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GUIDELINES FOR THE DEVELOPMENT OF CONSUMABLES SUBSYSTEM REDLINES FOR ADVANCED SPACECRAFT

Prepared by

M. A. Zamora

Systems Analysis Section

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1.0 INTRODUCTION

The purpose of this report is to present the findings of a study directed to the establishment of guidelines for the development of consumables subsystem redlines for advanced spacecraft systems. Although the basic redline function remains unchanged, the methodology employed in past programs is inadequate to support future spacecraft requirements. Techniques developed for the Apollo missions, for example, characterized by the developmental nature of each of its flights, must be reoriented to serve the needs of the highly repetitive and routine earth orbit operations of the advanced spacecraft systems.

The report is structured to present general redline concepts (Section 2.0) with a twofold purpose. The first is an attempt to establish general redline criteria; the second, to establish the basis for the evaluation of work performed in past programs in order to fully utilize those aspects applicable to advanced systems.

Section 3.0 presents a summary of the redline activity of past programs including development, implementation, and monitoring functions.

Requirements of the operational Space Shuttle spacecraft as an example of an advanced spacecraft system are included in Section 4.0. These requirements, especially the projected high flight density, strongly suggest the development of simplified methods that would be both responsive and cost effective in the new operating environment. Guidelines for the redline development process of the Space Shuttle are presented, and implementation of the function of a Redline Status Subprocessor is recommended as a substitute for the methods employed in past programs. The algorithms of the Redline Status Subprocessor are amenable for use in the Mission Control Center (MCC) at Johnson Space Center (JSC), the Launch Processing System (LPS) under development at the Kennedy Space Center (KSC), or the Space Shuttle onboard computer system.

2.0 GENERAL REDLINE CONCEPTS

2.1 REDLINE DEFINITION

A redline is that maximum or minimum limit that defines the safe operating range or condition of a given system. Primary factors that dictate the establishment of redlines include personnel safety and/or equipment protection. Secondary considerations not directly related to either personnel safety or equipment protection but influencing the attainment of specific objectives dictate the establishment of redlines to the extent required to ensure the achievement of these goals. Consequently, operation of a system outside the redline limit will result in serious personnel injury, severe equipment damage, or failure to achieve specific objectives.

Redline values must represent realistic limits that effectively protect the system without restricting its operation. As a rule, redline violations are associated with an impending equipment or process failure and therefore are characterized by a definite response that must follow any limit violations. This action corresponds to: a) a preplanned course of action designed for the control and possible recovery from the situation giving rise to the violation; or b) the deleterious consequences ensuing if the violation is either undetected or ignored.

2.2 REDLINE SPECIFICATION

In the context of the given redline definition, limits can be specified as absolute or time dependent values. Absolute value redlines, although not restricted to, are used primarily for the control of two functions. First, they define a preconditional limit that must be met prior to the initiation of a given process or mechanism. Secondly, they define that absolute limit that may not be violated after the process has been initiated. Time dependent redlines are used to define a continuous limit that varies as a function of time for the duration of a process.

2.2.1 Absolute Value Redlines

Establishment of absolute value redlines although ultimately directed for the protection of life and equipment are principally associated with the fulfilling of specific objectives. When specified as a precondition for a process initiation, their observance relates to the degree to which goal achievement can be compromised. An aircraft traveling non-stop from point "A" to point "B" for example, must be loaded with a minimum fuel quantity "Q" sufficient to complete the trip. Thus, the absolute value of "Q" constitutes the redline which is designed to ensure the completion of the non-stop flight. Therefore, the trip may not be initiated with a fuel quantity less than "Q" if it is to be completed in the specified manner.

The redline specification process requires in addition to the limit value itself additional information which is used to aid in the decision making mechanism for the establishment of alternate courses of action if the limit is violated. Using "Q" as an example and assuming a fuel quantity less than "Q" at departure time, the information required should at least include:

a) A method for the verification of the actual quantity.

b) A method to determine the cause of the low quantity.

c) Possible corrective action once the cause is isolated.

d) Time required for recovery.

e) Effect of time delay on other systems.

f) Alternative courses of action (can a refueling stop be made between "A" and "B").

g) Effect of alternative courses of action (if refueling stop can be made, what are the consequences).

The above considerations regarding absolute value redlines assume that the worst consequences ensuing from a limit violation is the inhibition of the start of a process. Under such conditions, decisions as to what action is to be pursued are influenced primarily by the time and resources available for the determination of, and the recovery from, the cause of the redline violation.

The second function controlled by the absolute value redline is usually related to specific performance limitations of elements within a process. This redline is characterized by the fact that a deliberate action is required in order to produce a violation. The maximum cruising speed or altitude of an aircraft are good examples of the application of this redline. If a limit is set for these parameters, their violation can only occur as a result of a direct and deliberate action.

2.2.2 Time Dependent Redlines

Time dependent redlines define the limit by which a parameter can deviate with respect to a nominal value during the performance of a process; both the limit and the parameter value vary as a function of time. This redline is used to control elements of an ongoing process whose performance is critical to the overall operation. Violations of this redline are usually associated with irreversible failures that dictate an early process termination.

One of the principal functions of time dependent redlines is that of anticipating and predicting, as early as possible, violations. This is required for the formulation and implementation of timely and effective recovery procedures. This requires the continuous surveillance of the process and the performance of trend analysis of critical aspects of the operation.

Figure 1 illustrates the time dependent redline concepts as they apply to the aircraft flying from point "A" to point "B" discussed earlier. As in the previous example (Section 2.2.1) the quantity of fuel required to perform the flight is "Q", which was also specified as the absolute value redline. Also note from Figure 1 that the value of "Q" includes the flight fuel requirements and a reserve quantity "q".

The fuel depletion profile for the nominal flight is denoted by the QR line of Figure 1 such that if the flight is flown as planned, the aircraft will land with exactly the reserve quantity "q" in its storage tanks.

The time dependent redline is defined by the line PS which marks the limit by which deviations are permitted from the nominal value QR. It should be noted that the area bounded by QRSP corresponds to the reserve fuel quantity included to account for expected inaccuracies and errors.

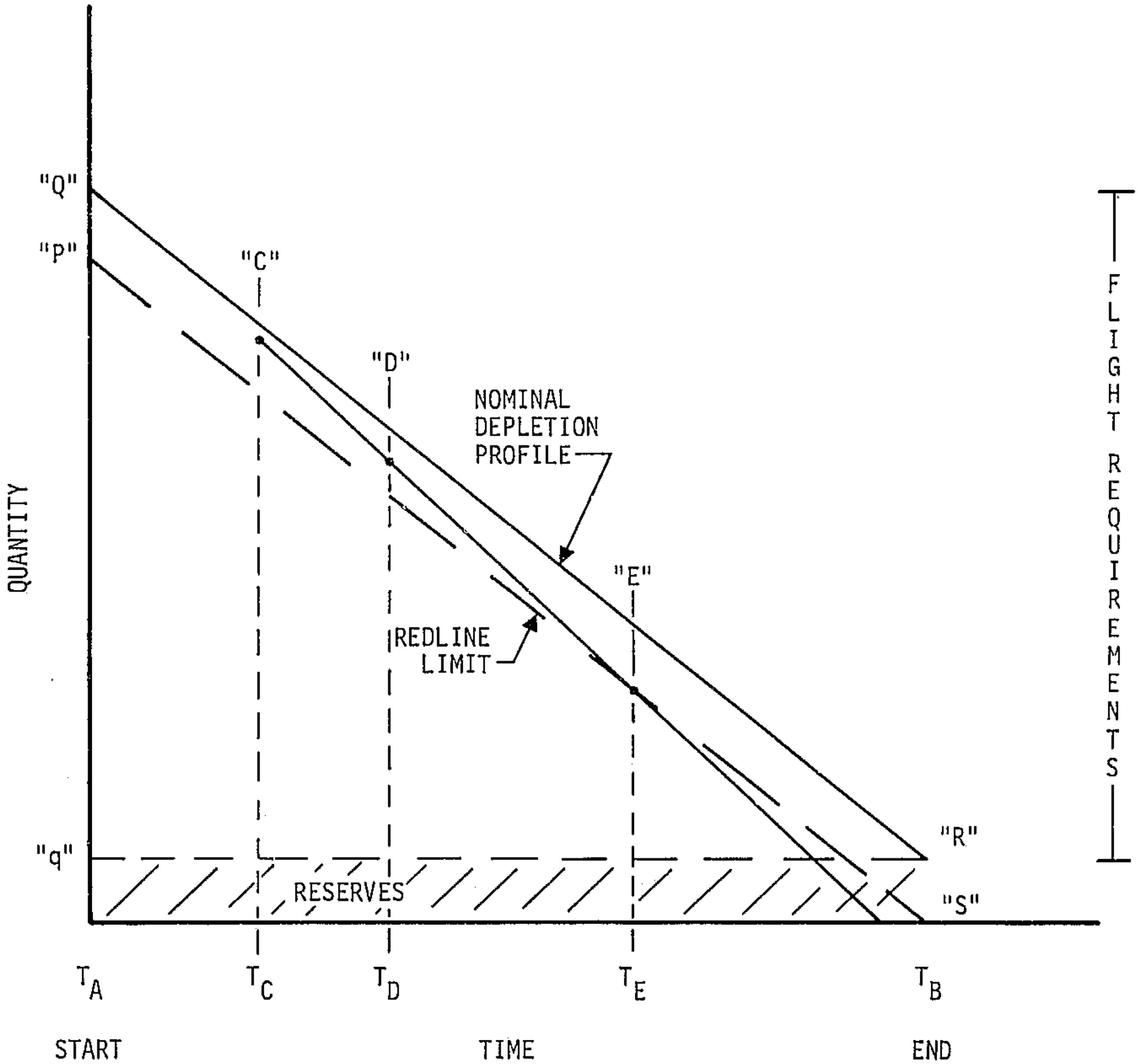

Figure 1. Time Dependent Redline

Assume at some point "C" between "A" and "B" that a deviation (not a redline violation) from the nominal depletion QR is observed for the first time. The redline function is to advise the crew of the apparent deviation and to continue monitoring the fuel depletion rate. This process continues until a trend of the consumption rate deviation is established, and at some point "D" a projection is made of the fuel required to complete the flight at the deviated rate. Such projection will show that there is not enough fuel to complete the flight at the deviated consumption rate, and that the redline will be actually violated at point "E".

With the above information at point "D", the decision process discussed in Section 2.2.1 can be initiated and the redline violation at point "E" avoided.

Continuous monitoring and projection capabilities are essential elements of the time dependent redline function, to preclude the discovery at point "E" that the redline has been violated and that there is not enough fuel to complete the trip.

2.3 REDLINE MONITORING

An integral part of the redline specification process includes the measuring and monitoring mechanisms. Sensors, gauges, meters, and other display devices must be available to monitor the redline parameters. Inaccuracies and probable errors of these devices must be considered along with instrumentation checks to filter out false redline violation indications.

Priorities must be established for the selection of instrumentation including redundant, alternate, or backup monitoring for critical functions in the process.

Monitoring of time dependent redlines should include the capability to compare the actual parameter value with those of the nominal and redline values. Depending on the observed differences, an assessment should be made of their short and long term impact on the progress of the process, thus providing timely advisories of potential problem situations.

2.4 REDLINE DEVELOPMENT

Redline values correspond to the actual limit or condition imposed on a parameter that must be observed during the performance of a given process operation. These values are derived from evaluation of the capabilities and operating characteristics of a given mechanism, together with the process objectives and requirements.

Specification of redline values is initiated by a detail analysis of the performance capabilities of a system in support of the given process. A failure mode and effects analysis is virtually required for every element of the process. The analysis should include operation of the system under nominal as well as under alternate conditions designed to simulate contingency situations. The following specific information must be made available along with the redline limit itself, which should specify the parameter's units, tolerance, frequency at which must be obtained, etc:

a) The rationale and justification for the selection of the redline value including its relation to the general and particular aspects of the process.

b) Instrumentation and monitor requirements, including expected errors induced by these elements in the establishment of the redline value.

c) Alternate mechanisms for the verification of the instrumentation and monitor process information.

d) Short and long term effects and consequences of redline violations to the overall process.

e) Procedural steps for fault isolation if a redline violation is detected and verified.

f) Special procedures to effect the repair of faults arising from redline violations.

g) Options available to proceed in case the redline violations occur from irreversible failures.

Any and all of the above is intended to provide the means by which effective decisions can be made for the protection of life and equipment in case of redline violations. Any other information not listed here but deemed helpful for a particular situation should also be included.

3.0 REDLINES ON PAST SPACECRAFT PROGRAMS

This section directs its attention to the redline development process of past manned spacecraft programs (Apollo, Skylab, ASTP) as it relates to consumables subsystems. An attempt to highlight the principal points of those processes has been made with a view toward the establishment of effective redline mechanisms for advanced spacecraft systems.

During the early stages of the Apollo Program, beginning with the AS-504, AS-505 unmanned flights, redlines evolved from a comprehensive set of documents, including: Mission Definition, Mission Requirements, Detail Test Objectives, Launch and Flight Rules, Flight Plan, etc. Guidelines for redline development emerged from the detail evaluation of the mission objectives as postulated in the above documents, and the systems capabilities. The detail test objectives demanded a rigorous analysis of each subsystem and served in most cases as the basis for the establishment of the redline limits and the instrumentation and monitor requirements.

The consumables subsystem redline development concepts employed during the Apollo Program, and subsequently used in the Skylab and ASTP Programs, are outlined in References 1 and 2. These redlines can be characterized as "absolute value redlines" in accordance with the definition given in Section 2.1.1.

Consumables subsystem redlines, especially those for the lunar landing missions, were developed as "launch redlines". These redlines values specified the minimum quantity of each of the various consumables that must be onboard prior to liftoff so that the launch could be effected. The particular values corresponded to the quantitites required to perform the mission as specified in the flight plan, plus any additional contingency requirements dictated in the launch and flight rules.

Observance and implementation of the launch redlines were successfully carried out with the support and cooperation of the Fluids Servicing Group at KSC. In conjunction with this group, a loading quantity was specified for each consumable used during pre-launch such that the remaining quantity at liftoff was equal to or greater than the redline value.

The unique aspects of space flight and the peculiar phases of the lunar missions made necessary the implementation of a comprehensive monitoring process. Each lunar mission was in effect a development flight. The variation in lunar orbits, landing sites, and the different lunar stay periods demanded the implementation of tailor-made analysis, including the consumables redlines, for each flight.

In addition to the launch operations, the redlines were of paramount significance during other phases of the flight where major commit decisions were required, such as the Translunar Injection and Lunar Landing Operations.

Redline monitoring during flight was effected with the aid of spacecraft meters and quantity gauges onboard, and with the telemetry system at the Mission Control Center (MCC). The redline values were provided to the crew and flight control personnel by the Flight Crew and Console Charts, respectively, furnished by the Consumables Analysis Section (CAS) of the Mission Planning and Analysis Division (MPAD) that depicted the predicted pre-mission depletion profiles of the various consumables. Trend development and quantities remaining projection during flight was strictly performed at the MCC by the Flight Control Crew with support of consumables specialists from CAS on a 24 hours a day basis. Telemetry data would be plotted on the console charts at MCC to show the relation of the actual vs. the predicted quantities as the flight progressed. This process, when deviations were noted, was instrumental in the correction of some flight procedures, and in the enhancement of the consumables analysis process of subsequent missions, by the use of actual flight data.

The redline activities as outlined in the preceding paragraphs were carried through and implemented in all Apollo flights and extended to the Skylab and ASTP flights as well.

4.0 REDLINES ON FUTURE SPACECRAFT PROGRAMS

Future manned spacecraft programs demand the development and implementation of mission planning methods that are both responsive and cost effective in the new operating environments. The projected flight density (50 flights per year) for the operational Space Shuttle, for example, coupled with its hardware reuseability feature, make the streamlining and the efficient utilization of the available resources imperative to cope with these requirements.

New techniques, applicable to the Space Shuttle, are being developed to perform the consumables management function during the mission planning and operational phases of advanced spacecraft systems. This new methodology based on experience gained on past programs and during the developmental phase of the Space Shuttle flights emphasizes the simplification of the analysis process. The repetitive and routine nature of the operational Space Shuttle flights also suggest a requirement for the standardization of all aspects of operations planning. Redline development should, in as much as it is practical, emerge also as a routine process.

Redlines must fulfill the basic requirement of life and equipment protection while maximizing the achievement of flight objectives. Using these criteria as a guide, the following considerations are presented for the development of consumables subsystem redlines for the operational Space Shuttle as an example of advanced spacecraft systems.

Guidelines for the development of consumables subsystem redlines for the Space Shuttle must evolve from:

- Analysis of the overall operational objectives and requirements of the program
- The Space Shuttle systems capabilities
- The availability of flight support resources.

The exclusive earth orbit operational requirements of the Space Shuttle flights when contrasted with those of the lunar missions present new dimensions to be considered in the redline development. The consequences of consumables subsystem redline violations while on earth orbit, excluding catastrophic failures, at worst will necessitate an early flight termination which, due to replanning capabilities and reuseable spacecraft, may not adversely impact Space Shuttle operations.

Development of the Launch Processing System (LPS) at the launch site (KSC) for the servicing and checkout of the spacecraft during the prelaunch and launch operations requires the consumables subsystem redline functions to be attune with such mechanism.

While some of the operational aspects of the Space Shuttle tend to simplify the role of the consumables subsystem redlines, others introduce new requirements that must be considered. The reuseable function of the Space Shuttle hardware, for example, requires that finite operational and shelf life, as well as performance degradation effects of some equipment, be included as part of the overall redline development process. This information, together with redline value updating to conform with observed flight data, must be introduced into the operating stream within the short turnaround period.

4.1 LAUNCH REDLINES

The function of the consumables subsystems launch redlines of the Space Shuttle correspond to that of the absolute value redline defined in Section 2.2.1. Launch redlines define that minimum quantity of each subsystem consumable that must be available onboard before the Space Shuttle spacecraft can be launched.

Each consumables subsystem launch redline value corresponds to the sum of two quantities:

- The nominal mission requirements
- The mission reserves.

These quantities are illustrated in Figure 2 and generally can be defined* as follows:

* Terms definitions taken from Reference 3.

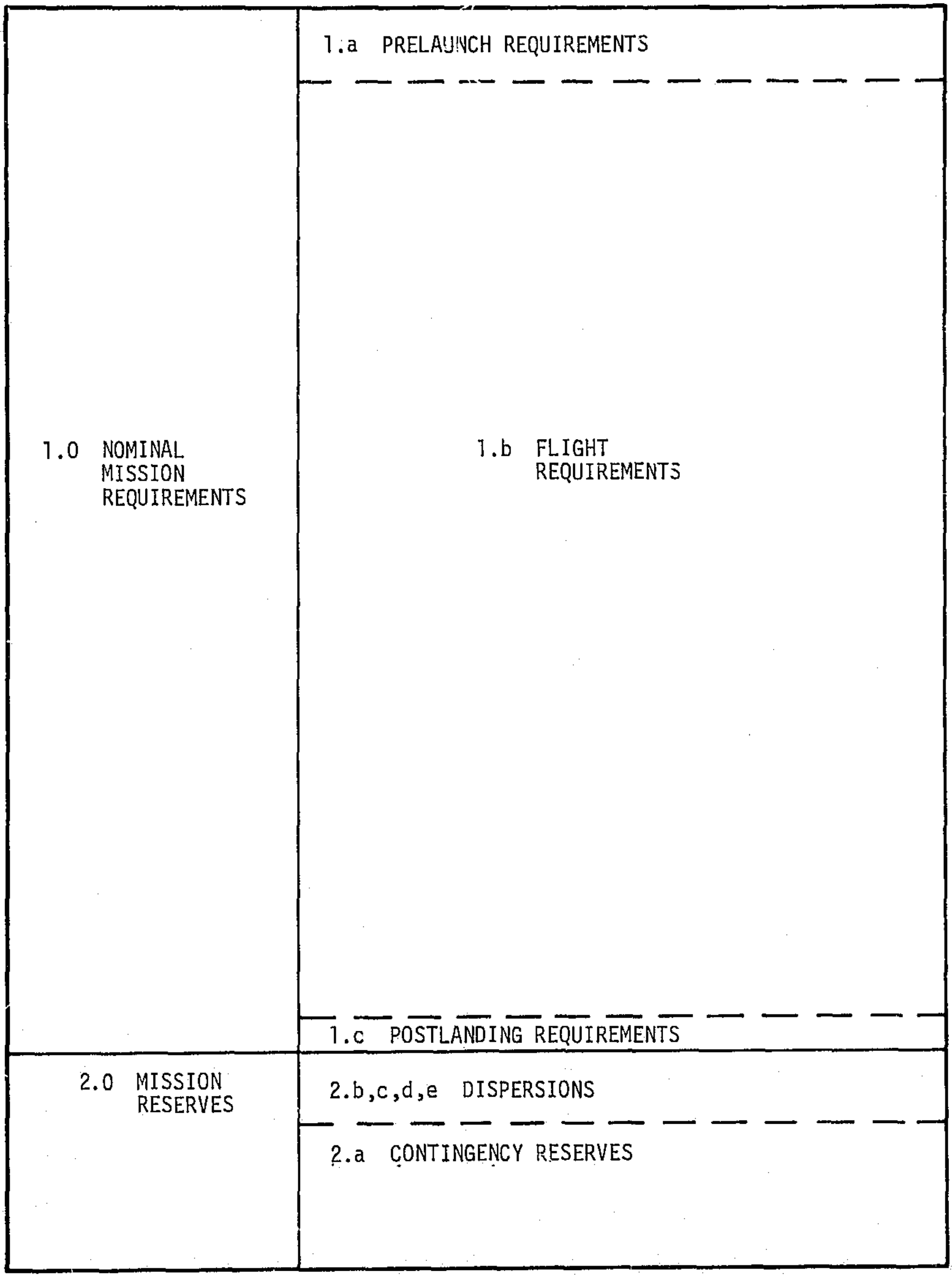

Figure 2. Consumables Subsystem Launch Redline

1) Nominal mission requirements equal prelaunch requirements plus flight requirements plus postlanding requirements

   a) Prelaunch requirements - consumables required to be utilized from loading to launch

   b) Flight requirements - consumables required to be utilized from launch to touchdown

   c) Postlanding requirement - consumables required to be utilized from touchdown to system shutdown.

2) Reserves equal contingency reserves, dispersion allowance, flight planning uncertainty, measurement error (loading or in flight), and leakage.

   a) Contingency reserves - consumables required for specific system malfunctions and mission emergencies

   b) Dispersion allowance - consumables required to allow for system consumption rate fluctuations or performance capability variations from the nominal

   c) Flight planning uncertainty - consumables allowed for mission planning purposes to compensate for unpredicted crew usage

   d) Measurement error equals loading error or in-flight measurement error

      o Loading error - consumables allowed for loading temperature variations, ground measurement accuracy, system volume inaccuracy, and consumable density variations

      o In-flight measurement error - consumables which cannot be relied upon due to the inability to ascertain their presence

   e) Leakage - consumables defined by specification to be leaked from the system.

The flight requirement should be the only variable quantity from mission to mission at the end of the developmental flights, when checkout of all Space Shuttle systems should be completed.

Thus, specification of launch redline values for the operational Space Shuttle should correspond to the sum of constant quantities (the prelaunch, postlanding, and reserve requirements) and the variable flight requirements quantity.

Consideration of the repetitive nature of the Space Shuttle flights, consumables kits availability, specific flight requirements (such as crew size, flight duration, propulsive maneuvers, payload support requirements, etc.) could lead to the establishment of a standard consumables quantity to support the flight requirements of most missions. This standard value, together with the constant quantity specified for the prelaunch, post-landing, and reserve requirements could be used to institute a "standard loading" philosophy for the launch redlines.

Regardless of the method employed to determine the launch redline value, the magnitude of the actual onboard quantities require monitoring and verification during the prelaunch and launch operations. This is required in order to detect potential redline violations and develop corrective measures as early as possible during the countdown. This monitoring function will be discussed further in Section 4.3.

Since the loading and prelaunch operations will be under control of the LPS facility under development at KSC, the launch redline function must be integrated into that facility. This requirement will be addressed in Section 4.3.

4.2 FLIGHT REDLINES

Consumables subsystems flight redlines functions for the Space Shuttle spacecraft are equivalent to the time dependent redlines defined in Section 2.2.2. These redlines are designed for the protection of life and equipment during the performance of a process. The flight redlines function is initiated at liftoff and concludes at the completion of the rollout operations when control is transferred to the ground support equipment.

The flight redline value for any subsystem consumable is that quantity that must be available onboard during orbital operations to effect an emergency deorbit and recovery of the crew and Space Shuttle. This absolute value corresponds to the contingency reserves quantity specified as item 2.a in Section 4.1.

Continuous monitoring and processing of the flight redlines is required for two reasons:

1. To ensure that consumables depletion during flight are never allowed to reach the redline value

2. To detect potential consumables redline violations as early as possible during the flight.

The first condition can be readily satisfied by the comparison of the redline value with the available quantity onboard. This could be implemented through the caution and warning system.

Satisfaction of the second condition requires the continuous projection of end-of-mission quantities remaining, based on comparison of premission predicted versus actual consumables values.

4.3 REDLINE MONITORING

The redline monitoring function of the time dependent redline discussed in Section 2.2.2 applies to both the prelaunch (launch redline) and flight (flight redline) operations of the Space Shuttle. Figure 3 illustrates this function.

Quantity Q_L corresponds to the total loading requirements which are equal to the nominal mission requirements plus the mission reserves. Quantities Q and q correspond to the launch and flight redline values respectively.

The prelaunch requirement (line Q_LQ_0) includes the nominal prelaunch requirements (line P_LQ_0) and a prelaunch dispersions allowance (line Q_LP_L). Line Q_LQ' corresponds to the nominal prelaunch depletion profile such that if the consumables depletion during prelaunch operations follows the planned rate, the Space Shuttle will have available at liftoff the excess quantity $Q' = Q_LP_L$. Line P_LQ defines the prelaunch dispersions limit such that if the consumption rate during that period is equal to the nominal plus the allowable prelaunch dispersions, the quantity available at liftoff will be equal to Q, the launch redline value.

The significance of the dispersion limit is that operation below these limits (shaded areas in Fig. 3) indicates an actual consumption rate exceeding the maximum allowed for nominal operations. Continued operation under this

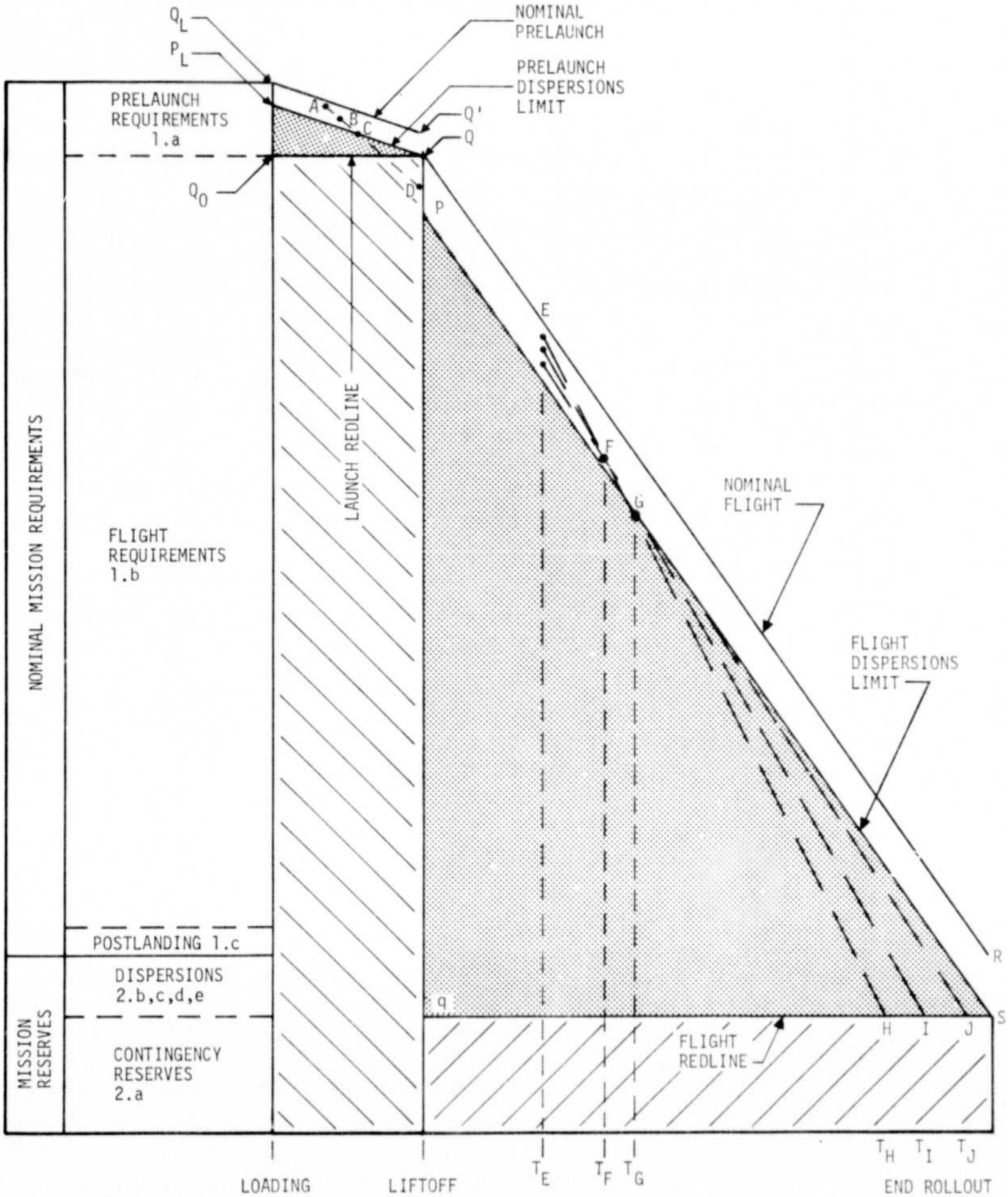

Figure 3. Consumables Subsystem Redline Monitoring

condition will lead to a violation of the launch redline value, which can only be precluded by an equivalent consumption rate reduction resulting from modifications to the spacecraft configuration and/or the mission.

Consider at some point A after the prelaunch operations are initiated that a deviation from the nominal depletion rate is detected. This deviated depletion rate, if allowed to continue, will fall below the dispersion limit line $P_L Q$ at point C and eventually violate the launch redline by falling to point D below the redline quantity Q at liftoff. The continuous redline monitoring and end-of-mission quantity remaining prediction function would have detected the deviated rate, established a trend at some point B and predicted at point C the imminent launch redline violation. This information is required prior to point C, as early as possible during the prelaunch operations, in order to maximize the recovery options.

Another function of the redline monitor process is the updating of the liftoff quantity to the actual value available onboard. This quantity may be greater than Q, the launch redline value.

Figure 3 also shows line QR as the depletion profile for the nominal flight, line PS as the flight disperions limit, and q as the flight redline value. Continuous monitoring is required during flight to detect potential flight redline violations. Three possible depletion rate deviations are shown occurring at point E which if allowed to continue will result in the reaching of the flight redline value at points H, I, or J. As in the prelaunch example, knowledge of the potential violation is required prior to point G to maximize the recovery options.

Determination of the cause of the higher depletion rate is not only significant to effect recovery procedures during specific flights, but also to account for these effects on subsequent flights.

4.4 AUTOMATED REDLINE MONITORING

The redline monitoring function requires the processing of the onboard instrumentation to first verify observance of the launch redline values during prelaunch, and second, to project end-of-mission quantities remaining and check for potential or actual launch or flight redline violations. This function was performed in past programs by the Fluids Servicing Group at KSC and the Flight Control Crew at the MCC at JSC, with direct support of consumables specialists from CAS.

Consideration of the Space Shuttle requirements for the operational era, indicate the desirability for the development and implementation of routine automated processing techniques for all aspects of mission planning and flight operations. Evidence of this includes the development of the LPS complex at KSC for the automatic servicing, checkout, and launch of the Space Shuttle spacecraft.

To provide redline support to the Space Shuttle operations it is recommended that the Redline Status Subprocessor or suitable equivalent be developed. This subprocessor forms a part of the Flight Operations Processor whose functional requirements are documented in Reference 4.

The function of the Redline Status Subprocessor is to check the measured consumables parameters against predetermined limit values to establish violations to the launch or flight redlines. Launch redline processing includes the comparison of the actual onboard quantities against the predetermined limit values, and the updating to the actual liftoff quantities. Flight redline processing includes, in addition to the comparison of predicted versus actual quantities, the projection of end-of-mission quantities remaining for the detection of potential redline violations.

The Redline Status Subprocessor was designed for the processing of consumables subsystem redlines, i.e., the launch and mission dependent redlines as part of the overall consumables management system, but its adaptation to handle mission independent redlines can be readily implemented. In addition, the algorithms are amenable for use in the MCC, adaptation to the LPS facility under development at KSC, or implementation in the Space Shuttle onboard computer system, as illustrated in Figure 4.

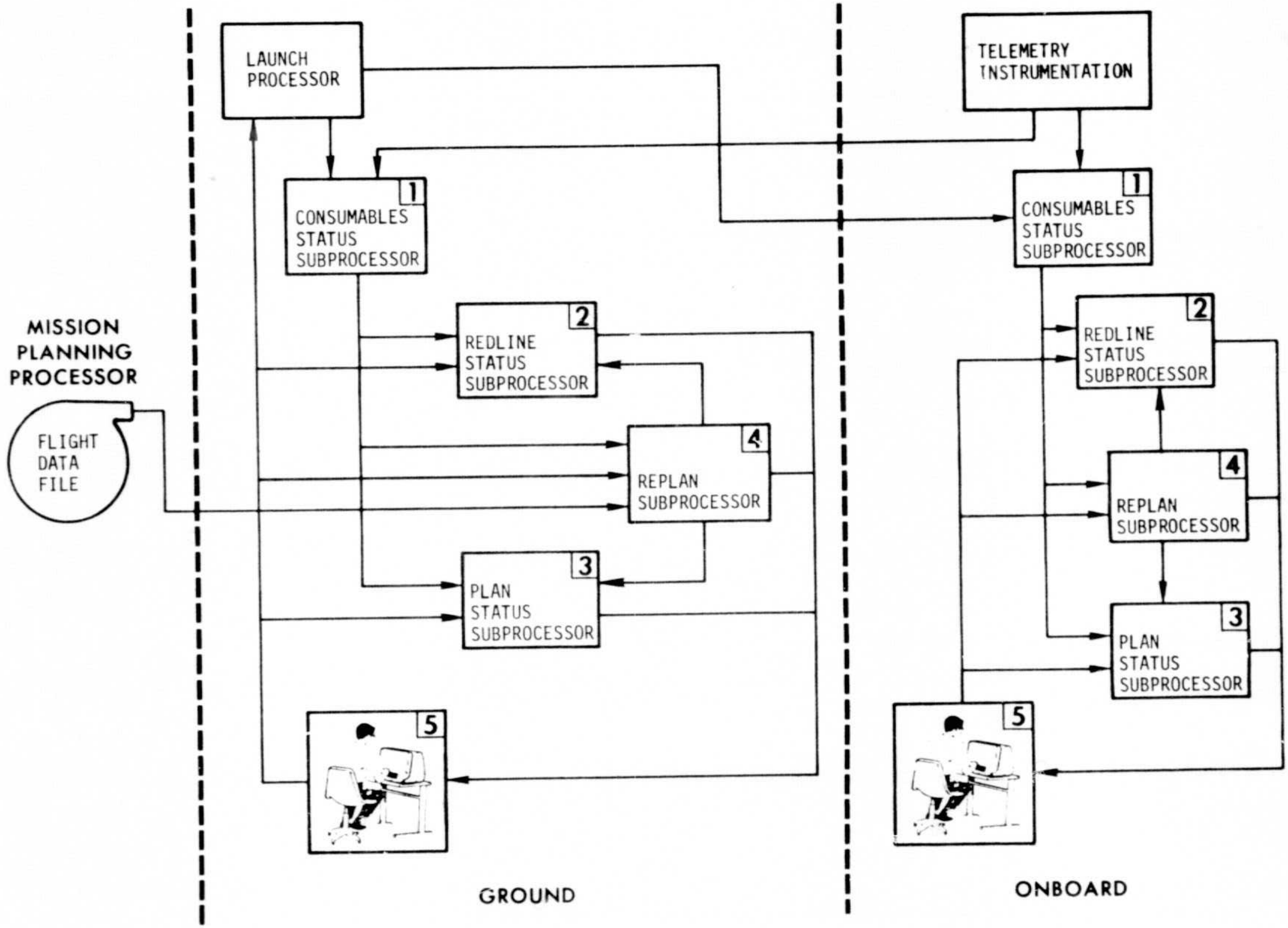

Figure 4. An Approach to Automated Monitoring of Consumables Subsystem Redlines

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