percent of total
Electrical systems overall	1914	328	17.1
Electrical Power System	786	171	21.8
Command and Data Handling	211	30	14.2
Communications and Tracking	498	73	14.7
Guidance, Navigation, and Control	46	19	41.3
Extravehicular Robotics	373	35	9.4
All systems	4076	770	18.9

Of the on-orbit problem reports, Russian hardware was first to be delivered to orbit and, therefore, accounts for a large portion of the problems in the early phases of assembly. Russia is an international partner and, as such, is not required to submit to NASA's engineering scrutiny. Provided that they do not pose an integration risk, Russian problems are handled by Russian contractors. A similar situation will arise as the European and Japanese elements are integrated with ISS. As a result, PRACA reports on Russian hardware provide little specific information regarding problem root cause or corrective actions. Thus, for this study, problem reports on Russian systems are included but are not counted as potential candidates for CLEAR diagnostics or repair. In reality, the Russian hardware is expected to be repairable by component-level replacement.

3.2 Electronic Orbital Replaceable Unit Component-Level Repair

3.2.1 Rationale

CLEAR's premise is that it is technically feasible to make repairs in space by replacing components. That is, the processes employed for replacing components that are soldered to a circuit assembly on Earth can be modified to operate in a spacecraft environment and provide reliable repairs. The examination of the PRACA data indicated that there were a number of problems that were or will eventually be repaired by replacing components.

For circuits with built-in spare channels, complete orbital replaceable unit (ORU) replacement can be deferred. This strategy is used in the EPS where on-orbit replacement can impact many dependent systems. The EPS Remote Power Controller Module (RPCM) ORUs have a graceful degradation approach, where spare channels can be accessed by swapping the position of two RPCMs. As more channels are lost, the ORU must ultimately be repaired at the component level.

A very limited number of ISS ORUs are composed of intermediate-level assemblies often referred to as "shop replaceable units" (SRUs) that are intended to be replaceable on orbit. The Multiplexer/Demultiplexer Module (MDM) of the C&DH system is designed to allow a crew to disassemble an ORU and quickly perform remove and replace (R&R) operations at the circuit-card level (e.g., SRU-level repair). The MDM's backplane design employs a common set of standardized circuit cards that also makes component-level repair easier to accomplish. The CLEAR task assumes that, with appropriate equipment, the SRU can be repaired in situ at the component level.

3.2.2 Description of CLEAR Repair Capability

Repair of circuit cards at the component level involves several steps, including removal of a conformal coating, removal of a component, cleaning, soldering of a new component, and ultimately replacing the conformal coating. Component-level repair may be performed manually in many instances, however, certain operations are best handled by dedicated preprogrammed equipment designed to reproduce many of the conditions used in manufacturing. For example, most high-density devices and particularly modern grid-array devices require a solder reflow capability that is beyond the reach of simple soldering irons. All of these processes require the containment of vapors, liquids, and debris.

CLEAR–DOC–008 describes a system architecture that employs both manual and semiautomated means to accomplish repairs within the confines of a spacecraft, and it includes some teleoperational concepts similar to how NASA ISS payloads operate today.

3.2.3 Potential Problems Resolved by On-Orbit Component-Level Repair

Most ORUs are composed of circuit-card assemblies (CCA), where electronic components are mounted on printed circuit board substrates. ORUs like the MDM are composed of CCAs that are selected from a standard CCA set. Another ORU, the RPCM, has multiple redundant channels that are not all used for a given application. If a circuit card on one RPCM fails, then the entire RPCM ORU can be swapped out with another from a different location, keeping both systems online. Although not the original intent of the design, such swapping is effectively the same as having SRU-level spares available. Other ISS ORUs, like audio and video equipment, are composed of specialized circuits that do not effectively support SRU replacement or have built-in spares. Certain electronic ORUs may be too difficult to retrieve from external locations to be repaired inside the cabin. These would normally be returned to Earth where component-level repairs would be performed at a depot or at the factory. Regardless of the design approach, most ORUs can be repaired at the component level.

The majority of electrical ORU assemblies are on a scale that can be repaired within the ISS maintenance workstation. Assuming that the internal components are accessible, a properly equipped and trained crew member could perform the repairs. The tables in Section 4.0 show instances where an in situ component-level repair resolved, or could have resolved, the problem if the repair capability and replacement components were made available.

3.2.4 Screening Criteria—Problems Not Suitable for Component-Level Repair

There are many reasons for initiating a problem report that do not require a repair. Sometimes the resolution may be as simple as correcting a document or updating a procedure. On-orbit PRACA reports tend to have a narrower set of issues, since most trivial problems have been screened out by acceptance testing and preflight tests. The following list indicates the most common problems that would not be resolved by the repair of an electronic component:

- ***ISS Lights***.—Many lighting assemblies have accumulated hours that are at or in excess of normal predicted service life. These are considered to be logistics consumable items.
- ***Russian Hardware***.—The Russians are responsible for their own hardware and are not required to provide detailed information to the PRACA database unless there is an impact to the ISS integration.
- ***Mechanical Interfaces***.—A number of electrical system problems have been related to mechanical interface problems not related to electrical repair.
- ***Thermal Environment***.—Components that are inadvertently exposed to very low temperatures that are out of the normal design specification normally do not require repair.
- ***Operations and Documentation Errors***.—These are simple operational errors that do not harm any electronics.
- ***Software.—***Software problems generally do not require component repair. An exception to this rule involves firmware where a physical component must be reprogrammed or replaced to fix the firmware.
- ***Obsolete Hardware Replacement***.—When an ORU or SRU is deemed to be obsolete, it is not repaired (e.g., the MDM mass data storage disk).
- ***False Error***.—This event occurs when the intervening communications make hardware appear to be faulty or if telemetry or software falsely indicates a failure.

3.3 On-Orbit Diagnostic and Test Capabilities

3.3.1 Rationale

ISS PRACA history shows that telemetry instrumentation and built-in tests (BITs) are used extensively but often cannot isolate specific faults. “Root cause unknown because of insufficient data” is stated frequently. This is a frustrating outcome when the problem has been investigated extensively, yet still cannot be isolated. “Insufficient data” also illustrates the need for more external diagnostics to augment existing BITs and telemetry. In general, the PRACA data are not detailed enough to describe the diagnostic and test equipment used to diagnose the problem. Often, measurements are listed, but specific diagnostic instruments are rarely identified within the reports. Therefore, this analysis on diagnostics and test needs should be considered to be preliminary, and further indepth study will be needed.

3.3.2 Description of CLEAR Diagnostic and Test Capability

In CLEAR–DOC–008, the CLEAR task proposed a suite of test and diagnostic equipment that includes the following:

- Imaging tools suitable for circuit board visual examination by both flight crew and ground teams
- Diagnostic instruments such as multifunction meters, oscilloscopes, and signal generators—which could be stand-alone instruments or, more preferably, could be incorporated as part of a synthetic instruments (SI) capability using common hardware that could be reconfigured as an instrument on demand
- A signature analysis capability to compare diagnostic probing data with known-good-board standards
- An ability to do some limited functional testing using the SI capability, including an analog front end with routing of digital signals, analog signals, and power
- A robotic positioning tool for camera positioning and diagnostic probing
- The capability to downlink all the needed diagnostic data for evaluation by system experts

3.3.3 Potential Problems Resolved by On-Orbit Component-Level Repair

There appear to be opportunities to expand diagnostic capability since many problem reports are unable to determine the root cause. Often a workaround scheme involving a change in operations, a software patch, or a periodic “preemptive refresh” is used to compensate for a persistent hardware problem. For this analysis, whenever a BIT and telemetry measurement failed to isolate faults and a root-cause-unknown status persisted, the problem was in clear need of additional external diagnostics. In many cases, the availability of a robust diagnostic and test capability would have altered the strategy for addressing the problem. For internal ORUs that are relatively easy to access, this capability could have resolved issues more quickly or, at minimum, provided additional supporting data.

For existing hardware on the ISS, the expansion of BIT and telemetry could reduce the diagnostics gap, but it would involve a costly design overhaul and a widespread R&R to upgrade ORUs. The cost tradeoff between a widespread upgrade versus external diagnostics for an existing ISS system will likely favor external diagnostics.

For new designs of CxP hardware, the allocation of BIT and telemetry capabilities is currently in the design tradeoff phase. Spacecraft weight, volume, power, and data handling and communications bandwidth limitations will constrain built-in capabilities to flight critical measurements. For practical design and programmatic reasons, the indepth diagnostics required to isolate faults may, once again, favor external diagnostics. Therefore, CLEAR diagnostic and test capability may provide a cost-effective, flexible solution for both ISS and the next generation of CxP spacecraft.

3.3.4 Screening Criteria—Problems Not Suitable for CLEAR Diagnostics

As discussed earlier, many problems not suited to component-level repair will still benefit from additional diagnostic capabilities. The criteria used to determine if a problem cannot be diagnosed by CLEAR diagnostic operations follows:

- ***Complete BIT and Telemetry Problems***.—When existing means of monitoring and BITs are successful and unambiguous, then additional CLEAR diagnostic instruments are not needed.
- ***Russian Hardware Problems.*—**These problems are out of scope; Russians are responsible for their own hardware.
- ***Mechanical Problems.*—**These problems are out of scope; most do not require diagnostic instruments.
- ***Software Problems.*—**Diagnostics may not be needed if self-diagnosing software is effective.

3.3.5 Software-Hardware Ambiguity

There have been a number of instances where a problem has occurred, but it was unclear whether the root cause was actually hardware or software. Transients involving multiple interacting software modules are particularly difficult to isolate. In some cases, it is necessary to use external diagnostics to locate a software flaw or at least exonerate the hardware. There has been at least one occasion where BIT software collided when different parts of the system ran BITs concurrently.

4.0 Problem Reporting and Corrective Action Analysis

4.1 Electrical Power System

The EPS includes photovoltaic power generation, power distribution, and power loads. Of the 171 electrical system problems, 66 were related to lighting. Lighting hardware is life limited, and the problems are deemed to be logistics end-of-life (EOL) problems rather than engineering problems. Thus, lighting problems were not considered for this and subsequent system reviews. Table II shows the EPS PRACA report types.

TABLE II.—INTERNATIONAL SPACE STATION ELECTRICAL POWER SYSTEM (EPS) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

EPS subsystem	PRACA reports		Candidate for CLEAR repair	Would benefit from CLEAR diagnostics
	Number	Percent of EPS total		
Remote Power Controller Module (RPCM)	60	56.1	56 (93% of RPCM)	57 (95% of RPCM)
Electrically Erasable Programmable Read-Only Memory (EEPROM) bit flip	24		24	24
Field-effect transistor (FET) controller/FET driver	28		28	28
FET charge pump	1		1	1
Electromotive force (EMF) voltage due to fan windmill	1		0	1
Low-temperature exposure	2		0	0
Wire damage	1		1	1
Single event upset (SEU)	1		0	0
Data acquisition hybrid	1		1	1
Lost resistance temperature detector (RTD)	1		1	1
DC–DC Converter Unit (DDCU)	7	6.5	4	6
EMF voltage due to fan windmill	1		0	1
EEPROM bit flip	2		2	2
FET controller	2		2	2
Micrometeoroid and Orbital Debris (MMOD) damage	1		0	0
SEU	1		0	1
Battery Charge/Discharge Unit (BCDU)	4	3.7	1	3
EEPROM bit flip	1		1	1
Incorrectly configured	2		0	1
SEU	1		0	1
Direct-Current Switching Unit (DCSU)	2	1.9	1	1
Inadvertent cold soak	1		0	0
Unknown intermittent	1		1	1
Sequential Shunt Unit (SSU)	2	1.9	1	2
Mechanical adhesive failure	1		1	1
SEU	1		0	1
Main Bus Switching Unit (MBSU)	3	2.8	3	3
Faulty sensor	1		1	1
EEPROM bit flip	2		2	2
Pump Flow Control Subassembly (PFCS) firmware error	1	0.9	0	1
Floating potential measurement unit (FPMU)	1	0.9	1	1
Assembly Power Converter Unit (APCU)	2	1.9	1	1
Heater circuit delamination	1		1	1
Operations error	1		0	0
Plasma contactor unit (PCU)	2	1.9	0	0
Mechanical valve leak	1		0	0
Mechanically insufficient xenon heater	1		0	0
Utility outlet panel	3	2.8	1	2
Circuit failed due to poor construction	1		1	1
Ground fault circuit interrupter (GFCI) trip	1		0	1
Mechanical fastener missing	1		0	0
Rack power switch (RPS) assembly	3	2.8	0	1
Part serial number error	2		0	0
Switch configuration error because of software change	1		0	1
Russian equipment	17	15.9	0	0
Total EPS on-orbit PRACA reports[a]	107	100	69 (64% of EPS)	78 (73% of EPS)

[a]Does not include 66 lighting PRACA reports.

When lighting problems are excluded, over 56 percent of EPS on-orbit PRACA reports are related to the RPCM. Of those RPCM problems, 87 percent are dominated by two very persistent problems. Russian-related hardware problems account for 16 percent of problems; as noted earlier, these problems are too ambiguous to properly analyze. Beyond lighting, RPCM, and Russian hardware, a diverse set of problems appear to be distributed over several other ORU packages. Individual or isolated problems tend to represent 1 to 2 percent of total EPS on-orbit PRACA reports.

4.1.1 Electrical Power System On-Orbit Component-Level Repair

EPS spans the breadth of all power applications throughout ISS. The varied components require unique problem resolutions. For example, the utility outlet panel (UOP) is equivalent to the simple surge-protected outlet boxes used in homes and offices to protect computers and peripherals from power surges. The ISS UOP was rather unique in that all units had innate design flaws, workmanship, and material flaws from their construction. Because the UOPs were few in number and easy to access, the program resolved the problems by simply replacing the entire inventory with new upgraded units. Widespread R&R, however, is an extremely rare solution.

In contrast, RPCMs are essential and appear in numerous locations in the ISS power system, both internal and external to the ISS cabin environment; thus, wholesale R&R of RPCMs is not feasible. Despite the relatively high number of RPCM faults, a single fault does not normally disable the entire unit. For example, if the RPCM loses only one of several channels, rerouting power through spare channels can resolve the problem. Furthermore, a given RPCM may experience multiple faults before it is necessary to R&R it.

There are two recurring faults with RPCMs that also appear in other EPS ORUs (i.e., DDCU, BCDU, MBSU, PCU, and SSU):

- ***FET Controller Hybrid.—***30 problem reports
- ***RM2667–001 EEPROM.—***29 problem reports

Both devices have problems where the root cause is a flaw in the original manufacturing process. The nature of the ORU and the specifically identified components make these problems attractive targets for CLEAR repair processes. Developing repair solutions for these two problems would have resolved 59 of the 107 EPS problem reports.

Overall, the analysis shows that up to 64 percent of EPS problems could have been resolved by a component-level repair.

4.1.2 Electrical Power System On-Orbit Diagnostic and Test Operations

As discussed earlier, the PRACA system generally lacks details about diagnostic techniques and equipment. Some lower-level failure analysis reports or tear down, test, and evaluations describe diagnostic measurements but only on equipment that has been returned from orbit.

For the EPS, there are a significant number of unknown but suspected root causes. Many problem reports attribute anomalies to the FET controller or EEPROM problems, but because of insufficient data, they are not entirely conclusive. Therefore, regardless of the approach to repair, there is substantial evidence that additional diagnostics is needed for power system problems.

SEU incidents, which occur when space radiation causes a semiconductor device to suddenly change state, are often blamed for anomalies. Although SEUs are not reproducible events, external diagnostics can be used to eliminate other potential causes and provide confidence in the SEU prognosis.

As shown in Table II, up to 73 percent of EPS problems could employ external diagnostic and test capabilities. Unlike adding BIT and telemetry instrumentation, CLEAR diagnostic equipment would require no retrofit or design impact.

4.2 Command and Data Handling

The C&DH system governs the command, data transmission, and processing throughout the ISS. The common ORU element is the MDM. MDMs serve as the primary interface and subsystem controller. Note that MDMs appear at different levels in a system's hierarchy. That is, multiple redundant MDMs may be managing a system at the top level, but subordinate MDMs will also appear at lower levels. MDMs communicate on an STD 1553 data bus.

The MDMs of the C&DH system employ a chassis that is a backplane connector, or card cage, design that provides simplified access, removal, and replacement at the SRU level. The intent was to provide a limited number of common, on-orbit SRU spares to reduce the weight and mass of the spare hardware. ORUs composed of SRUs actually make component-level removal and replacement easier because of the increased accessibility at the component level.

Low-level MDMs have a variety of analog and digital input/output (I/O) cards for interacting with hardware and instruments. The top-level MDMs provide data storage. Early in the program, the most common on-orbit MDM problem reports were due to the Mass Storage Device (MSD), which used common hard disk technology for data storage and had limited operating life. These problems were resolved by a major R&R of MSD disks with Solid State Mass Memory Units (SSMMUs). Table III shows the C&DH PRACA report types.

TABLE III.—INTERNATIONAL SPACE STATION (ISS) COMMAND AND DATA HANDLING (C&DH) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

C&DH subsystem	PRACA reports		Candidate for CLEAR repair	Would benefit from CLEAR diagnostics
	Number	Percent of C&DH total		
Multiplexer/Demultiplexer Module (MDM)	24	80	4	9
5-V Power supply (component level)	1		1	1
Mass Storage Device (MSD) replaced by Solid State Mass Memory Unit (SSMMU) at shop replaceable unit (SRU) level	5		0	5
Material issue	2		0	0
Drawing error	2		0	0
Cable, wiring, or connectors	3		3	3
Software	11		0	0
Automated Payload Switch (APS)	3	10	0	3
Single event upset (SEU)	3		0	3
Russian Service Module	3	10	0	0
Total C&DH on-orbit PRACA reports	30	100	4 (13% of C&DH)	12 (40% of C&DH)

4.2.1 Command and Data Handling On-Orbit Component-Level Repair

Only the 5-V power supply and the cable, wiring, or connector problems appear to be suited to a component-level repair. MDMs are configured as a backplane card cage and are very suited to SRU-level replacement. The replacement of MSD modules with a SSMMU was the single major SRU replacement that affected several units. Software fixes and upgrades make up 36 percent of the problem resolutions.

Component-level repairs on these SRUs would be easily accommodated because of the ease of access that the backplane design provides. In addition, the standard circuit card makes it easier to develop card-handling fixtures that simplify the repair process. So far, there has been little need for component-level repairs, but MDM circuits would be quite amenable to such future repairs.

4.2.2 Command and Data Handling On-Orbit Diagnostic and Test Operations

The C&DH system has strong telemetry and self-diagnostic capability. Since data storage or software codes were the primary problems, BIT diagnostics proved to be quite adequate in isolating most problems. Only 27 percent appear to be problems that would benefit from the external diagnostics provided by CLEAR. The MDM is the only ORU that is supported by additional diagnostic capability known as the MDM on-orbit tester (MOOT).

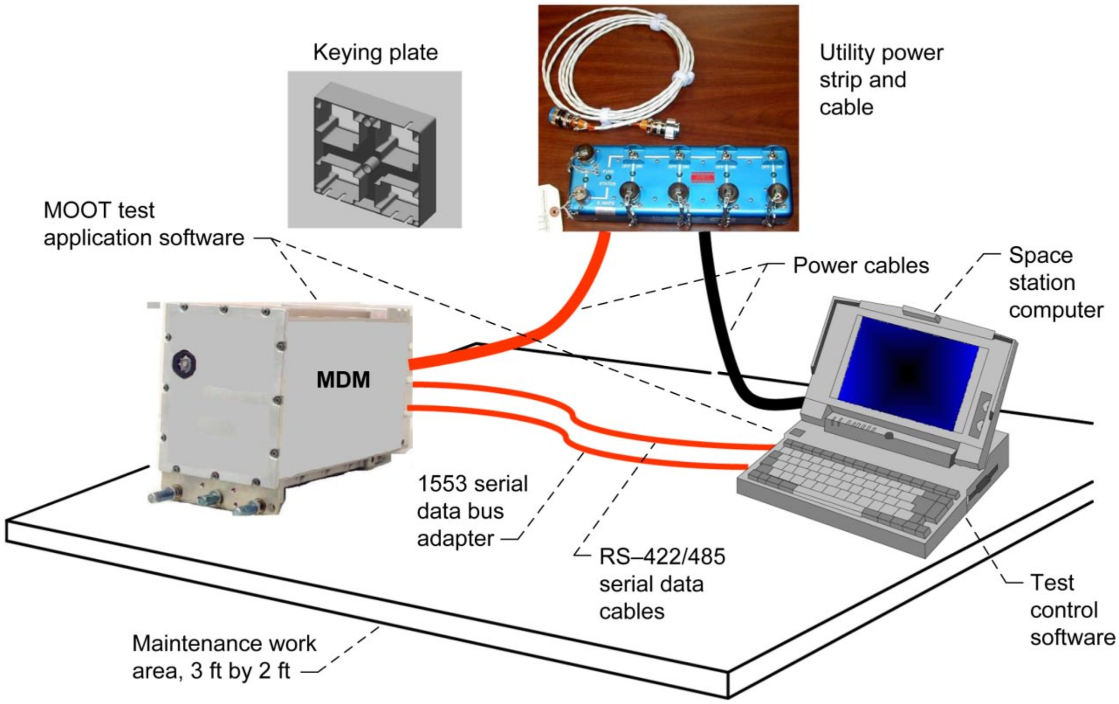

Figure 1.—The Multiplexer/Demultiplexer Module (MDM) on-orbit tester (MOOT) serves as an interface kit between an MDM and a space station computer and utility power strip.

The MOOT is not a traditional test instrument. It would be more accurate to describe it as an interface kit. It is composed of a power supply along with an RS422 and 1553 data bus cables and an adapter. The MOOT provides a special keying plate that assures that only the correct pins are connected so that the crew cannot damage the MDM. The MOOT also includes an existing space station computer (SSC) that acts as an external terminal to command BITs and acquire test data. Figure 1 shows a simple schematic of the MOOT.

Data systems, by nature, are most suited to self-diagnostics since they can easily expand data handling to incorporate internal measurements and system states. If the main controller card and power supply are operational, BIT diagnostics can be used. The weakness is an inability to resolve problems where the power or main processors are inoperative. In those cases, external diagnostics is required.

4.3 Communications and Tracking

C&T is composed of a very diverse set of hardware ranging from audiofrequency circuits, to video, to ultrahigh frequency (UHF), S-band, and Ku-band radiofrequency (RF) communications.

Audio is composed of low-frequency analog circuits with channel switching linked by a 1553 data bus. Video is composed of numerous video cameras mounted internally and externally, including some used in critical EVR activities. Video is also supported by videotape recorders (VTRs) and display monitors. RF communications includes antennas and their related pointing mechanisms. RF thus has a substantial number of mechanical problems.

4.3.1 Communications and Tracking On-Orbit Component-Level Repair

Analysis of the PRACA C&T data indicated that 21 percent of the problems would have been suited to in situ repairs that CLEAR could perform on orbit. Most C&T ORUs have problems where the root cause remains unknown. There would be more opportunities for repairs if these causes could be isolated. C&T mechanical and thermal problems have been exclusively in the RF portion of the system.

The audio subsystem appears to be plagued by hardware quality problems. Video support equipment like VTRs and video monitors are experiencing EOL failures. Some VTR problems were resolved by performing periodic recording head cleaning. This is a recurring service item that consumes both crew time and logistics. Tape recorders wear out and become obsolete; thus, an upgrade to durable solid-state memory is preferred over component repairs.

4.3.2 Communications and Tracking On-Orbit Diagnostic and Test Operations

Problems with an unknown root cause represent a full 25 percent of the C&T problem reports, and this is due in part to lack of adequate telemetry data and in part to the intermittent nature of many C&T problems. Loss-of-communication faults that occurred for audio, video, and RF equipment often resulted in a loss of data that would help diagnose the problem.

Since C&T is the main conduit for telemetry measurements, it is natural that a C&T fault could interfere with the diagnosis of a problem. There is some evidence that BITs ran, but efforts to reestablish communications often required a reset of hardware resulting in the loss of diagnostic data records. Without tangible data, engineering was forced to speculate on the root cause of problems. Of the problems listed, 63 percent would benefit from independent external diagnostics in isolating the root cause of faults. Table IV shows the C&T PRACA report types.

TABLE IV.—INTERNATIONAL SPACE STATION (ISS) COMMUNICATIONS AND TRACKING (C&T) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

C&T subsystem	PRACA reports		Candidate for CLEAR repair	Would benefit from CLEAR diagnostics
	Number	Percent of C&T total		
Audio	18	25	6	17
Wire and connector	1		1	1
Connector pin	1		1	1
Connector contamination	1		1	1
Root cause unknown	8		?	8
Operations error	1		0	0
1553 bus (suspect)	2		1	2
Microphone electromagnetic interference (EMI)	1		0	1
Earpiece receiver	1		1	1
Data glitch	1		0	1
Defective switch	1		1	1
Video	22	31	5	20
Wire and connectors	1		1	1
Videotape recorder (VTR) cleaning	4		1	4
Root cause unknown	7		?	7
Suspect single event upset (SEU)	1		0	1
Software fault	1		0	0
1553 hybrid	2		1	2
High-frame-rate circuit-card assembly (CCA)	1		1	1
VTR operations	1		0	0
End of life (EOL)	1		0	1
SEU	1		0	1
VTR reel motor binding	1		1	1
VTR EOL	1		0	1
S-band	13	18	1	3
Mechanical	10		0	0
SEU	1		0	1
Solder	1		1	1
Root cause unknown	1		?	1
Ku-band	10	14	3	5
Mechanical	3		0	0
Root cause unknown	2		?	2
Software	1		0	0
Heater	1		1	1
Components	2		2	2
Flight operations	1		0	0
Ultrahigh frequency (UHF)	1	1	0	0
Mechanical	1		0	0
Russian equipment	7	10	0	0
Total C&T on-orbit PRACA reports	71		15 (21% of C&T)	45 (63% of C&T)

4.4 Guidance, Navigation, and Control

The GN&C system has a low occurrence of problems in comparison to other systems. The control moment gyroscope (CMG) system represents a full 60 percent of the problems. This is an important and rather large electromechanical ORU with spinning gyros. The CMG system is essential to maintaining orbital attitude of the entire ISS.

4.4.1 Guidance, Navigation, and Control On-Orbit Component-Level Repair

On the basis of the data from the PRACA database, communication-related faults and gyro spin motor controllers appear to be the best candidates for on-orbit repair because of the electronic nature of these problems.

4.4.2 Guidance, Navigation, and Control On-Orbit Diagnostic and Test Operations

Roughly 50 percent of the problems appear to benefit from external diagnostics in isolating the root cause of faults. Table V shows the GN&C PRACA report types.

TABLE V.—INTERNATIONAL SPACE STATION (ISS) GUIDANCE, NAVIGATION, AND CONTROL (GN&C) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

GN&C subsystem	PRACA reports		Candidate for CLEAR repair	Would benefit from CLEAR diagnostics
	Number	Percent of GN&C total		
Control moment gyroscope (CMG)	11	61	6	8
Mechanical	3		0	0
Loss of CMG communications	4		4	4
Angular bias	1		0	1
Spin motor control	2		2	2
Over rate error	1		0	1
Rate Gyro Assembly (RGA)	2	11	0	1
Attitude walk off	1		0	1
Mechanical pressure leak	1		0	0
Russian equipment	5	28	0	0
Total GN&C on-orbit PRACA reports	18	100	6 (33% of GN&C)	9 (50% of GN&C)

4.5 Extravehicular Robotics

EVR involves a very large remote manipulator arm that can move around the ISS truss, move payloads, and recover and install external ORUs. Although mechanical in nature, it is surprisingly complex in terms of instrumentation and imaging support. Over 66 percent of EVR PRACAs are electrical.

4.5.1 Extravehicular Robotics On-Orbit Component-Level Repair

This system has a mix of controllers and instruments. Motor controllers for joint drives (and braking) are sophisticated closed loops with careful monitoring of motor currents. For teleoperations, a number of cameras and related video support are required. Roughly 39 percent of EVR problems appear to be suitable for on-orbit repair.

4.5.2 Extravehicular Robotics On-Orbit Diagnostic and Test Operations

Roughly 55 percent of the problems appear to benefit from external diagnostics in isolating the root cause of faults. Table VI shows the EVA PRACA report types.

TABLE VI.—INTERNATIONAL SPACE STATION (ISS) EXTRAVEHICULAR ROBOTICS (EVA) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

EVR subsystem	PRACA reports		Candidate for CLEAR repair	Would benefit from CLEAR diagnostics
	Number	Percent of total		
Lighting	3	9	1	1
Camera and video	6	18	4	6
Software control and telemetry	6	18	0	3
Motor and controller	4	12	4	4
Electromechanical switches	2	6	2	2
Connector cable	2	6	2	2
Mechanical	10	30	0	0
Total EVR on-orbit PRACA reports	33		13 (39% of EVR)	18 (55% of EVR)

5.0 Summary of Potential of CLEAR Diagnostic and Repair Operations

CLEAR reviewed PRACA reports for ISS electrical systems to help define the repair and diagnostic needs. CLEAR is aimed at developing repair and diagnostic capabilities for the CxP. The ISS is the first spacecraft with a relatively long on-orbit experience base, and it is the first instance where an ORU logistics strategy has been used. The CLEAR Project was also interested in determining how often an in situ repair and diagnostics capability could be applied. Table VII summarizes the ISS PRACA reports.

TABLE VII.—SUMMARY OF INTERNATIONAL SPACE STATION (ISS) PROBLEM REPORTING AND CORRECTIVE ACTION (PRACA) REPORTS

ISS system	PRACA reports	On-orbit PRACA reports
ISS (all systems)	4076	770
Electrical system	1914	328

Electrical system PRACA reports compose about 42 percent of all on-orbit PRACA reports. This is not to say that all electrical system problems are purely electrical. However, mechanical systems will also have electrical problems. To keep the analysis within time and cost constraints, the CLEAR team limited the scope of the effort to electrical systems. The EVR system was included because of the high percentage of electrical problems.

To further limit the analysis set of this review, the CLEAR team did not consider the 66 ISS light fixture problems from the EPS since they involve items that had reached or exceeded their predicted EOL. Lighting has been described as a logistics issue rather than a repair issue. In addition, two duplicate problem reports were extracted from the C&DH set. The remaining 259 problem reports were evaluated to determine if a potential CLEAR repair or diagnostics capability could have resolved the problem.

Table VIII and the chart in Figure 2 show the number of potential repairs and diagnostic capabilities for each system. The percentage indicates the fraction of the system's problem set that could employ CLEAR repair or diagnostics. Overall, in situ CLEAR repair appears to cover 42 percent of the electrical problems. CLEAR diagnostic and test capabilities appear to cover 63 percent of the electrical problems.

TABLE VIII.—POTENTIAL IMPACT ON INTERNATIONAL SPACE STATION (ISS) ELECTRICAL PROBLEMS BY A ROBUST COMPONENT-LEVEL DIAGNOSTIC AND REPAIR CAPABILITY

ISS system	On-orbit PRACA reports		Candidate for CLEAR repair		Would benefit from CLEAR diagnostics	
	Number	Percent of total	Number	Percent of total	Number	Percent of total
Electrical Power System (EPS)	107	41	69	64	78	73
Command and Data Handling (C&DH)	30	12	4	13	12	40
Communications and Tracking (C&T)	71	27	15	21	45	63
Guidance, Navigation, and Control (GN&C)	18	7	6	33	9	50
Extravehicular Robotics (EVR)	33	13	16	48	18	55
All electrical on-orbit PRACA reports	259	100	110	42	162	63

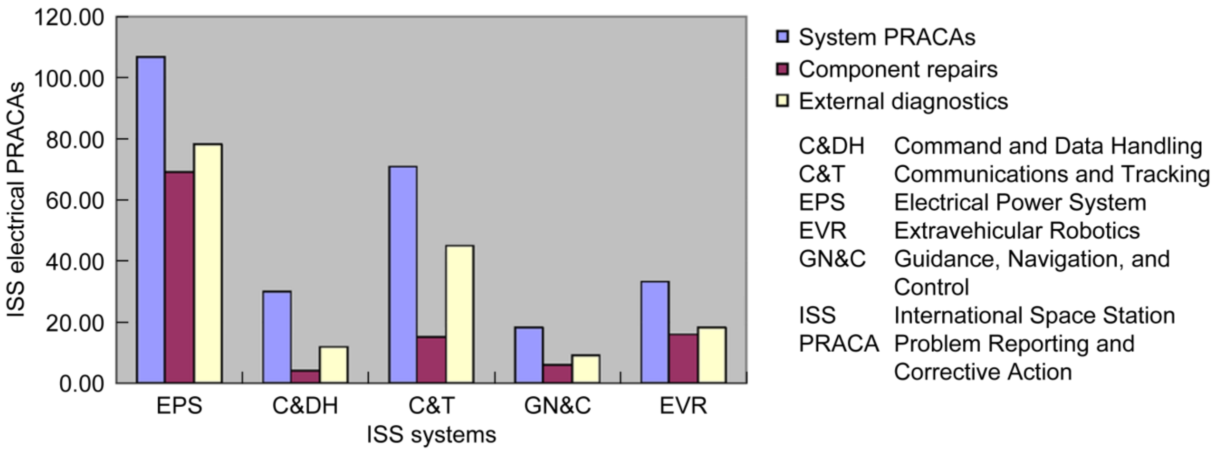

Figure 2.—This chart shows that the portion of problems that benefit from component-level repair varies from system to system. External diagnostics, however, appears to provide a substantial impact across all systems.

The disparity between diagnostics and repair is due to the number of problems where symptoms are observed but a repair cannot be defined because of the root-cause-unknown status. Often the root cause remained unknown because the problem involved a loss of communications needed to transmit health data or the problem prevented the execution and storage of BIT diagnostics. With external in situ diagnostics, many of the root causes could be established and appropriate corrective actions, including repair could be performed. In general, CLEAR diagnostic capabilities have more widespread application than repair because of the need for diagnosing problems that are out of reach of existing BIT diagnostics or health-monitoring telemetry.

In situ electronics repair was not applied to mechanical, thermal, or structural problems. Furthermore, problems that stem from software, operations, or documentation errors are not applicable. Another category is the SEU problem that occurs when digital electronics are exposed to space radiation. Generally, a memory register or a logic gate is corrupted, and this can be cleared by a register refresh or by executing an error correction code. If no permanent damage occurs, then a component repair is not needed.

6.0 Conclusions

International Space Station (ISS) electronics is proving to be somewhat more reliable than predicted. The on-orbit Problem Reporting and Corrective Action (PRACA) history indicates, however, that tens of thousands of operating hours are accumulating on ISS and that failures are inevitable. The ISS PRACA history also indicates that a number of persistent problems seem to evade normal telemetry measurements and built-in tests. The number of “root cause unknown due to insufficient data” statements would be alarming if it was not for the robustness of the system design and the resourcefulness of operations and engineering. It also indicates that telemetry and built-in tests need to be augmented with external diagnostic capabilities to unveil the elusive root causes. It appears that as high as 63 percent of electrical problems would benefit from additional external diagnostics and test capability. In most cases, the instruments would augment existing capability; in other cases, the external instruments could quickly isolate a problem that currently has an unknown root cause.

PRACA history only describes component-level repairs in Earth-based depot and vendor facilities. Multiplexer/Demultiplexer Modules are the only hardware where actual shop replaceable unit-level replacements of circuit-card assemblies have been performed. In regards to problems that can be repaired by in situ component-level repair, it appears that 42 percent of the problems are linked to component faults. PRACAs represent instances of problems, and thus, many component repairs may be addressed by very few executable repair procedures. For example, roughly 56 percent of Electrical Power System problems can be traced to only two components: the field-effect transistor controller hybrid and Electrically Erasable Programmable Read-Only Memory (EEPROM). It may be practical to perform both repairs with a single orbital replaceable unit processing procedure.

The Component-Level Electronic-Assembly Repair (CLEAR) team concludes that problems amenable to component-level repairs exist on ISS and in significant numbers. Many nagging problems hang unresolved while hardware continues to age and degrade. With the shuttle flights ending in the near future, diagnostic and repair capabilities could meet real needs and could be employed immediately. Further definition of specific solutions requires direct interaction with the ISS system managers, engineers, and contractors.

Appendix.—Acronyms and Abbreviations

APCU	Assembly Power Converter Unit
APS	Automated Payload Switch
BCDU	Battery Charge/Discharge Unit
BIT	built-in test
C&DH	Command and Data Handling
C&T	Communications and Tracking
CCA	circuit-card assembly
CLEAR	Component-Level Electronic-Assembly Repair
CMG	control moment gyroscope
CRE–1	Component Repair Experiment 1
CxP	Constellation Program
DCSU	Direct-Current Switching Unit
DDCU	DC–DC (direct-current to direct-current) Converter Unit
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMF	electromotive force
EMI	electromagnetic interference
EOL	end of life
EPS	Electrical Power System
ETDP	NASA Exploration Technology Development Program
EVR	Extravehicular Robotics
FET	field-effect transistor
FPMU	floating potential measurement unit
GFCI	ground fault circuit interrupter
GN&C	Guidance, Navigation, and Control
I/O	input/output
ISS	International Space Station
MBSU	Main Bus Switching Unit
MDM	Multiplexer/Demultiplexer Module
MMOD	Micrometeoroid and Orbital Debris
MOOT	MDM On-Orbit Tester
MSD	Mass Storage Device
ORU	orbital replaceable unit
PCU	plasma contactor unit
PFCS	Pump Flow Control Subassembly
PRACA	Problem Reporting and Corrective Action
RF	radiofrequency
R&R	remove and replace
RGA	Rate Gyro Assembly
RPCM	Remote Power Controller Module
RPS	rack power switch

RTD	resistance temperature detector
SEU	single event upset
SI	synthetic instrument
SoRGE	Soldering in Reduced Gravity Experiment
SRR	System Requirements Review
SRU	shop replaceable unit
SSC	space station computer
SSMMU	Solid State Mass Memory Unit
SSU	Sequential Shunt Unit
UHF	ultrahigh frequency
UOP	utility outlet panel
VMDB	Vehicle Master Database
VTR	videotape recorder

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14. ABSTRACT The NASA Constellation Program is investigating and developing technologies to support human exploration of the Moon and Mars. The Component-Level Electronic-Assembly Repair (CLEAR) task is part of the Supportability Project managed by the Exploration Technology Development Program. CLEAR is aimed at enabling a flight crew to diagnose and repair electronic circuits in space yet minimize logistics spares, equipment, and crew time and training. For insight into actual space repair needs, in early 2008 the project examined the operational experience of the International Space Station (ISS) program. CLEAR examined the ISS on-orbit Problem Reporting and Corrective Action database for electrical and electronic system problems. The ISS has higher than predicted reliability yet, as expected, it has persistent problems. A goal was to identify which on-orbit electrical problems could be resolved by a component-level replacement. A further goal was to identify problems that could benefit from the additional diagnostic and test capability that a component-level repair capability could provide. The study indicated that many problems stem from a small set of root causes that also represent distinct component problems. The study also determined that there are certain recurring problems where the current telemetry instrumentation and built-in tests are unable to completely resolve the problem. As a result, the root cause is listed as "unknown." Overall, roughly 42 percent of on-orbit electrical problems on ISS could be addressed with a component-level repair. Furthermore, 63 percent of on-orbit electrical problems on ISS could benefit from additional external diagnostic and test capability. These results indicate that in situ component-level repair in combination with diagnostic and test capability can be expected to increase system availability and reduce logistics. The CLEAR approach can increase the flight crew's ability to act decisively to resolve problems while reducing dependency on Earth-supplied logistics for future Constellation Program missions.						
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