Robust Strategy for Rocket Engine Health Monitoring

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Executive Summary

The inference phase of rocket engine health monitoring involves analysis of results from the acquisition phase, comparison of analysis results to establish health measures, and assessment of health indications. A particular model based procedure developed for the inference phase of engine health monitoring and referred to as Generalized Data Reduction (GDR) was the subject of this effort. The GDR method can be considered a strategy for solving the inverse performance analysis problem often referred to as data reduction. The primary objective of this research effort was to investigate methods of enhancing the GDR strategy in order to make it a flight capable real-time diagnostic platform for the engine system of choice.

A brief conceptual description of the basic GDR strategy punctuated by significant mathematical results and a description of major components is presented. The MC-1 engine system was specified as the test platform for evaluating GDR capabilities and assessing candidate enhancement procedures. Data from the R2 and R3 series of MC-1 engine tests conducted at Rocketdyne's Santa Susanna Field Laboratory in California were utilized to seed the data reduction process. A ROCETS performance model of the MC-1 engine was used to generate influence matrices used by GDR and a modified ROCETS data reduction model provided conventional data reduction results used to assess the accuracy potential of GDR predictions.

The basic GDR procedure was shown to provide consistent approximation of hardware function that agreed well with the recognized standard for MC-1 engine data reduction. Modifications to the basic procedure were explored to increase the effective solution range as well as improve computational speed, accuracy, and stability of the solution procedure. An efficient procedure based on singular value decomposition (SVD) of the hardware influence matrix was implemented and tested as was a partial second order extension of the basic GDR procedure. Computational efficiency was improved using the SVD technique. No improvement was observed using the partial second order extension.

The original MC-1hardware parameter set used for data reduction was functionally regrouped and GDR analyses were performed with the revised hardware set. Agreement of predictions with accepted standards was excellent. Single source anomaly resolution capability was found to be excellent using the revised parameter set. A study was performed to determine the effects of single sensor failure on reduction predictions. Degradation of reduction results in the presence of sensor failure was characterized. GDR analyses were also performed using a highly restricted flight measurement suite. Loss of hardware discrimination capability using only flight available measurements was characterized and results were evaluated as reasonable for real-time monitoring applications.

Two automated subset selection procedures were developed in order to identify compatible sets of measurements and hardware parameters for data reduction applications. Results of preliminary testing are reported and the shortcomings of sequential subset selection procedures are identified.

Summary evaluation of GDR performance for MC-1 data reduction is provided and recommendations for future development are presented.

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1.0 Introduction

Monitoring the health of rocket engine systems is essentially a two-phase process. The acquisition phase involves sensing physical conditions at selected locations, converting physical inputs to electrical signals, conditioning the signals as appropriate to establish scale or filter interference, and recording results in a form that is easy to interpret. The inference phase involves analysis of results from the acquisition phase, comparison of analysis results to established health measures, and assessment of health indications.

A variety of analytical tools may be employed in the inference phase of health monitoring. These tools can be separated into three broad categories: statistical, rule based, and model based. Statistical methods can provide excellent comparative measures of engine operating health. They require well-characterized data from an ensemble of "typical" engines, or "golden" data from a specific test assumed to define the operating norm, in order to establish reliable comparative measures. Statistical methods are generally suitable for real-time health monitoring because they do not deal with the physical complexities of engine operation. The utility of statistical methods in rocket engine health monitoring is hindered by practical limits on the quantity and quality of available data. This is due to the difficulty and high cost of data acquisition, the limited number of available test engines, and the problem of simulating flight conditions in ground test facilities. In addition, statistical methods incur a penalty for disregarding flow complexity and are therefore limited in their ability to define performance shift causality.

Rule based methods infer the health state of the engine system based on comparison of individual measurements or combinations of measurements with defined health norms or rules. This does not mean that rule based methods are necessarily simple. Although binary yes-no health assessment can sometimes be established by relatively simple rules, the causality assignment needed for refined health monitoring often requires an exceptionally complex rule base involving complicated logical maps. Structuring the rule system to be clear and unambiguous can be difficult, and the expert input required to maintain a large logic network and associated rule base can be prohibitive.

Model based methods incorporate physical relations and empiricisms in the inference phase of health monitoring. Such methods are typically more involved because the flow physics of rocket engines is generally described by complex and interdependent, nonlinear relations. The attending computational complexity presents a significant impediment to the use of model based methods in real-time health monitoring. However, the addition of physical detail does provide a basis for determining performance shift causality at the component level. Recent surveys of model based inference procedures applicable to propulsion systems are available [1, 2].

A particular model based procedure referred to as Generalized Data Reduction (GDR) [3, 4] was the subject of this effort. GDR was initially developed at Marshall Space Flight Center (MSFC). Mathematically, GDR can be considered a strategy for solving the inverse performance analysis problem often referred to as data reduction. More specifically, the GDR method inverts a canonical representation of the engine system performance model to estimate parameters that characterize the operation of hardware components such as pumps, turbines, injectors, nozzles, orifices, valves, etc., consistent with test data. As a propulsion system analysis procedure, the basic form of GDR is similar to gas path analysis techniques [see e.g. 5] commonly used for fault detection and isolation in air-breathing systems. GDR has been applied to mainstage data reduction of both the Space Shuttle Main Engine (SSME) [3] and the MC-1 engine system [4].

In these applications GDR demonstrated computational speeds consistent with real-time monitoring requirements.

2.0 Objectives

The primary objective of the subject research effort was to investigate methods of enhancing the Generalized Data Reduction strategy in order to make it a flight capable real-time diagnostic platform for the engine system of choice. The principal areas targeted for enhancement were as follows:

1. Basic algorithm refinement to improve computational efficiency and reduction cycle speed
2. Extensions to incorporate additional engine system knowledge, especially uncertainty estimates
3. Subset selection refinement to improve stability and sensitivity of hardware-measurement compatibility assessment and selection process
4. Range extension methods to expand the engine operating range of application
5. Techniques for responding to sensor degradation /failure
6. Methods of incorporating creep scale transients within main stage engine diagnostics.

Secondary topics of study that depended on the GDR development path were identified in the grant supplement as described below:

7. Methods for improving the gateway for input of statistical parameters to the data reduction process
8. Methods for improving data reduction stability with expanded measurement and/or hardware sets
9. Methods for improving performance model feedback from data reduction predictions
10. Methods for improving test data/model accuracy assessment
11. Methods for improving reduction model capability with limited measurement sets.

A brief description of the basic GDR method is presented in the next section of this report in order to introduce terminology and define the development baseline.

3.0 The GDR Strategy

A detailed development of the basic GDR strategy can be found in two recent papers [3, 4]. A brief conceptual description punctuated by significant mathematical results and a description of major component procedures is provided below.

The mainstage performance model of a rocket engine system can be thought of as a set of functional relations **F** between the following parameter sets.

1. known/measured system control settings and/or input/output conditions **C**; e.g., valve positions, inlet/outlet temperatures, pressures, etc.
2. nominally fixed parameters **H** describing component hardware function; e.g., efficiencies, discharge coefficients, head coefficients, line resistances, etc., and
3. internal engine conditions **P** at various locations; e.g., temperatures, pressures, flows, heat transfer rates, thrust, etc.

The objective of performance analysis is to predict the internal engine conditions **P**, given known or assumed values for the members of **H** and **C**.

If the performance model relations between **P**, **H** and **C** are assumed to be linear near some known base state designated by the subscript "**o**", then they can be approximated in the following form.

Linearized Performance Model Relations

$$\Delta \mathbf{P} = \mathbf{J}_{\mathbf{Ho}}\, \Delta \mathbf{H} + \mathbf{J}_{\mathbf{Co}}\, \Delta \mathbf{C} \tag{1}$$

where

$$\mathbf{J}_{\mathbf{Ho}} = \left[\frac{\partial P_i}{\partial H_j}\right]_{\mathbf{o}} \approx \left[\frac{\Delta P_i}{\Delta H_j}\right]_{\mathbf{o}} \qquad \mathbf{J}_{\mathbf{Co}} = \left[\frac{\partial P_i}{\partial C_k}\right]_{\mathbf{o}} \approx \left[\frac{\Delta P_i}{\Delta C_k}\right]_{\mathbf{o}} \tag{2}$$

$$\Delta \mathbf{H} = \mathbf{H}-\mathbf{H}_{\mathbf{o}} \qquad \Delta \mathbf{C} = \mathbf{C}-\mathbf{C}_{\mathbf{o}} \qquad \Delta \mathbf{P} = \mathbf{P}-\mathbf{P}_{\mathbf{o}} \tag{3}$$

$$\mathbf{H} = [\, H_1\, H_2 \ldots H_n \,]^{\mathbf{T}} \qquad \mathbf{C} = [\, C_1\, C_2 \ldots C_L \,]^{\mathbf{T}} \qquad \mathbf{P} = [\, P_1\, P_2 \ldots P_m \,]^{\mathbf{T}} \tag{4}$$

$\mathbf{J}_{\mathbf{Ho}}$ m×n Jacobian matrix of **P** with respect to **H** at base state **o**

$\mathbf{J}_{\mathbf{Co}}$ m×L Jacobian matrix of **P** with respect to **C** at base state **o**

The Jacobian matrices defined in relations (2) above are commonly referred to as first order influence matrices. Elements can be approximated using a standard finite difference scheme and results of performance model simulation runs at incremented values of each hardware and control component about its defined base state value.

The problem of determining values of the hardware shifts **ΔH** so that equation system (1) is satisfied, given measurement indicated values for **ΔP** and **ΔC**, is the linear data reduction problem. Unfortunately determination of the hardware parameter solution **ΔH** is complicated by several factors. In general, the number of hardware parameters H_j is greater than the number of available measurements P_i, i.e. n>m. This prevents straightforward inversion of the hardware Jacobian to obtain a unique solution to equation system (1). It also presents the problem of selecting the correct hardware operating state from an infinite set of candidate hardware states for the given observation set. Added to the discrimination problem is another related to computational stability. If the hardware Jacobian is ill conditioned, the data reduction solution **ΔH** may be unstable. Little confidence can be placed in the solution to an ill conditioned system even with low levels of measurement noise.

The basic GDR strategy attempts to address these problems using a two-stage solution process. Terminology pertinent to the solution procedure is given below.

$\mathbf{H_s}$ vector subset of n_s hardware parameters selected for adjustment in reduction analysis

$\mathbf{P_s}$ vector subset of m_s measured internal conditions selected for reduction analysis matching

$\mathbf{J_{Hso}}$ $m_s \times n_s$ submatrix of hardware Jacobian $\mathbf{J_{Ho}}$ corresponding to selected hardware, $\mathbf{H_s}$, and measured internal conditions, $\mathbf{P_s}$

$\kappa_2(\mathbf{A})$ L_2 condition number of the indicated matrix $\mathbf{A}$

$\mathbf{W}$ $n_s \times n_s$ diagonal matrix of weighting factors associated with selected hardware $\mathbf{H_s}$

QR-Pi column pivoted **QR** factorization of selected $m \times n$ matrix $\mathbf{A}$, i.e., $\mathbf{APi} = \mathbf{QR}$ where $\mathbf{Q}$ is an orthogonal $m \times m$ matrix, $\mathbf{R}$ is a $m \times n$ upper triangular matrix, and $\mathbf{Pi}$ is a $n \times r$ permutation matrix

Using the above terminology, the basic GDR strategy can be described as follows.

<u>Basic GDR Strategy</u>

Process 1. *Subset Selection*

Select $\mathbf{H_s} \subseteq \mathbf{H}$ and $\mathbf{P_s} \subseteq \mathbf{P}$

using **QR-Pi** factorization of $\mathbf{J_{Ho}}$ to select $\mathbf{H_s} \subseteq \mathbf{H}$
QR-Pi factorization of $\mathbf{J_{Ho}}^T$ to select $\mathbf{P_s} \subseteq \mathbf{P}$

such that $\kappa_2(\mathbf{J_{Hso}}) < \kappa_{2\text{-threshold}}$

Process 2. *Optimized Reduction*

Select $\Delta\mathbf{H_s}$ to

minimize $\Delta\mathbf{H_s}^T \mathbf{W} \Delta\mathbf{H_s}$

subject to $\Delta\mathbf{P_s} = \mathbf{J_{Hso}} \Delta\mathbf{H_s} + \mathbf{J_{Cso}} \Delta\mathbf{C_s}$

The subset selection process provides a method of identifying appropriate combinations of hardware parameters and internal measurement variables that limit the solution error bound. The L_2 condition number of the hardware Jacobian, $\kappa_2(\mathbf{J_{Hso}})$, affords a measure of the computational limits of solution accuracy separate from model and measurement uncertainty effects. This is reflected in a general guideline for underdetermined linear systems which estimates the number of significant digits lost in the solution process to be equal $\log(\kappa_2)$.

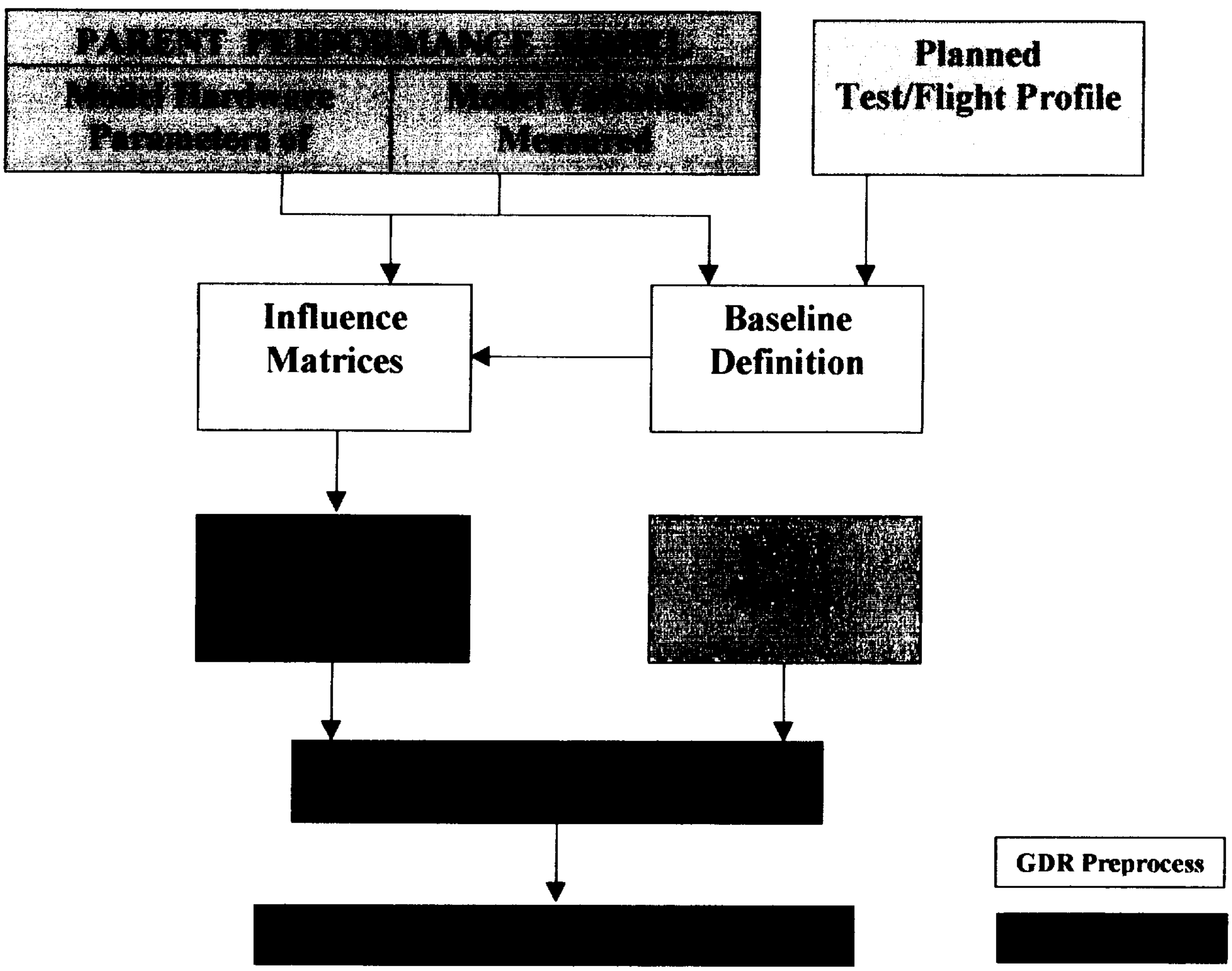
The pivoted **QR** factorization process [see, e.g. 6, 7] sequentially arranges hardware parameter columns and internal measurement rows of the influence matrix $\mathbf{J_{Ho}}$ in descending order of independence up to the rank of the matrix. After pivoting, elimination of parameters associated with later columns and measurements associated with later rows tends to reduce the resulting submatrix condition number, thereby reducing the computational error bound. The penalty associated with column elimination is artificial reduction in the hardware parameter state space range. The penalty associated with row elimination is loss of state space discrimination.

The accuracy trade-offs for underdetermined systems are clearly indicated in a perturbation result presented by Golub, et al [6, page 273].

The optimized reduction process requires solution of a weighted least squares problem with equality constraints. Orthogonalization methods based on **QR** factorization or singular value decomposition (SVD) are effective and dependable solution procedures for problems of this type [6 7 8 9 10]. However, the basic GDR strategy utilizes Powell's implementation of the Goldfarb and Idnani dual quadratic programming algorithm [11] as the solution procedure. This method, although less efficient, provides the flexibility to include inequality constraints as well as linear and covariant terms in the optimization merit measure.

A conceptual view of the GDR strategy is presented in the figure below.

Figure 1 GDR Conceptual Strategy



4.0 Study Components

To define the study basis, a description of three specific components is needed: the engine system that served as the test platform for evaluation of GDR, the test data source for the specified engine system, and the parent engine performance model that was used to derive engine system influences. Definition of these components is provided below.

4.1 Engine System

The MC-1 engine system was specified as the test platform for evaluating GDR capabilities and assessing candidate enhancement procedures. The MC-1 engine is a 60,000 lb thrust, pump-fed liquid fuel rocket engine that was developed by the Marshall Space Flight Center (MSFC) [12]. It burns a mixture of RP-1 hydrocarbon fuel and liquid oxygen. Hot gas produced by a gas generator is used to power a turbine that rotates an inline turbopump assembly. The engine uses five orifices to control engine thrust and mixture ratio. These are the gas generator liquid oxidizer orifice, the gas generator RP-1 orifice, the main liquid oxidizer orifice, the main RP-1 orifice, and the gas generator nozzle orifice. The MC-1 engine is intended to be reusable with the exception of the ablative nozzle. A conceptual schematic displaying major components of the engine system is presented in Appendix A, Figure A1.

4.2 Test Data Source

Three series of MC-1 tests were recently conducted on the Alfa-1 test stand at Rocketdyne's Santa Susanna Field Laboratory in California. The R1 series was focused on resolving any issues associated with the new test stand. The R2 and R3 series consisted of several tests of Engine 3 and Engine 5, respectively. Engines 1 and 2 had previously been tested in the horizontal test facility at NASA Stennis Space Center (SSC), and Engine 3 had previously been tested at the Propulsion Test Article Facility at SSC. The R2 series used a 15:1 area ratio nozzle and the R3 series used a 30:1 area ratio nozzle. Both series were conducted at test stand altitude.

Both R2 and R3 series data sets were utilized in this study. The R2 series consisted of five tests: the first four – R2-1, R2-2, R2-3a and R2-3b - were 24 seconds in duration, and the final test – R2-4 – was a full duration test of 159 seconds. The R3 series consisted of two tests: R3-1a and R3-2b, each 24 seconds in duration.

The tests had varying objectives [13]. R2-1 established an Engine 3 calibration baseline. The effects of LOX inlet pressure variations on pump run characteristics were investigated in R2-2. R2-3a was intended to evaluate engine calibration in response to an orifice change; however, due to a leak in the oxidizer bleed valve, this was not accomplished until test R2-3b. Finally, R2-4 was intended to assess engine calibration during a full duration test of 159 seconds.

The main liquid oxidizer orifice and gas generator nozzle orifice were not changed during the R2 series. All other orifices were changed after tests R2-2 and R2-3b. Therefore, tests R2-1 and R2-2 contained identical orifice configurations, as did tests R2-3a and R2-3b. The Engine 5 calibration baseline was established in test R3-1a. Data from this test was used to guide selection of an appropriate orifice configuration for use with the high area ratio nozzle. Test R3-2b used the same orifice configuration as R2-4 and was used to evaluate Engine 5 calibration in response to an orifice change. A summary of engine configuration and test definition information for the R2 and R3 test series is provided in Appendix G, Table G1.

4.3 Parent Performance Model

A ROCETS [14] performance model of the MC-1 engine was developed at MSFC to support engine design and testing. Fluid conditions in all of the major engine components and flow ducts were modeled using one-dimensional flow physics and empiricisms. This model was the nonlinear simulation platform used to generate engine system influence matrices for GDR analyses. The ROCETS/MC-1 mainstage model was also modified to run in data reduction (DR) mode. This fully nonlinear reduction model, herein designated ROCETS DR, provided the conventional data reduction results used to assess the accuracy potential of GDR predictions.

For computational testing of the GDR strategy, 25 engine system measurements, corresponding to performance model variables, were recorded at sampling rates from 25 Hz to 250 Hz. These measurements and their associated variable names in the ROCETS/MC-1 engine model are provided in Appendix G, Table G2. They include four inlet condition measurements and 21 internal engine measurements. Fourteen pressures, seven temperatures, two flows, one turbopump shaft speed, and the engine thrust comprise the measurement list.

A total of 22 candidate hardware parameters was originally selected for reduction analysis consideration. These are also listed in Table G2 and include four duct/line resistances, four valve area ratios, four injector discharge coefficients, two pump head coefficient multipliers, two pump torque coefficient multipliers, and one each turbine efficiency multiplier, gas generator (GG) exhaust duct orifice coefficient, turbopump friction factor, nozzle discharge coefficient, main combustion chamber (MCC) C* efficiency multiplier, and GG liquid oxygen (LOX) inlet duct heat transfer rate.

Only 17 of the 22 candidate hardware parameters were employed in standard data reduction analyses performed with the ROCETS DR model. The five parameters not used in conventional reductions included the two pump torque multipliers, two main flow valve area ratios, and one turbine efficiency. In addition, only 17 of the 21 available internal measurements were targeted for matching in conventional reduction analyses. The four measurements not used in standard data reduction analyses included the gas generator oxidizer valve (GGOV) inlet pressure, the LOX dome temperature, the fuel manifold temperature, and the turbine discharge temperature. Hardware parameters and measurements not used in standard data reduction analyses are identified in Table G2. Subsystem schematics depicting the approximate flow path location of all measurements relative to major hardware components are presented in Appendix A, Figures A2 through A5.

5.0 GDR Pre-analysis

In order to evaluate both the capabilities and limitations of the basic GDR strategy, it is necessary to understand the analysis set-up procedure and characteristics of the reduction study test data. The next two subsections provide the following information: an outline of the GDR analysis setup procedure and a summary of characteristics of the R2 and R3 test series data used in reduction analyses.

5.1 GDR Preprocessing Tasks

Once candidate measurements and hardware parameters were identified for the MC-1 engine system, five off-line preprocessing tasks were performed to prepare for a basic GDR analysis sequence. These tasks are identified below.

Preprocessing Tasks

1. Identify an appropriate baseline state, $\mathbf{H_0}$ $\mathbf{C_0}$ and $\mathbf{P_0}$

2. Normalize all measurement variables and hardware parameters
3. Compute elements of the normalized influence matrices at the base state
4. Assign weighting factors **W** for the least squares terms
5. Assimilate information into appropriately formatted input files.

Baseline values were selected to closely approximate expected operating conditions of the engine system. Baseline values of performance model variables corresponding to internal measurements are also required to be an achievable solution of the parent performance model with specified baseline values of the hardware parameters and model variables corresponding to control/input measurements. The parent performance model for this GDR study was the ROCETS/MC-1 mainstage engine model.

For purposes of this study, baseline values were defined for each MC-1 engine test by the following procedure.

Baseline Definition Procedure

1.1 The average of data sampled at rates from 25 Hz to 250 Hz (depending on the specific measurement) was computed over the time interval from 22 to 23 seconds for each of the 17 internal measurements and 4 input measurements used in standard data reduction.

1.2 The averages obtained in the previous step were used as inputs to the ROCETS DR model to obtain test specific baseline values for the hardware parameters $\mathbf{H_0}$.

1.3 Input variables were assigned the baseline values $\mathbf{C_0}$ indicated below.

PSVL10 – LOX inlet pressure	47 psia
TTVL10 – LOX inlet temperature	164.5 R
PSRPFV – Fuel inlet pressure	43 psia
TTRPFV – Fuel inlet temperature	505 R

1.4 Baseline values $\mathbf{P_0}$ for variables associated with the internal measurements were then obtained by running the ROCETS/MC-1 performance model with hardware parameters assigned baseline values $\mathbf{H_0}$ from step 2 and input variables assigned the baseline values $\mathbf{C_0}$ indicated in step 3.

This four-step procedure was adopted to provide a baseline state indicative of the best available information regarding engine operation with standard inputs. It was also meant to approximate an operational procedure that uses information available from engine acceptance tests. Baseline information derived using the above procedure for each MC-1 test is presented in Appendix G, Tables G3 and G4.

The second preprocessing procedure involving normalization of variables is essential for robust reduction analysis. The normalization procedure generally affects the parameter selection process, the reduction solution $\mathbf{H_s}$, and the confidence bounds associated with the solution. The preferred scaling procedure involves uncertainty measure normalization. In the absence of reliable uncertainty estimates, one approach is to normalize the shift from baseline value for each variable by the baseline value for that variable. This is equivalent to uncertainty normalization under the assumption that the uncertainty as a percentage of baseline value is the same for all variables. Variable and Jacobian normalizations using this assumption are specified below.

Normalization Groups

$$\Delta H^* = \left[\frac{H_j - H_{jo}}{H_{jo}}\right] \qquad \Delta C^* = \left[\frac{C_k - C_{ko}}{C_{ko}}\right] \qquad \Delta P^* = \left[\frac{P_i - P_{io}}{P_{io}}\right] \tag{5}$$

$$J_{Ho}^* \approx \left[\frac{\Delta P_i^*}{\Delta H_j^*}\right]_o \qquad J_{Co}^* \approx \left[\frac{\Delta P_i^*}{\Delta C_k^*}\right]_o \tag{6}$$

The mathematical forms of both the normalized selection process and the normalized reduction process in the basic GDR strategy are unchanged using the above groups despite the fact that both the selection and solution results may be significantly altered by the rescaling.

A central difference scheme utilizing ROCETS/MC-1 engine simulation results was employed to approximate all Jacobian components. The standard mathematical form of this approximation is indicated below.

$$J_{Ho\text{-}ij} \approx \frac{P_i(H_{oj}+\delta H_j) - P_i(H_{oj}-\delta H_j)}{2*\delta H_j} \tag{7}$$

In this expression, $P_i(H_{oj}\pm\delta H_j)$ is the ROCETS/MC-1 output value for dependent variable P_i corresponding to an internal measurement with all hardware parameters and input conditions at base state conditions except H_j. Baseline incremented values of the hardware parameter, $H_j = H_{oj}\pm\delta H_j$, are used in the simulation runs that determine values of P_i for the numerator difference. A similar central differencing procedure was used to obtain the control Jacobian elements $J_{Co\text{-}ik}$.

The diagonal weighting matrix **W** provides a means of incorporating information that augments the physical and empirical basis of the parent model. If reliable hardware parameter uncertainty estimates are available, the diagonal components of the weighting matrix afford an effective means of incorporating this information. In this study, the weighting matrix was set equal to the identity matrix for all basic GDR analyses. This is consistent with the parameter normalizations described in equation (5) and effectively assumes the same level of confidence for estimates of all hardware parameters.

The GDR input file accumulates information required for a reduction run including: parameter names and baseline values, parameter normalizing factors, weighting matrix components, normalized hardware and control influences, and other parameter designations that identify the dimension of the reduction problem. In this study, test data was embedded in the GDR input file and processed sequentially, one time slice at a time, to simulate an actual data input stream. For real time processing of test or flight data, preloading of data within the input file would be replaced by an appropriate interface to the data stream.

5.2 MC-1 Engine Test Data

MC-1 engine R2 and R3 test series data for each of the 25 measured quantities identified in Table G2 were used. Data gathered during the first five seconds of operation after engine ignition were not considered in this study in order to reduce the influence of start up transients. One second averaged data over the operating interval from 6 to 23 seconds were used for all tests except R2-4. Test R2-4 was a full duration test of 159 seconds, and one second averaged data over the operating interval from 6 to 158 seconds were used for this test. Data for each measured variable over the operating interval from 6 to 23 seconds for all tests are displayed in Appendix B, Figures B1 through B25. One second averaged data for all seven tests are provided in Appendix H, Tables H1 through H7.

General information describing characteristics of the R2 series test data are presented in Appendix H, Table H8. For a specific test, the characteristic increase (or decrease) in a measured parameter that occurred during the 17 second test interval from 6 to 23 seconds was computed by determining the slope of the best fit line relating the measured parameter to time; multiplying this result by the 17 second interval length; and then dividing by the test baseline value of the parameter. The result is a characteristic increase expressed as a percentage of the baseline value. The five-test average increase (or decrease) computed in this fashion is presented in Table H8. These values indicate the magnitude and direction of data trends over the 17 second interval from 6 to 23 seconds. The absolute values of these trends generally fell in the interval from one to three percent. A significant exception was the inlet LOX pressure which exhibited an average increase of more than 6%.

As mentioned earlier, the same orifice set - number 5 - was used in tests R2-1 and R2-2. For each measured parameter, the absolute value of the difference between the test R2-1 observed value at a given time slice, and the test R2-2 observed value at the same time slice, averaged over all time slices, provides an indication of the normal dispersion of the measured parameter for a constant configuration engine system. Similar dispersion information for a constant configuration engine system using orifice set 6 was obtained by examining data from tests R2-3a and R2-3b. These test-to-test dispersion measures are presented in Table H8 for each measured parameter. The observed differences are caused by inlet condition, hardware function, and measurement system variation. For example, the effects of engine fuel inlet pressure (PSRPFV) variation are clearly mirrored by the fuel pump inlet pressure (PSVL00) difference in the orifice set 5 test sequence R2-1 R2-2. The large difference in turbine discharge temperature (TTHTGD) for the orifice set 5 test sequence was caused by a temperature sensor failure during test R2-1.

The effects of inlet condition variation can be removed by adjusting values of all measured internal parameters for standard conditions, i.e., expected values given baseline inlet conditions and baseline hardware conditions. Using the linearized performance model relations from equation (1), expected values of the measured internal parameters adjusted for standard baseline inlet conditions can be estimated by the relation below.

$$\mathbf{P_{std} = P_{meas} - J_{Co}\,(C_{meas} - C_o)} \qquad \textbf{(8)}$$

Plots of R2 series test data adjusted for standard inlet conditions are shown in Appendix C, Figures C1 through C21. Examination of these plots indicates a significant reduction in the rates of increase (decrease) of most measured internal parameters over the sampled range from 6 to 23 seconds. These rate reductions are confirmed by the average R2 series rise (drop) values for standard inputs shown in Appendix H, Table H9. This suggests that much of the time dependent variation in measured parameters was due to inlet condition variation over the course of the test.

Orifice set 5 average absolute differences for the test sequence R2-1 R2-2 were reduced for all internal measurements adjusted for standard inlet conditions as shown in Table H9. However, orifice set 6 differences, associated with the test sequence R2-3a R2-3b, were generally greater after correction to a standard input state. For each internal measurement parameter, the observed test-to-test average absolute difference after adjustment for standard inlet conditions was caused primarily by hardware function and measurement system variation. The oxygen bleed valve leak that occurred in test R2-3a represents an additional unknown boundary condition variation that impacted orifice set 6 differences.

6.0 Initial GDR Analysis Results

In order to facilitate comparison with accepted reduction results obtained from the parent ROCETS DR model, the same 17 hardware parameters used in the parent reduction process were used in GDR analyses of the MC-1 engine. These 17 parameters have been identified previously and correspond to the unshaded hardware parameters shown in Appendix G, Table G2.

After preprocessing operations were completed, the automated subset selection process was performed to eliminate redundant or ill-scaled measurements, thereby reducing the L_2 condition number of the hardware Jacobian matrix to an acceptable value. In all cases the first four measurements eliminated by the automated selection process were as indicated below.

TTVL05	Fuel manifold temperature
TTVL14	LOX dome temperature
TTHTGD	Turbine discharge temperature
PSVL15	Gas generator oxidizer valve (GGOV) inlet pressure

These were precisely the four measurements eliminated by expert selection prior to ROCETS DR analyses. After elimination of these four measurement variables, the resulting Jacobian condition number was not small enough to guarantee stability. However, basic GDR analyses were run using the 17 remaining internal measurements and 4 inlet measurements to facilitate direct comparison to the accepted ROCETS DR standard.

Typical GDR and ROCETS data reduction results for test R2-1 are displayed in Appendix D, Figures D1-D17. These figures contain both GDR and ROCETS time history data reduction results for each of the 17 selected hardware parameters. Differences between GDR and ROCETS DR results are generally observed to be small over the entire test time interval. The largest differences are associated with the fuel pump inlet line resistance RKFL1 and the gas generator fuel valve area ration XMGGKO.

The difference between GDR and ROCETS DR predictions was computed for each hardware parameter at each one second time slice. Absolute values of these differences were averaged over all time slices in the test interval for each hardware parameter. This information is displayed in Appendix I, Table I1. Average absolute deviations greater than 0.5% of baseline were confined to test R2-1 and test R2-2. This indicates that the basic GDR procedure was capable of providing a consistent approximation of hardware behavior that agrees well with the recognized standard for MC-1 engine data reduction. However, average absolute deviations in excess of one percent for two parameters in each of tests R2-1 and R2-1 plus the large Jacobian condition number were concerns.

It should be noted that the primary motivation for constructing a simplified representation of the performance model is to improve analysis speed to support health monitoring. The basic GDR results for the MC-1 engine were processed at a rate greater than 200 time slice reductions per second on an 800 MHz Pentium III processor. This qualifies the procedure as a real-time analysis tool. There are other advantages to the simplified GDR representation of the engine related to stability and accuracy characterization that are addressed later in this report. The next section documents enhancements considered for the basic GDR procedure, which will henceforth be identified as GDRA, in order to improve computational speed, accuracy, and stability.

7.0 GDR Modifications

Three types of modifications to the basic GDR strategy were explored in efforts to improve the effective solution range of the method as well as the computational speed, accuracy, and stability of the solution process.

Types of GDR modifications

1. Modifications of the subset selection scheme
2. Modifications of the solution procedure
3. Modifications of the problem formulation

Specific changes investigated during the course of this effort are described in the following subsections.

7.1 Solution Procedure Using Singular Value Decomposition

A very efficient procedure for determining the minimum 2-norm solution to a linear system is based on the singular value decomposition (SVD) of the coefficient matrix. This procedure, applied to the balance relations described in equation (1), requires computation of the SVD of the hardware Jacobian matrix. The form of the decomposition is described below [see, e.g. 6].

$$\mathbf{U}^T \mathbf{J}_{Ho} \mathbf{V} = \Sigma \tag{9}$$

where

- **U** is a m×m orthogonal matrix with column partitioning $\mathbf{U} = [\,\mathbf{u}_1 \ldots \mathbf{u}_m\,]$
- **V** is a n×n orthogonal matrix with column partitioning $\mathbf{V} = [\,\mathbf{v}_1 \ldots \mathbf{v}_n\,]$
- Σ = diag($\sigma_1 \ldots \sigma_p$) is the diagonal matrix of singular values σ_i arranged in descending order of magnitude
- p = min(m,n)

Using information from the decomposition, the minimum 2 norm solution to the system

$$\mathbf{J}_{Ho}\, \Delta\mathbf{H} = \mathbf{b} = \Delta\mathbf{P} - \mathbf{J}_{Co}\, \Delta\mathbf{C} \tag{10}$$

can be computed directly using the relation

$$\Delta\mathbf{H} = \sum_{i=1}^{r} \frac{\mathbf{u}_i^T \mathbf{b}}{\sigma_i} \mathbf{v}_i \tag{11}$$

where $r \le p$ is the estimated rank of $\mathbf{J}_{Ho}$.

Equation (11) is obtained using a generalized inverse of the hardware influence matrix to isolate the hardware solution. Once the SVD of the Jacobian $\mathbf{J}_{Ho}$ is computed, hardware solutions may be obtained very quickly from the direct computation of $\Delta\mathbf{H}$ prescribed by equation (11). A version of GDR based on the SVD decomposition procedure described in equations (9) through (11) was implemented and will be referred to as GDRB.

Computational experiments were performed with GDRB to determine efficiency and to assess potential for reducing subset selection overhead. For near rank deficient Jacobians, reduction in the rank estimate r, which corresponds to elimination of near singular directions, can be used instead of parameter elimination to reduce redundancy and scaling problems. This effectively reduces the need for a separate subset selection process. Unfortunately, rank reduction has two significant drawbacks that disqualified it as a subset selection substitute.

1. If a rank estimate $r < p$ is used in equation (11), hardware shifts are no longer a continuous function of the data
2. Realistic single parameter shifts may not be recoverable upon elimination of singular direction(s) implicit with rank reduction.

Because of the computational overhead added to complete the initial SVD, improvements in GDRB reduction cycle speed were negligible for short duration test runs. The average reduction cycle rate for test R2-4 – the full duration test of 159 seconds – was increased by approximately 30%. Coupled with the **QR-Pi** subset selection routine, GDRB reduction solutions were essentially the same as those returned by the basic GDR procedure.

7.2 Partial Second Order Formulation and Solution Procedure

The primary range and accuracy restrictions of the GDR procedure are imposed by the model linearization leading to equation (1). There are many paths available to relax the linear approximation. Perhaps the most direct approach is to incorporate higher order effects in a sequence beginning with second order terms. For a system with 17 defining hardware parameters, there are 153 distinct second order terms – 136 covariant terms and 17 second order terms of the form $(\Delta H_j)^2$. If component hardware performance parameters are defined such that there is little interaction between the parameters, i.e., the performance parameters are independent, then the covariant terms are negligible.

Although the hardware parameters used for MC-1 engine reduction analyses were not strictly independent, a second order extension of GDR adding only terms of the form $(\Delta H_j)^2$ was implemented and tested. This extension, designated GDRC, used the approximate second order balance relations below to define the reduction solution.

$$\Delta\mathbf{P} \approx \mathbf{J}_{\mathbf{Ho}}\,\Delta\mathbf{H} + \mathbf{J}_{\mathbf{Co}}\,\Delta\mathbf{C} + \frac{1}{2}\,\mathbf{D}_{\mathbf{Ho}}\,\mathbf{diag}(\Delta\mathbf{H})\,\Delta\mathbf{H} + \frac{1}{2}\,\mathbf{D}_{\mathbf{Co}}\,\mathbf{diag}(\Delta\mathbf{C})\,\Delta\mathbf{C} \qquad \mathbf{(12)}$$

where

$$\mathbf{D}_{\mathbf{Ho}} = \left[\frac{\partial^2 P_i}{\partial H_j^{\,2}}\right] \qquad \mathbf{D}_{\mathbf{Co}} = \left[\frac{\partial^2 P_i}{\partial C_k^{\,2}}\right] \qquad \mathbf{(13)}$$

A five point central difference scheme was employed to compute elements of the second order influence matrices $\mathbf{D}_{\mathbf{Ho}}$ and $\mathbf{D}_{\mathbf{Co}}$. The measurement selection process was assumed static – utilizing only the first order hardware Jacobian at the base state in the **QR-Pi** factorization that identified measurements to eliminate. A Newton type iterative method [15] was used to solve balance relations (12) reorganized in the form below.

$$\left[\mathbf{J}_{\mathbf{Ho}} + \frac{1}{2} \mathbf{D}_{\mathbf{Ho}}\, \mathbf{diag}(\Delta\mathbf{H}) \right] \Delta\mathbf{H} \;=\; \Delta\mathbf{P} - \mathbf{J}_{\mathbf{Co}}\, \Delta\mathbf{C} - \frac{1}{2} \mathbf{D}_{\mathbf{Co}}\, \mathbf{diag}(\Delta\mathbf{C})\, \Delta\mathbf{C} \qquad (14)$$

Because deviations from standard DR results returned by GDRA were larger for tests R2-1 and R2-2 (see Appendix I, Table I1), nonlinear GDRC analyses were performed using only R2-1 and R2-2 test data. Comparisons to GDRA results are given in Appendix I, Table I2.

It is obvious from Table I2 that predicted deviations from standard DR results were not consistently improved using the nonlinear GDRC formulation. In addition, the deviation of GDRC predictions from standard DR results for the GG fuel valve area multiplier XMGGKO were significantly greater than those returned by GDRA. Further testing was not performed given the greater computational overhead and lack of significant improvement in solution accuracy.

7.3 Formulation with Hardware Parameter Functions

Modification of the original hardware parameter set was indicated based on the following observations.

1. Influences of the main fuel line calibrating resistance RCALMF were large relative to hardware specific resistances along the main fuel line.
2. Influences of the main oxidizer line calibrating resistance RCALMO were large relative to hardware specific resistances along the main oxidizer line.
3. Shaft friction factor FRICFACT shifts were very large as a percent of baseline at the reduction solution. This indicated that FRICFACT was not well scaled and could artificially dominate a linear systems solution process.
4. All valve area multipliers and injector discharge coefficients were proportional to one over a driving pressure difference squared (i.e., valve XM's and injector CD's $\propto 1/\Delta P^2$). Therefore, pressure dependence on XM's and Cd's is inherently nonlinear.

These observations motivated a revision of the set of hardware parameters used for MC-1 engine reduction analyses as indicated in Table 1 below. The complete set of hardware parameters used in data reduction analyses after incorporating the revisions below is given in Appendix G, Table G5.

Table 1 MC-1 engine revised hardware parameters

Original Hdwe parameter	Modified hdwe parameter	Modified hdwe description	Spanning Pressures
CDGGKI	RGGKI	GG fuel injector equivalent resistance	PSVLO9 - PTHTGI
CDGGOI	RGGOI	GG oxidizer injector equivalent resistance	PSVL18 - PTHTGI
CDKINJ	RKINJ	MCC fuel injector equivalent resistance	PTVL05 - PTMCHY
CDOINJ	ROINJ	MCC LOX injector equivalent resistance	PTVL14 - PTMCHY
XMMCKO and RCALMF	RMMCRP	Main fuel line equivalent resistance	PSVL01 - PTVL05
XMMCOO and RCALMO	RMMCOX	Main LOX line equivalent resistance	PSOXDS - PSVL13
XMGGKO	RMGGRP	GG fuel line equivalent resistance	PSVL01 - PTVL09
XMGGOO	RMGGOX	GG LOX line equivalent resistance	PSVL15 - PSVL18
FRICFACT	PWRFACT	Turbopump power factor	

PWRFACT in the above list can be thought of as the ratio of actual pump shaft delivered power to actual turbine shaft supplied power. It combines the effects of turbine efficiency multiplier, pump torque multipliers, and shaft friction factor such that the following proportionality applies

$$\text{PWRFACT} \propto \frac{\text{1-FRICFACT}}{\text{ETAMHTGT} * \text{(2 pump equivalent torque multiplier)}} \qquad (15)$$

The switch to equivalent resistances is a way of converting the original hardware parameter set to a more natural parameter set composed of linearly independent nonlinear functions of the original parameters. Since resistance is by definition proportional to spanning pressure drop, measured pressures are more naturally represented as linear functions of the equivalent resistances.

In general terms, the data reduction problem with the modified hardware parameters can be represented as follows.

Find $\mathbf{\Delta f(H)}$ such that

$$\mathbf{\Delta P} \approx \mathbf{J_{f(H_o)}\, \Delta f(H)} + \mathbf{J_{C_o}\, \Delta C} \qquad (16)$$

where

$$\mathbf{f(H)} = [\, f_1(\mathbf{H}) \ldots f_n(\mathbf{H})\,]^T \qquad \mathbf{\Delta f(H)} = [\, f_1(\mathbf{H})\text{-}f_1(\mathbf{H_o}) \;.\;.\;.\; f_n(\mathbf{H})\text{-}f_n(\mathbf{H_o})\,]^T \qquad (17)$$

$$\mathbf{J_{f(H_o)}} = \left[\frac{\partial P_i}{\partial f_j(\mathbf{H})}\right]_{\mathbf{o}} \qquad (18)$$

For the MC-1 engine, the functions $\mathbf{f(H)}$ represent the modified hardware parameter set identified in Table G5.

7.3.1 GDRA and ROCETS DR Comparisons

GDRA analyses of the MC-1 engine were performed using the revised hardware parameter set listed in Table G5. The deviation of GDR predicted values from standard ROCETS DR results, converted to display values of the revised hardware parameters, is provided in Appendix I, Table I3. The agreement is observed to be excellent. Over the seven test R2 and R3 series, only the inlet fuel resistance RKFL1 in test R2-1 exhibited an average deviation greater than one percent. Time slice reduction cycles were performed at a rate greater than 200 per second on a system equipped with an 800 MHz Pentium III processor. The accuracy of these reduction results coupled with high cycle speed qualifies the process as a real time monitoring candidate for nominal MC-1 engine operation.

7.3.2 Single Source Anomaly Resolution Capability

In order to assess GDR capability to identify single source anomalies, a series of simulations were performed with single source hardware anomaly input. Simulated test data for each single source anomaly was obtained as output of ROCETS/MC-1 runs with one hardware parameter modified from its baseline value. This data was provided for GDRA reduction analyses to determine if the anomaly would be identified. Results are presented in Appendix E, Figures E1 through E20. Each figure identifies the magnitude of the input anomaly and the distribution of causation allocated by each of ROCETS data reduction and GDRA using simulated test data. Two GDRA results are presented, one that employed the standard 17 measurement set also used to derive ROCETS DR results, and one using only 16 measurements as an example of lost measurement effect on anomaly resolution capability. The additional measurement eliminated for the 16 measurement case was the LOX GG inlet temperature TTVL18.

High fidelity anomaly recovery is generally observed. The following comments address specific characteristics of the simulation results.

1. Figure E13. A fuel pump torque multiplier (TRQMKPMP) anomaly reduction is recovered as a clearly identifiable power factor (PWRFACT) increase by all reduction procedures. This is consistent with the definition of power factor.
2. Figure E16. Same comments as number 1 for a turbine efficiency multiplier (ETAMHTGT) reduction.
3. Figure E20. LOX inlet duct heat transfer (QDOTVL18) shift was not recovered by GDRA using 16 measurements. This is because the GG LOX inlet duct temperature TTVL18 is a direct indicator of duct heat transfer. When this measurement is lost, the ability to identify heat transfer rate is also lost. This is an example of a very specific loss of discrimination effect. Other effects of TTVL18 measurement loss on anomaly resolution capability are negligible.
4. Figure E14. An oxygen pump torque multiplier (TRQMOPMP) reduction was allocated as various effects: a main oxygen line equivalent resistance (RMMCOX) increase, a gas generator oxygen line equivalent resistance increase (RMGGOX), and a power factor (PWRFACT) increase by all reduction methods, and a LOX duct heat transfer (QDOTVL18) reduction by both ROCETS DR and GDR using 17 measurements. This was the only case in which no reduction procedure, including the parent ROCETS DR procedure, could allocate a single source anomaly to a single predominant reduction

parameter. This indicates a need to modify the measurement suite and/or the parent performance model to allow clear identification of anomaly operation.

It should be noted that shifts in both the fuel pump torque multiplier (TRQMKPMP) and the turbine efficiency multiplier (ETAMHTGT) have a clear power factor (PWRFACT) signature. This suggests that shifts in these parameters can be detected but not discriminated using the revised reduction parameter set. The oxygen pump torque multiplier (TRQMOPMP) is the only parameter that did not have a clear anomaly signature.

7.3.3 Sensor Failure Response

A study was performed to determine the effects of single sensor failures on reduction analysis predictions using the revised set of hardware parameters. GDRA solutions with individual sensors eliminated were obtained and compared to standard ROCETS DR results using all 17 measurements. Results using test R2-4 data are reported in Appendix I, Table I4, in the form of average absolute deviations from ROCETS DR results as a percentage of baseline hardware parameter value.

In each column of Table I4, measurements eliminated by subset selection are identified in addition to the measurement eliminated to simulate sensor failure. Hardware parameters with deviations in excess of 2% are identified as unreliable with the indicated sensor failure. Parameters with deviations between 1% and 2% are identified as only marginally reliable with the indicated sensor failure. Results indicate that the total LOX flow (WOXTOTL) and the turbine inlet temperature (TTHTGI) are the most critical for reduction accuracy.

7.3.4 Results with Flight Measurement Suite

Only five internal measurements in addition to the four inlet measurements were planned for MC-1 flight engines. The flight measurement set is identified in Appendix G, Table G6, and includes one temperature at the turbine inlet (TTHTGI), and four pressures: two pump discharge pressures (PSOXDS and PSVL01), the gas generator pressure (PTHTGI), and the main chamber pressure (PTMCHY). No flow measurements were anticipated for the flight engine.

The candidate hardware parameter set was reduced to 12 by combining resistances between pressure measurements and by eliminating the nozzle discharge coefficient characterized primarily by thrust. The set of candidate hardware parameters for flight data reductions is defined in Table G6.

Three of the flight candidate hardware parameters were further eliminated because relevant temperature measures were not available. These included the two pump torque multipliers (TRQMKPMP and TRQMOPMP) and the turbine efficiency multiplier (ETAMHTGT). GDRA analyses were performed using data from test R2-4 for five internal measurements and four inlet condition measurements to estimate the nine remaining hardware parameters. Results of these analyses are compared to ROCETS DR results with a full suite of 17 measurements in Appendix F, Figures 1 through 9. Summary observations are provided below.

1. Loss of detail discrimination is evident for main fuel line series resistance R3MCRP in Figure F1.

2. Some loss of detail and trending is observed for main oxidizer line series resistance R3MCOX in Figure F2.
3. Little or no resolution loss is observed for GG inlet series resistances R3GGRP in Figure F3 and R3GGOX in Figure F4.
4. Little discrimination loss and only slight tail end trending loss is observed for the fuel pump head coefficient multiplier in Figure F5.
5. Some trending loss is observed for the LOX pump head coefficient multiplier in Figure F6.
6. Very slight trending loss is observed for the power factor term PWRFACT in Figure F7.
7. Some trending loss is observed for the MCC efficiency multiplier in Figure F8.
8. Heat transfer effects QDOTVL18 were not recovered at all as indicated in Figure F9.

Average and maximum absolute deviations of GDRA results, obtained using only flight measurements, from standard ROCETS DR predictions, obtained using a full suite of 17 measurements, are provided in Appendix I, Table I5. Considering the limited measurement input, results were judged to be quite good with only one parameter (QDOTVL18) deviating over 2% from its standard value.

In an attempt to correct some of the detail and trending losses apparent in Figures F1 through F9, fixed LOX and fuel flow rates obtained by averaging flow data over the time interval from 20 to 23 seconds were added to the flight data for reduction analysis. This was intended to simulate the use of best available flow information from acceptance testing. Reduction results obtained using the fixed flow rates are presented in Appendix F, Figures F10 through F18. Summary observations are provided below.

1. Most of the discrimination loss reported for R3MCRP was recovered as shown in Figure F10.
2. Most of the trending loss reported for R3MCOX was recovered as shown in Figure F11.
3. Most of the trending loss reported for PSIMOPMP was recovered as shown in Figure F15.
4. Trending losses were exacerbated for PWRFACT as shown in Figure F16.
5. Most of the trending loss reported for ECSMMCHB was recovered as shown in Figure F17. Detail discrimination was reduced however.
6. No improvement in QDOTVL18 recovery was observed as shown in Figure F18.

Average and maximum absolute deviations of GDRA results, obtained using flight measurements with 20-23 second average flows, from standard ROCETS DR predictions, obtained using a full suite of 17 measurements, are also given in Appendix I, Table I5. With the exception of QDOTVL18, some improvement is evident especially in the standard deviation of the absolute differences. GDRA reduction result using flight measurements augmented with fixed average flows indicative of actual engine operation, such as available from acceptance tests, were evaluated as reasonable for real-time monitoring applications.

7.4 Subset Selection Procedures

One of the key components of the GDR strategy is a parameter selection strategy. Automated parameter subset selection is applied primarily to eliminate measurements and stabilize ill-conditioned underdetermined systems. In the basic GDR method, this is accomplished using a **QR-Pi** factorization of the transpose of the hardware Jacobian matrix. Although heuristic, this method appears to effectively isolate and eliminate measurement redundancy and scaling problems.

Automated hardware parameter selection is inherently more difficult. For robust engine health monitoring, hardware parameters should be selected based primarily on failure/degradation risk and impact. Failure/degradation potential can only be established by examining the experience base of like components and engine systems. Lacking effective estimates, hardware parameter elimination is difficult to justify and can be detrimental if components with significant failure risk are eliminated.

Despite the above observations, two automated procedures for selecting both hardware and measurement variable eliminations were constructed and implemented. One was based on sequential **QR-Pi** factorization of the hardware Jacobian and its transpose. The second was based on sequential condition number reduction. In both cases, the order of hardware and measurement eliminations is user specified.

Computational experience with the dual selection strategies is still limited. Typical results, obtained using the **QR-Pi** dual elimination algorithm to select 5 measurements from the available suite of measurements for the MC-1 engine, are presented in Appendix I, Table I6. The leftmost shaded section of the table displays the flight internal measurement set specified for the MC-1 engine. The remainder of the table presents results of four automated subset selection sequences differing by user specified front-end eliminations and measurement-hardware elimination sequence. Candidate measurement variables, before any elimination, were the 21 MC-1 internal measurements identified in Appendix G, Table G2. Candidate hardware parameters, before any elimination, included only members of the revised hardware set defined in Table G5.

The procedure designated "Auto-Selection 1" in Table I6 was a measurement only elimination sequence beginning with four user defined hardware eliminations and one measurement parameter - engine thrust - elimination. The automated procedure eliminated 15 additional measurements. The five remaining measurements variables were the LOX pump discharge pressure (PSOXDS), the turbine inlet temperature (TTHTGI), both the fuel and LOX total flows (WRPTOTL and WOXTOTL), and the turbine discharge pressure (PTVL22). Only two of the five selected measurements is included in the flight list. There are many possible reasons for this difference that have nothing to do with the mathematical characteristics of the hardware Jacobian. These include a host of practical consideration including cost, ease of installation and maintenance, reliability, life, uncertainty, etc.

"Auto-Selection 2" is another measurement only elimination sequence, but beginning with three user defined eliminations including both propellant flow rates. The selection process identified five measurements from a list that does not include the propellant flows. The five selected measurements include three on the flight list.

"Auto-Selection 3" is a repeated measurement-hardware elimination sequence that selects five measurements and five compatible hardware parameters. The selected measurements are the same as identified in auto-selection 2. The selected hardware parameters include critical turbopump (PSIMKPMP, PSIMOPMP, and PWRFACT), chamber (ECSMMCHB), and gas generator nozzle (CDGGNZ) characteristics.

"Auto-selection 4" is another repeated measurement-hardware elimination sequence that, because of user eliminations, begins with a smaller set of hardware parameters. The parameters selections are similar to those of "Auto-Selection 3" and the reader is referred to Table I6 for detailed information.

It is important to understand that sequential selection procedures do not identify globally optimum subsets in general. This is a major drawback and suggests the need for computational testing to validate the suitability of parameter selections.

The mathematical and statistical literature dealing with subset selection is extensive [see e.g., 6, 15, 16, 17, 18]. A robust selection strategy must incorporate risk and uncertainty information that goes beyond classical analytical considerations of stability. Uncertainty scaling is one natural method of incorporating uncertainty information within the selection procedure; however, the assignment of risk and uncertainty estimates appropriate for MC-1 engine operation was beyond the scope of this effort.

8.0 Summary of Research Effort

The following procedures were developed and implemented during the course of this research effort.

1. An efficient generalized inverse solution procedure based on singular value decomposition of the hardware Jacobian. This solution procedure was incorporated in the code version identified as GDRB.
2. A version of GDR that incorporates a restricted second order approximation model of engine performance and a Newton type solution scheme. This approximation model and solution procedure was incorporated in the code version designated GDRC.
3. A redefined hardware parameter formulation for the MC-1 engine that improves the linear system approximation and a general formulation that characterizes hardware combination schemes
4. Two dual sequential subset selection schemes that identify computationally compatible combinations of hardware parameters and measurement variables for data reduction.

The following GDR performance measures for MC-1 engine system reduction analysis were obtained.

1. GDRA reduction analysis cycle rate >200 cycles per second, GDRB > 250 cycles per second, GDRC > 50 cycles per second
2. Average hardware parameter deviation from full nonlinear parent model data reduction results using full measurement suite and revised hardware list, < 0.5% except for isolated cases (Table I3)
3. Single source anomaly recapture capability with full measurement suite and revised hardware list (based on simulations), >90% of parent model signature with one possible exception (Figures E1 through E20)
4. Qualified integrity of reduction hardware parameter recovery for single sensor losses and identified loss of discrimination parameters for each sensor loss (Table I4)
5. Average deviation of GDRA hardware predictions, using only the flight measurement set, from full nonlinear parent model DR results using full measurement suite, <1% with two exceptions, <2% with one exception (Table I5)

9.0 Assessments and Recommendations

The following assessments are specific for the MC-1 engine system instrumented with the standard measurement suite (Table G2) and GDRA using the revised hardware parameter set (Table G5).

1. Assuming sensor integrity, GDR would be an effective real time monitoring tool for the MC-1 engine system.
2. GDR is capable of detecting and isolating most single source hardware anomalies and should be capable of resolving many multiple source anomalies. GDR cannot identify oxygen pump efficiency anomalies and cannot discriminate between efficiency losses in the turbine or fuel pump.
3. GDR can reliably track the behavior of most hardware parameters in the presence of a single sensor failure if the failure is recognized.
4. GDR can predict nominal trends of flight revised hardware parameters (Table G6) given the five specific internal flight measurements identified in Table G6 and good estimates of engine component propellant flows. Reliable anomaly resolution capability using only the designated flight measurements is unlikely.

The following are general assessments and recommendations based on results of this study.

1. The **QR-Pi** dual subset selection routine developed during this effort provides an effective sequential method of specifying compatible measurement and hardware sets for reduction analyses. It is limited to considerations of scale and redundancy based on information from the best available system model.
2. Significant improvement in selection of appropriate measurements for robust health monitoring will require reliable estimates of both measurement and model uncertainty.
3. If reasonable uncertainty estimates of measurement and model uncertainty are available, GDR should be modified to incorporate uncertainty scaling. This would improve both the subset selection process and the solution procedure.
4. A globally optimum measurement and hardware selection procedure should be developed.
5. The GDR development path is incremental. Reliable extensions will require application to an engine system with a larger controlled operating range.
6. GDR predictions are susceptible to data bias. GDR should be used in conjunction with a reliable sensor qualification algorithm, or a qualification procedure should be incorporated in GDR.
7. A simulation platform to study the effects of noise and measurement uncertainty on prediction reliability should be developed.

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Appendix A

MC-1 engine propellant flow schematics

Figure A1 MC-1 Engine Conceptual Schematic

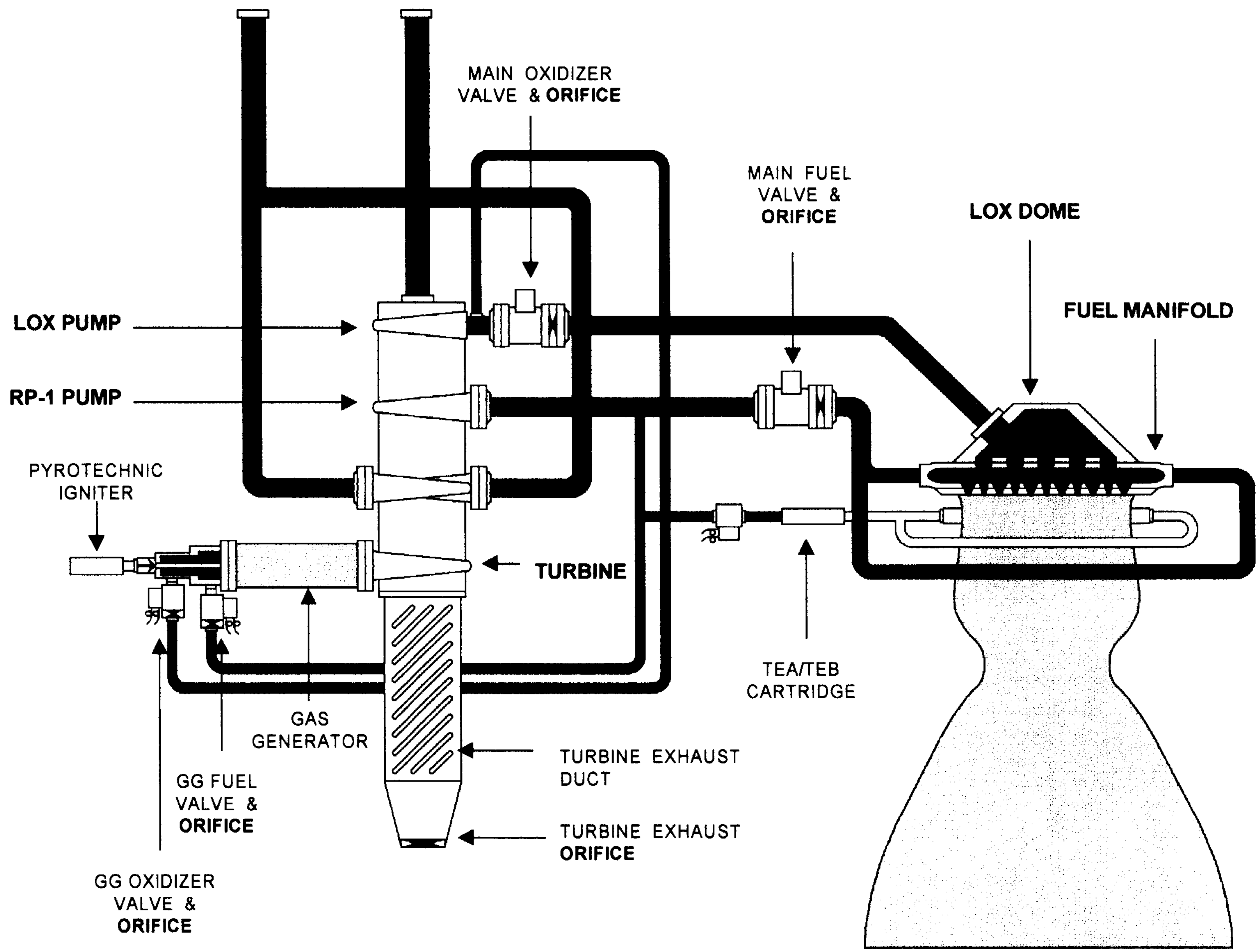


Figure A2   MC-1 Engine Oxygen System

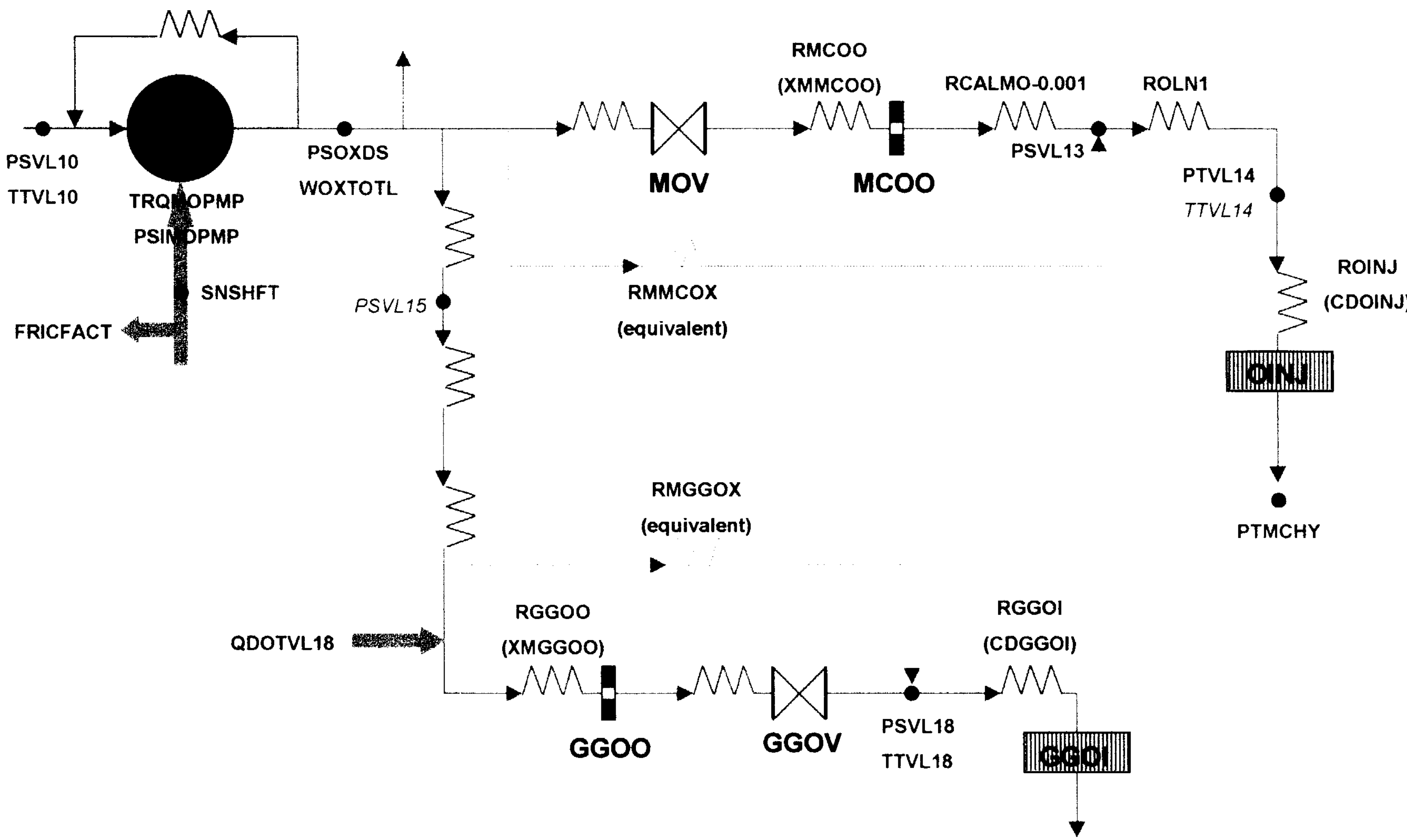


Figure A3 MC-1 Engine Fuel System

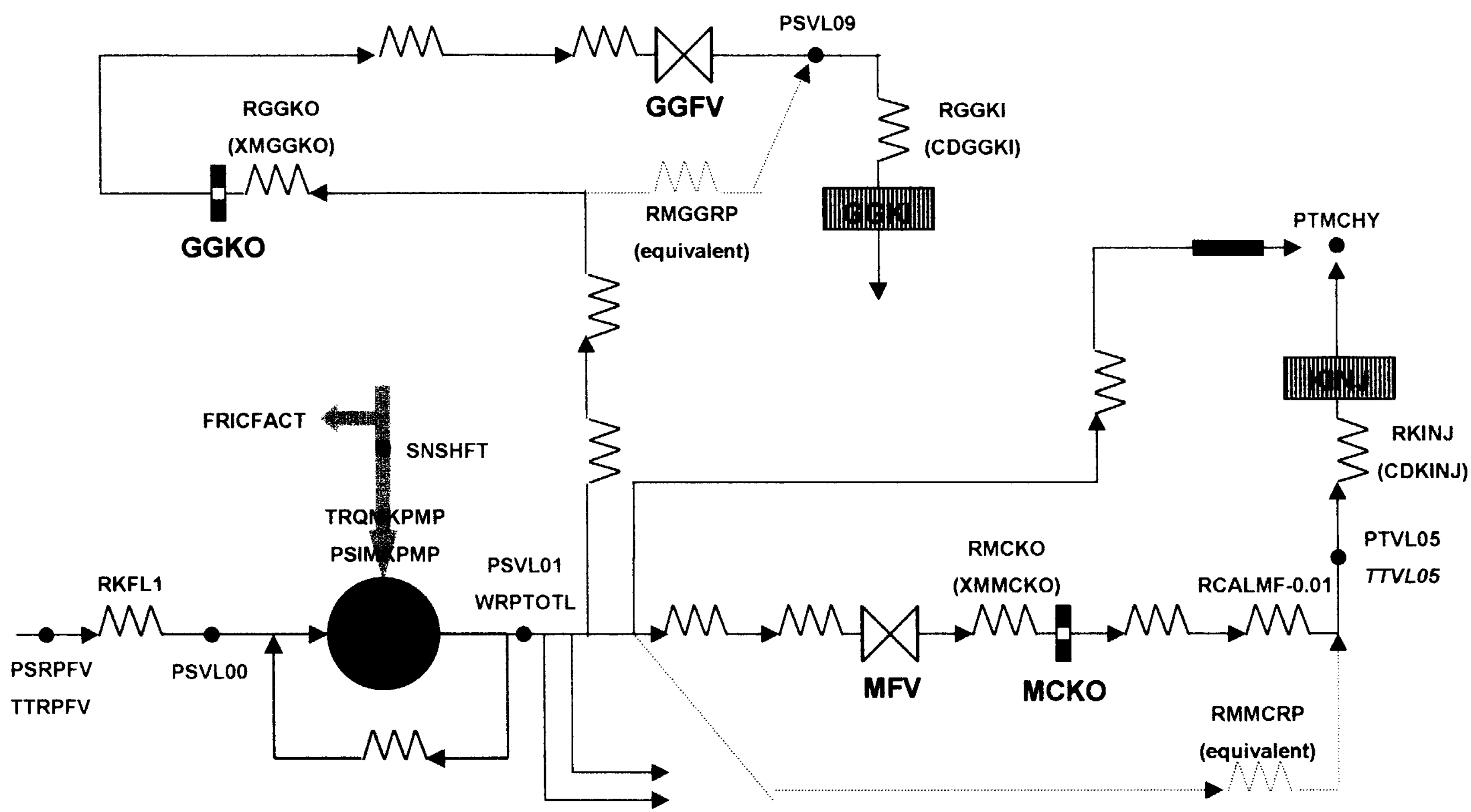


Figure A4 MC-1 Engine GG/Turbine System

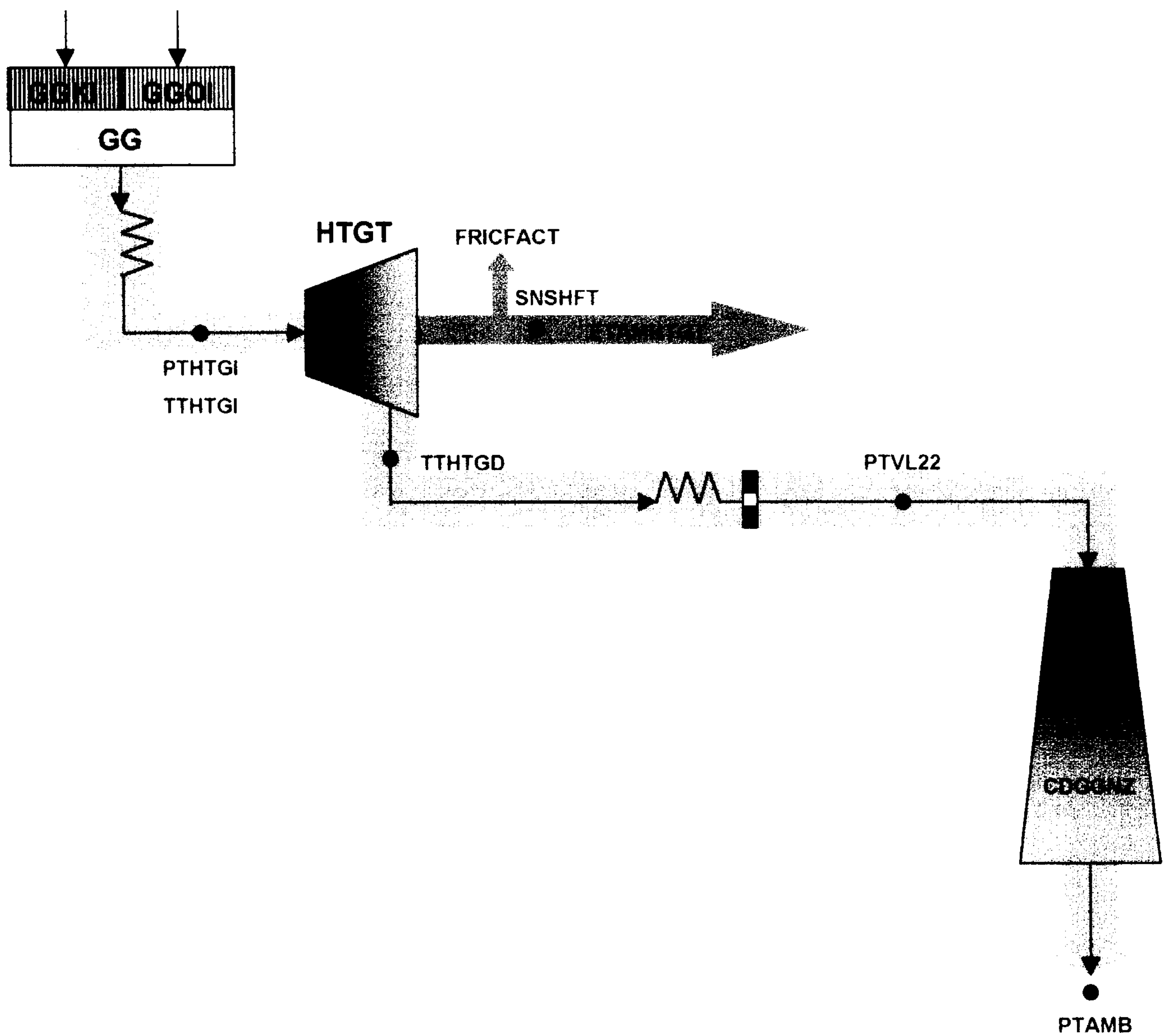
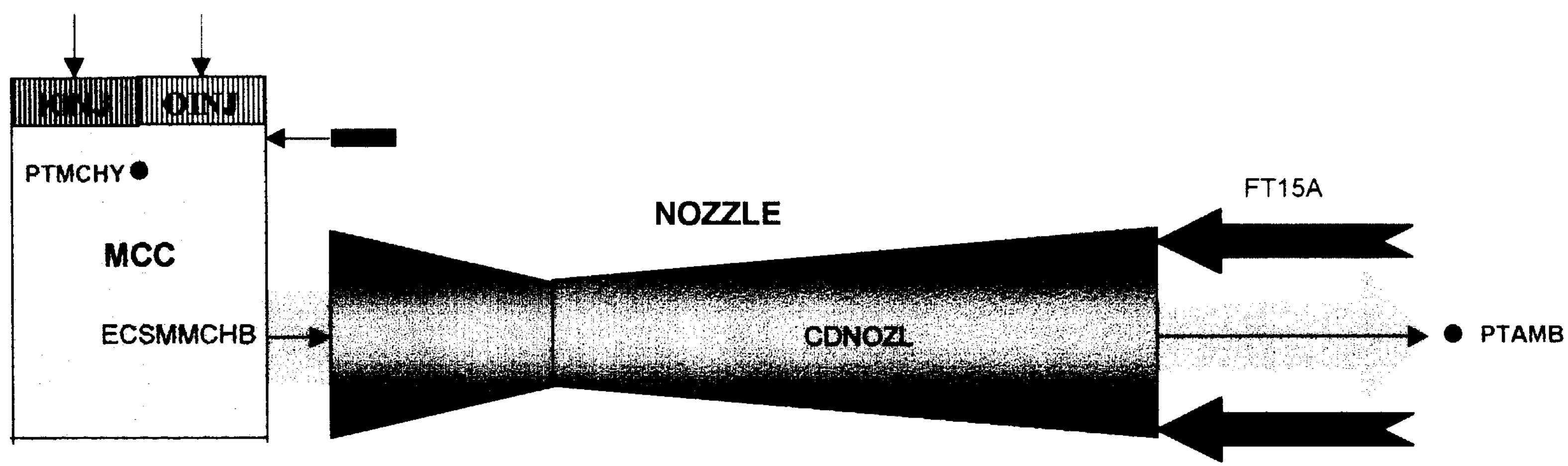


Figure A5 MC-1 Engine MCC/Nozzle System



Appendix B

MC-1 engine
Temporal plots of R2 and R3 test series
One second averaged data

Figure B1 PSVL10 one second average test data

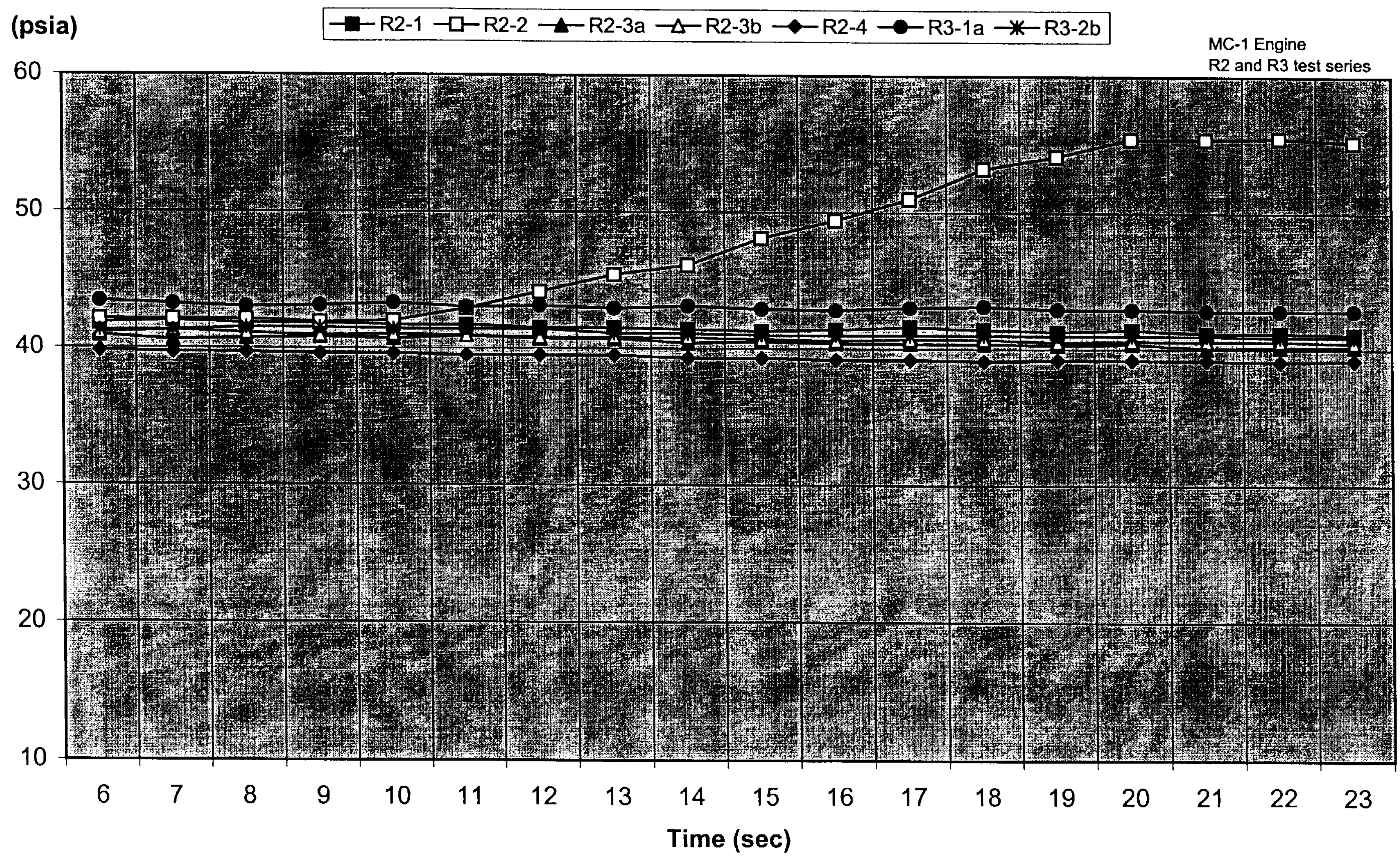


Figure B2 TTVL10 one second average test data

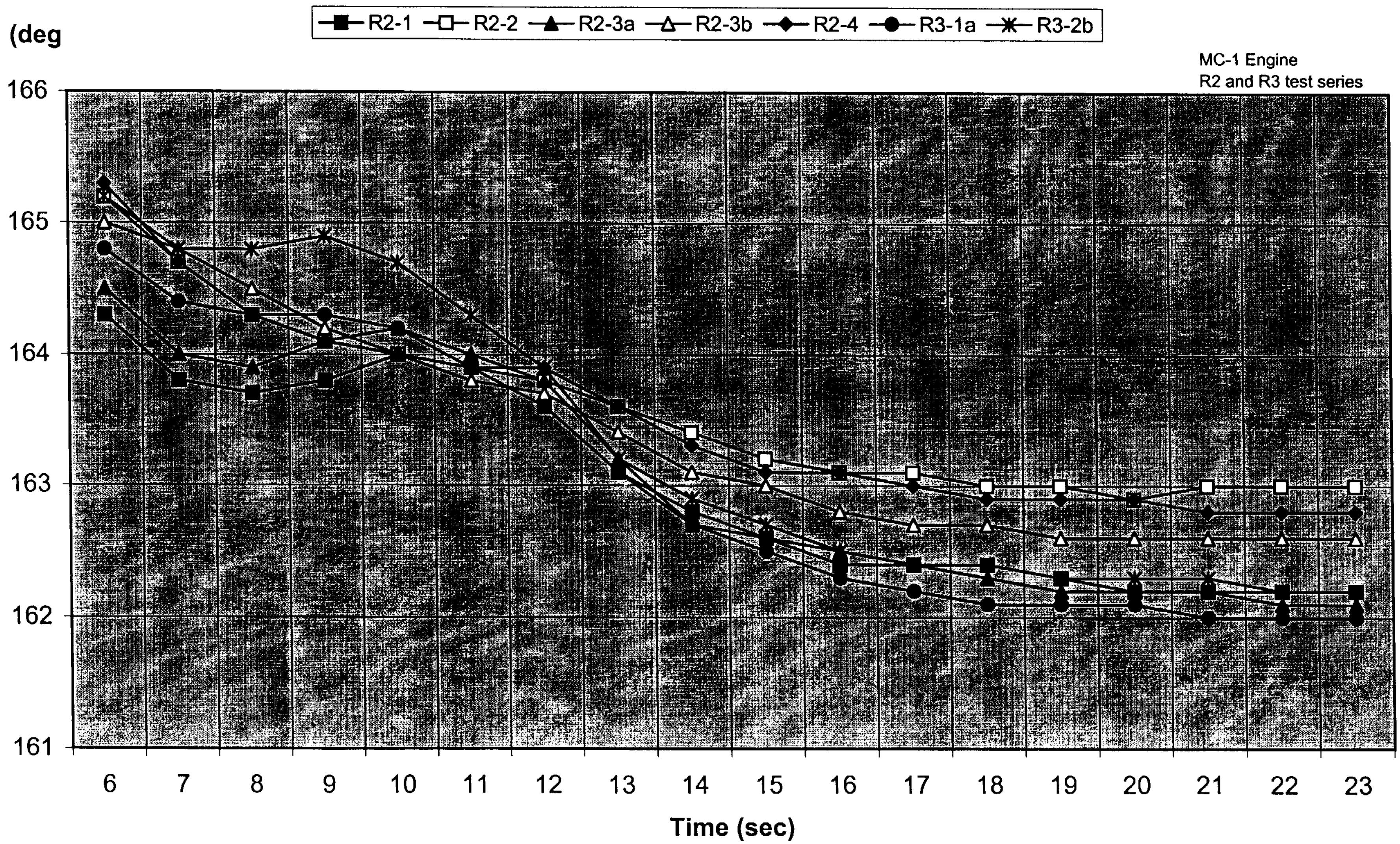


Figure B3 PSRPFV one second average test data

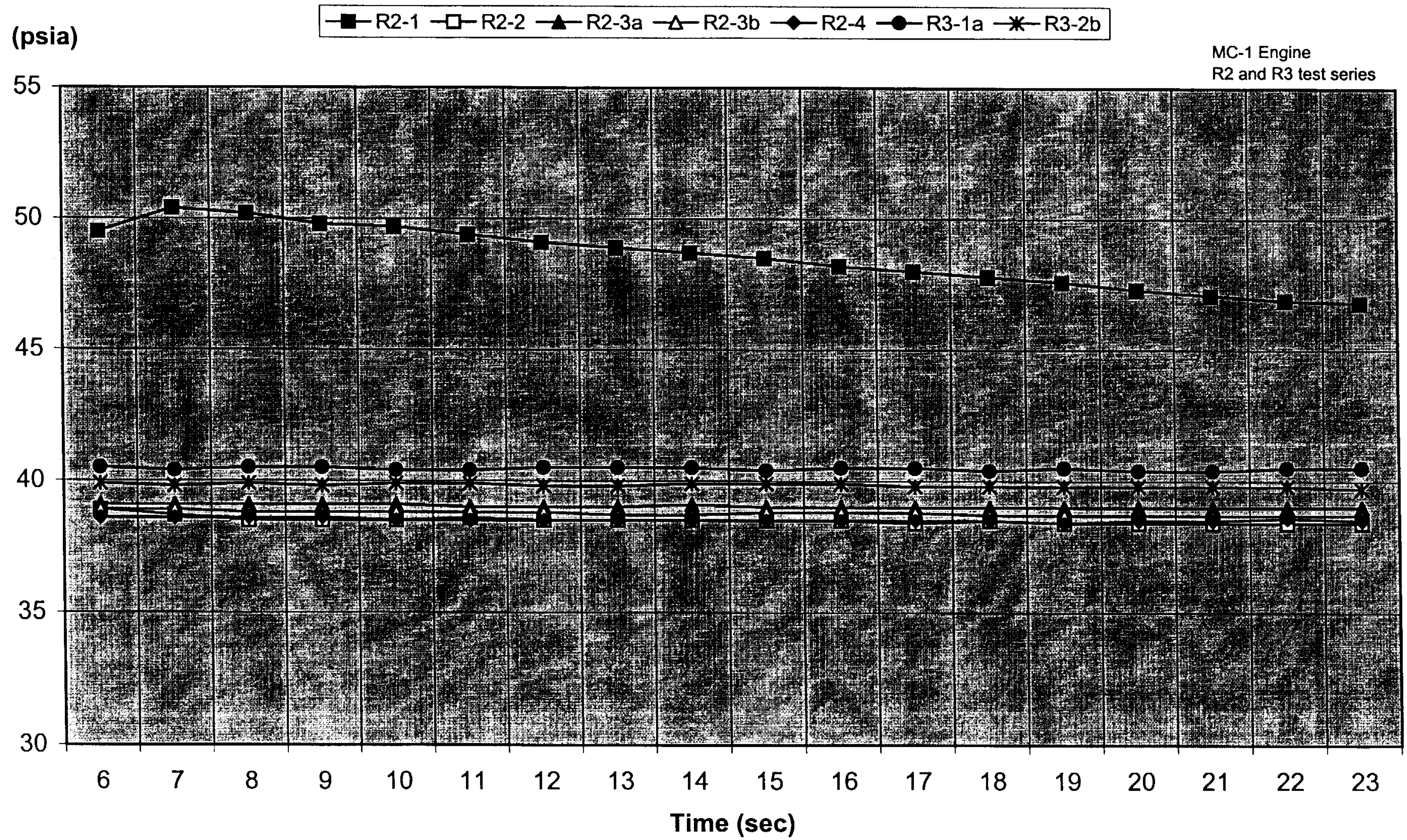


Figure B4 TTRPFV one second average test data

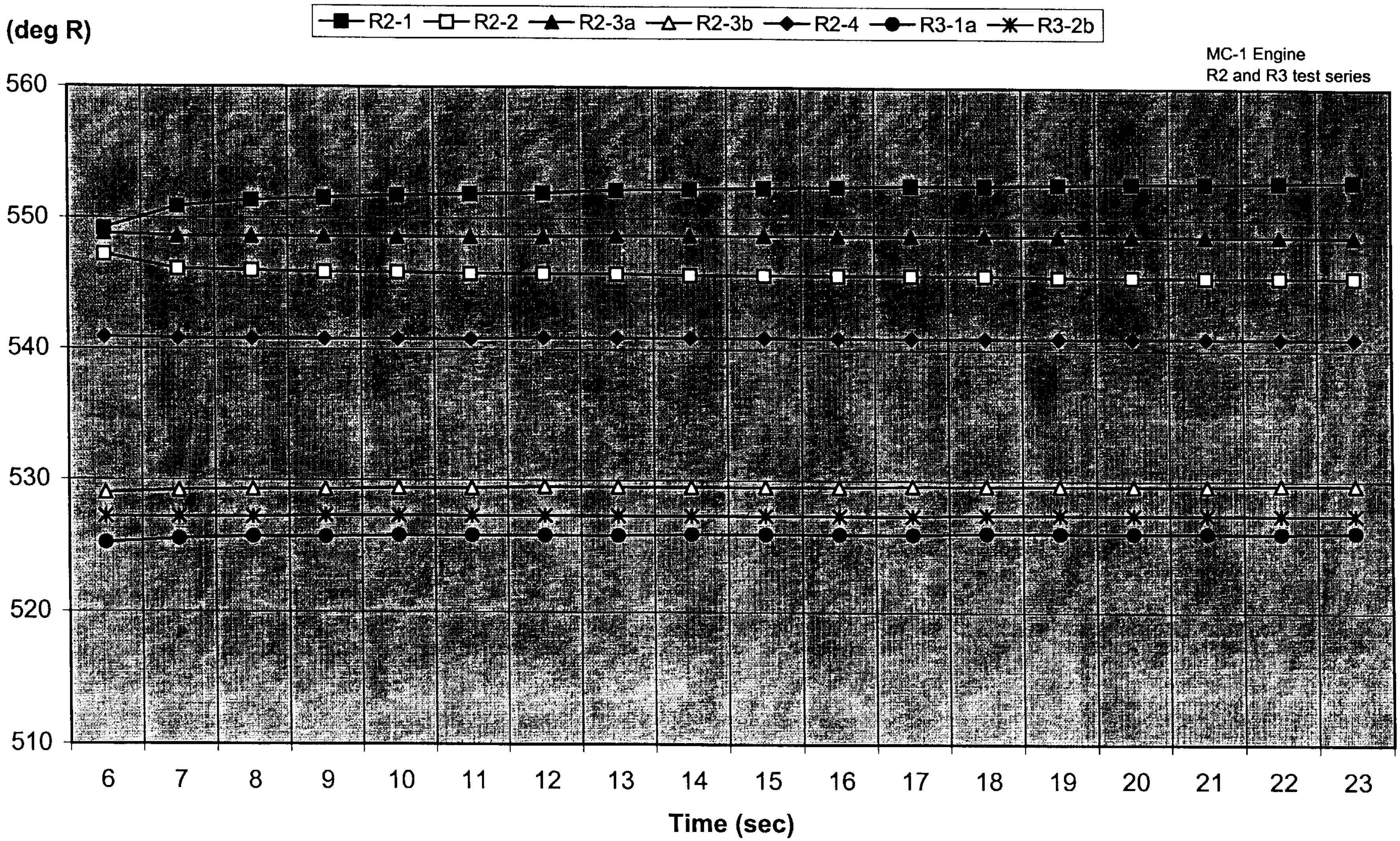


Figure B5 PSOXDS one second average test data

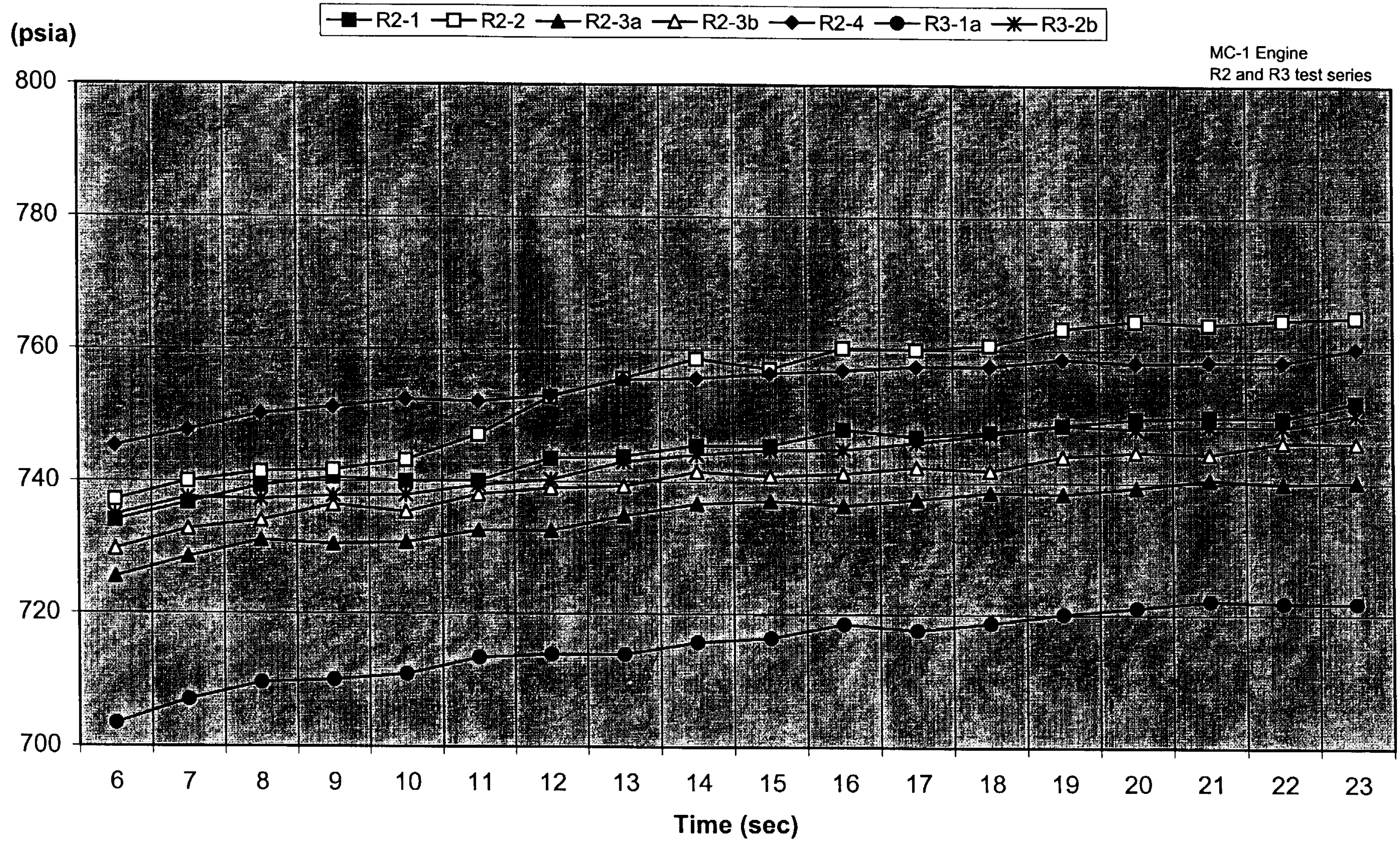


Figure B6 PSVL13 one second average test data

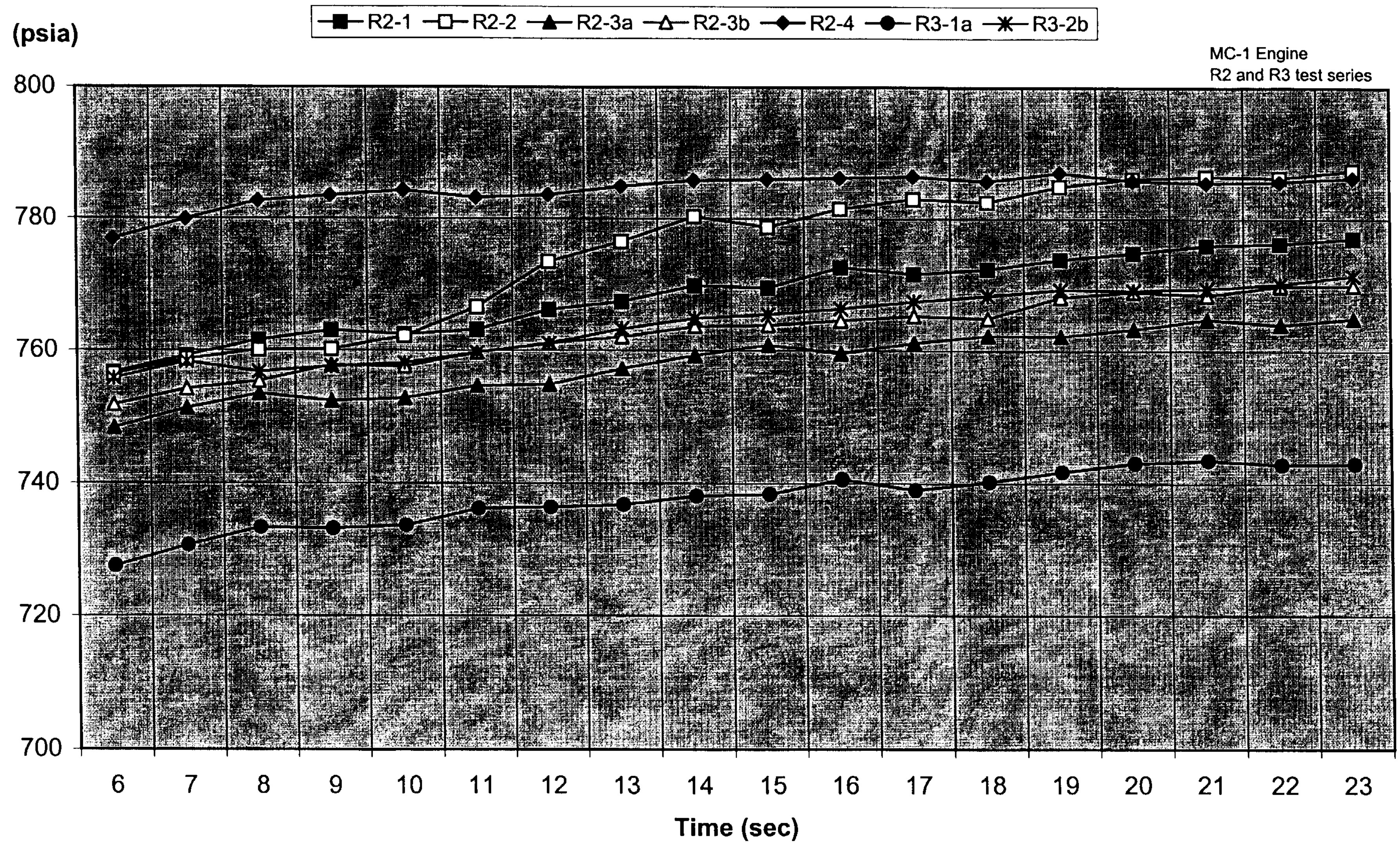


Figure B7 PTVL14 one second average test data

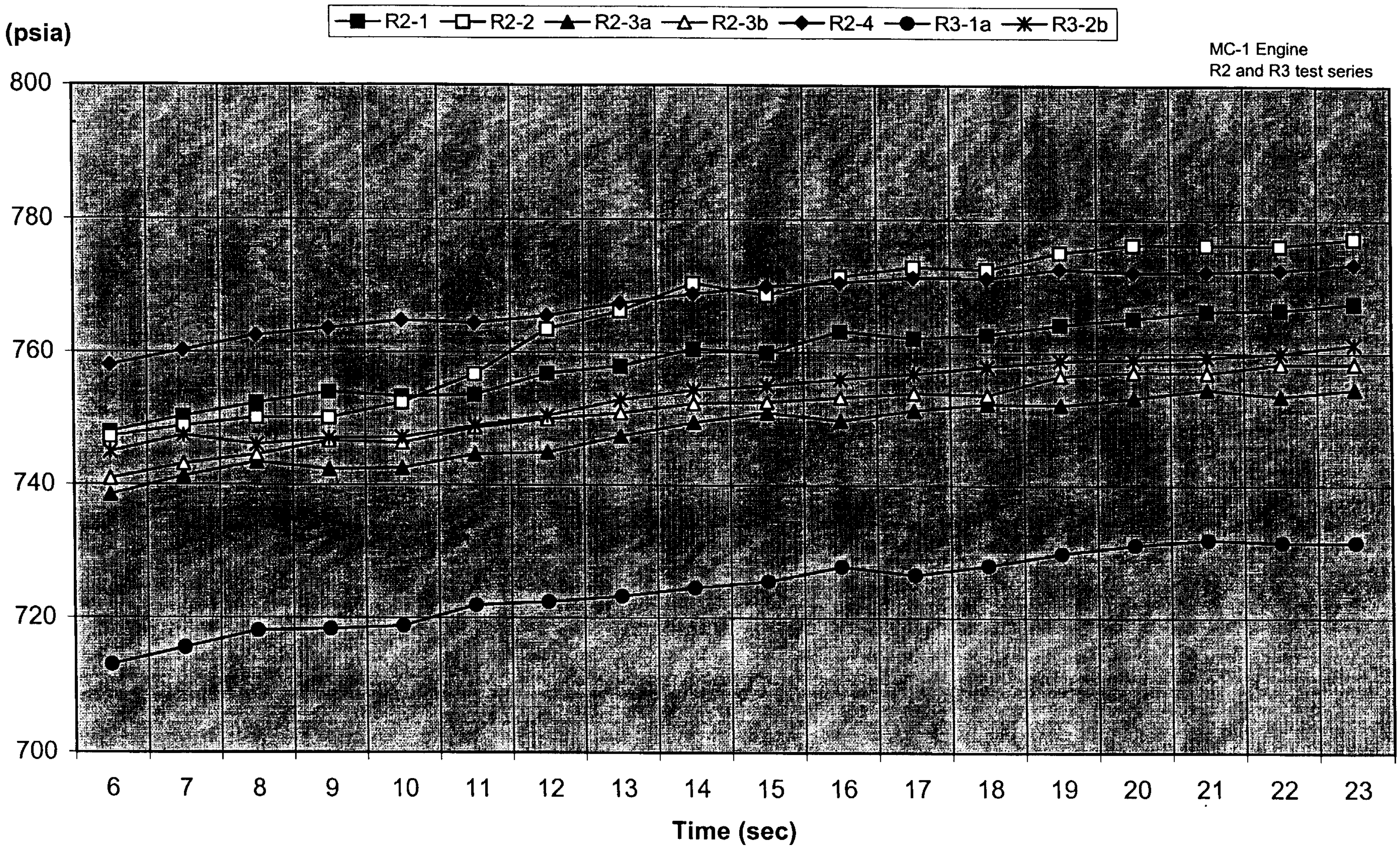


Figure B8 PSVL15 one second average test data

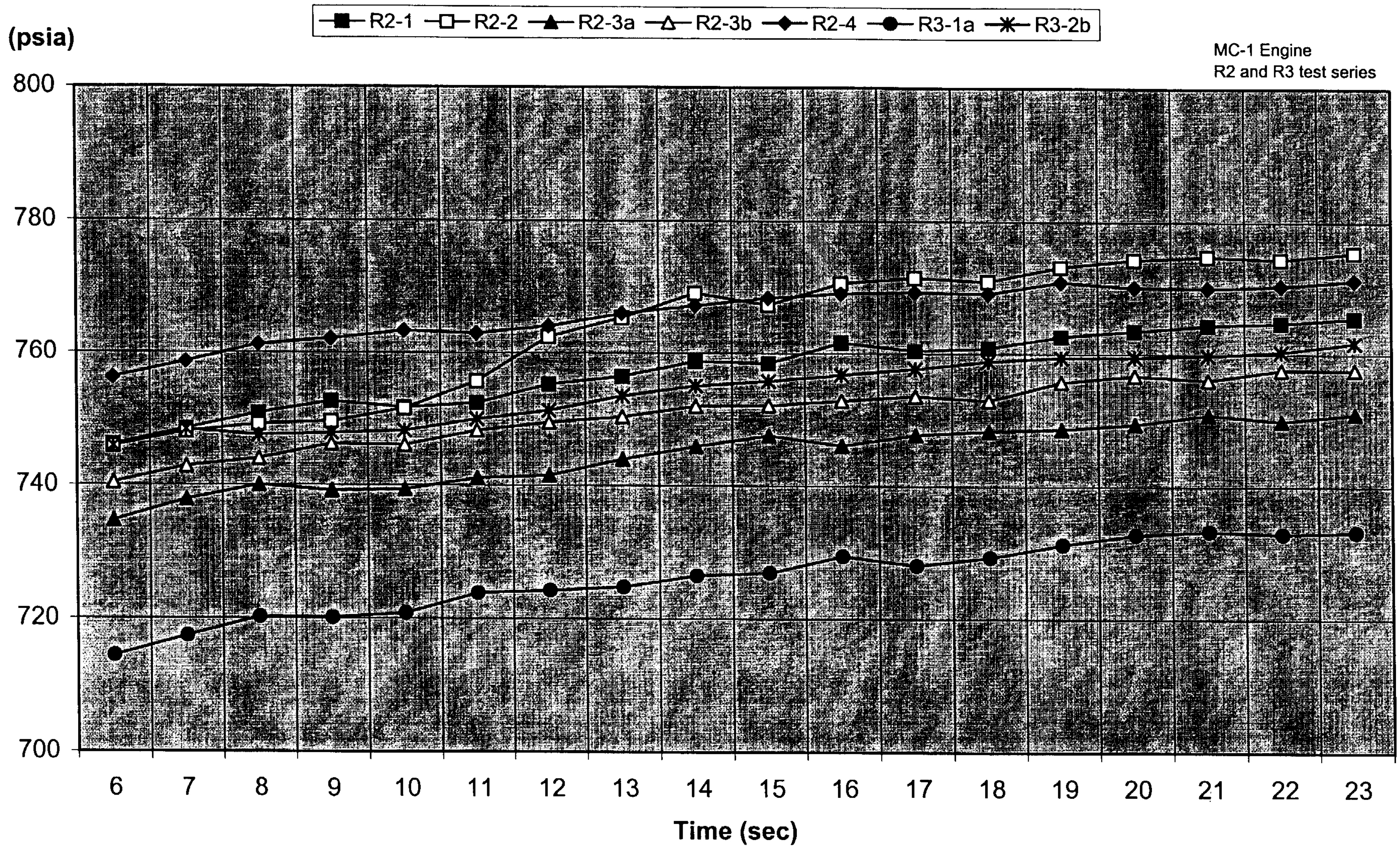


Figure B9 PTVL18 one second average test data

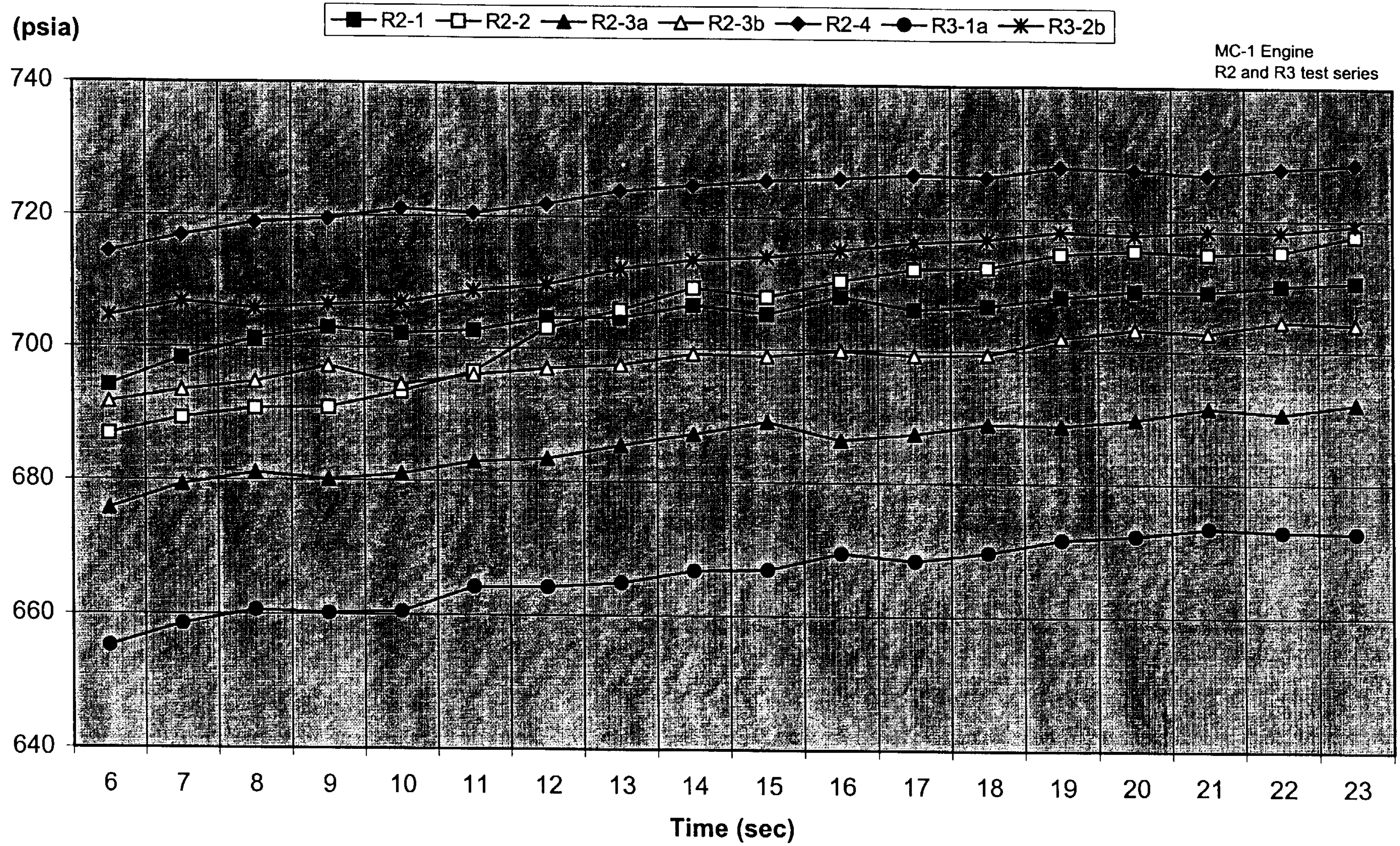


Figure B10 TTVL14 one second average test data

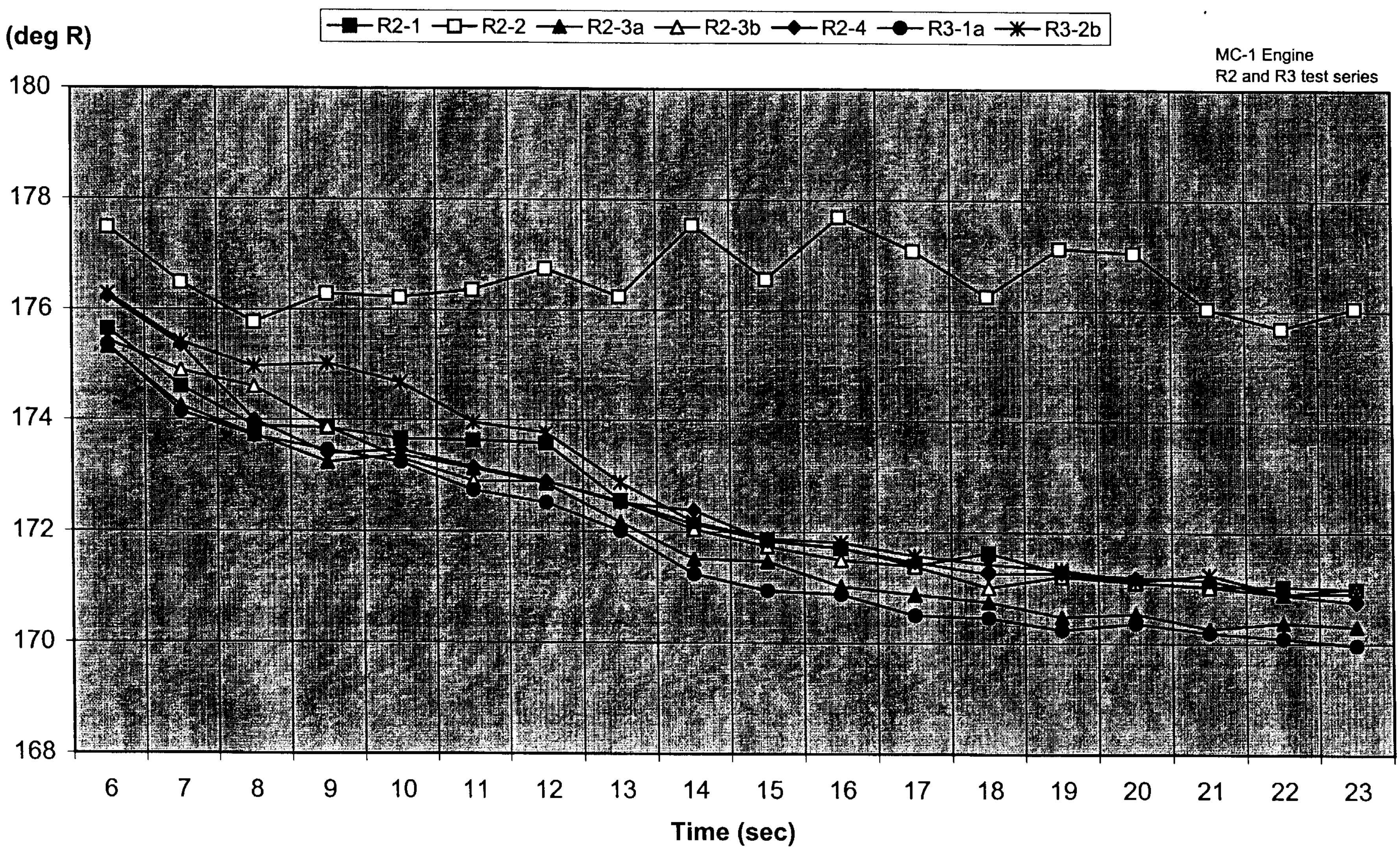


Figure B11 TTVL18 one second average test data

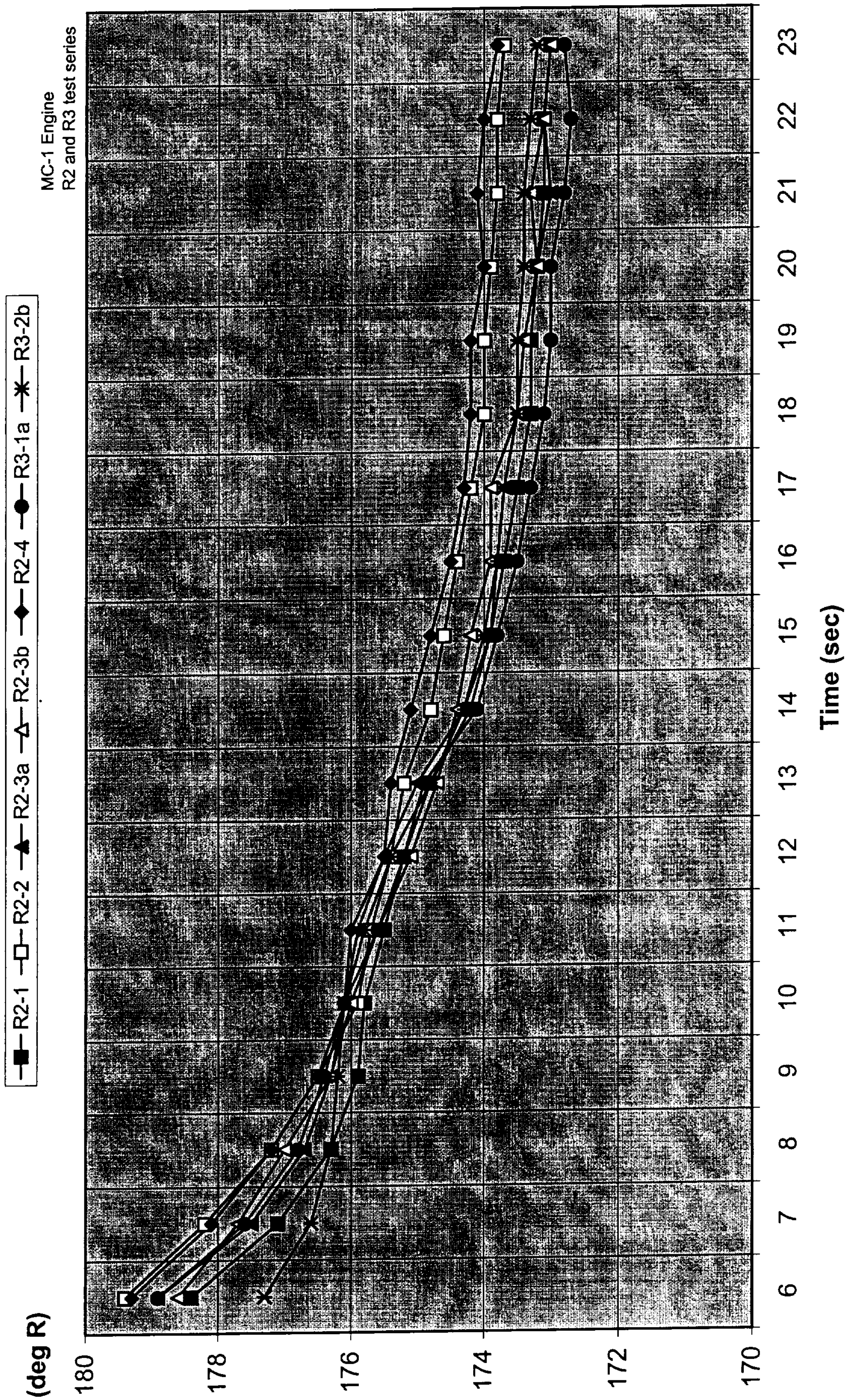


Figure B12 WOXTOTL one second average test data

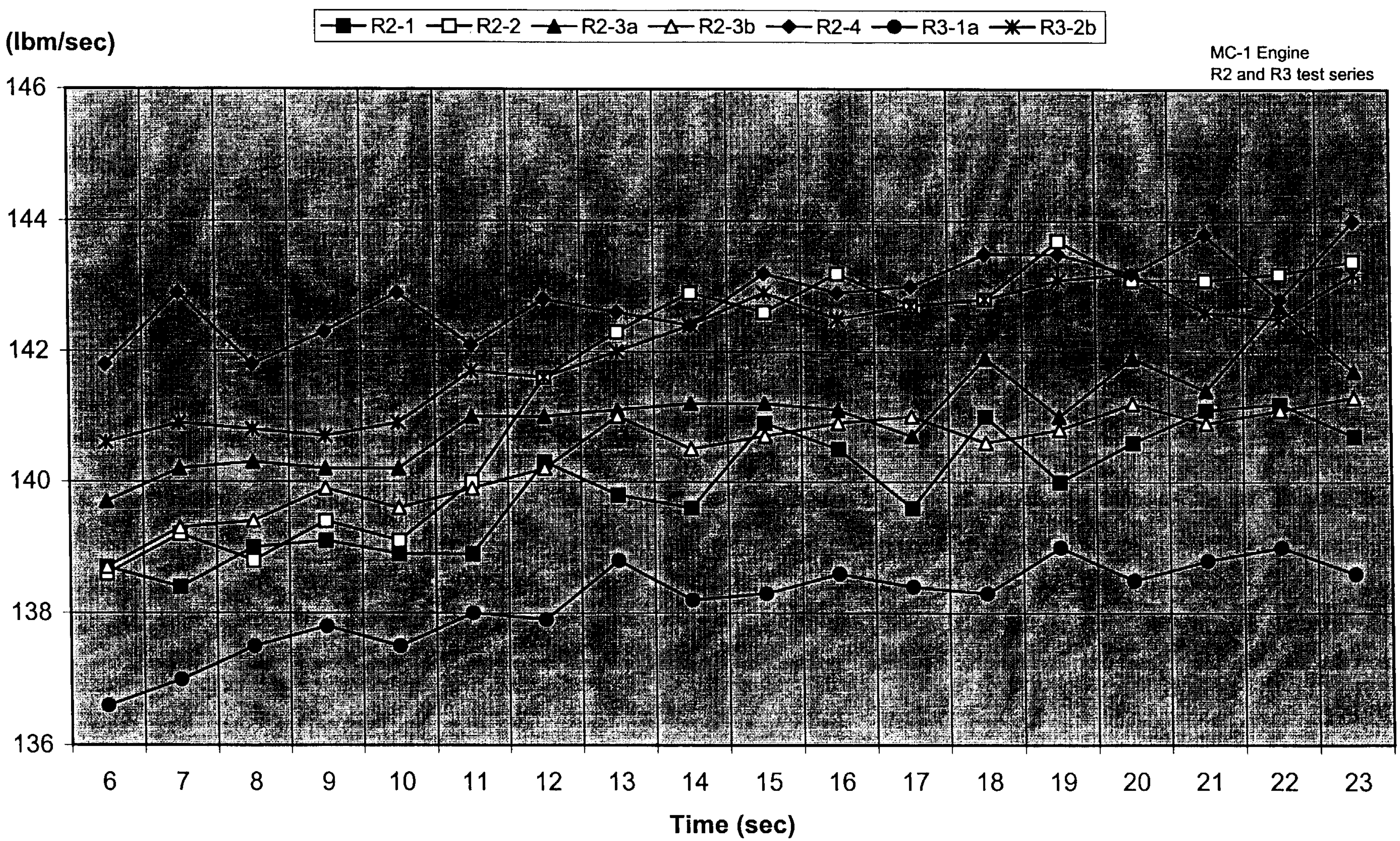


Figure B13 PSVL00 one second average test data

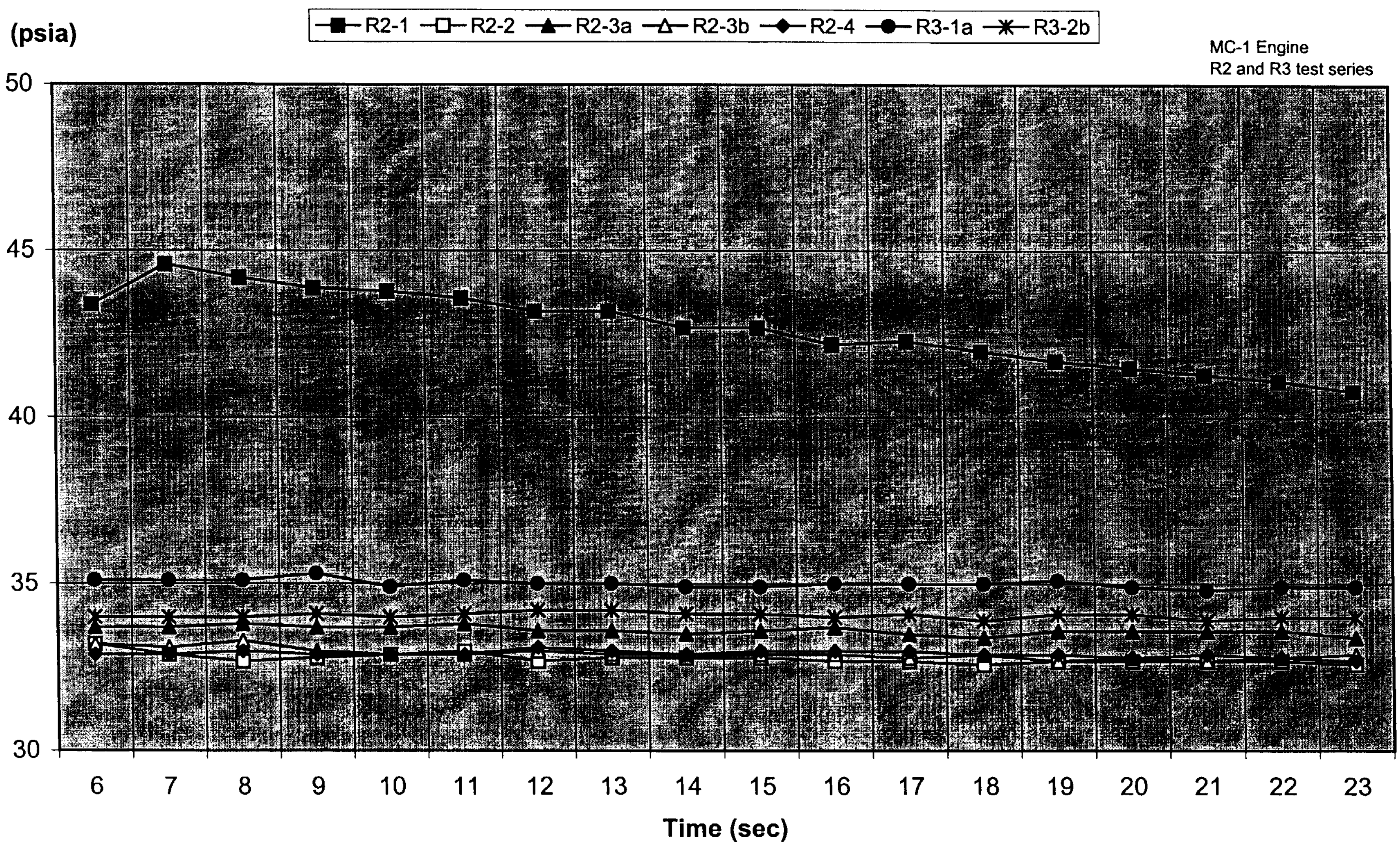


Figure B14 PSVL01 one second average test data

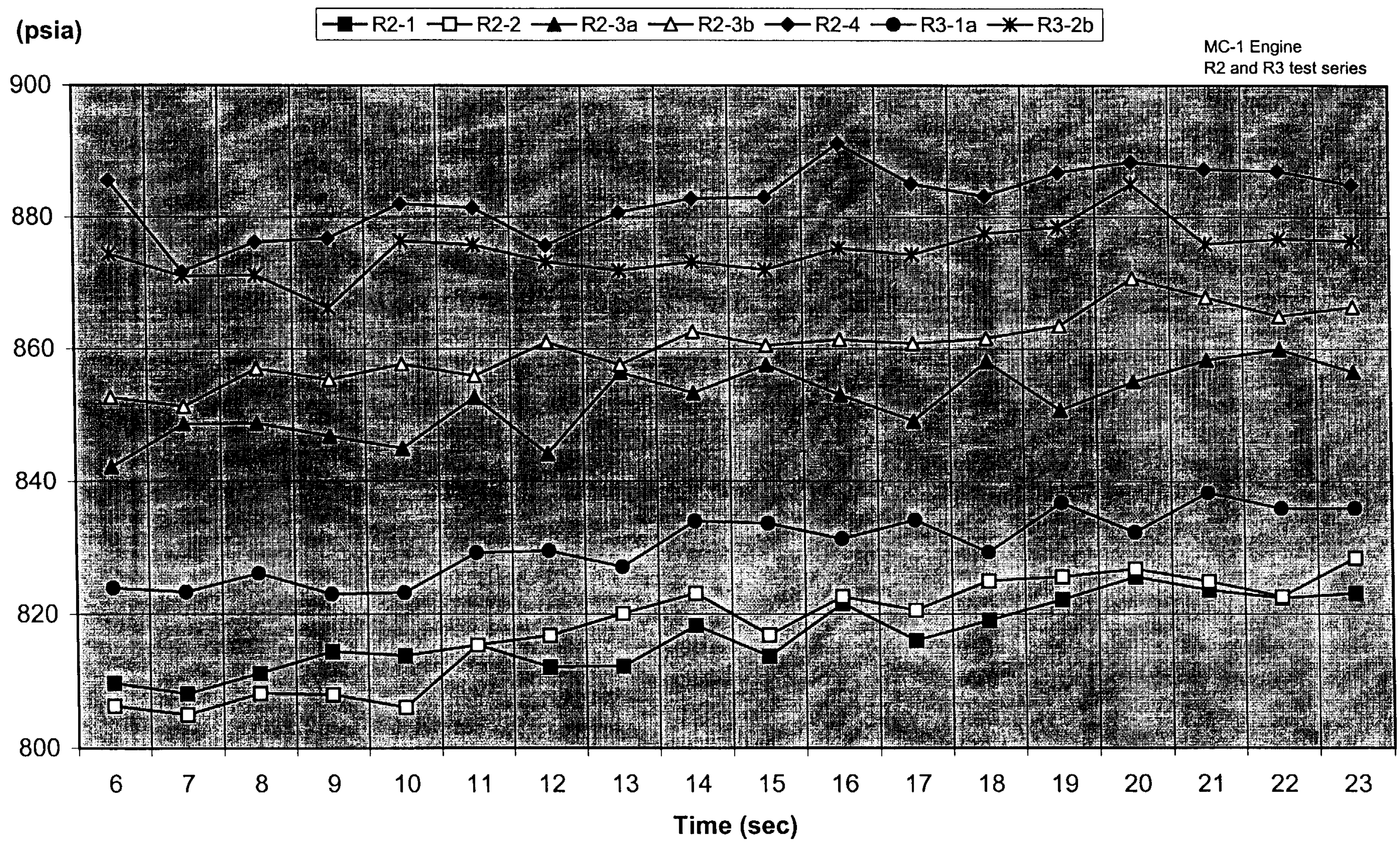


Figure B15 PTVL05 one second average test data

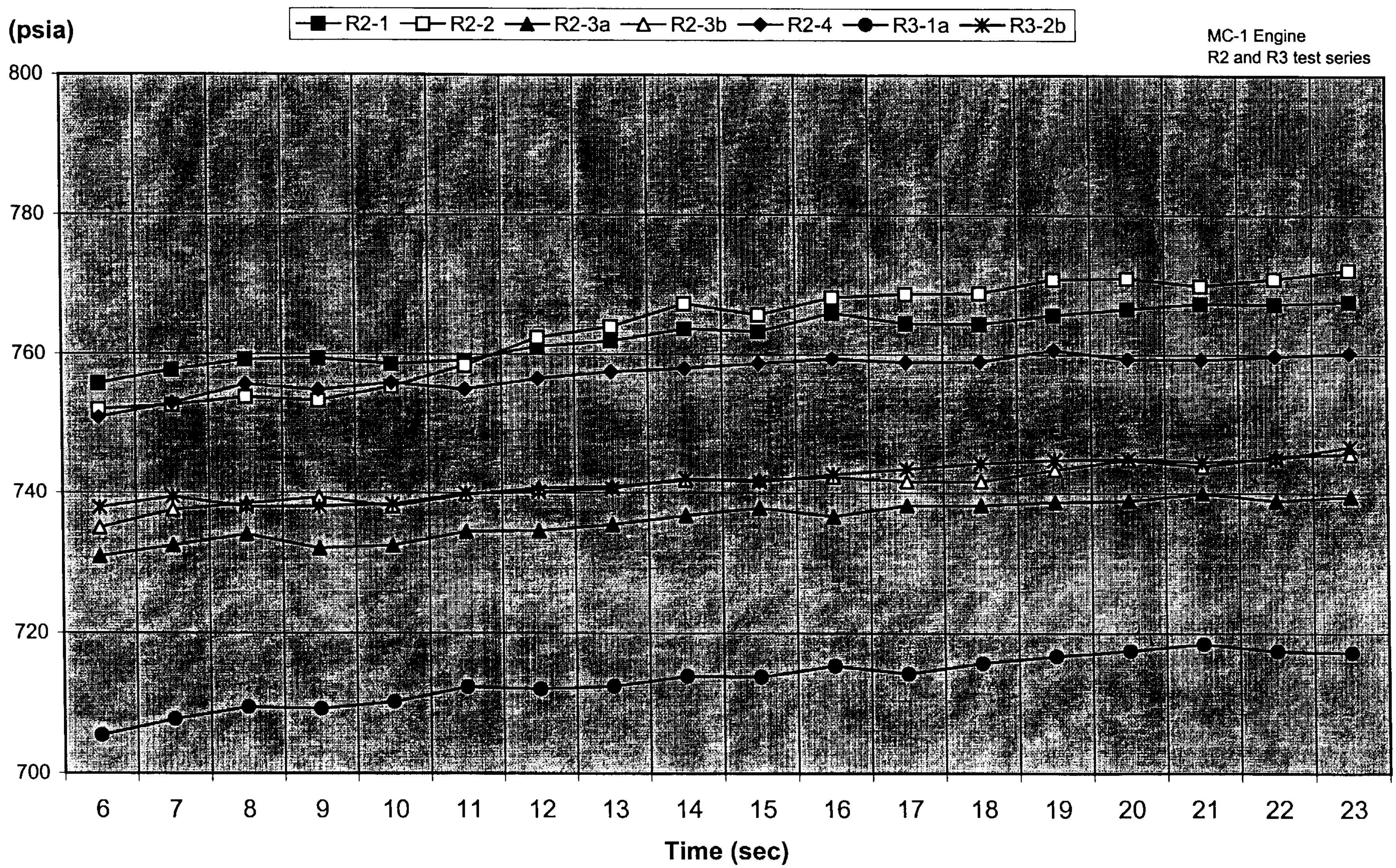


Figure B16 PTVL09 one second average test data

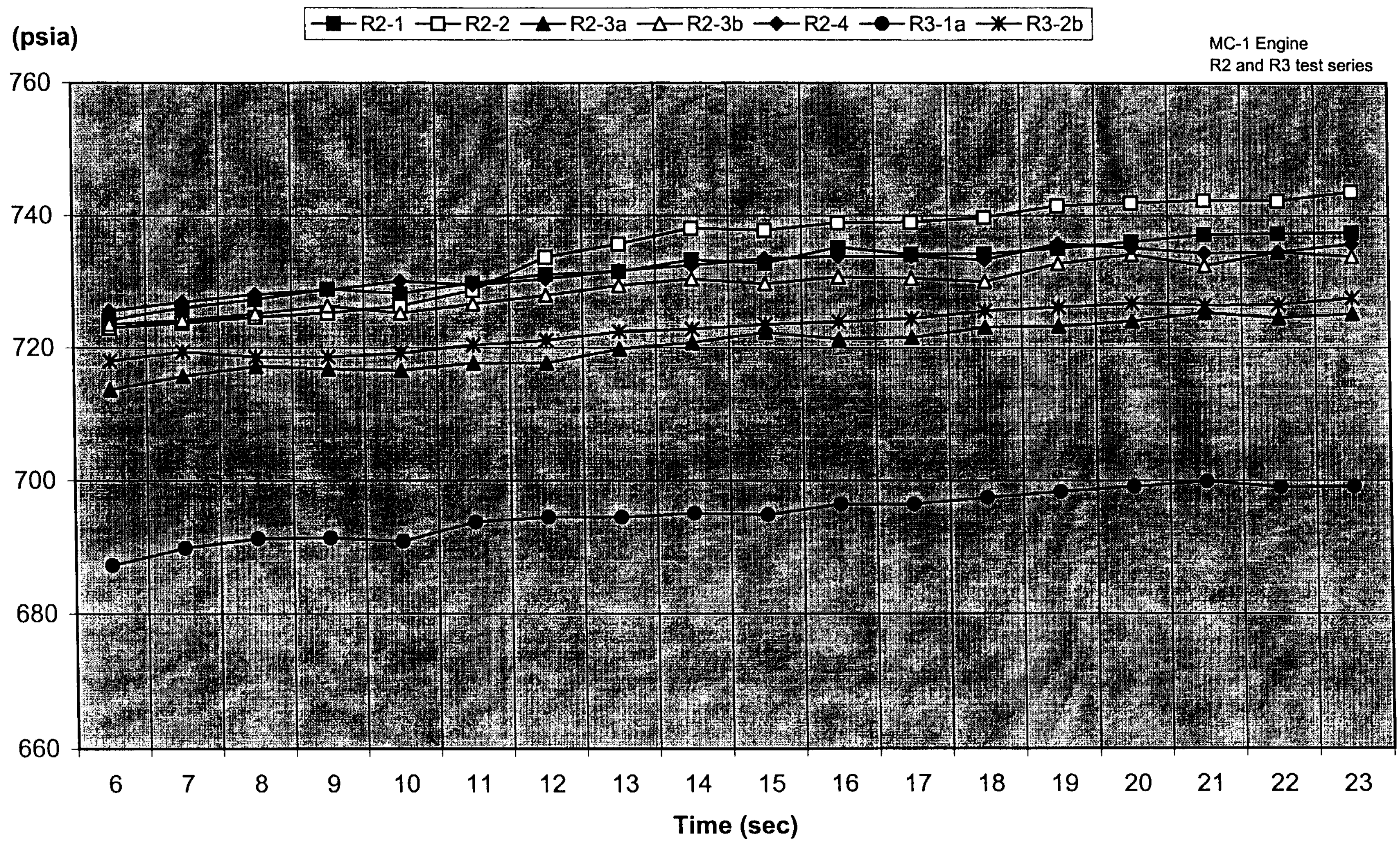


Figure B17   TTVL05 one second average test data

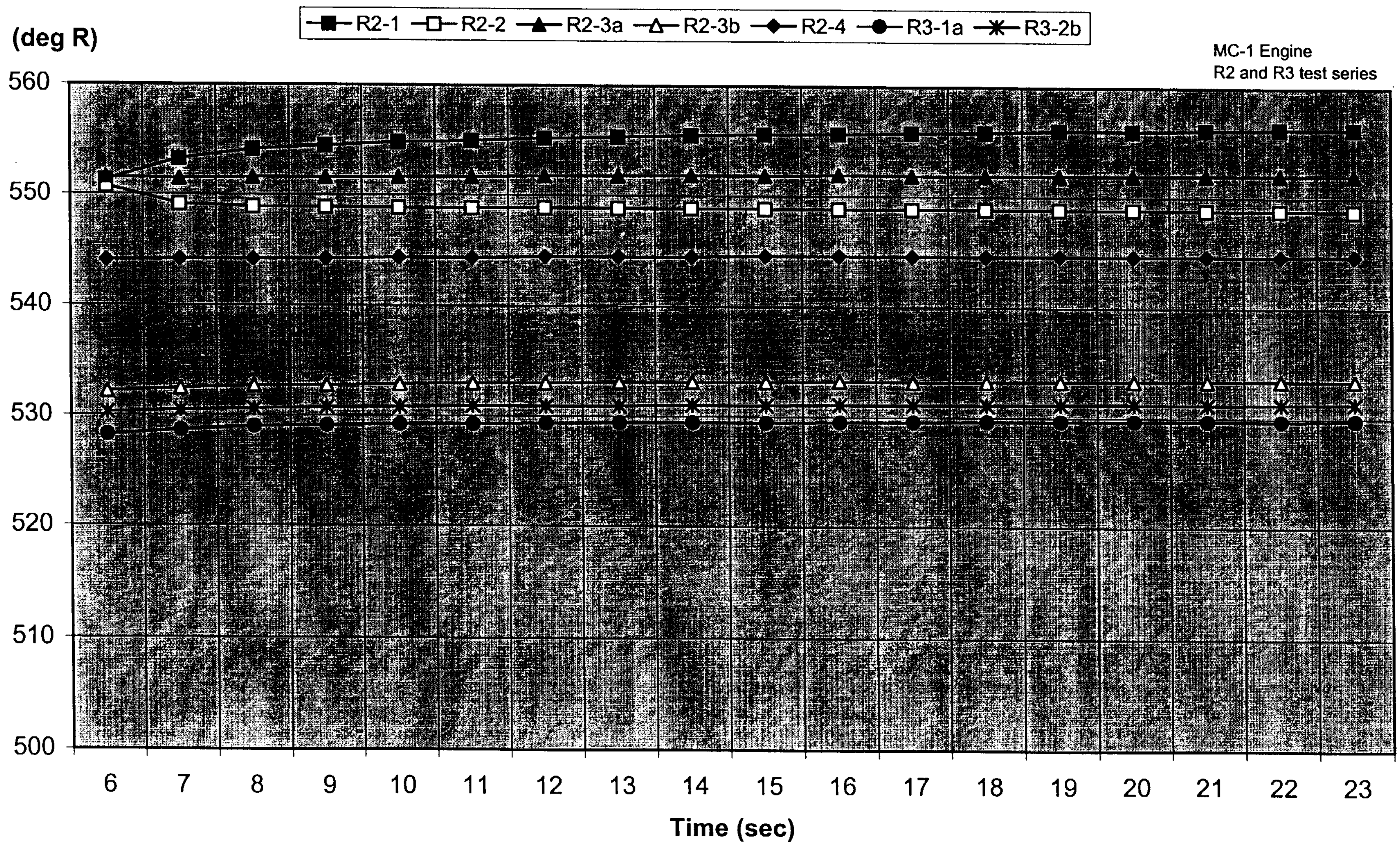


Figure B18 WRPTOTL one second average test data

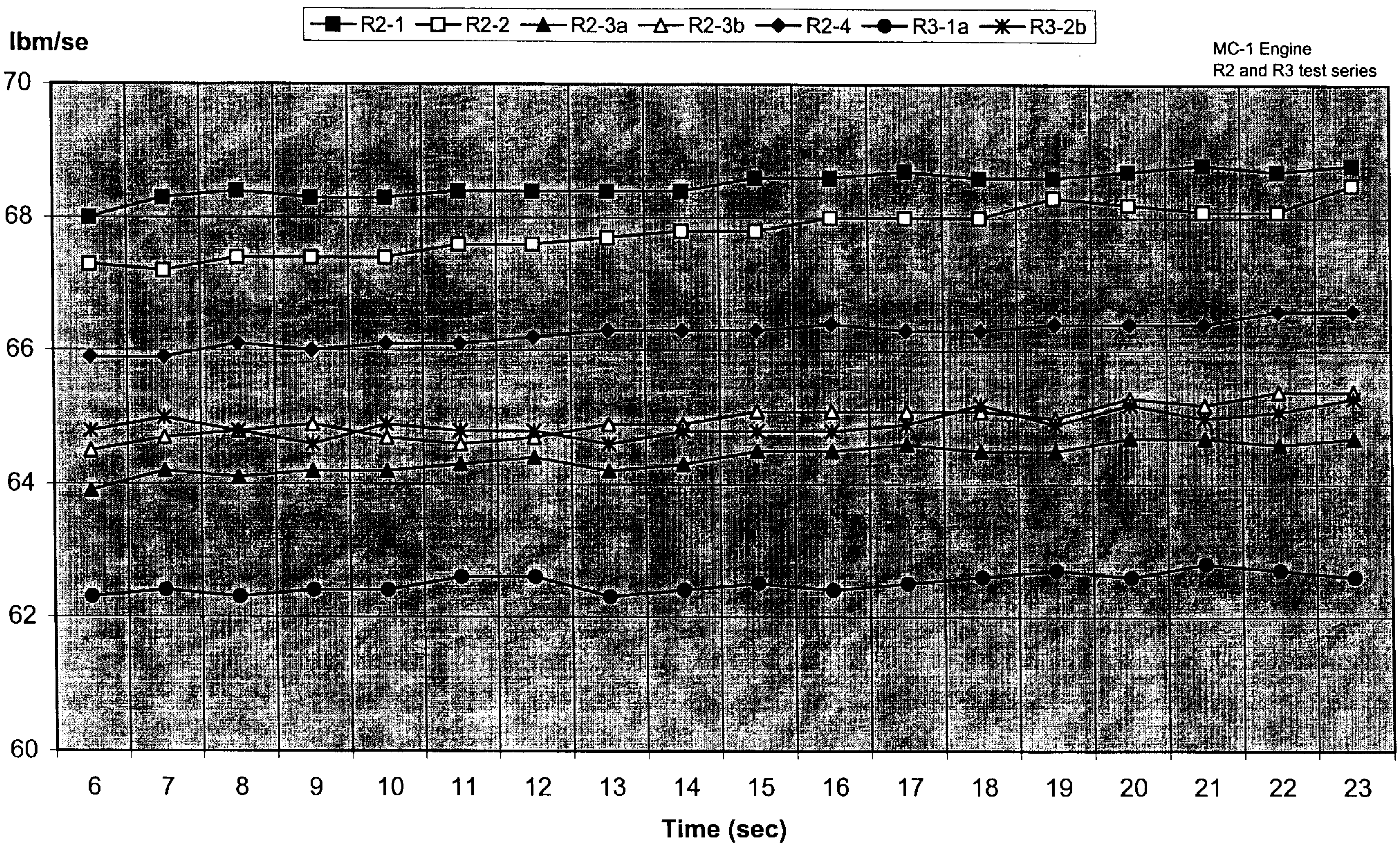


Figure B19 PTHTGI one second average test data

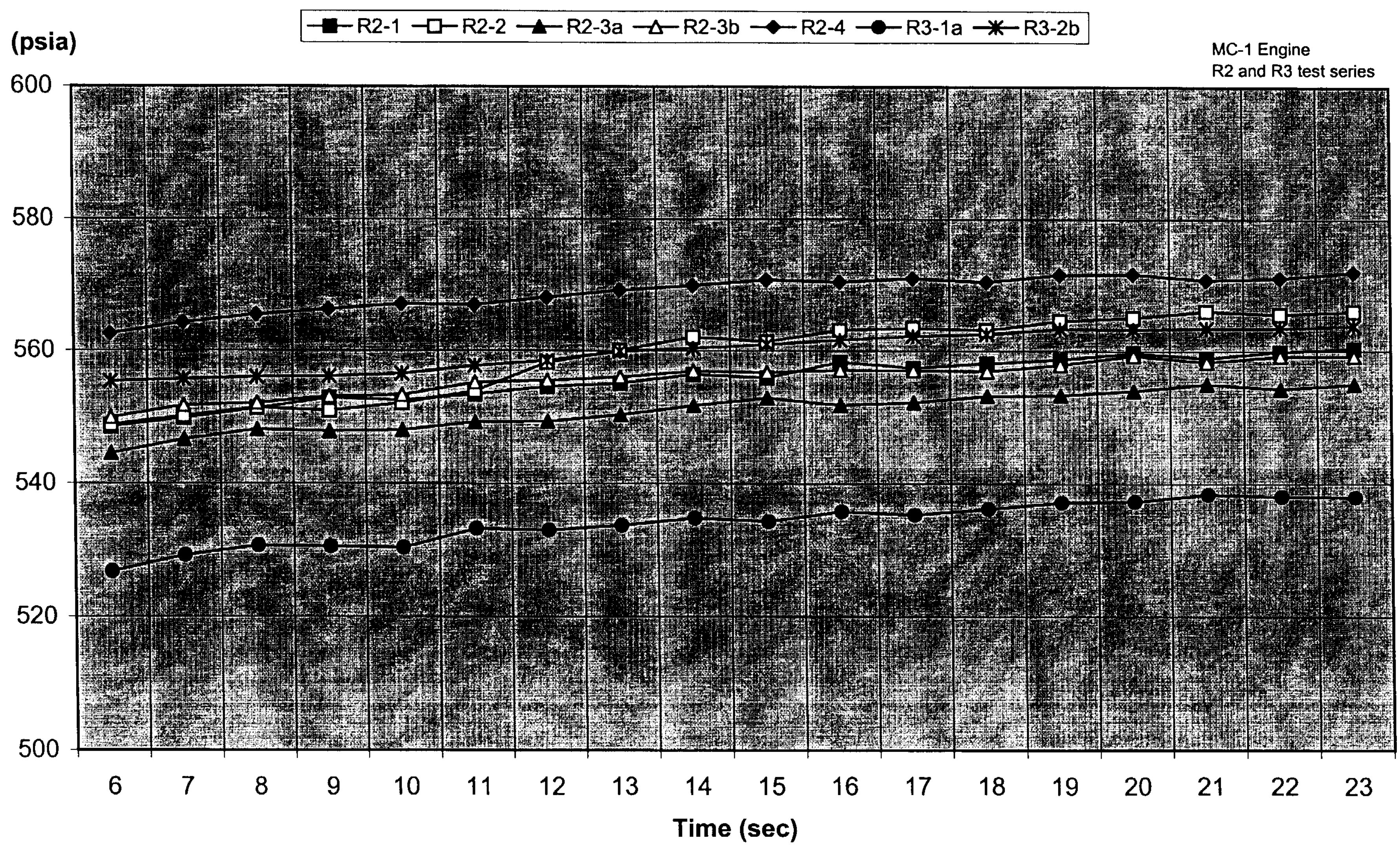


Figure B20   PTVL22 one second average test data

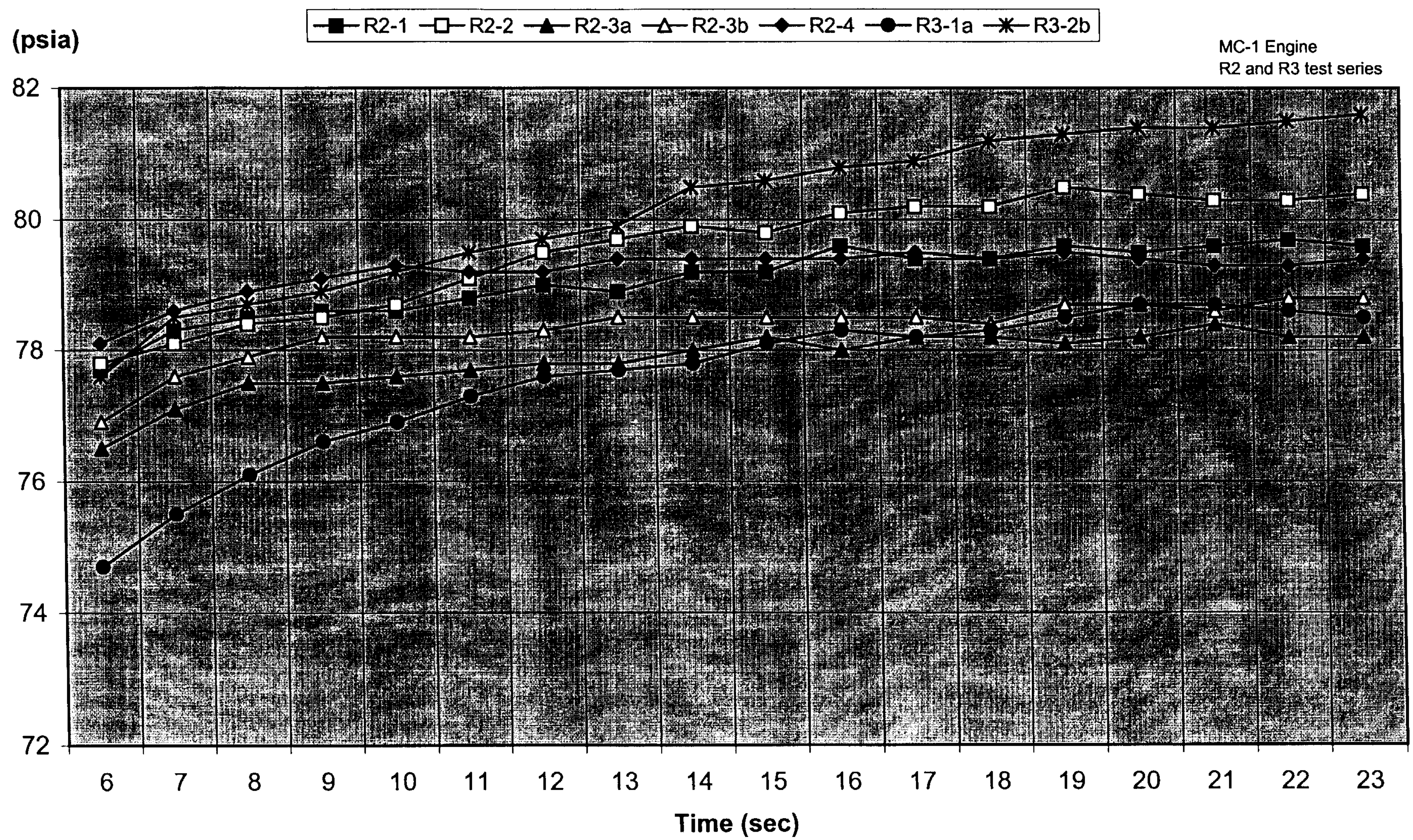


Figure B21   TTHTGI one second average test data

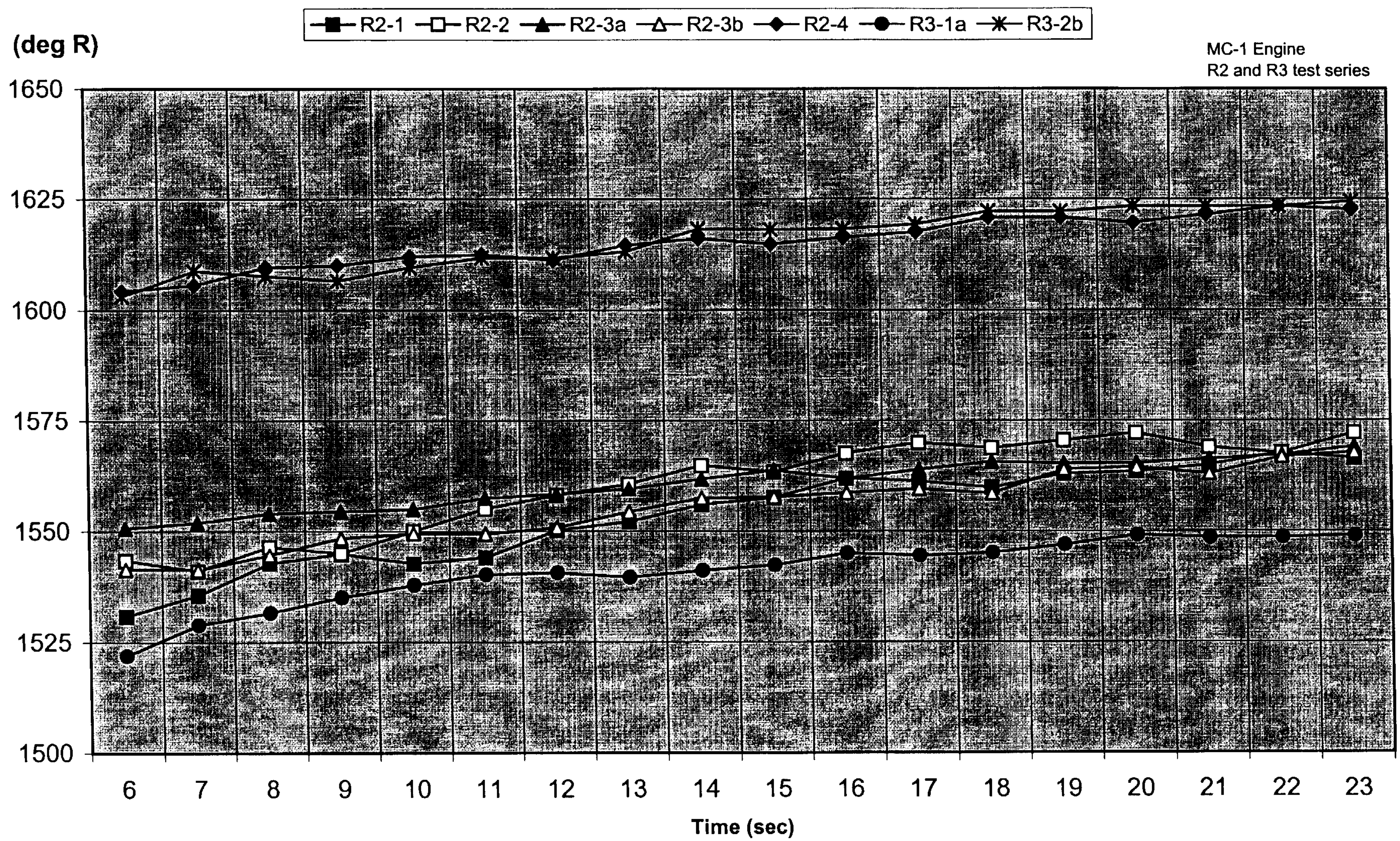


Figure B22   TTHTGD one second average test data

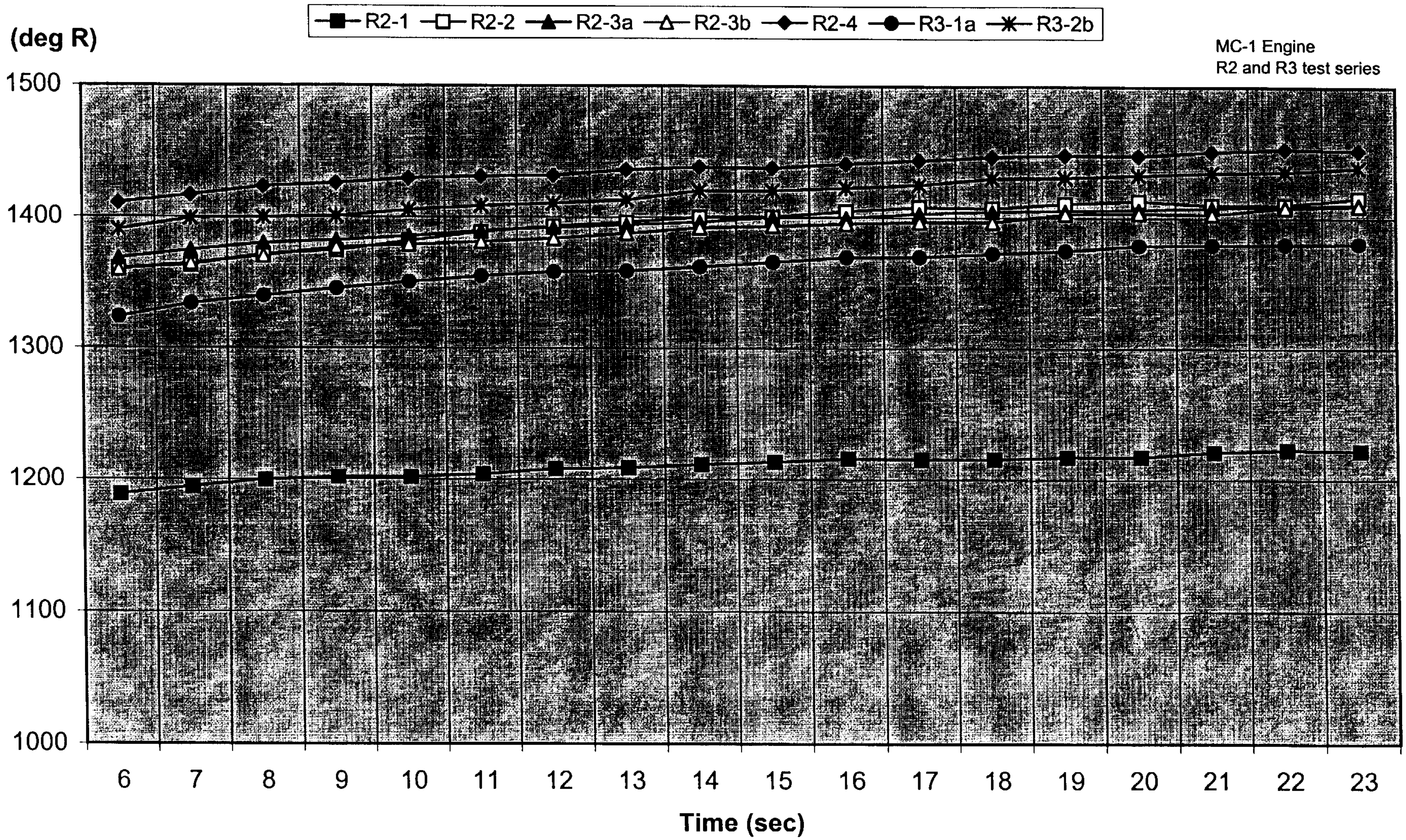


Figure B23   PTMCHY one second average test data

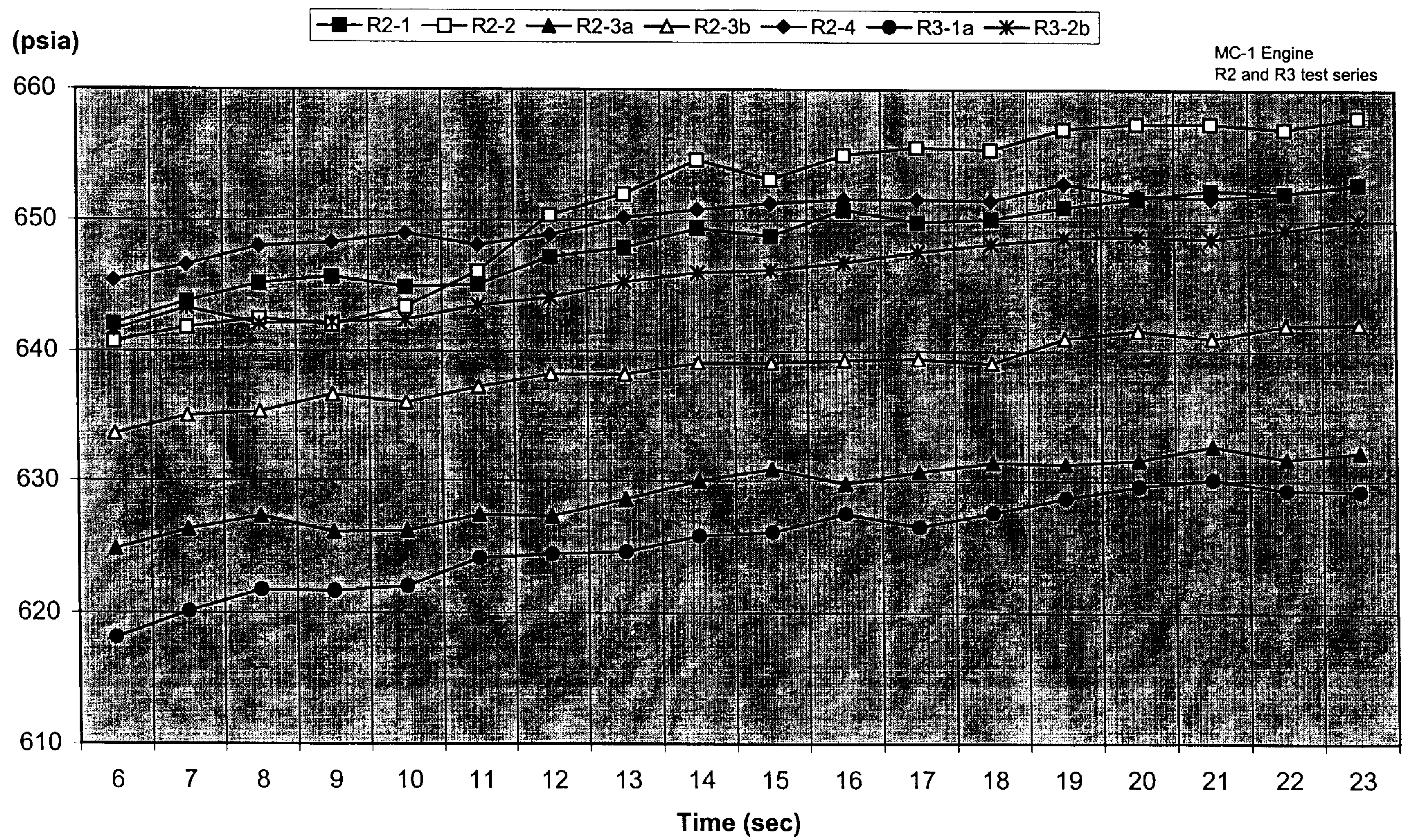


Figure B24 SNSHFT one second average test data

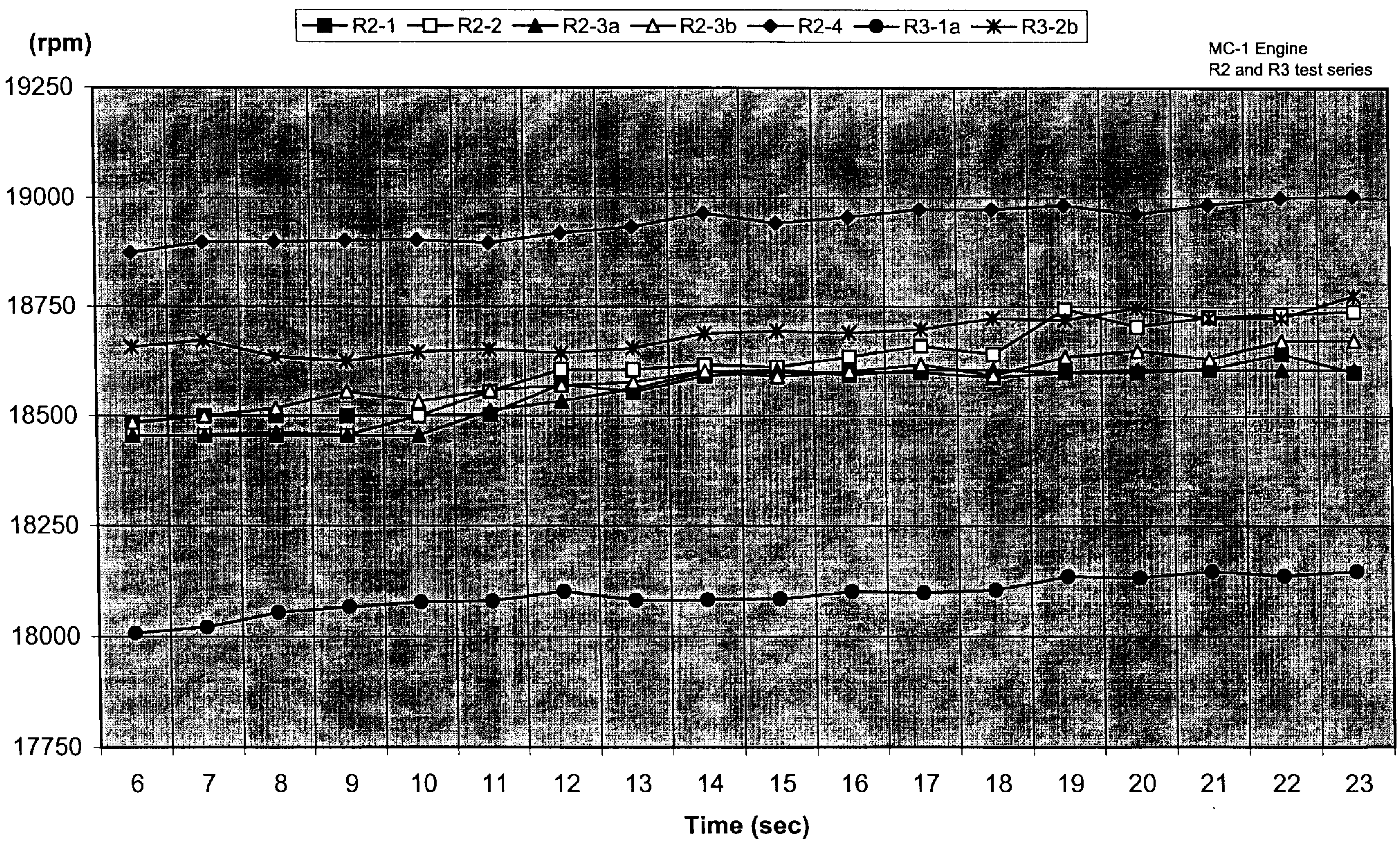
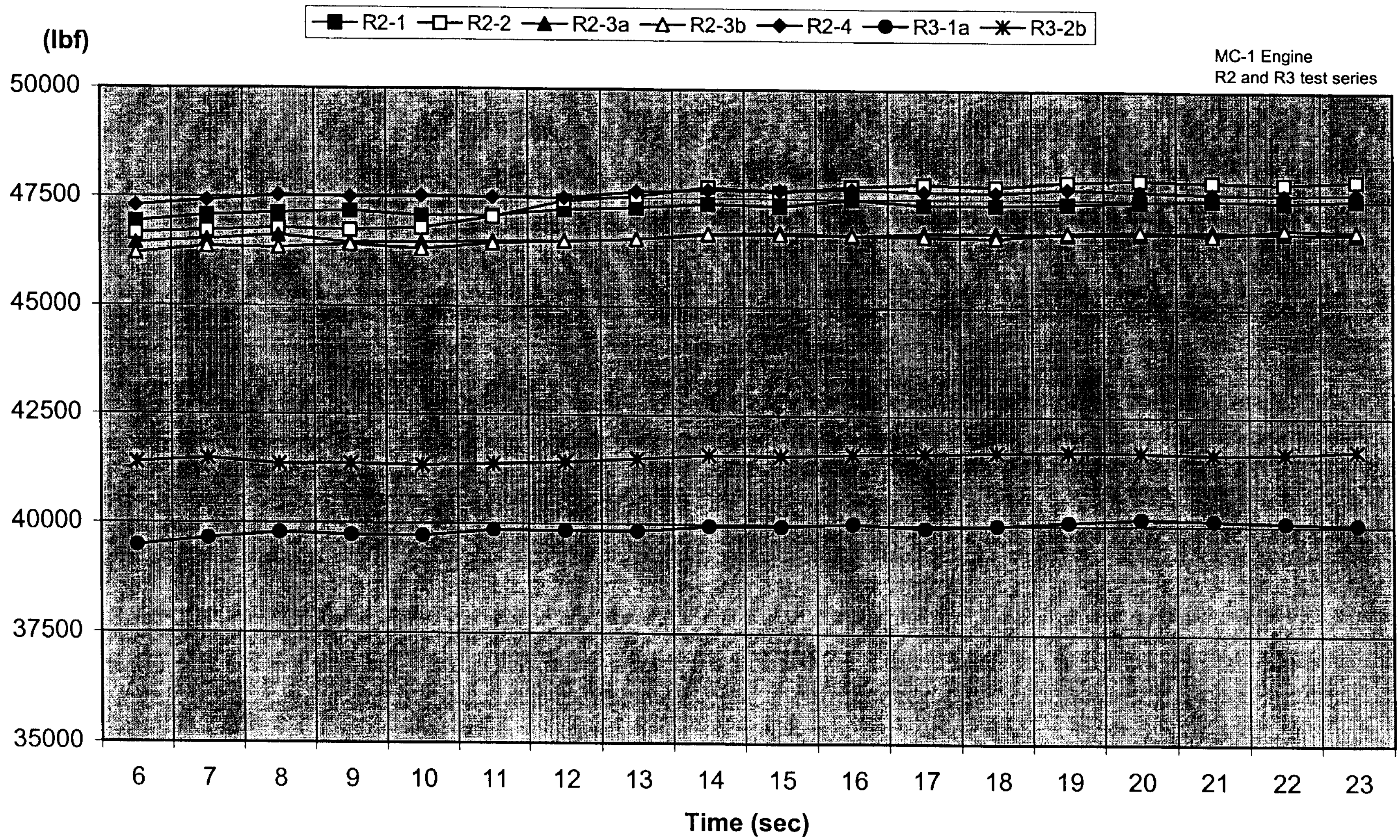


Figure B25   FT15A one second average test data



Appendix C

MC-1 engine
Temporal plots of R2 and R3 test series
One second averaged data adjusted
to standard inlet conditions

Figure C1 PSOXDS test data adjusted to standard inlet conditions

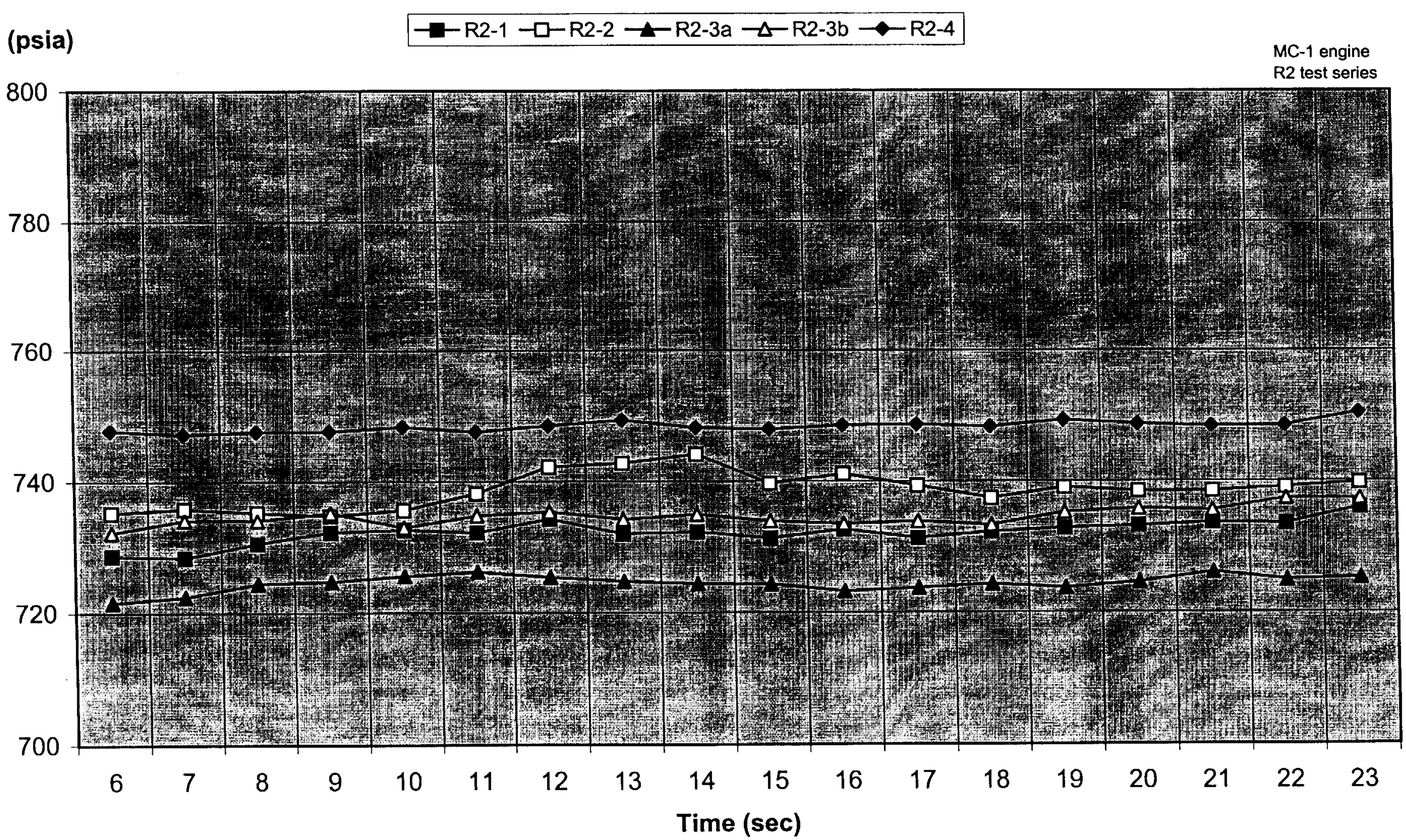


Figure C2 PSVL13 test data adjusted to standard inlet conditions

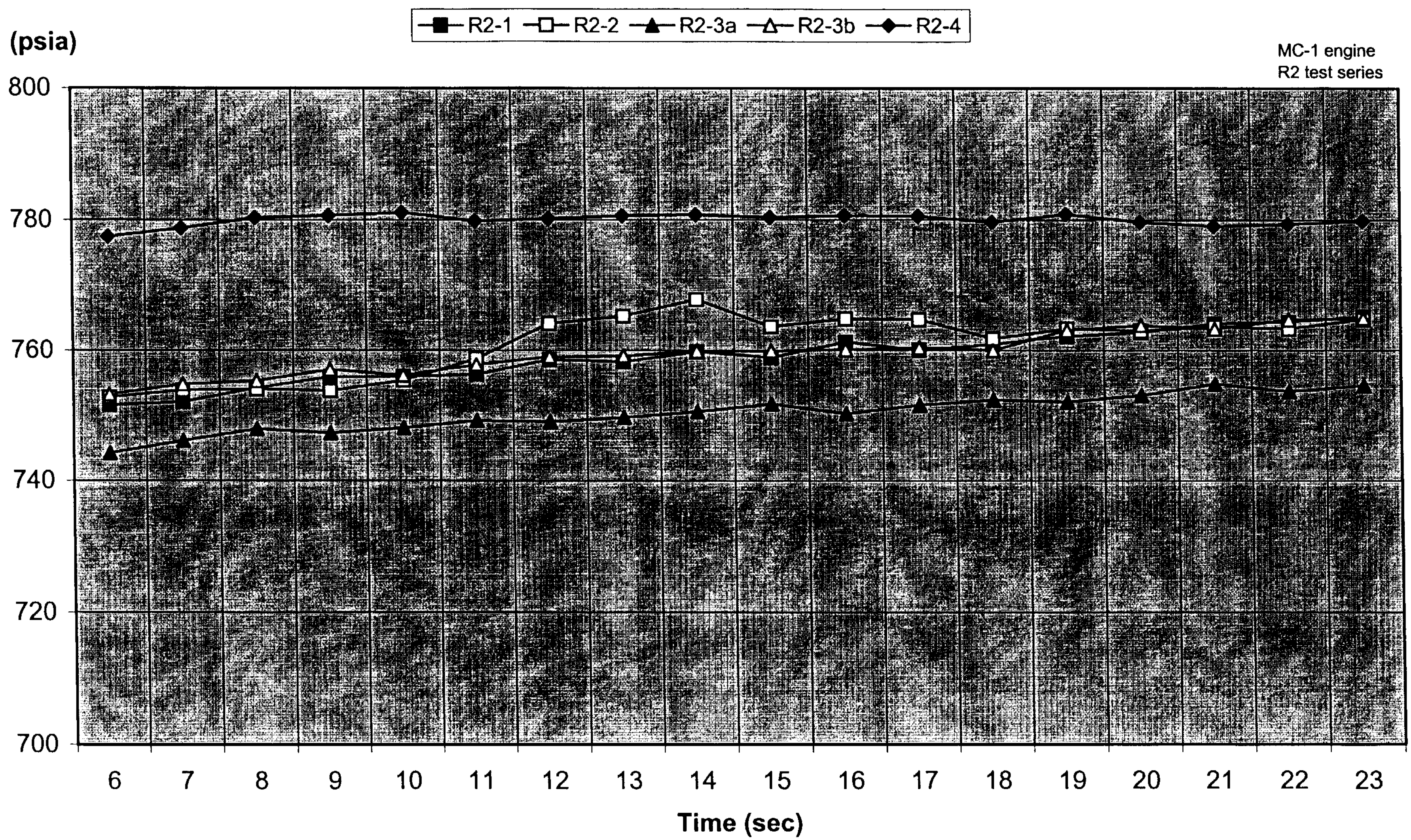


Figure C3 PTVL14 test data adjusted to standard inlet conditions

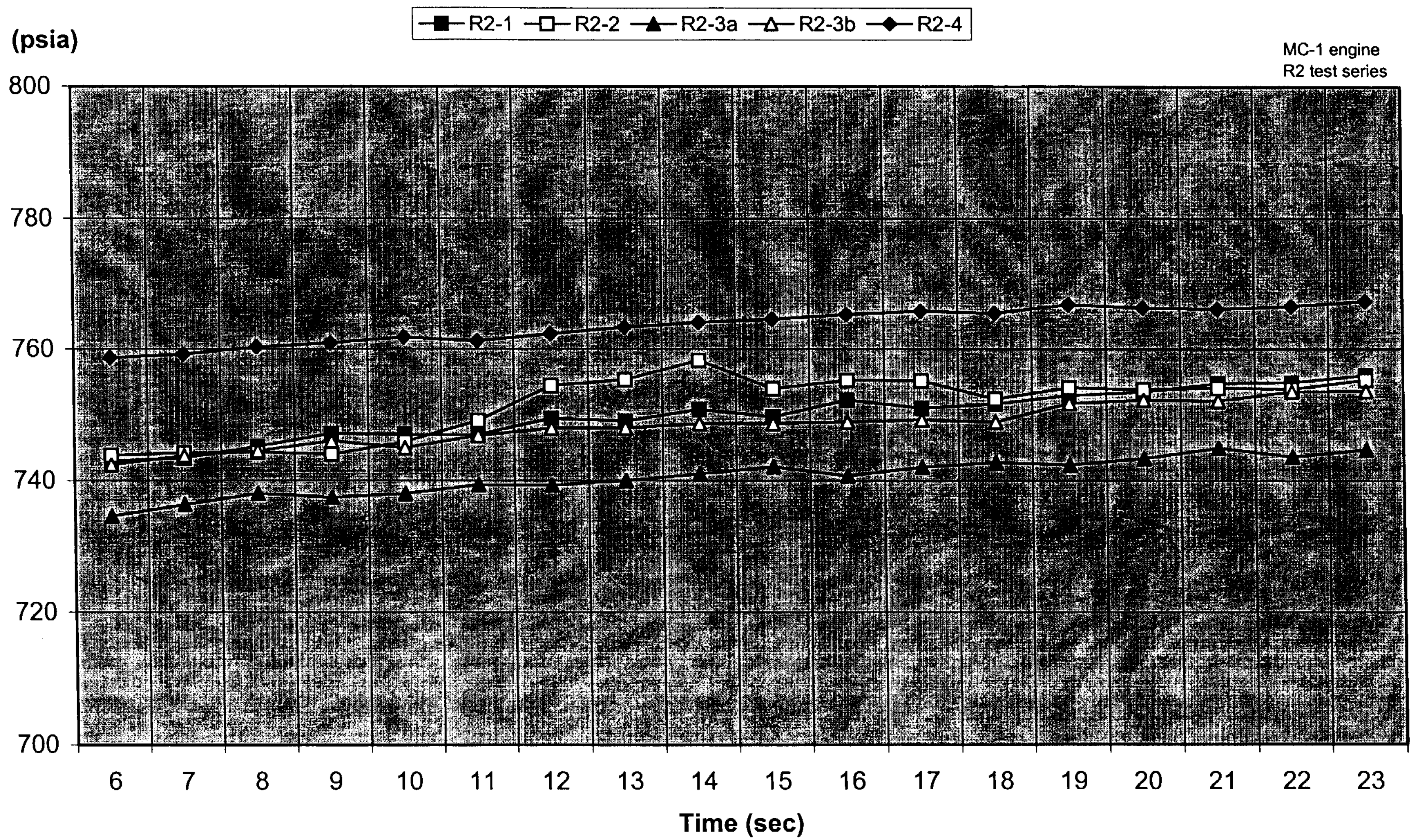


Figure C4 PSVL15 test data adjusted to standard inlet conditions

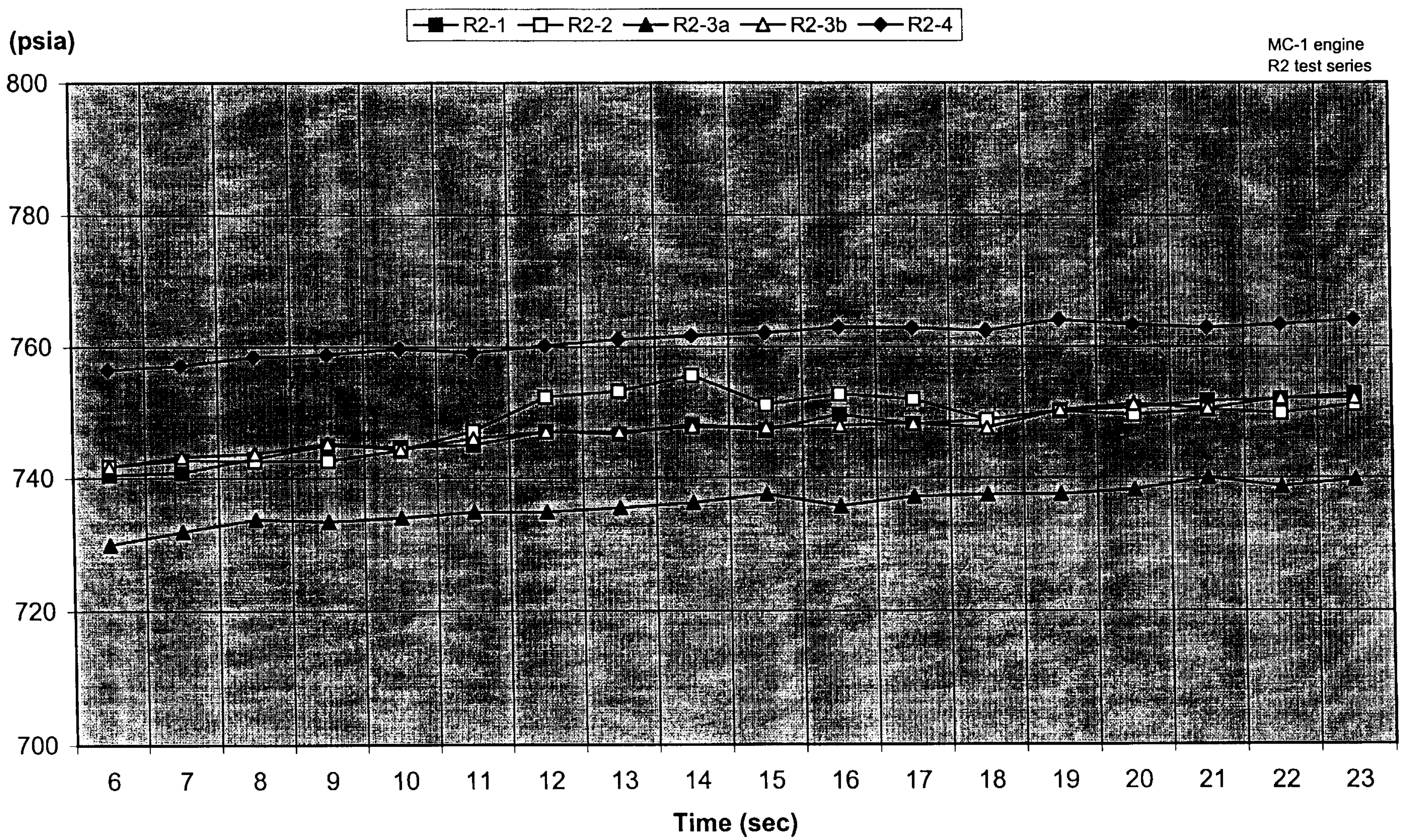


Figure C5 PTVL18 test data adjusted to standard inlet conditions

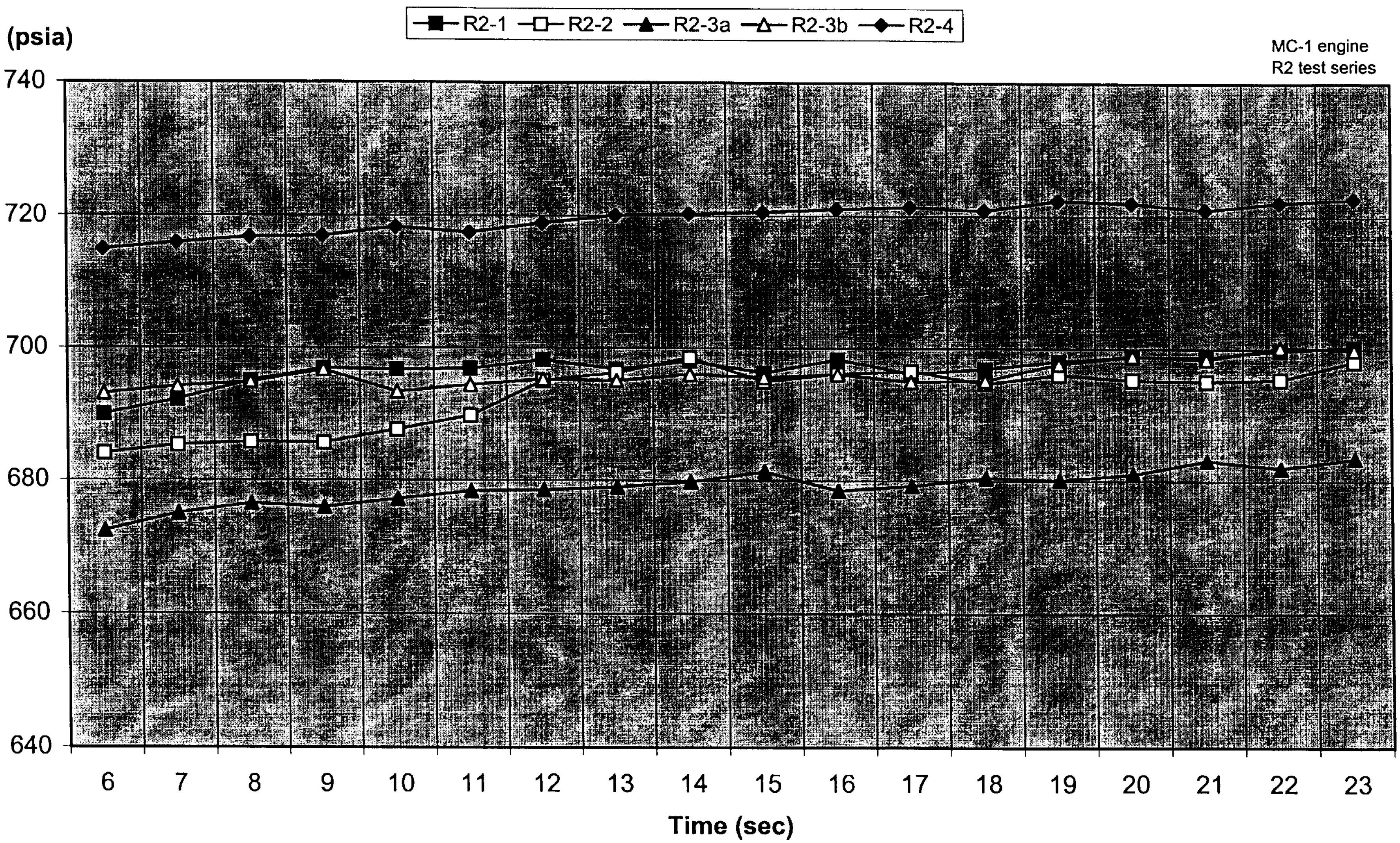


Figure C6 TTVL14 test data adjusted to standard inlet conditions

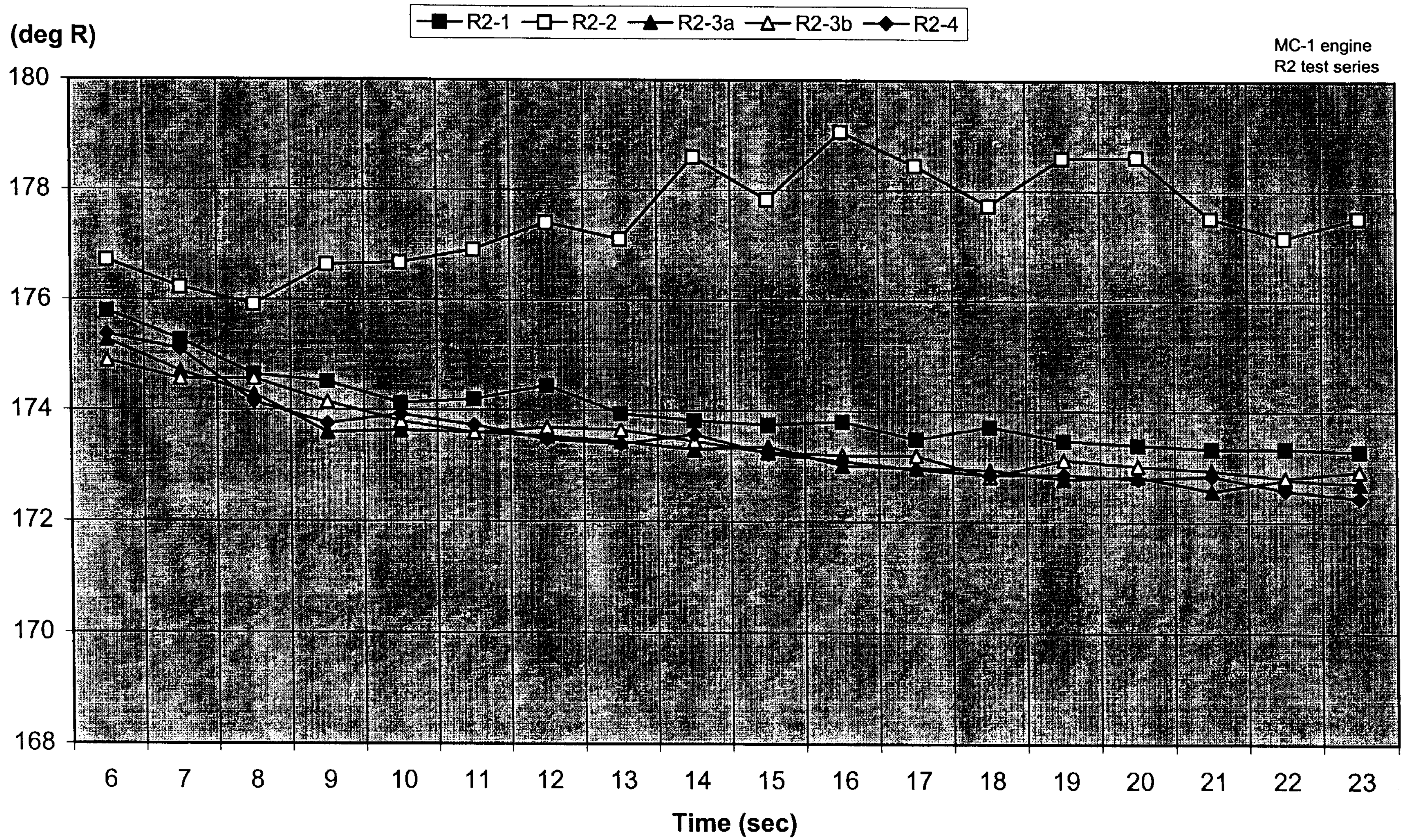


Figure C7 TTVL18 test data adjusted to standard inlet conditions

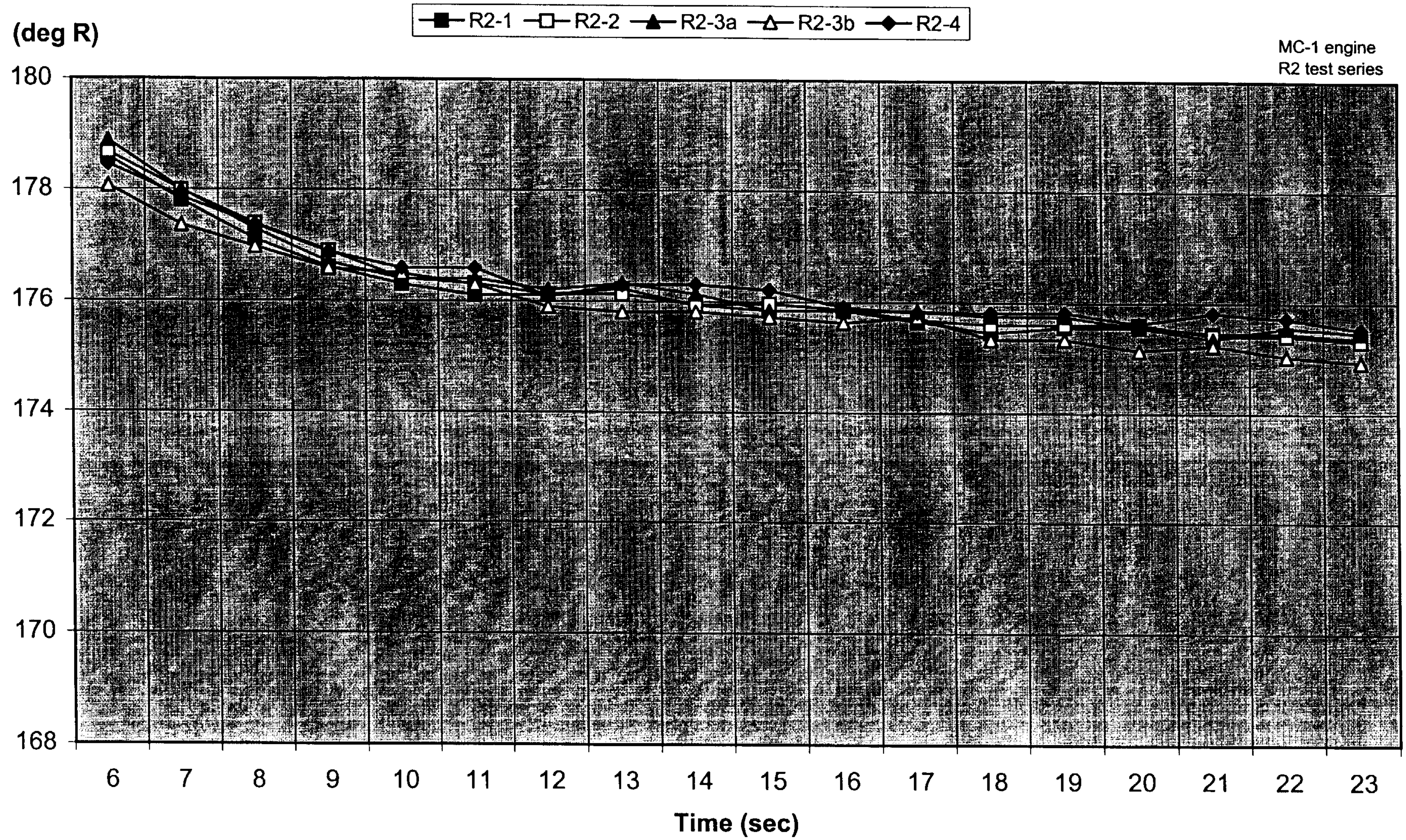


Figure C8 WOXTOTL test data adjusted to standard inlet conditions

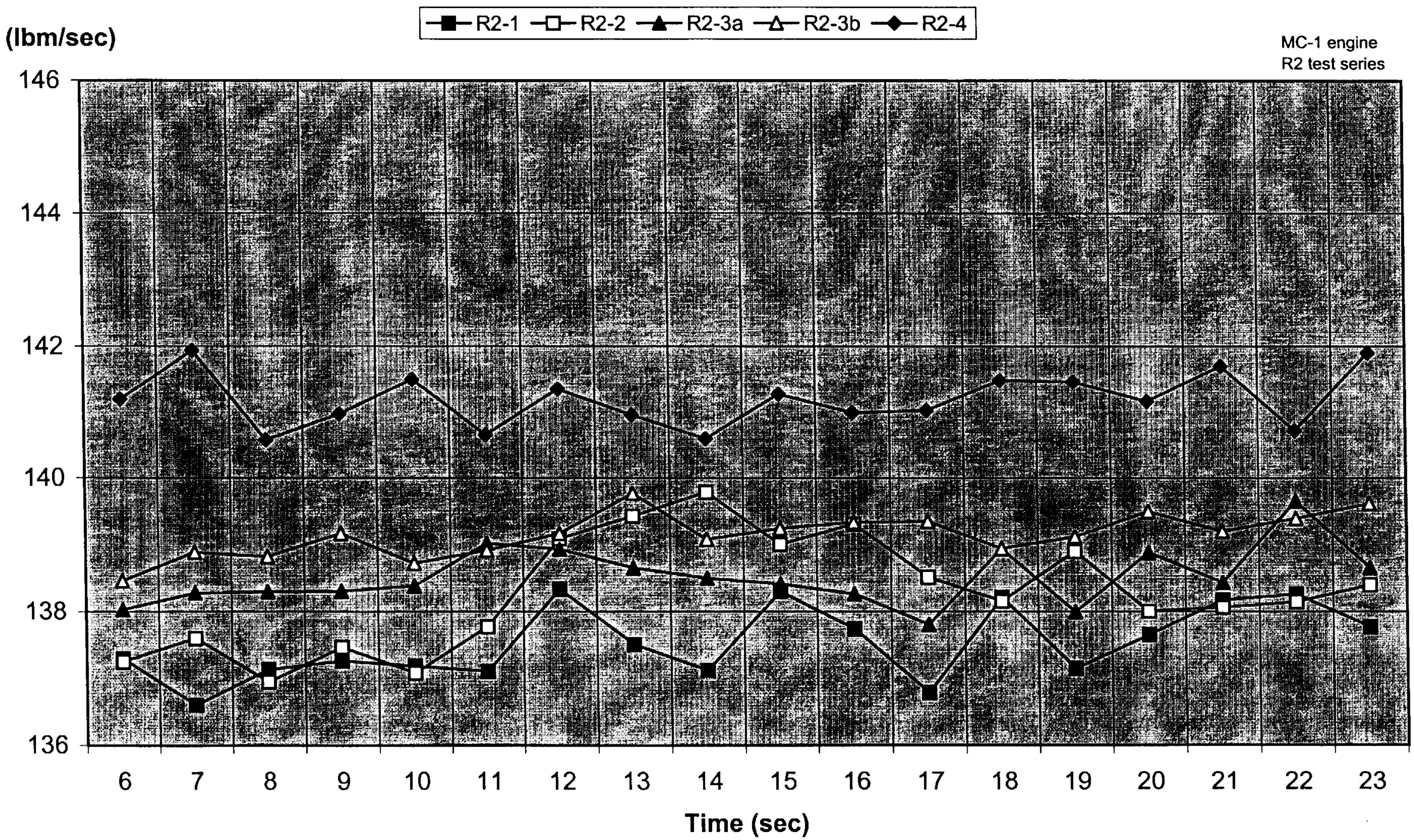


Figure C9 PSVL00 test data adjusted to standard inlet conditions

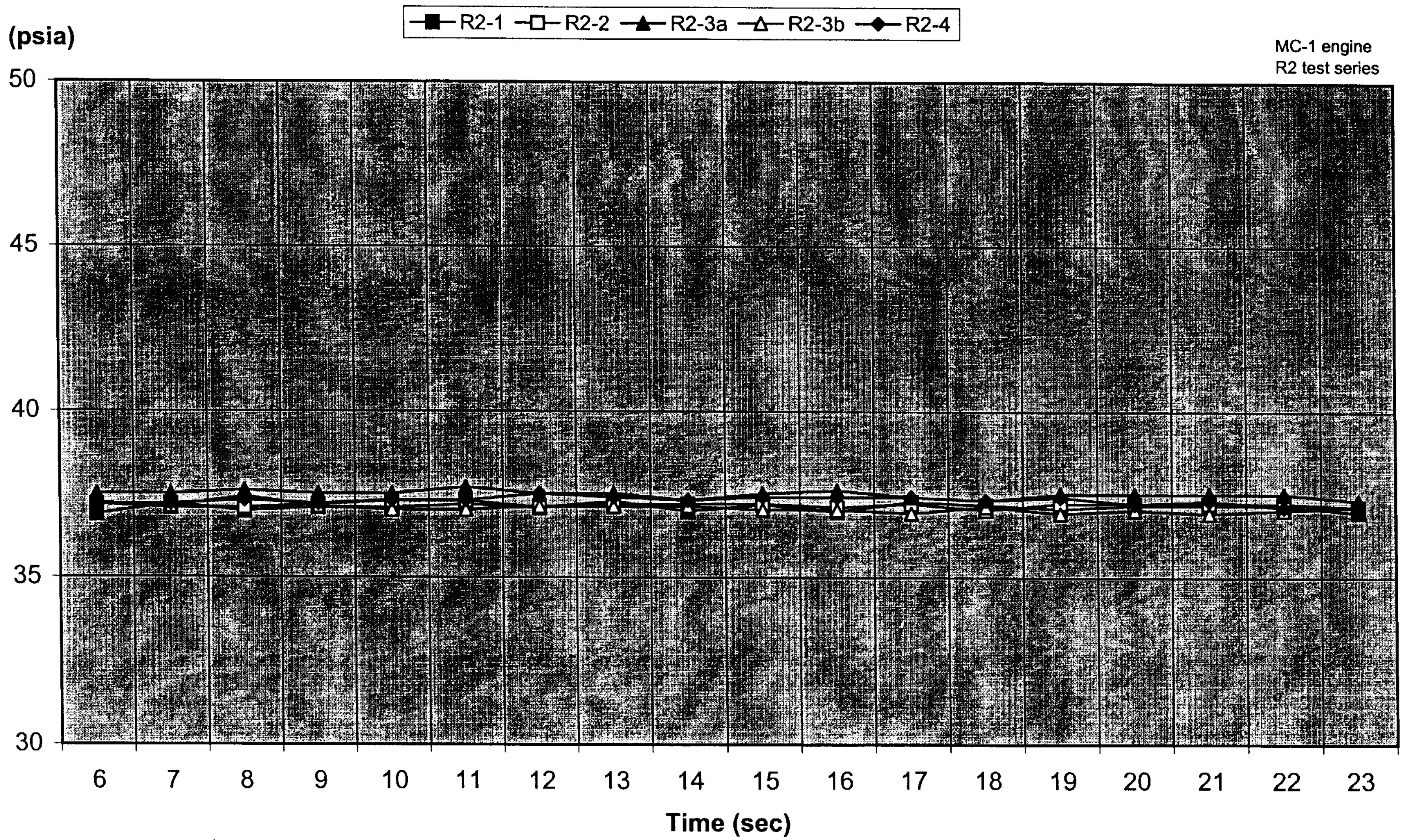


Figure C10 PSVL01 test data adjusted to standard inlet conditions

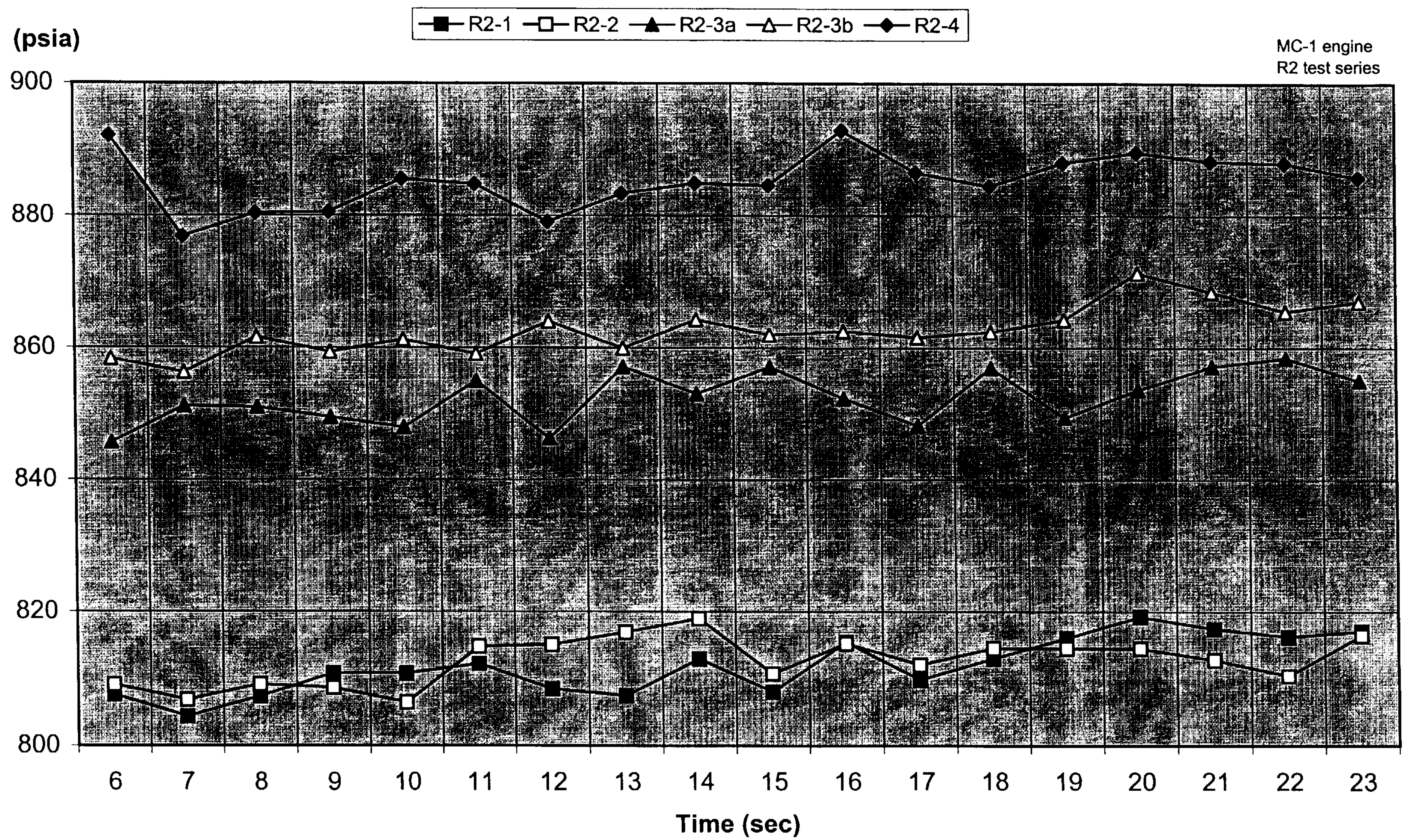


Figure C11 PTVL05 test data adjusted to standard inlet conditions

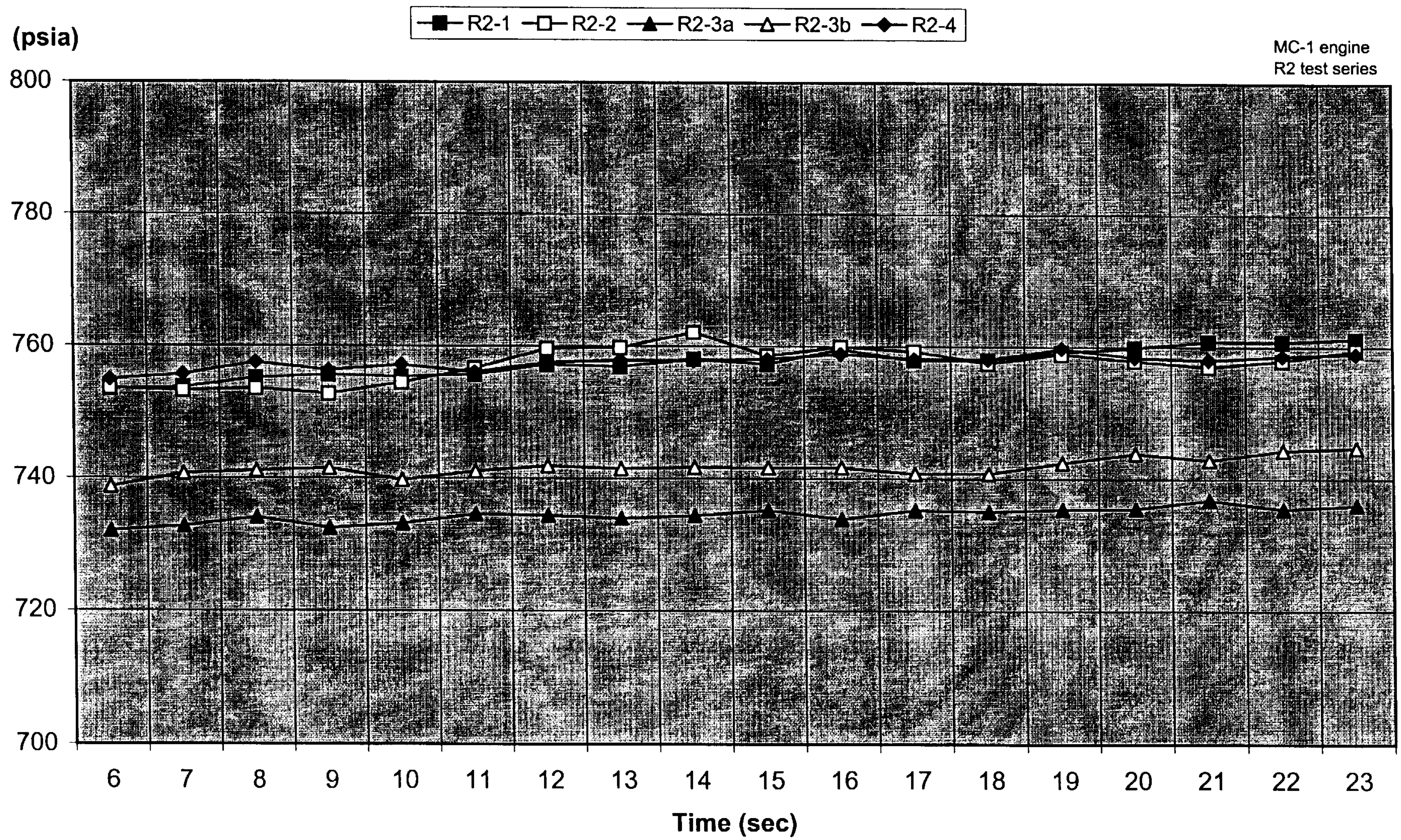


Figure C12   PTVL09 test data adjusted to standard inlet conditions

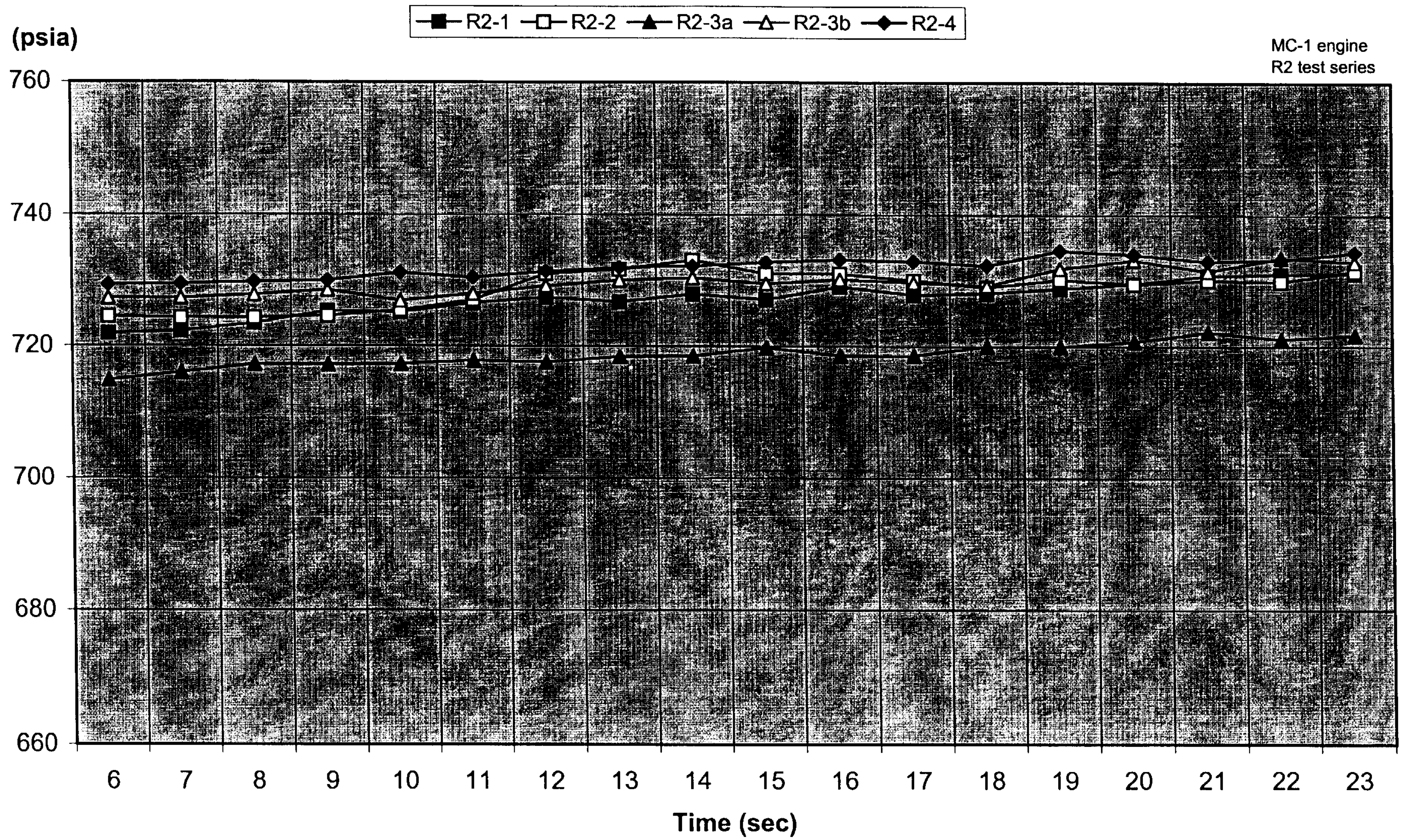


Figure C13 TTVL05 test data adjusted to standard inlet conditions

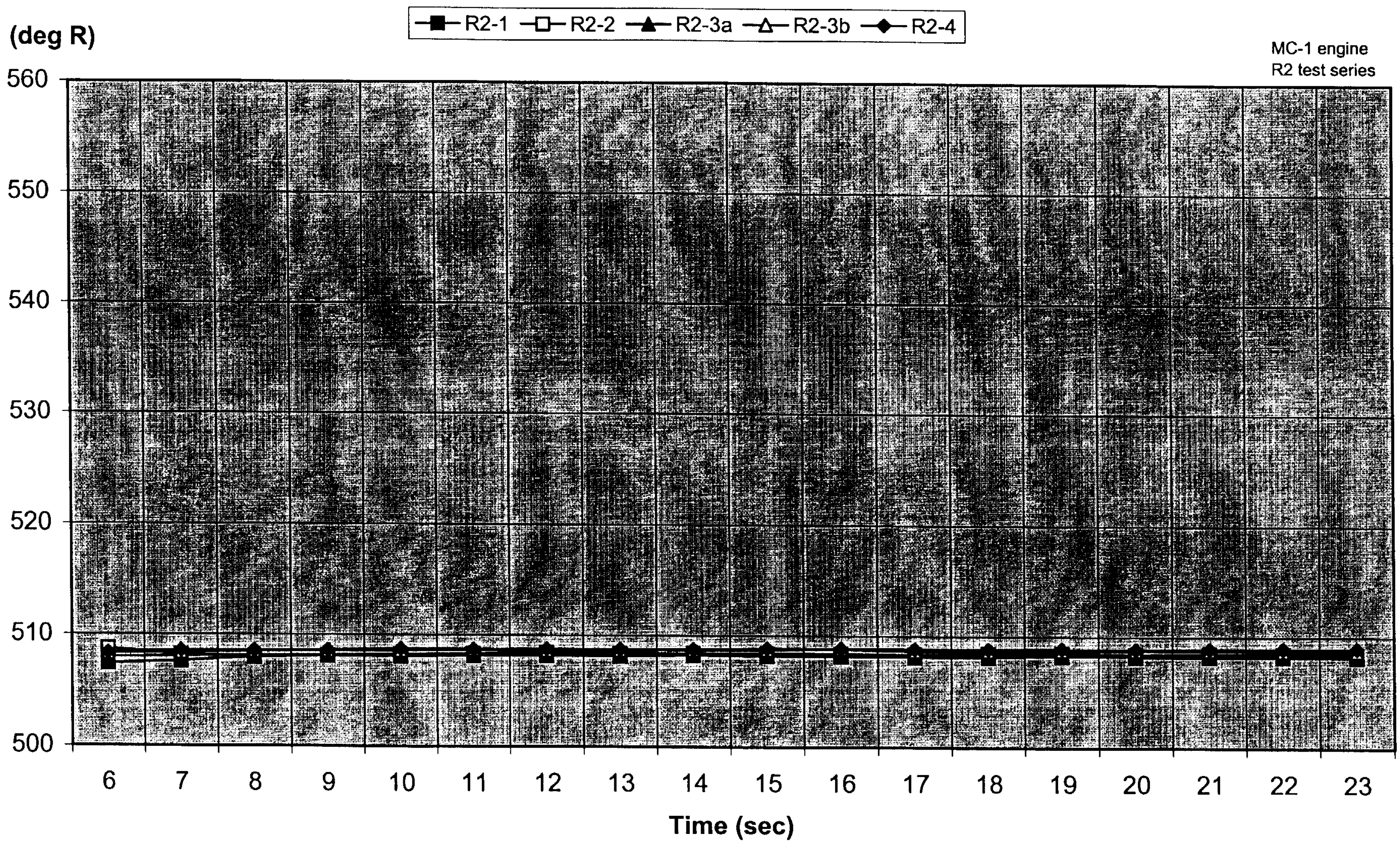


Figure C14 WRPTOTL test data adjusted to standard inlet conditions

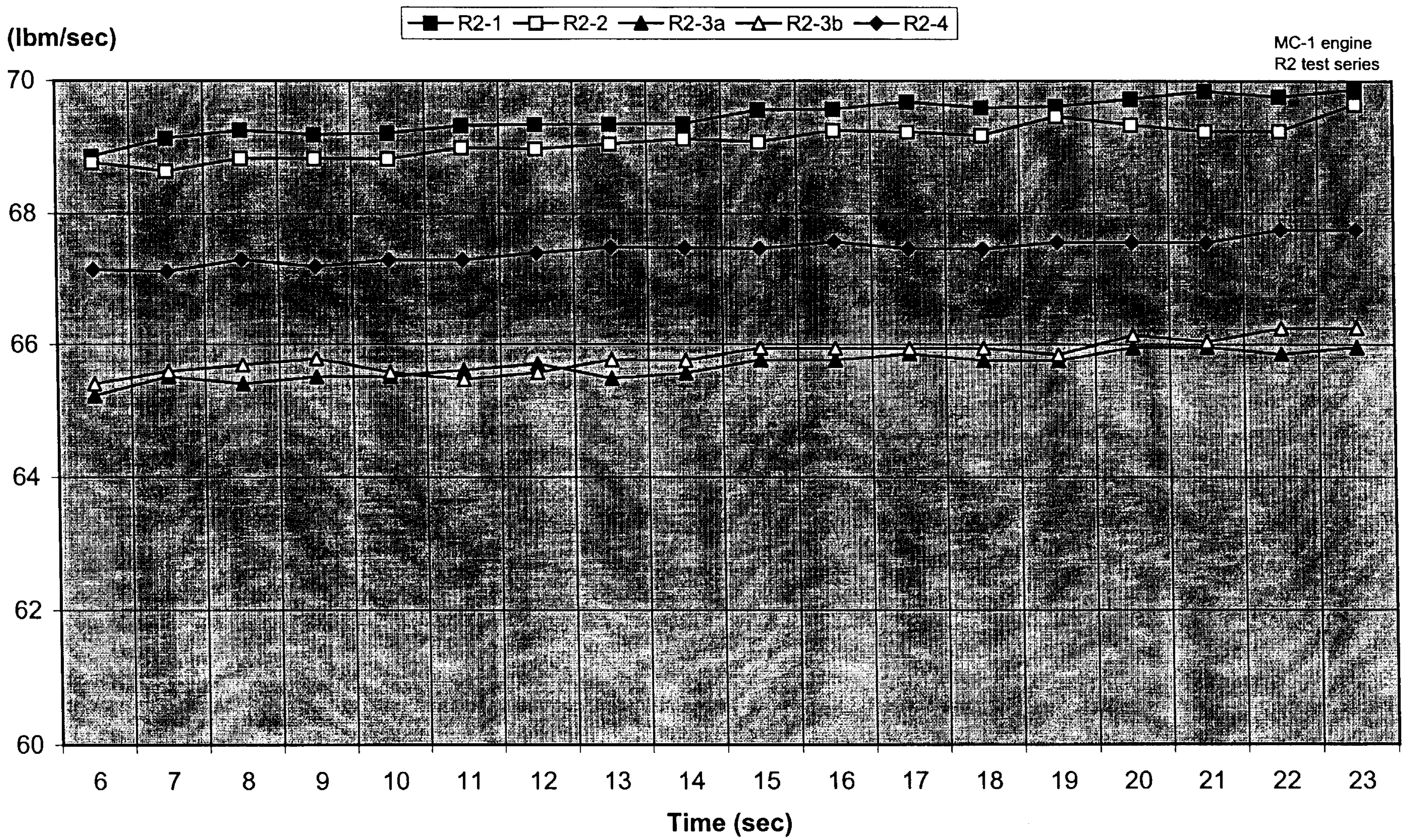


Figure C15   PTHTGI test data adjusted to standard inlet conditions

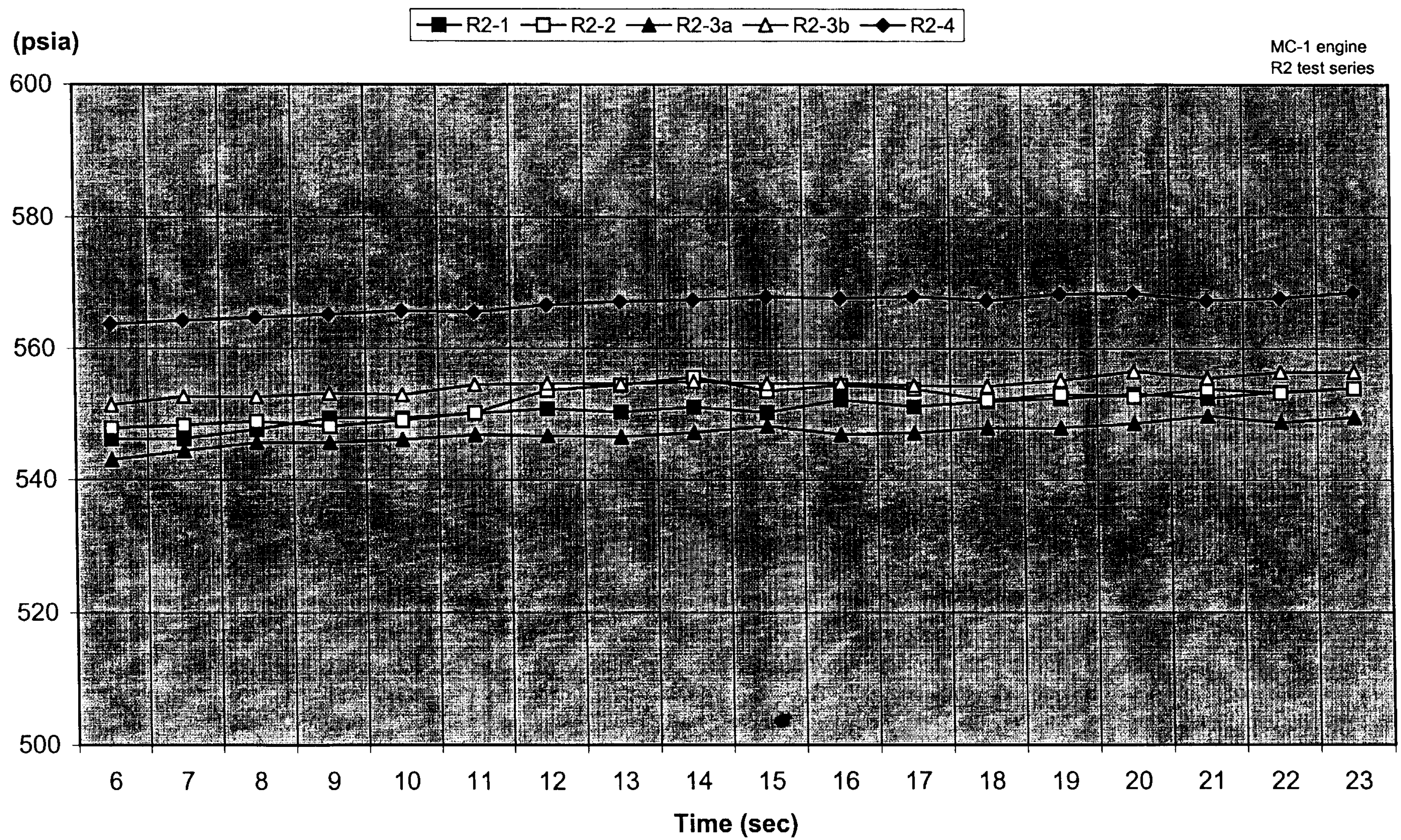


Figure C16 PTVL22 test data adjusted to standard inlet conditions

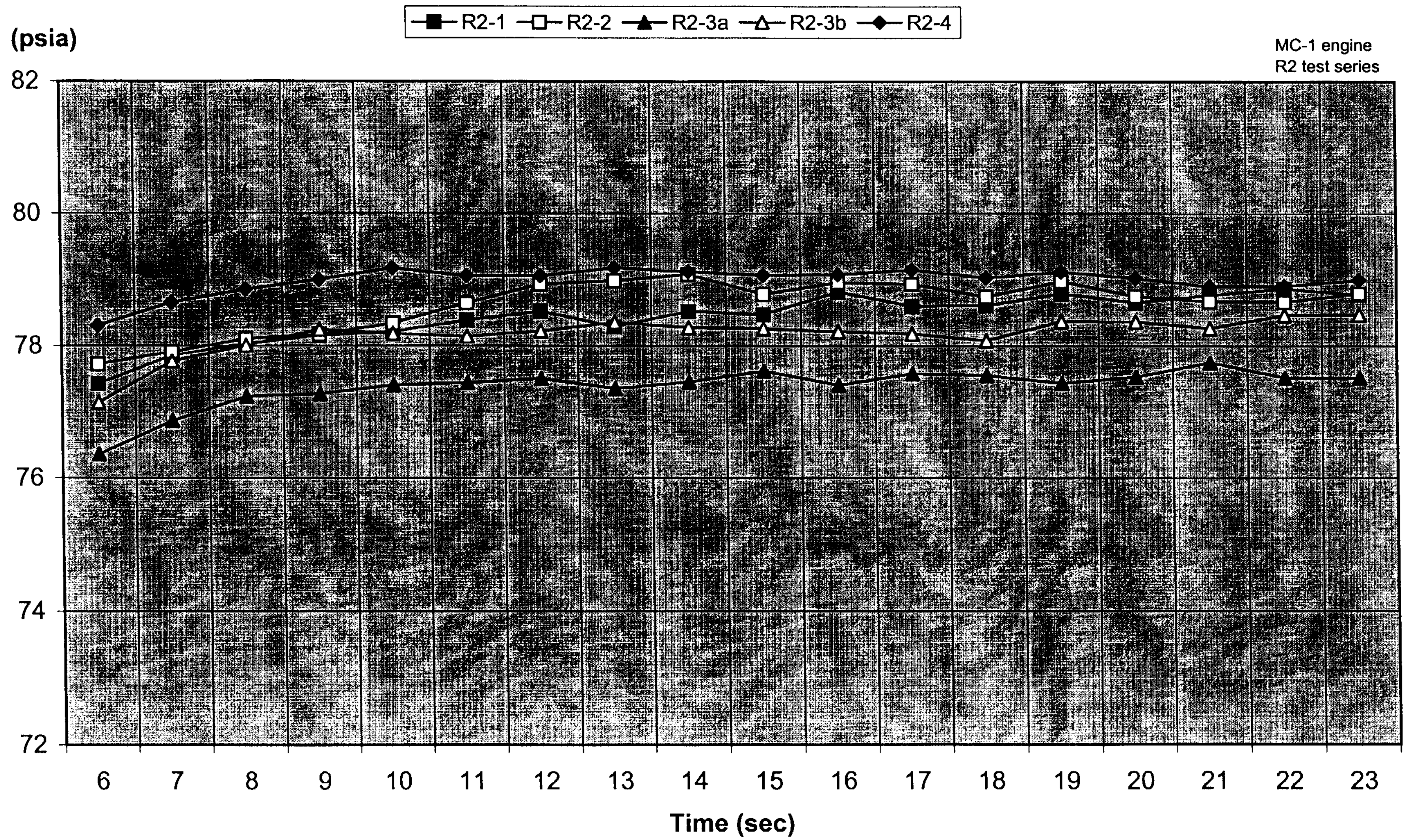


Figure C17 TTHTGI test data adjusted to standard inlet conditions

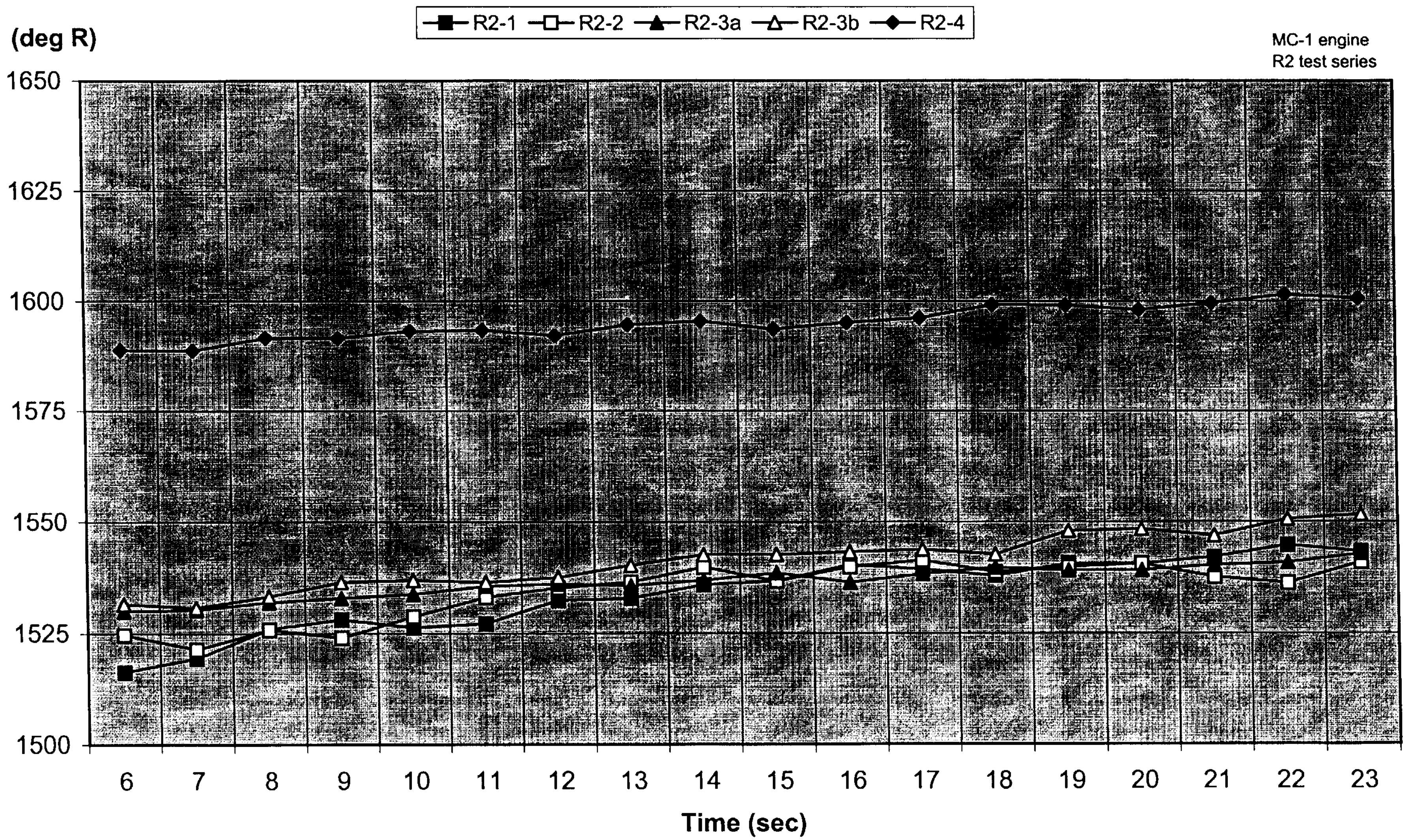


Figure C18 TTHTGD test data adjusted to standard inlet conditions

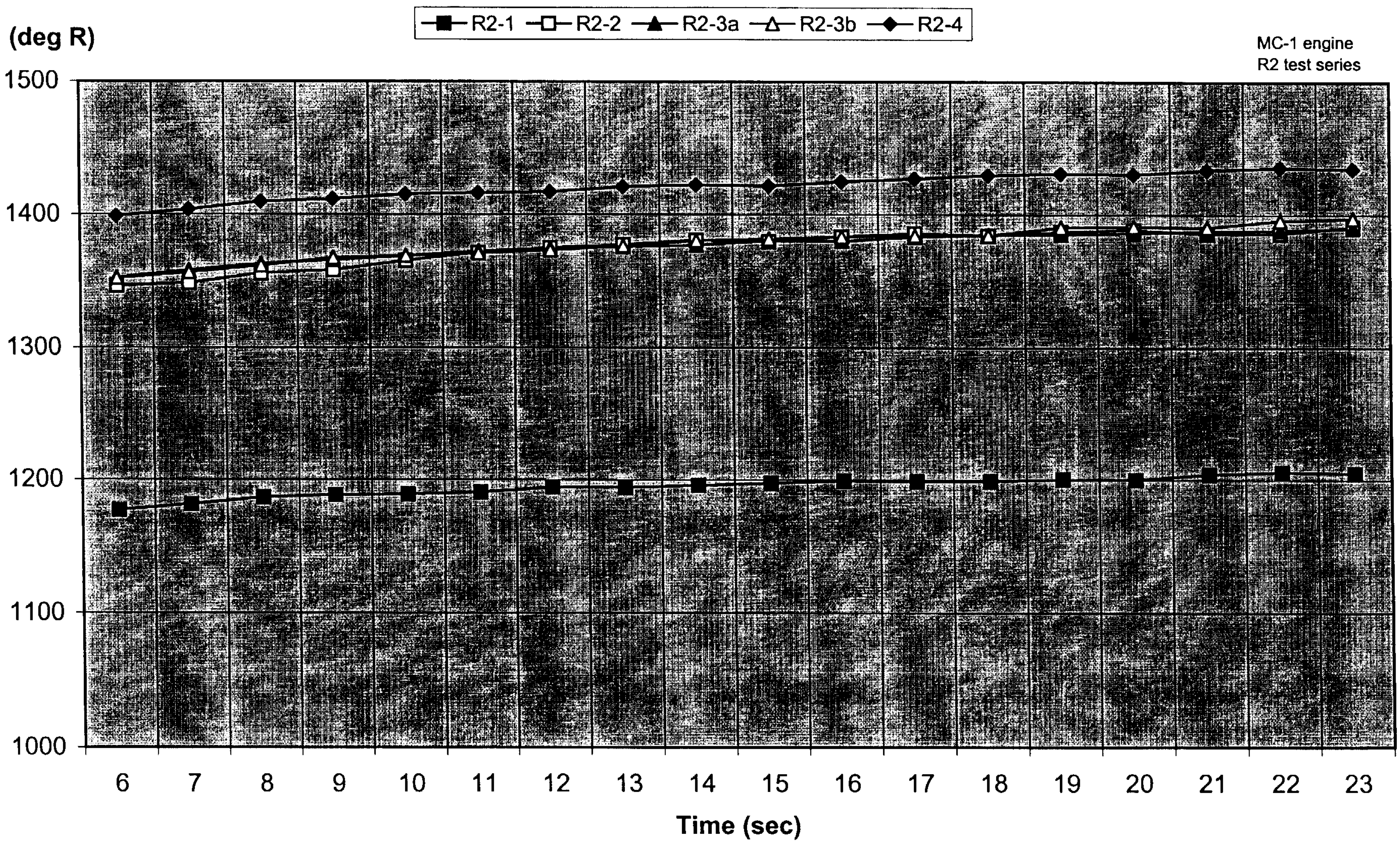


Figure C19 PTMCHY test data adjusted to standard inlet conditions

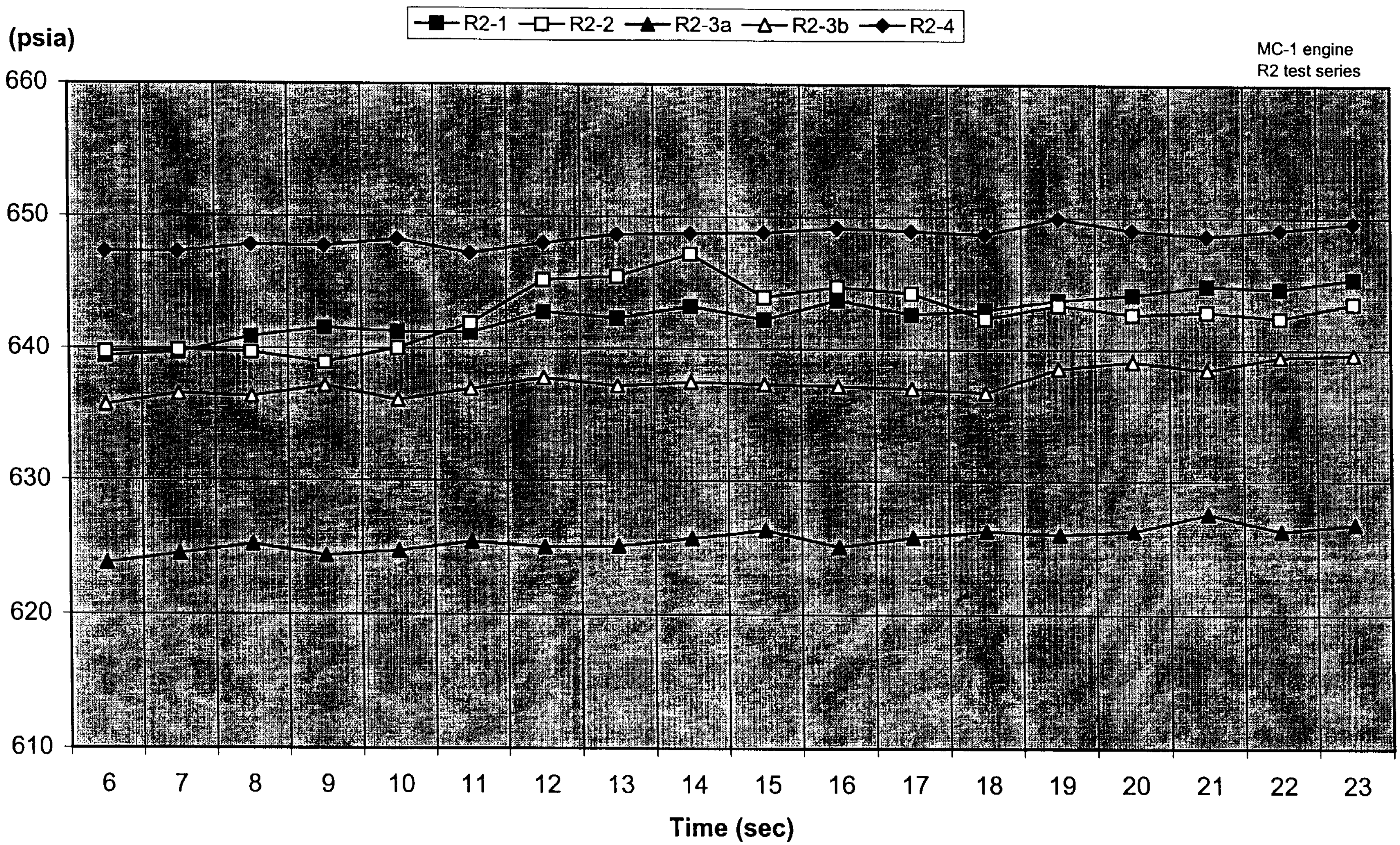


Figure C20 SNSHFT test data adjusted to standard inlet conditions

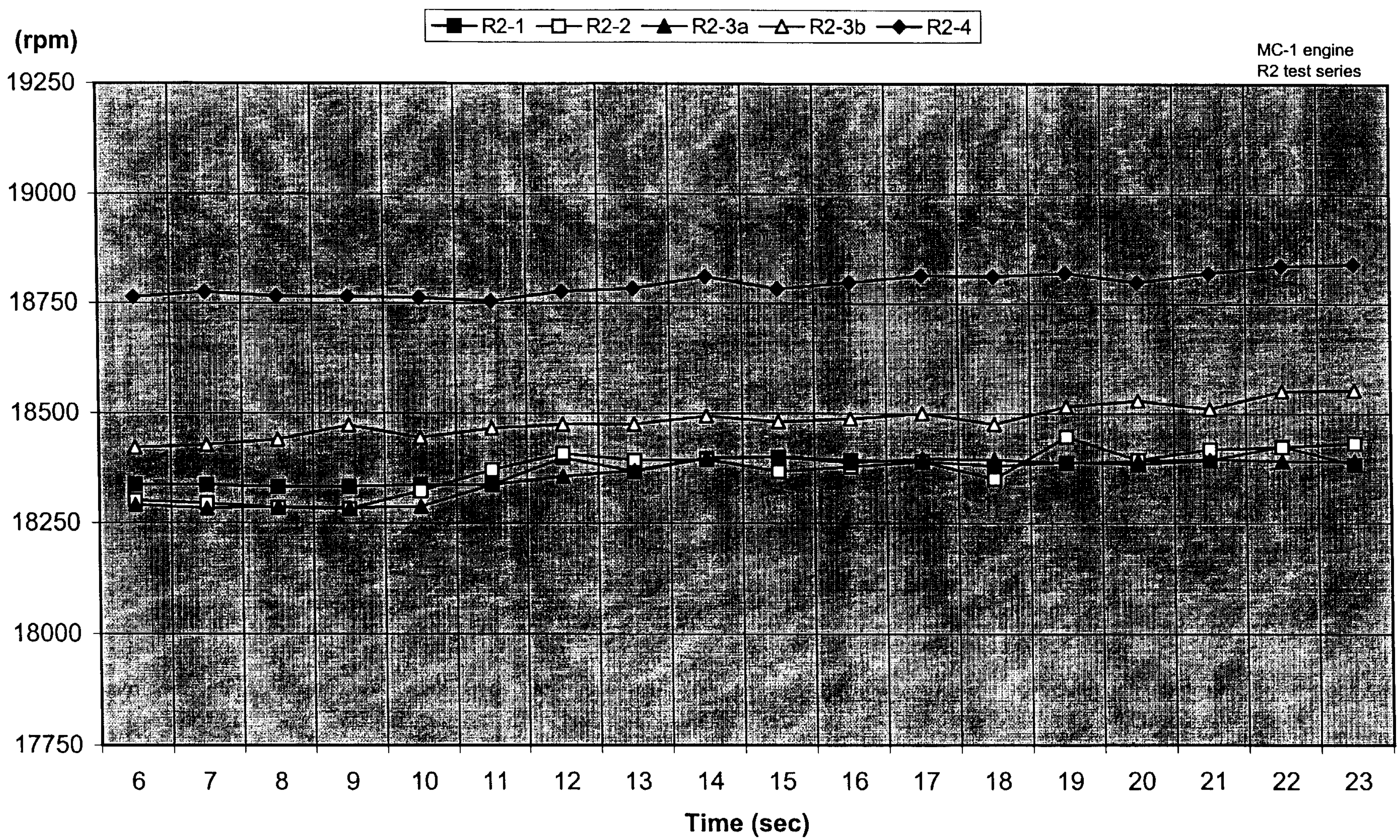
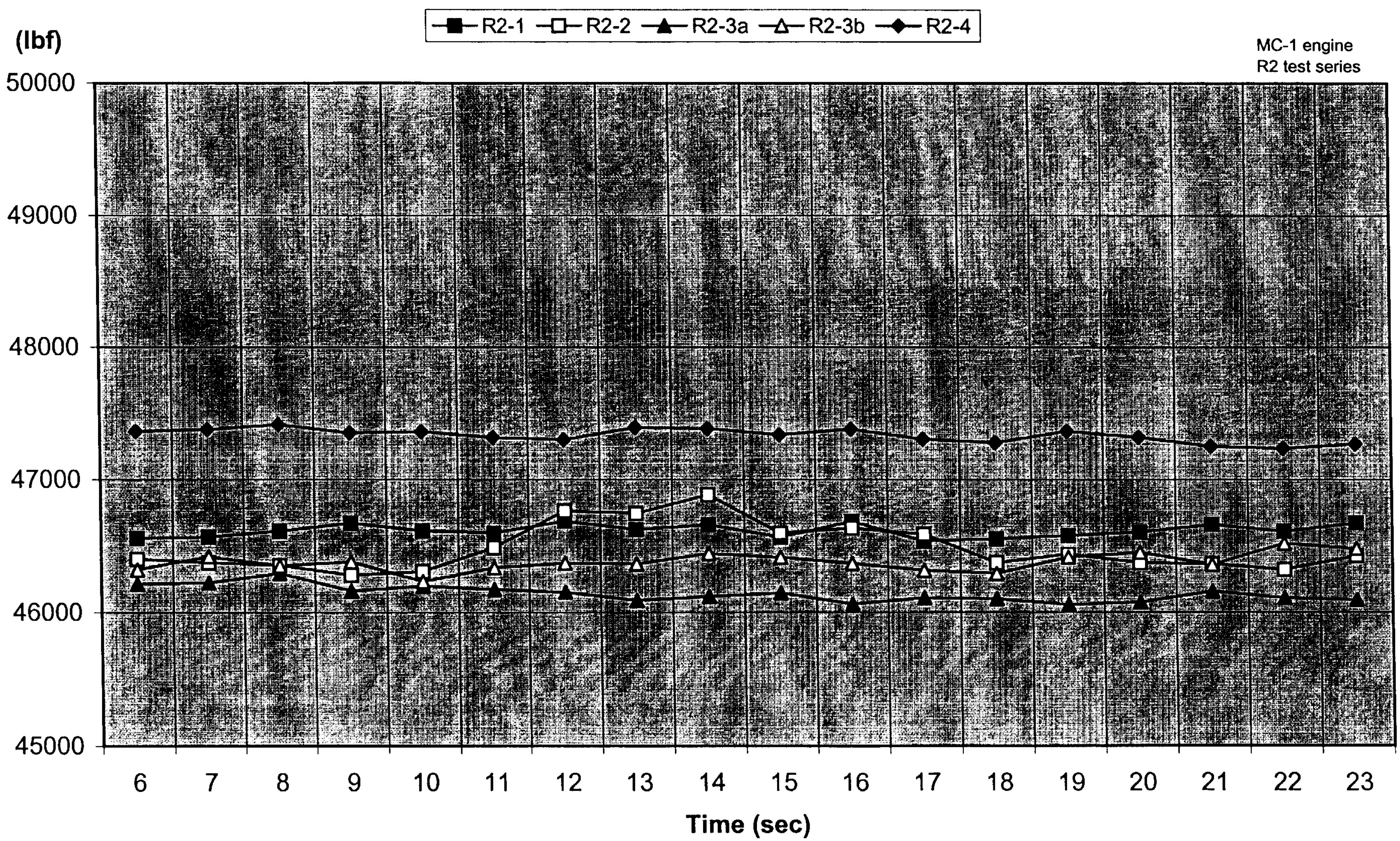


Figure C21 FT15A test data adjusted to standard inlet conditions



Appendix D

MC-1engine
Temporal plots for test R2-1
Hardware parameter variation with the standard reduction variable set

Figure D1 Comparison of GDR and ROCETS/DR results RCALMF

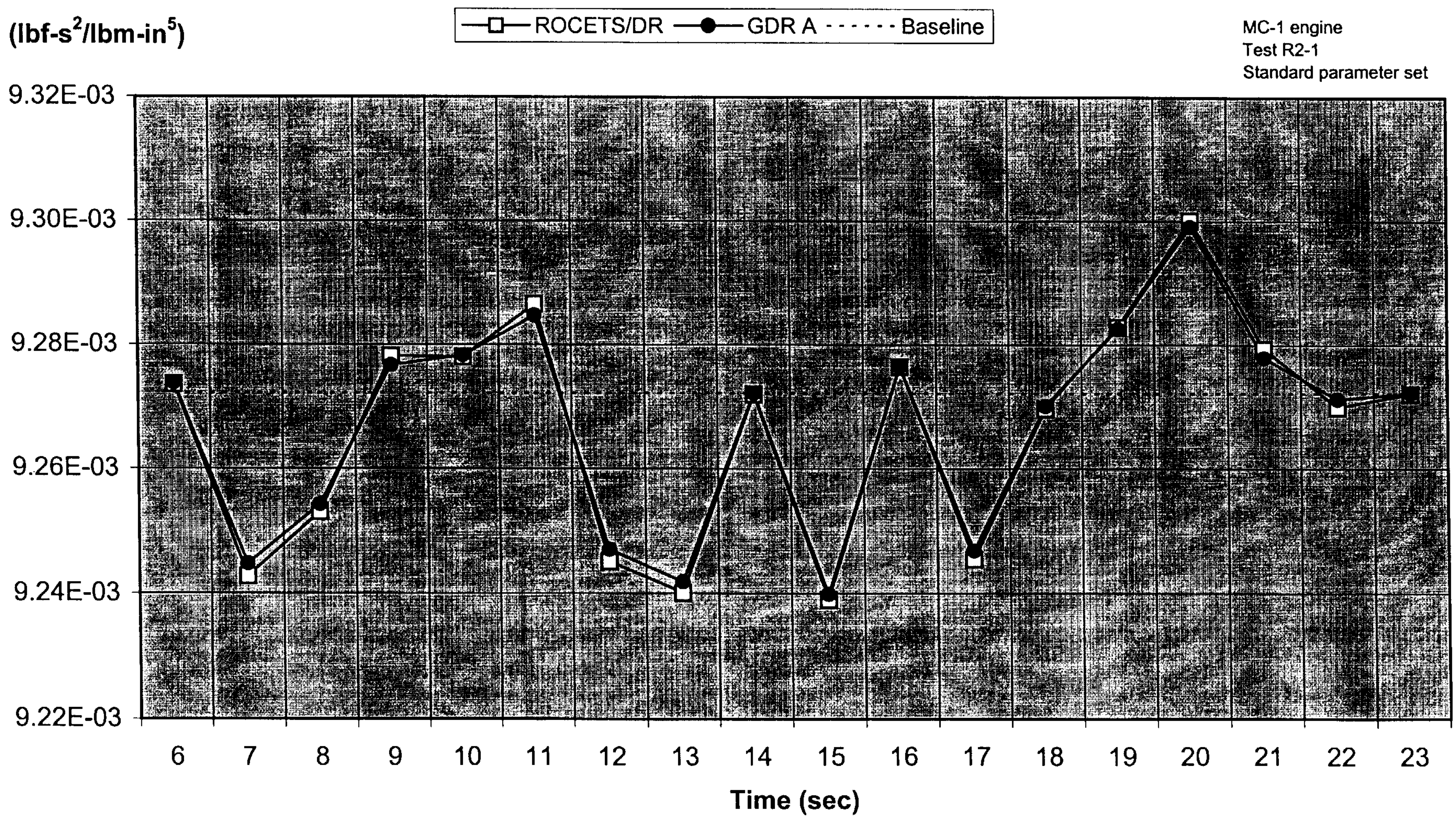


Figure D2 Comparison of GDR and ROCETS/DR results RCALMO

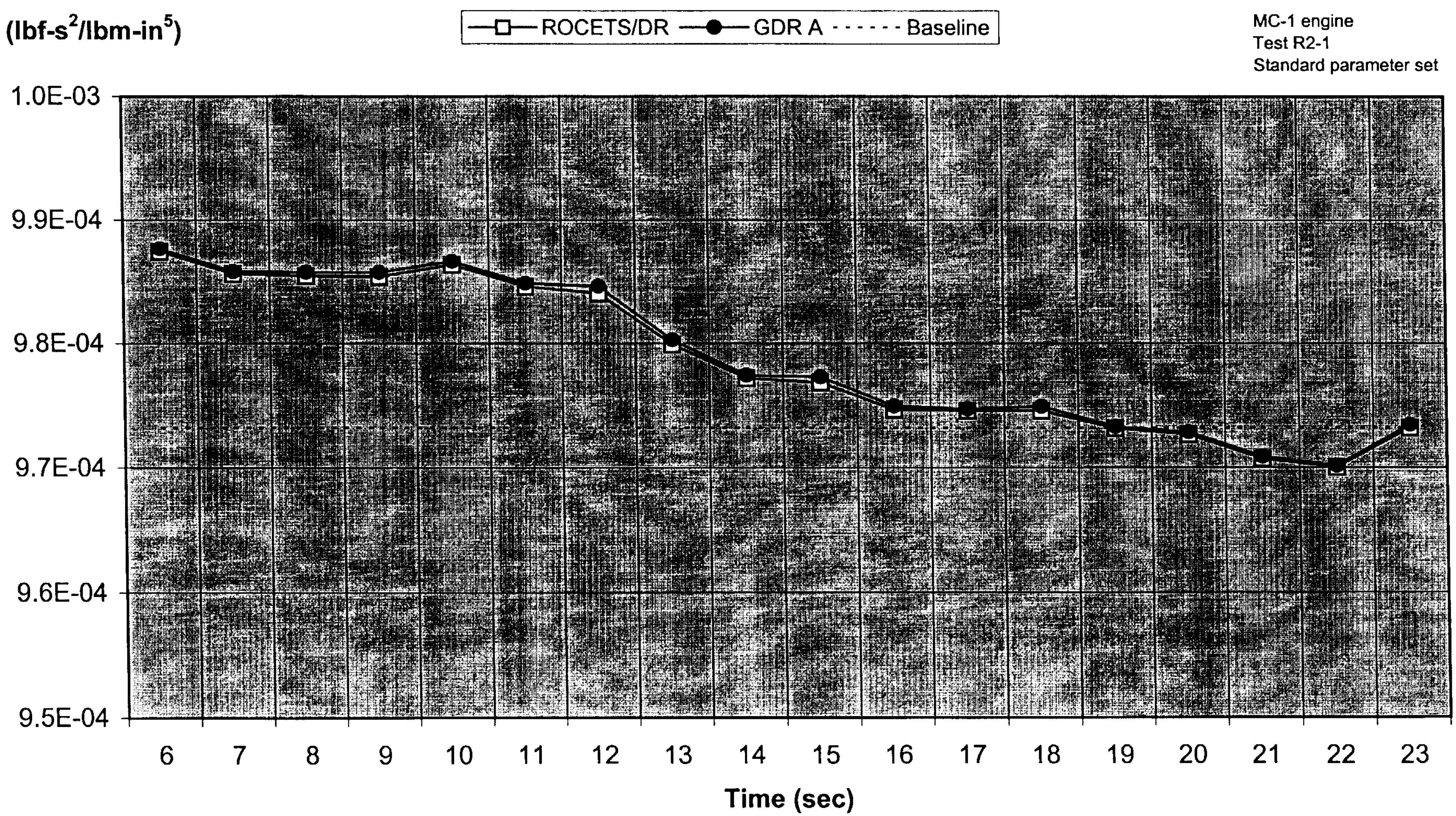


Figure D3 Comparison of GDR and ROCETS/DR results RKFL1

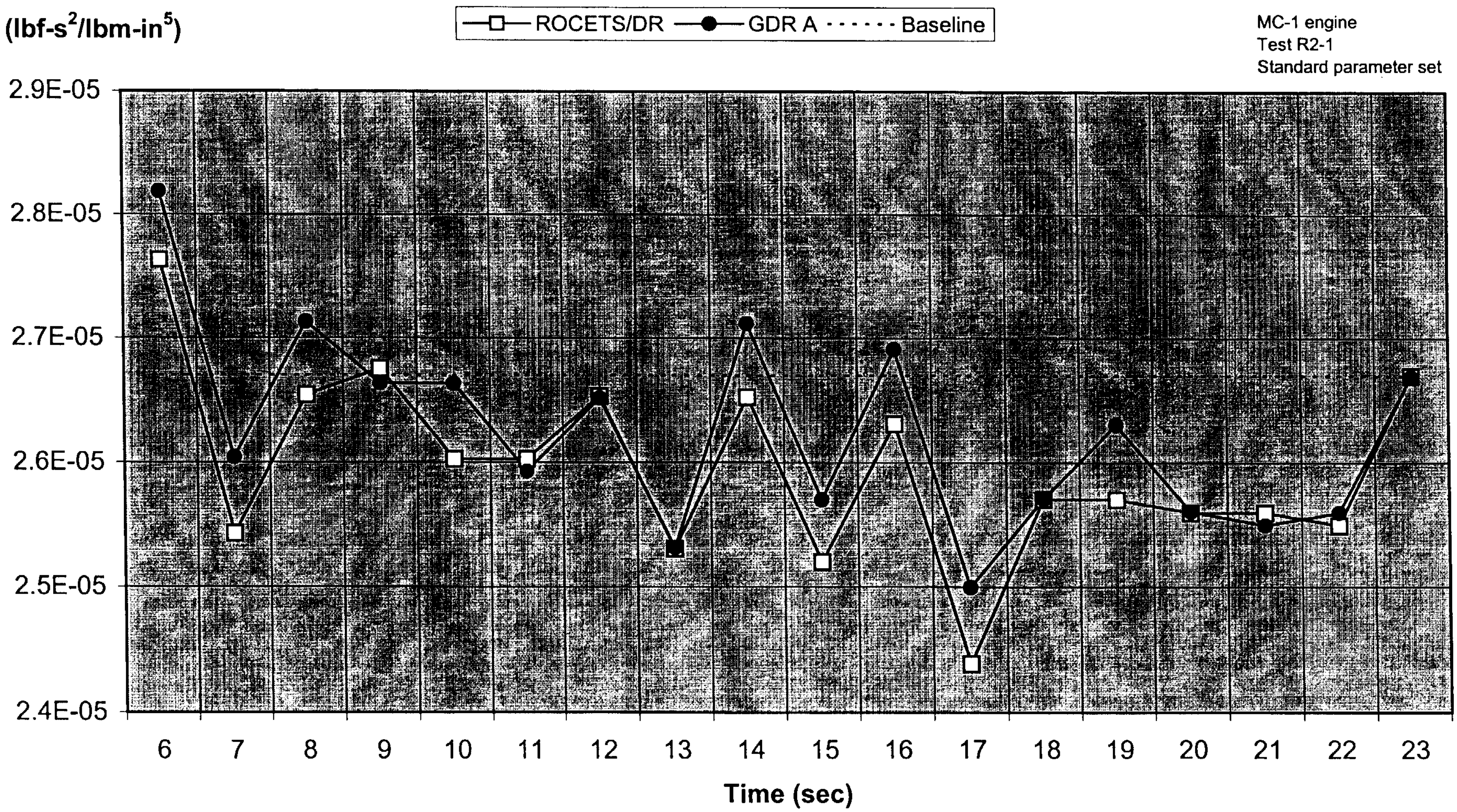


Figure D4 Comparison of GDR and ROCETS/DR results ROLN1

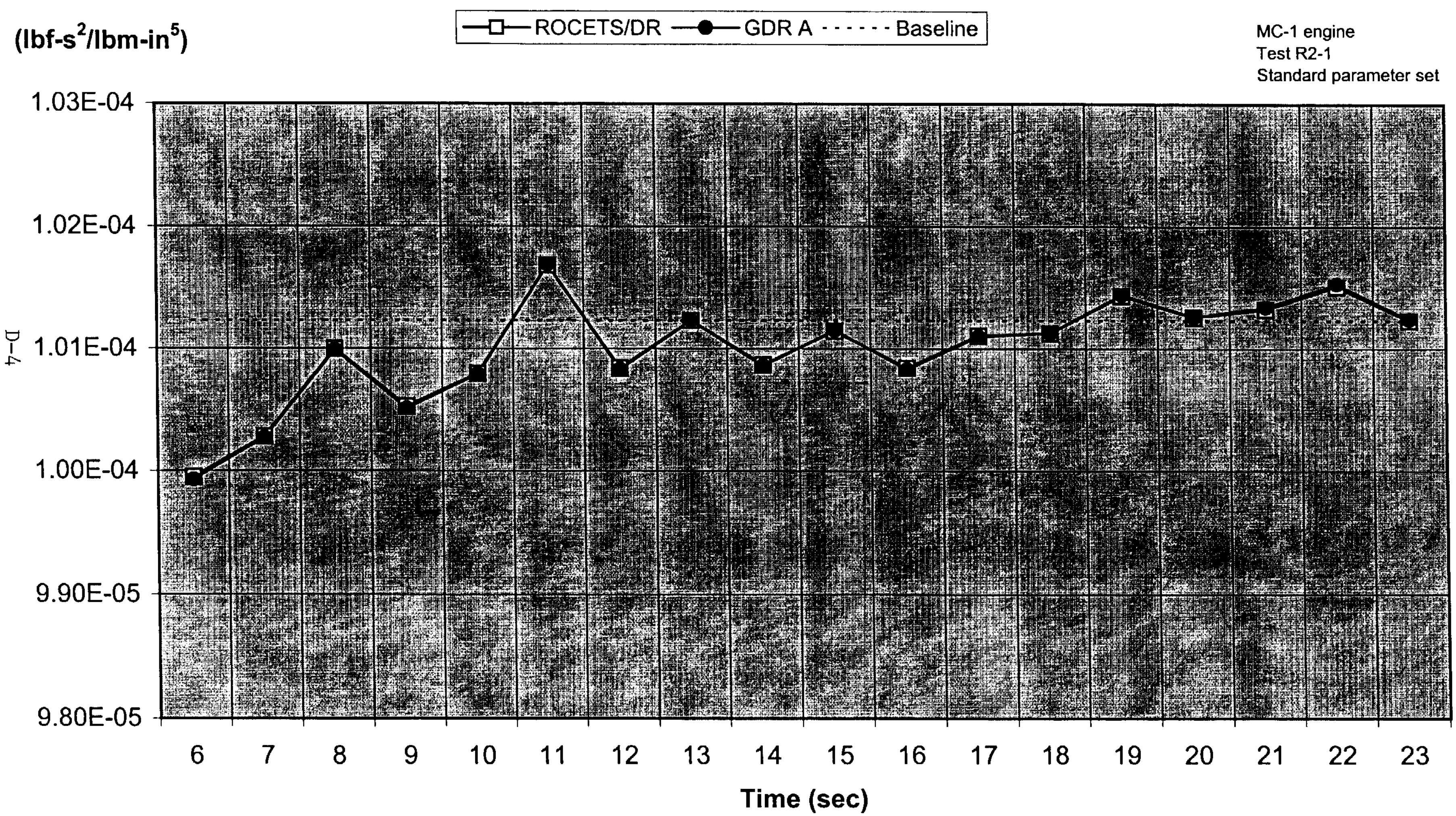


Figure D5 Comparison of GDR and ROCETS/DR results XMGGKO

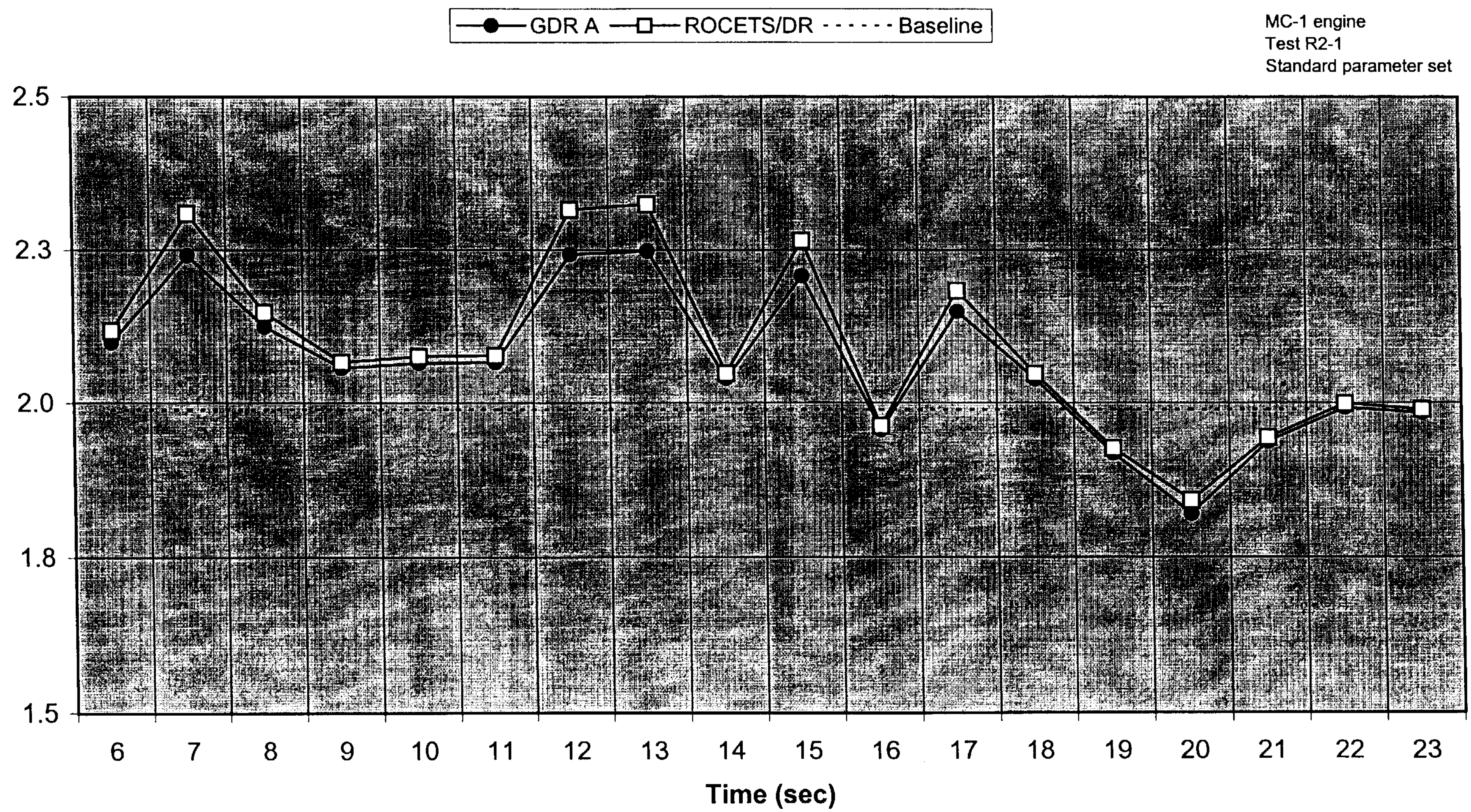


Figure D6 Comparison of GDR and ROCETS/DR results XMGGOO

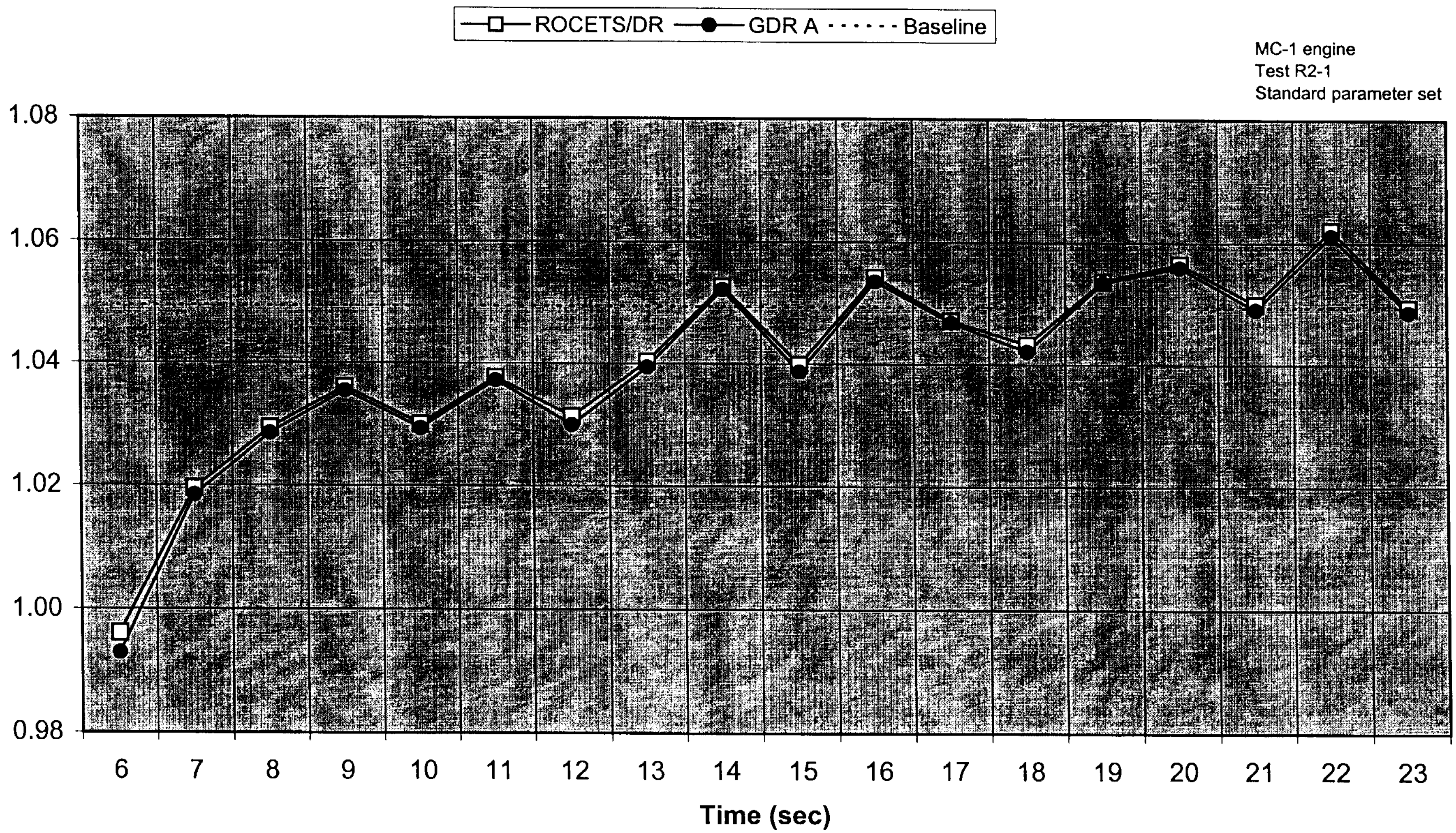


Figure D7 Comparison of GDR and ROCETS/DR results CDGGKI

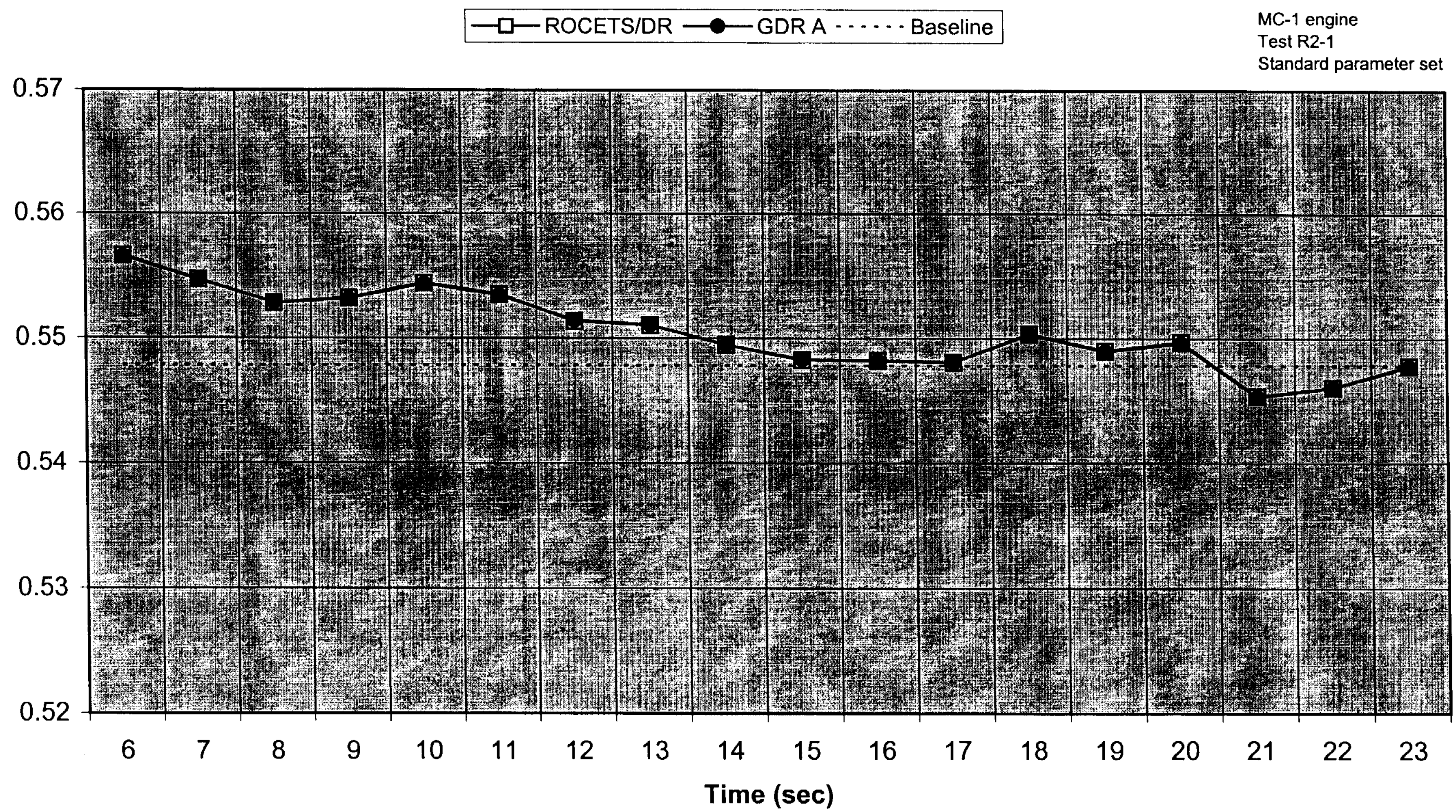


Figure D8 Comparison of GDR and ROCETS/DR results CDGGOI

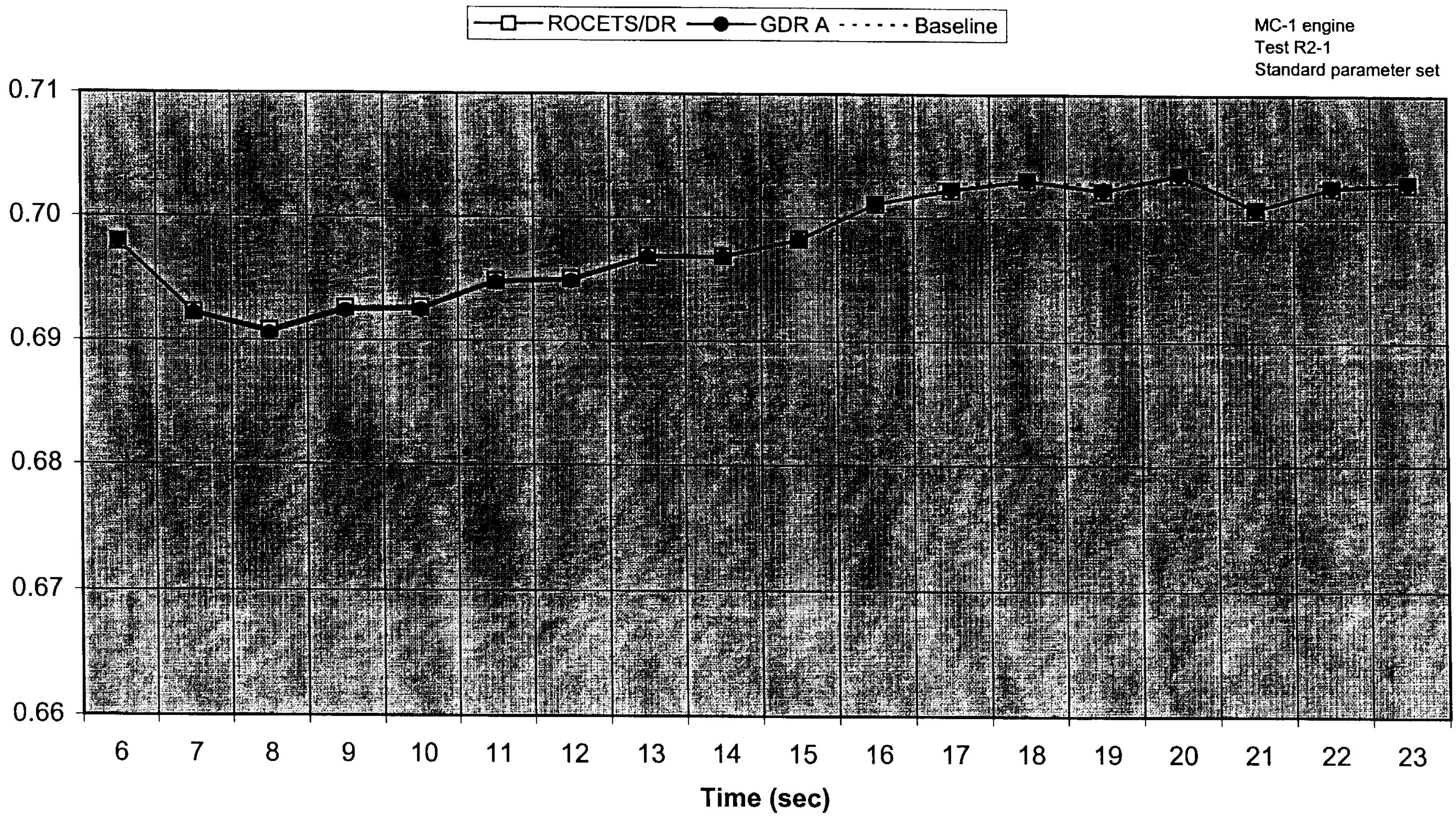


Figure D9 Comparison of GDR and ROCETS/DR results CDKINJ

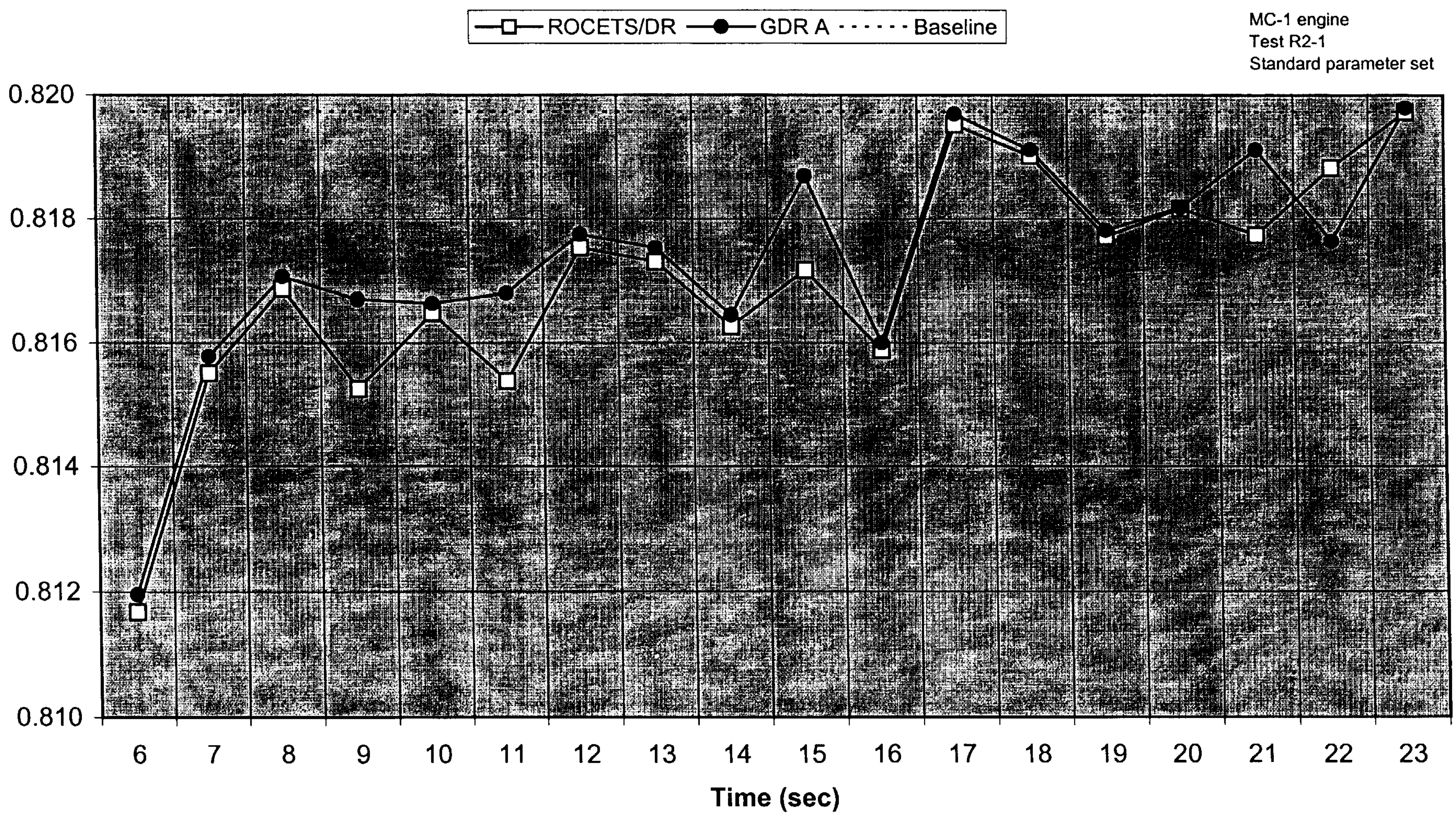


Figure D10 Comparison of GDR and ROCETS/DR results CDOINJ

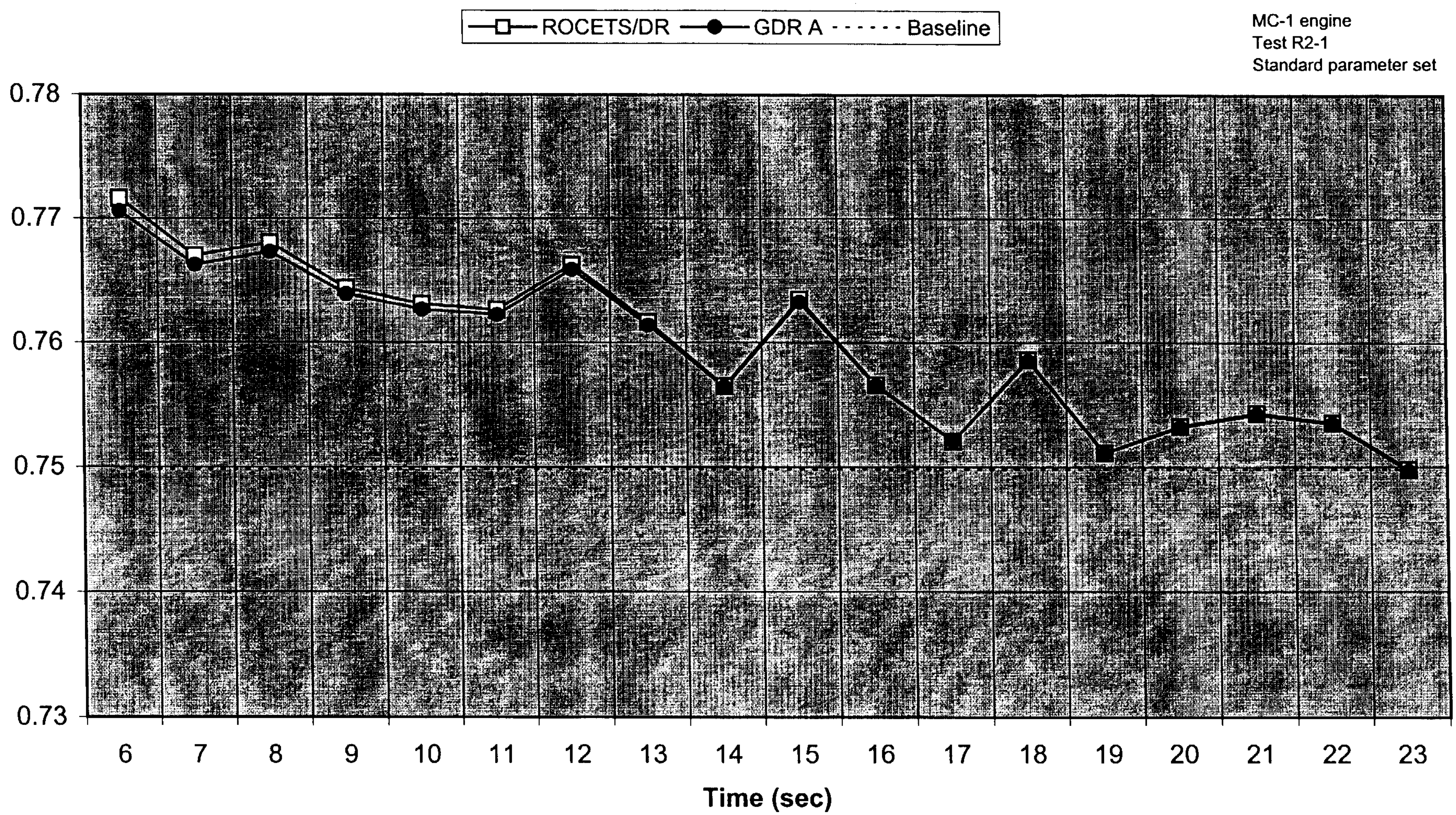


Figure D11 Comparison of GDR and ROCETS/DR results PSIMKPMP

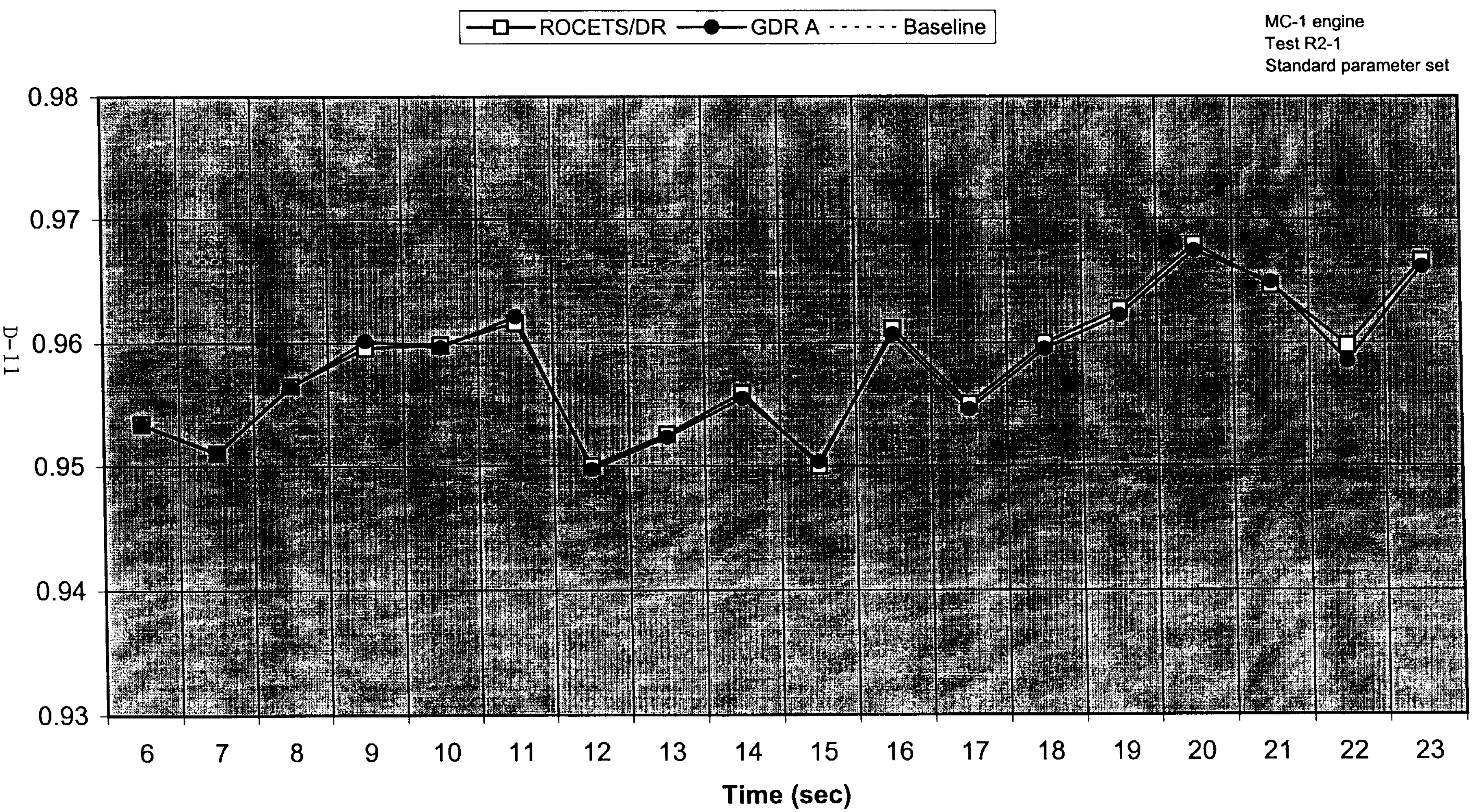


Figure D12 Comparison of GDR and ROCETS/DR results PSIMOPMP

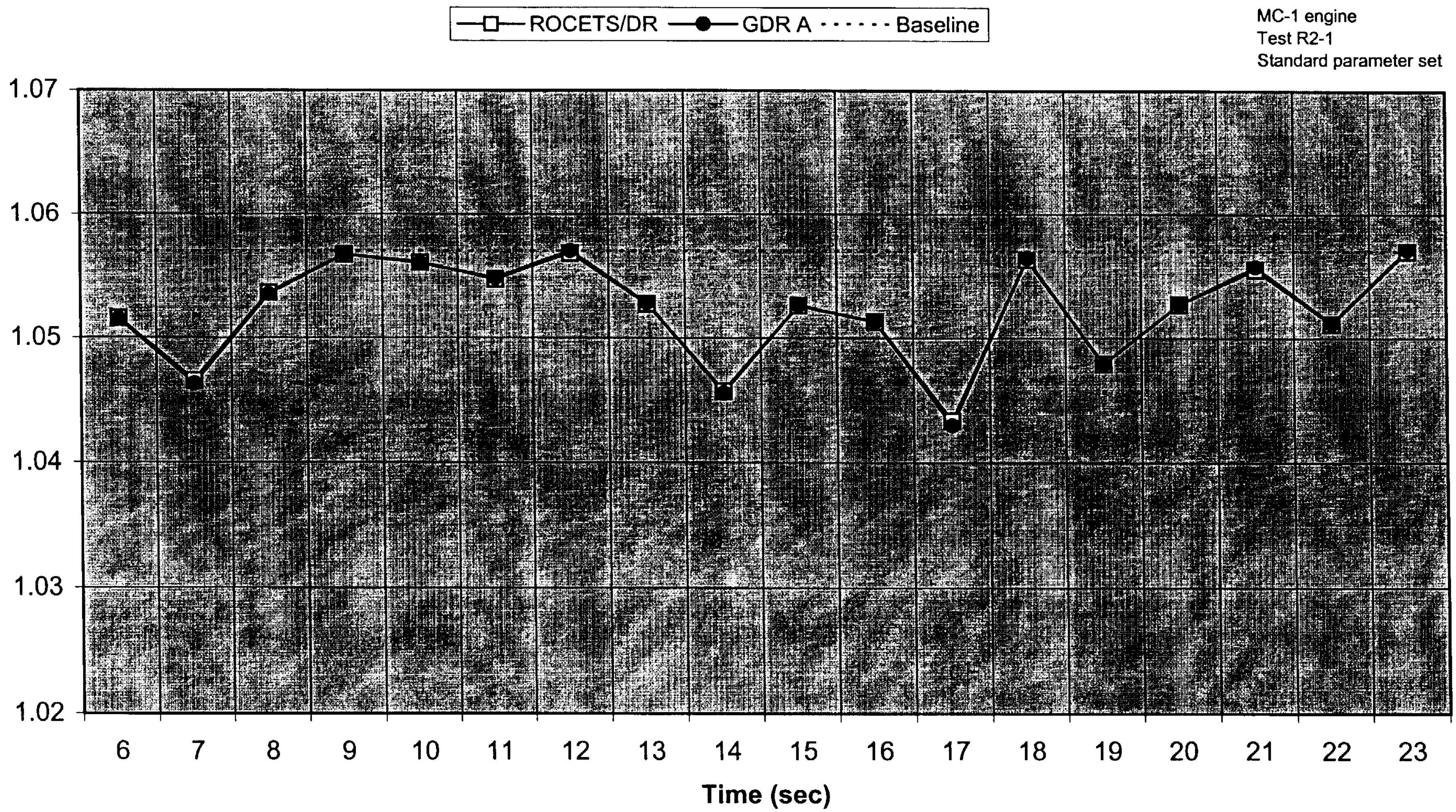


Figure D13 Comparison of GDR and ROCETS/DR results CDGGNZ

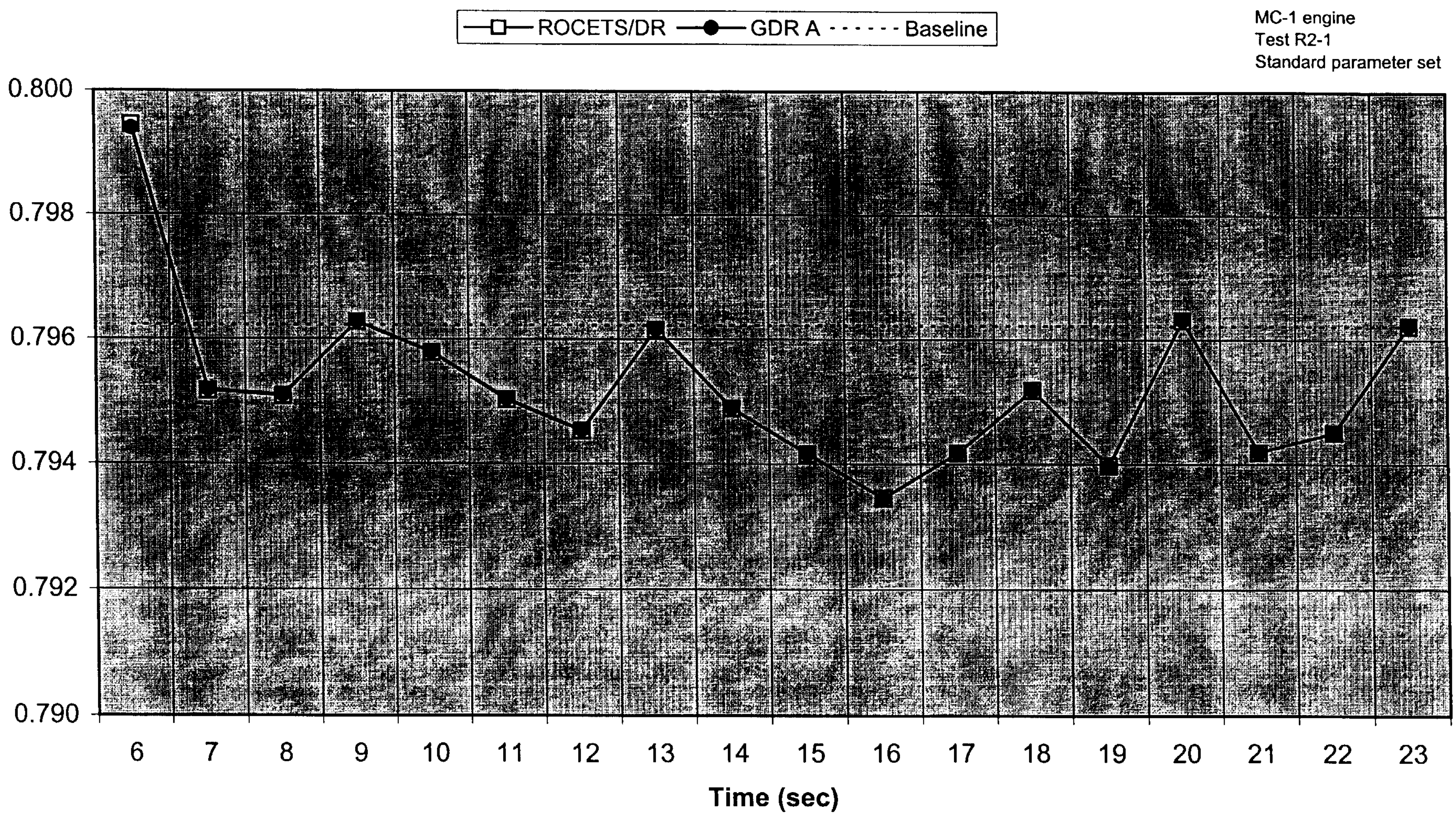


Figure D14 Comparison of GDR and ROCETS/DR results FRICFACT

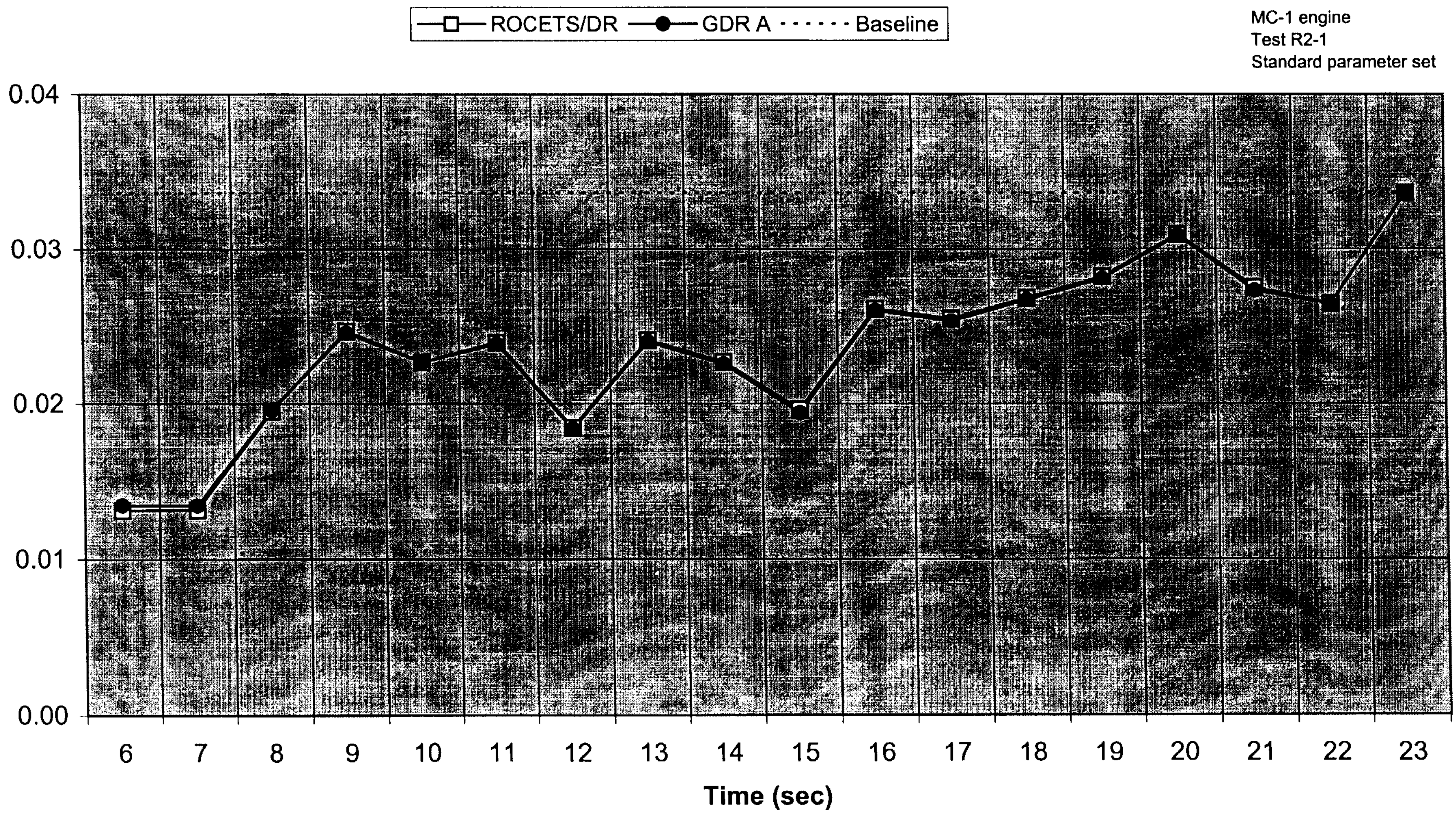


Figure D15 Comparison of GDR and ROCETS/DR results CDNOZL

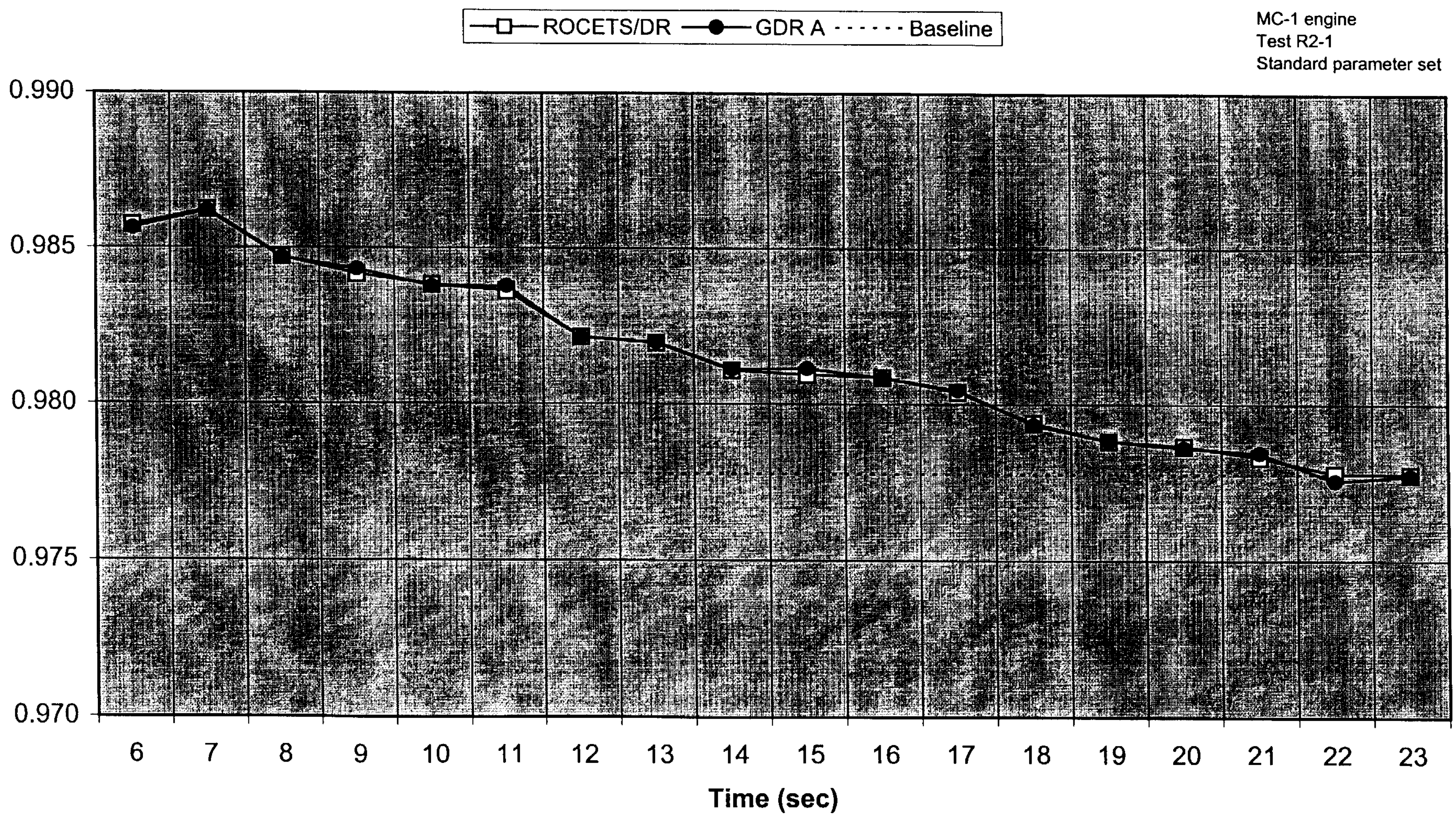


Figure D16 Comparison of GDR and ROCETS/DR results ECSMMCHB

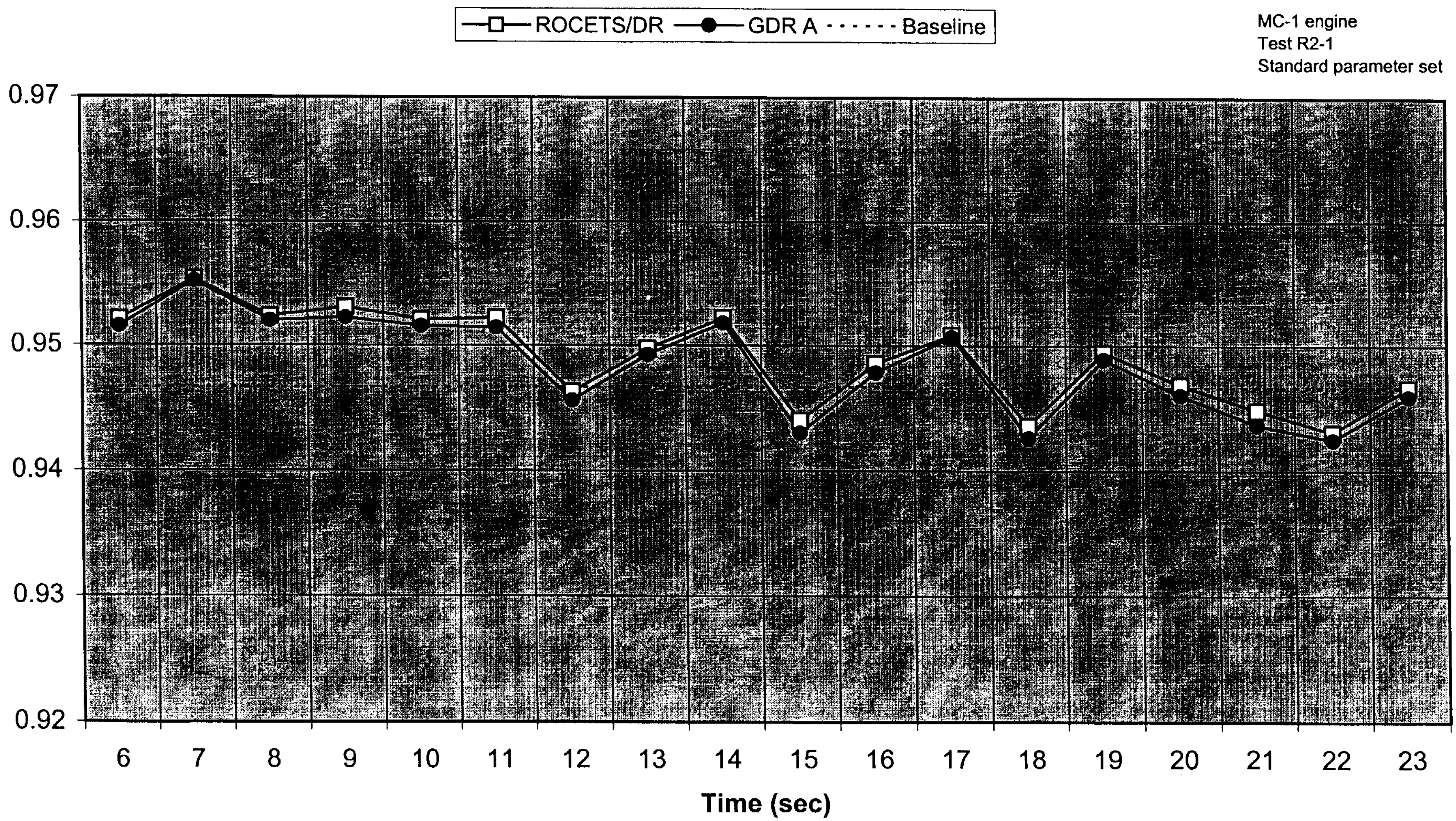
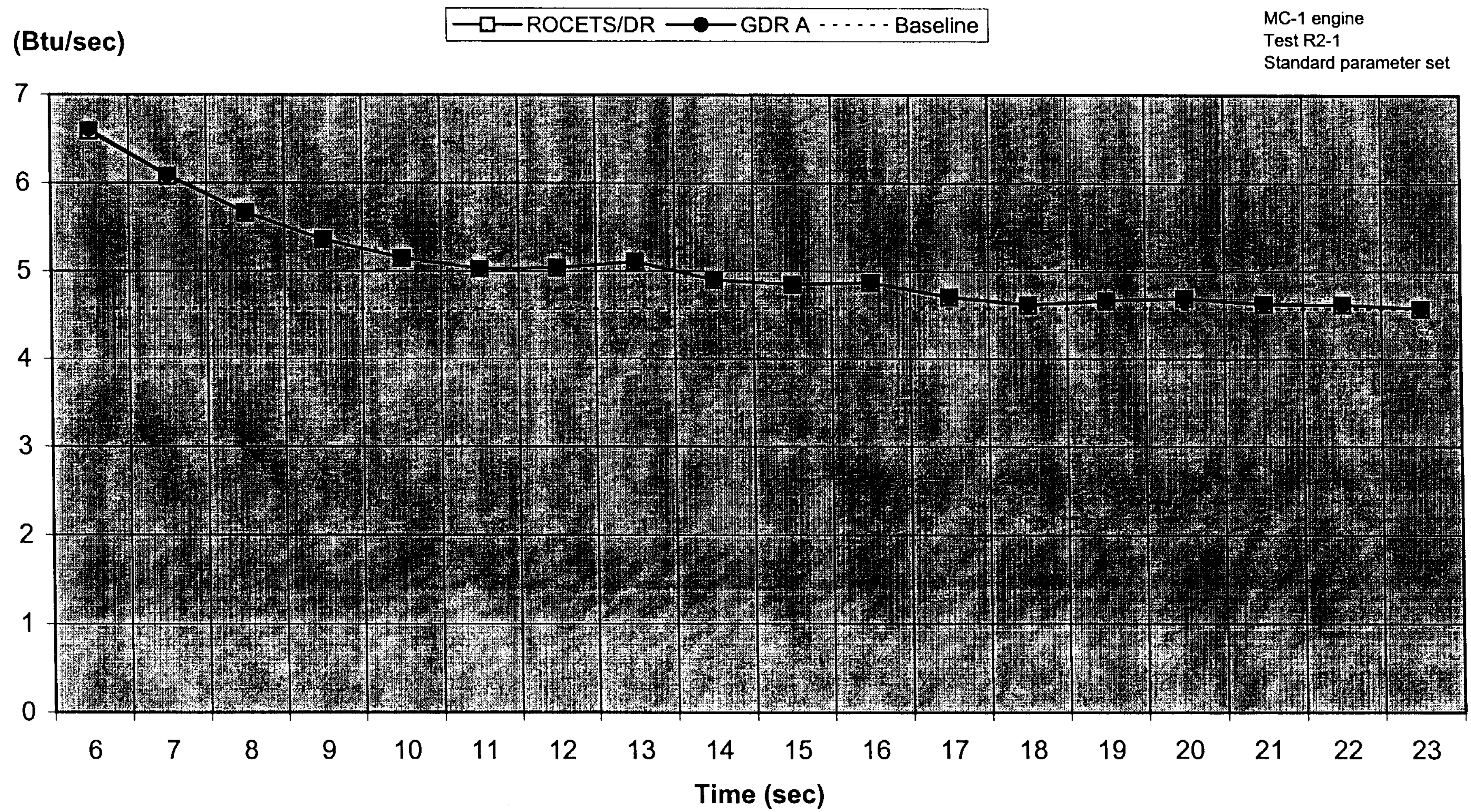


Figure D17 Comparison of GDR and ROCETS/DR results QDOTVL18



Appendix E

MC-1 engine
Allocation of single source anomaly effects by data reduction

Figure E1 RMMCRP single source anomaly allocation

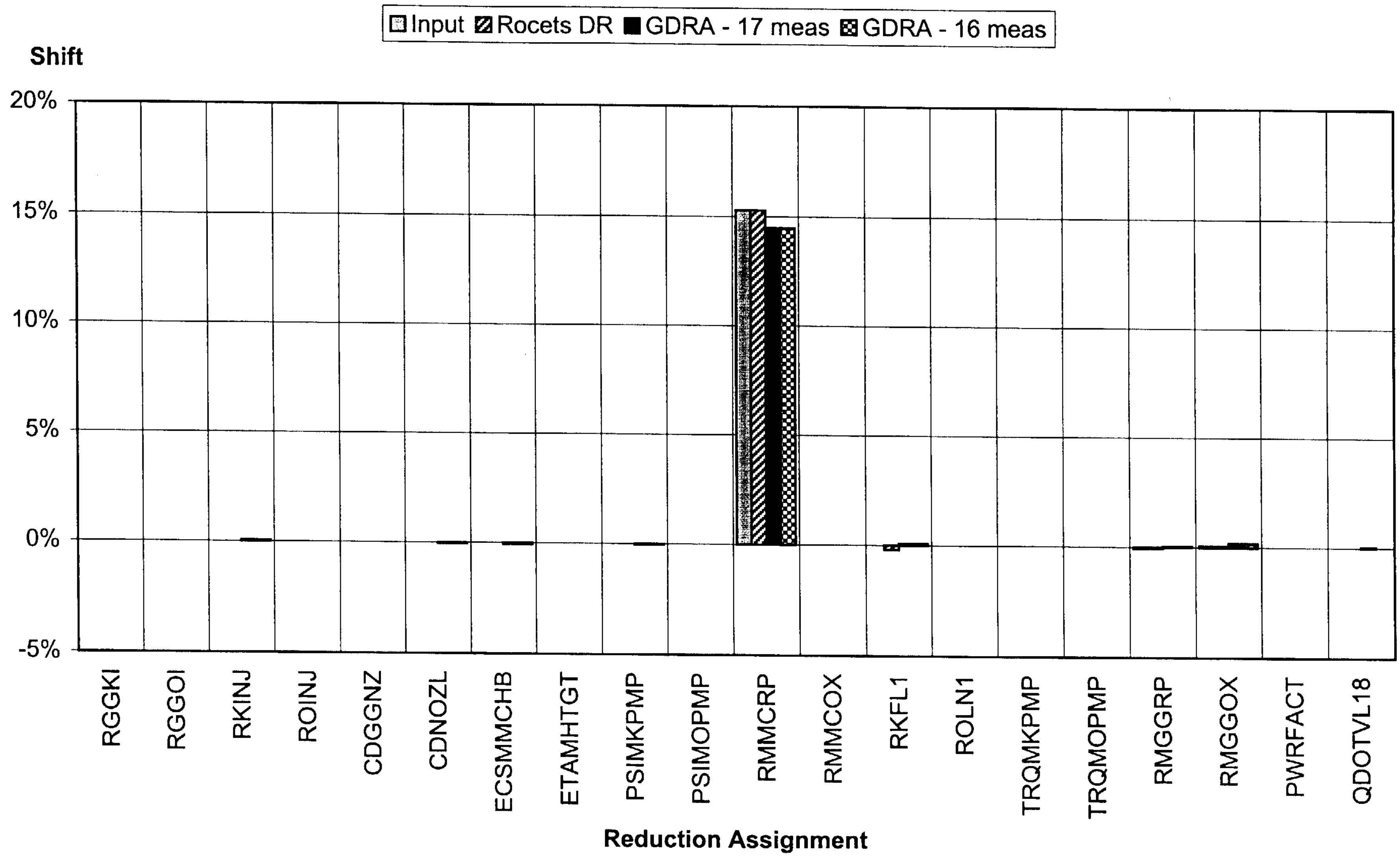


Figure E2 RMMCOX single source anomaly allocation

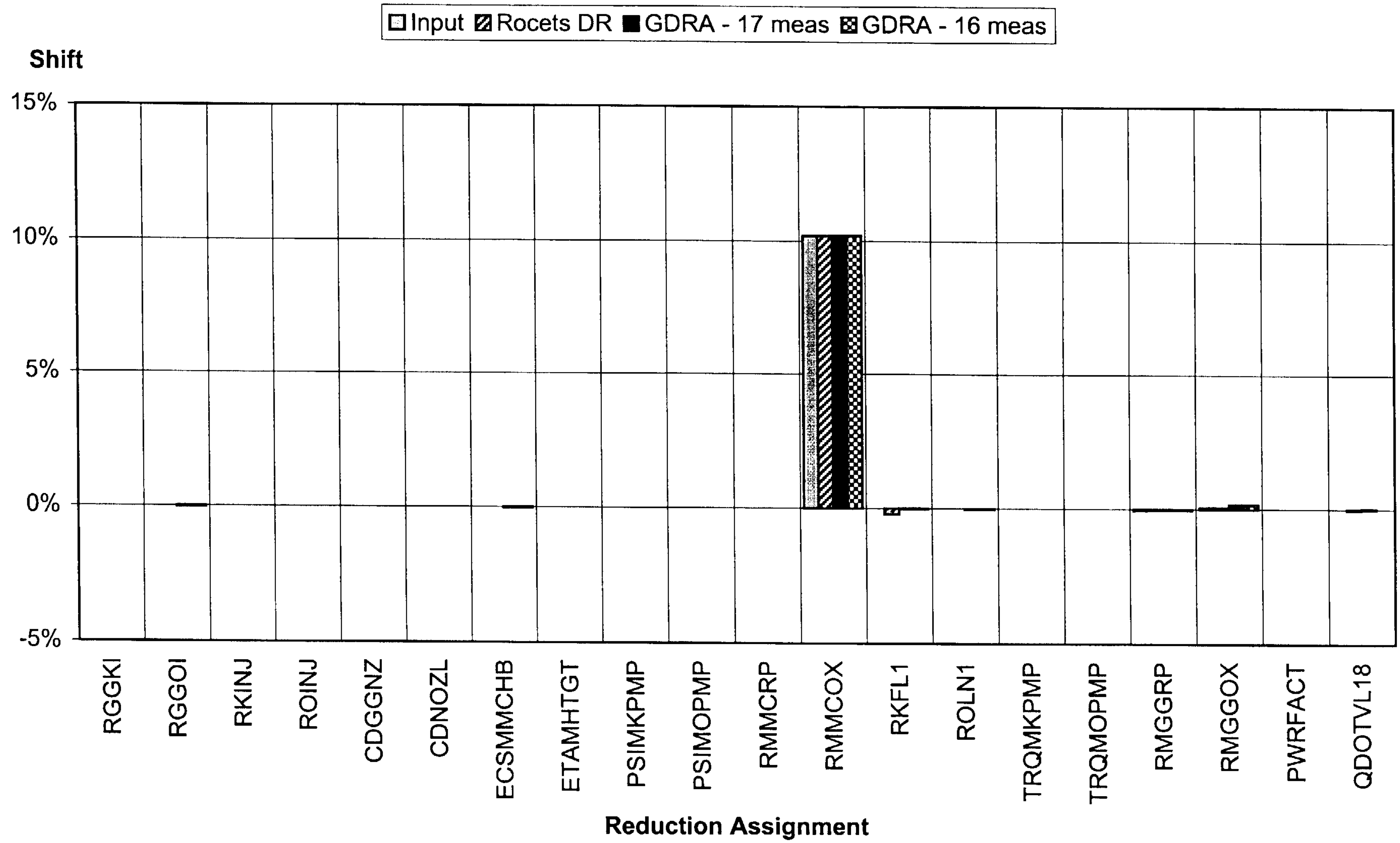


Figure E3 RKFL1 single source anomaly allocation

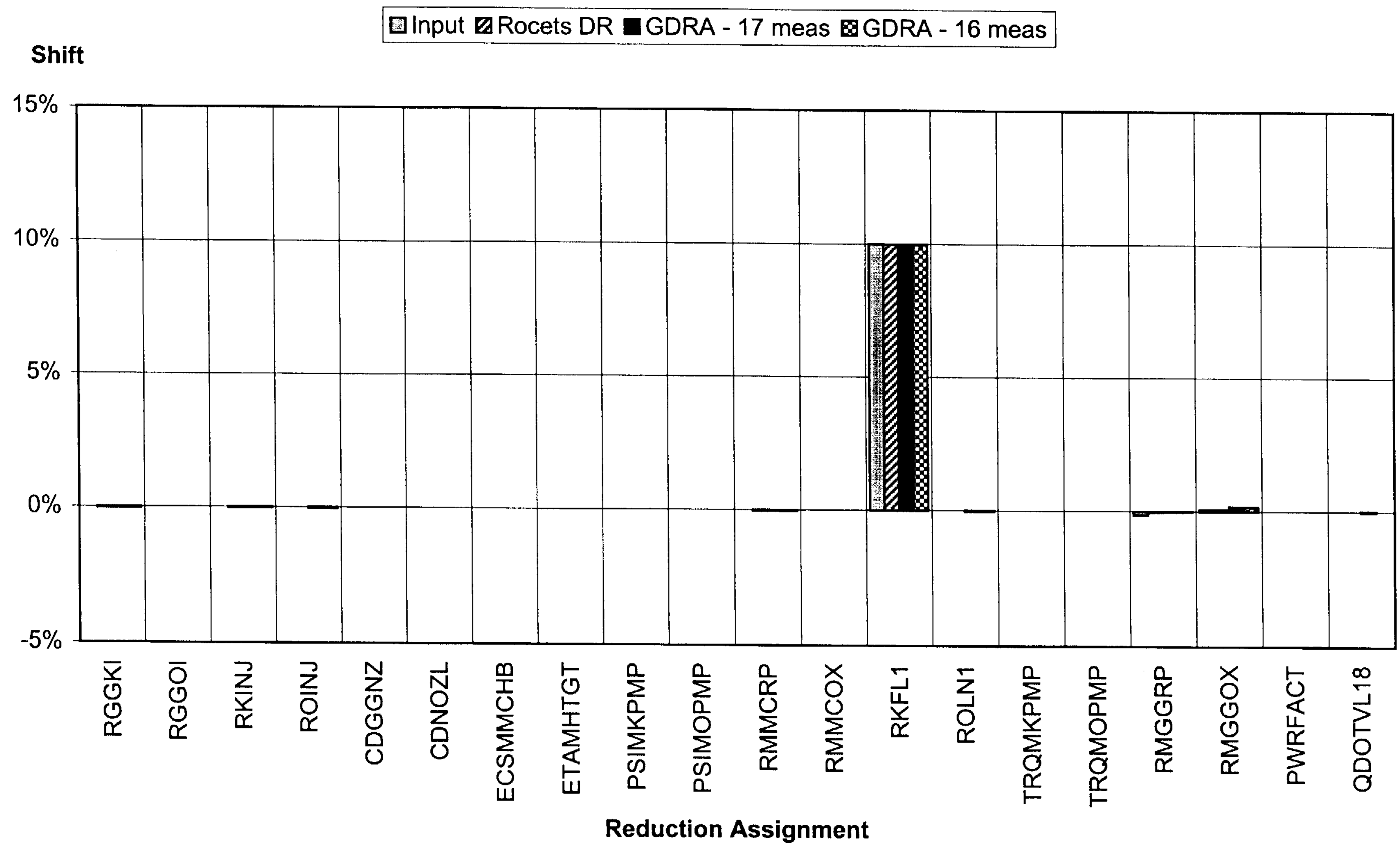


Figure E4   ROLN1 single source anomaly allocation

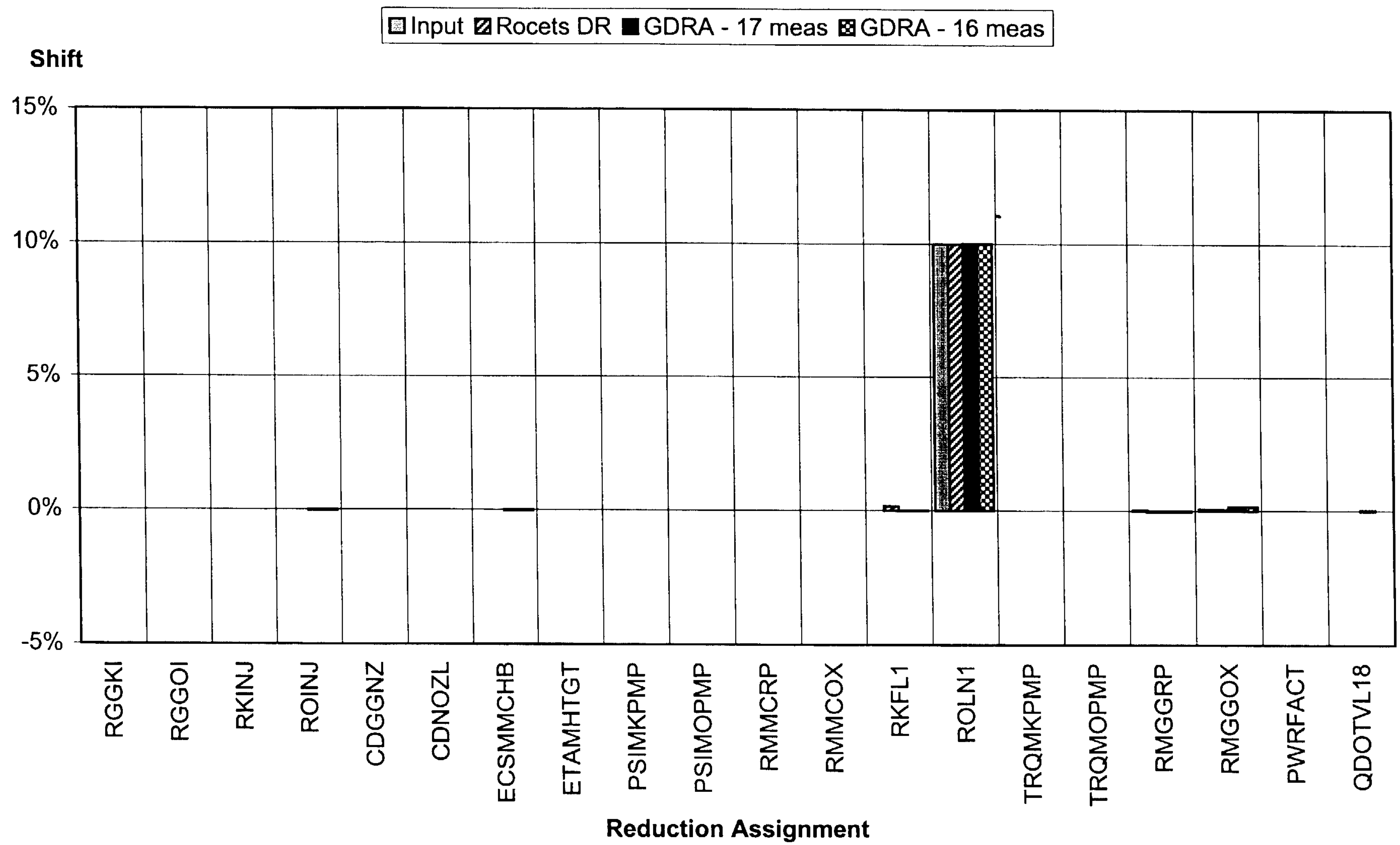


Figure E5 RMGGRP single source anomaly allocation

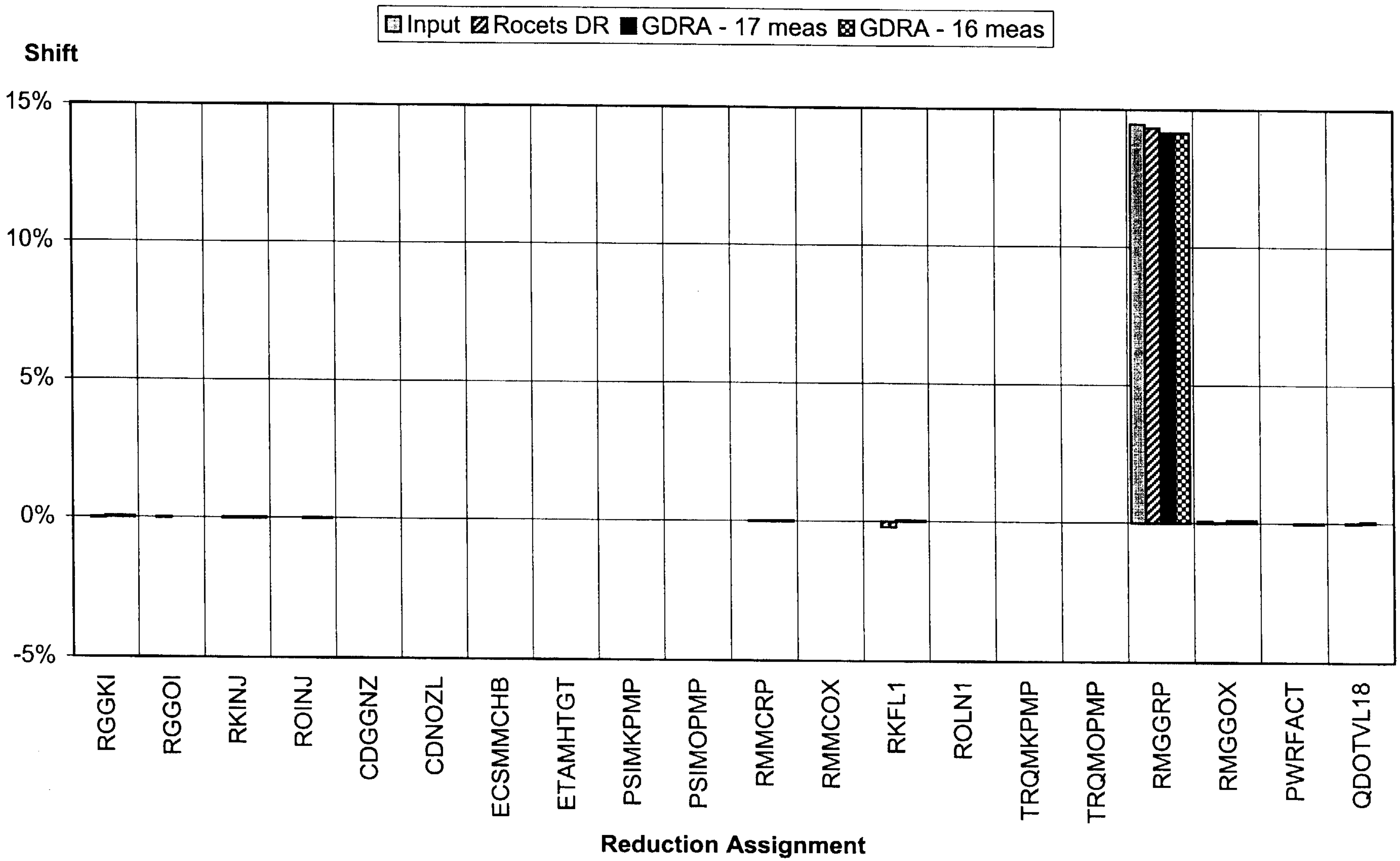


Figure E6 RMGGOX single source anomaly allocation

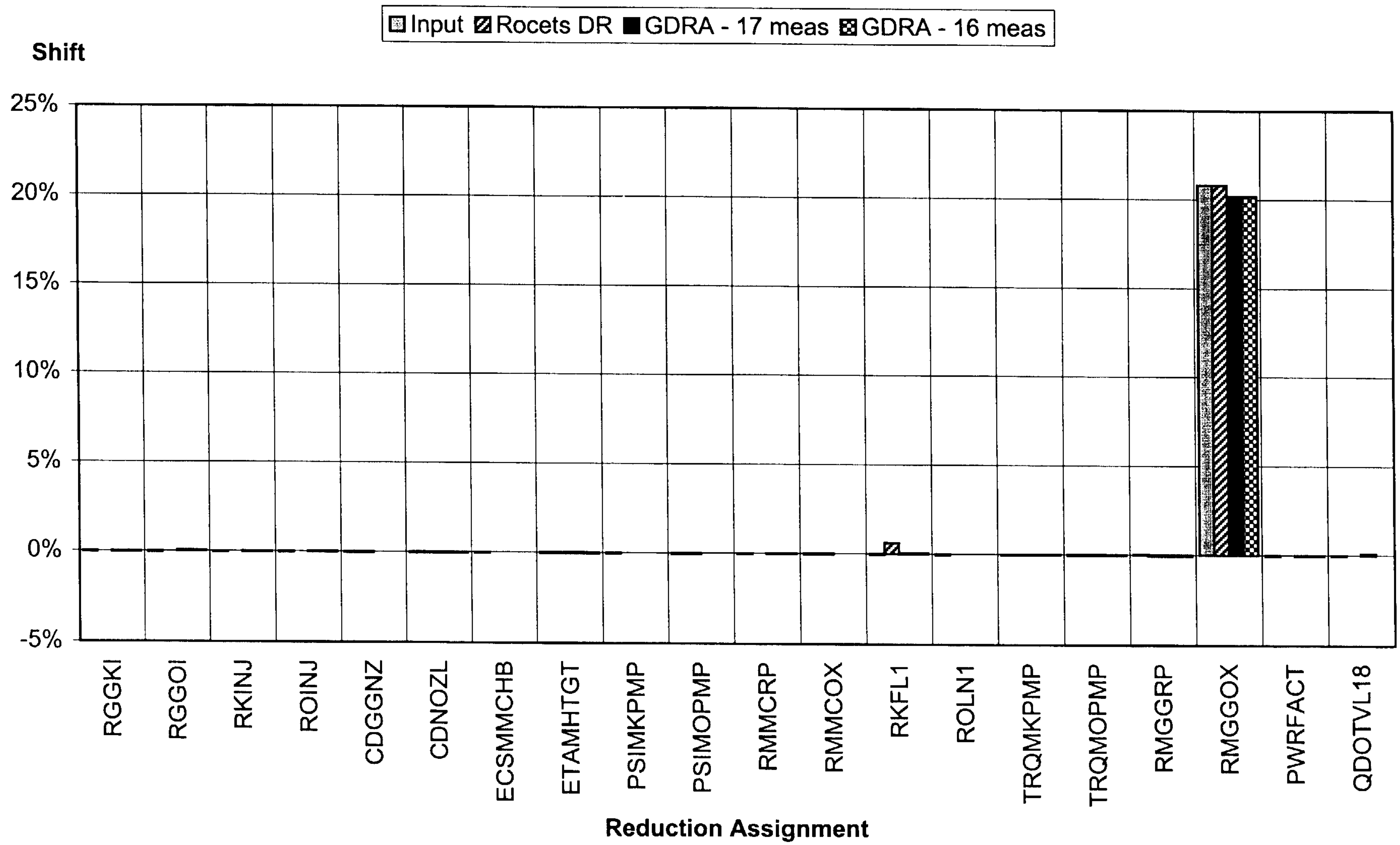


Figure E7 RGGKI single source anomaly allocation

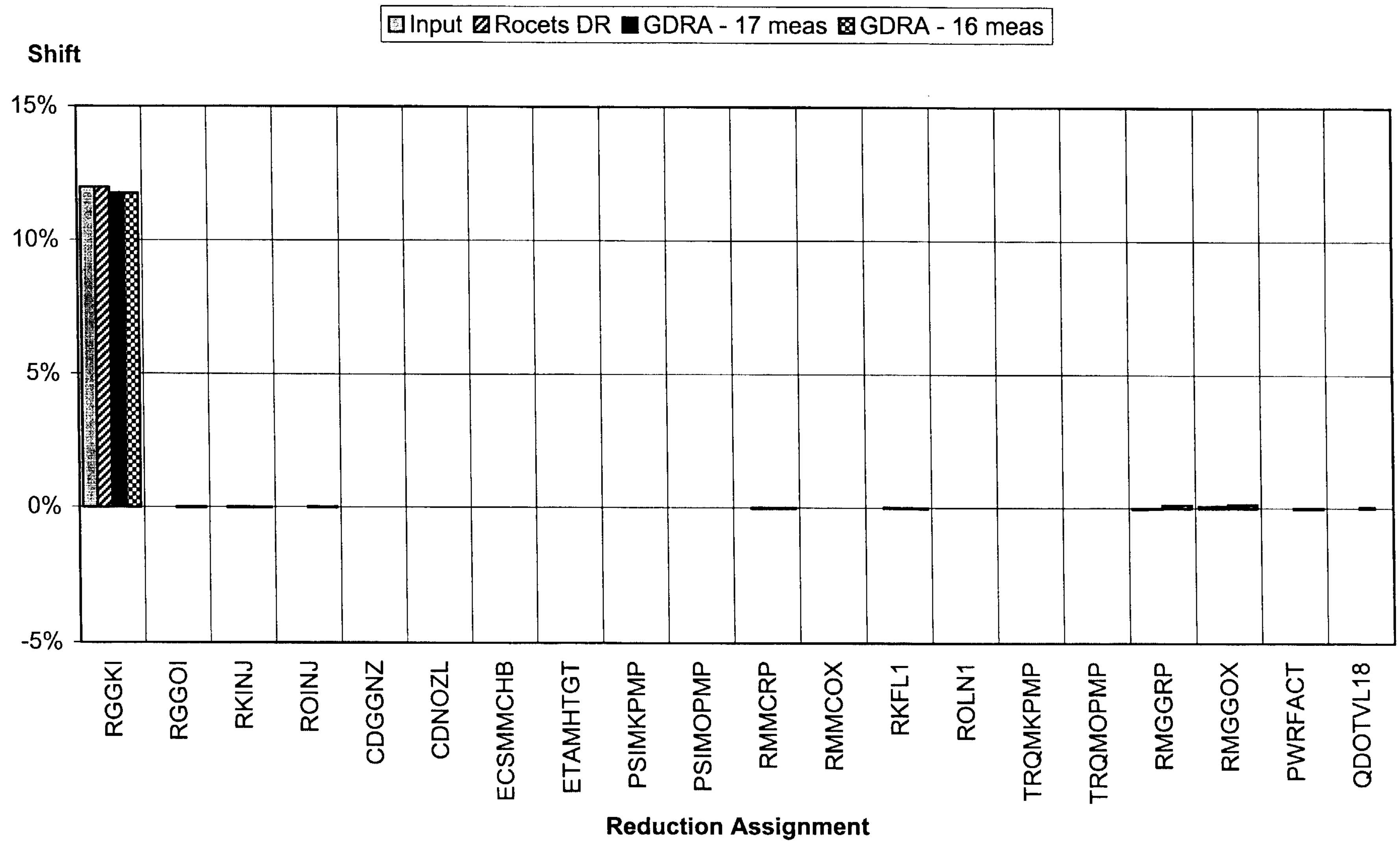


Figure E8 RGGOI single source anomaly allocation

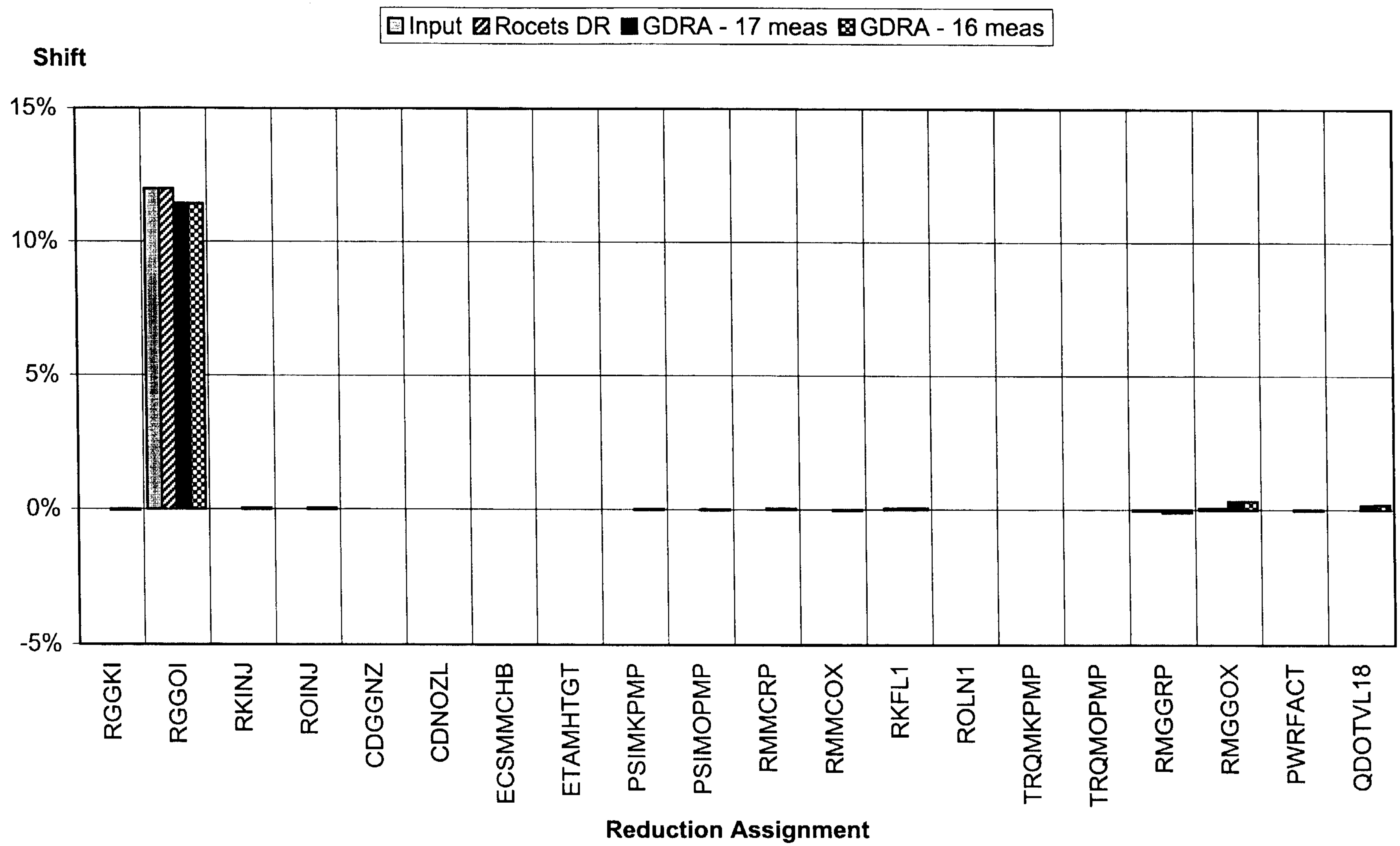


Figure E9 RKINJ single source anomaly allocation

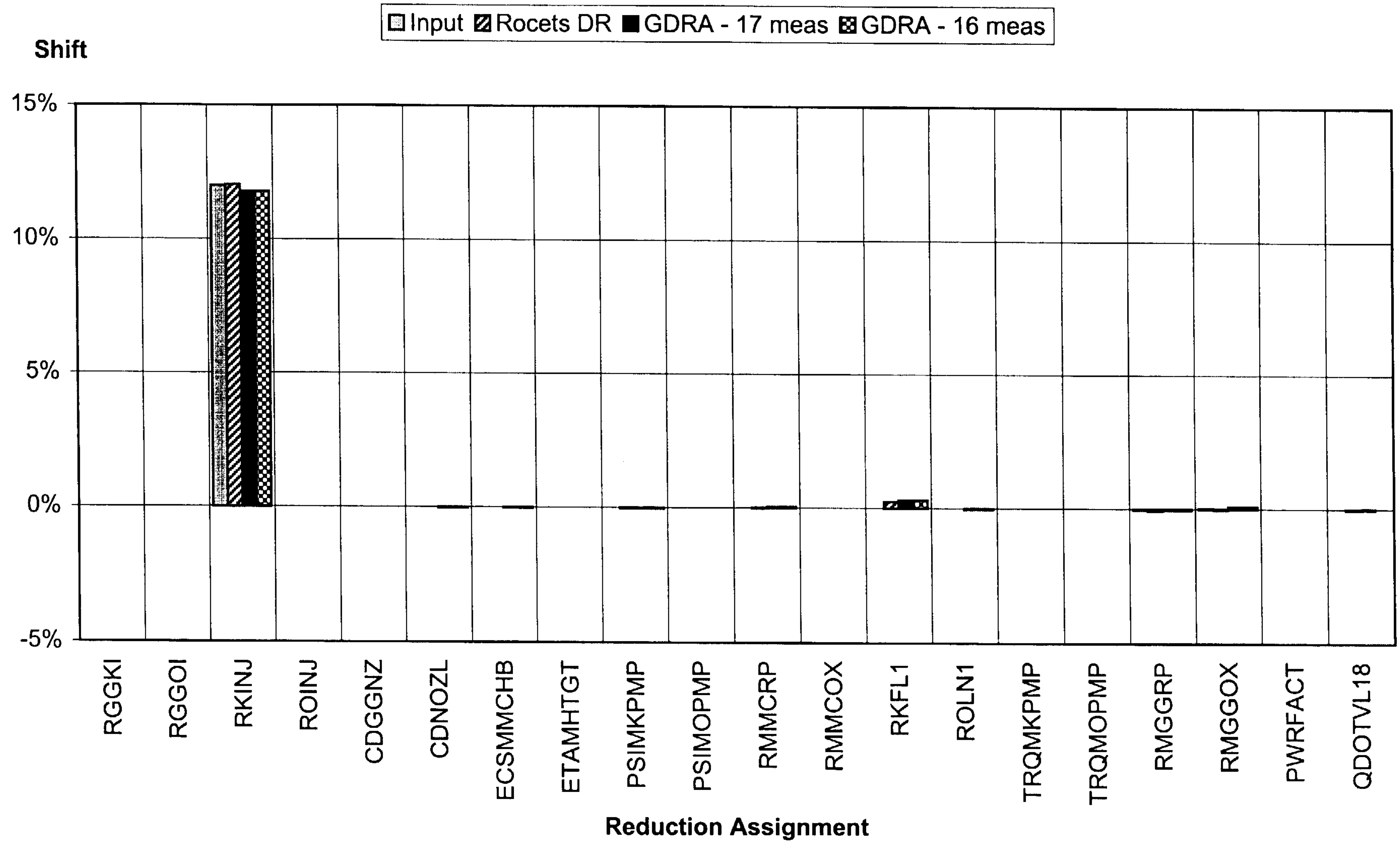


Figure E10 ROINJ single source anomaly allocation

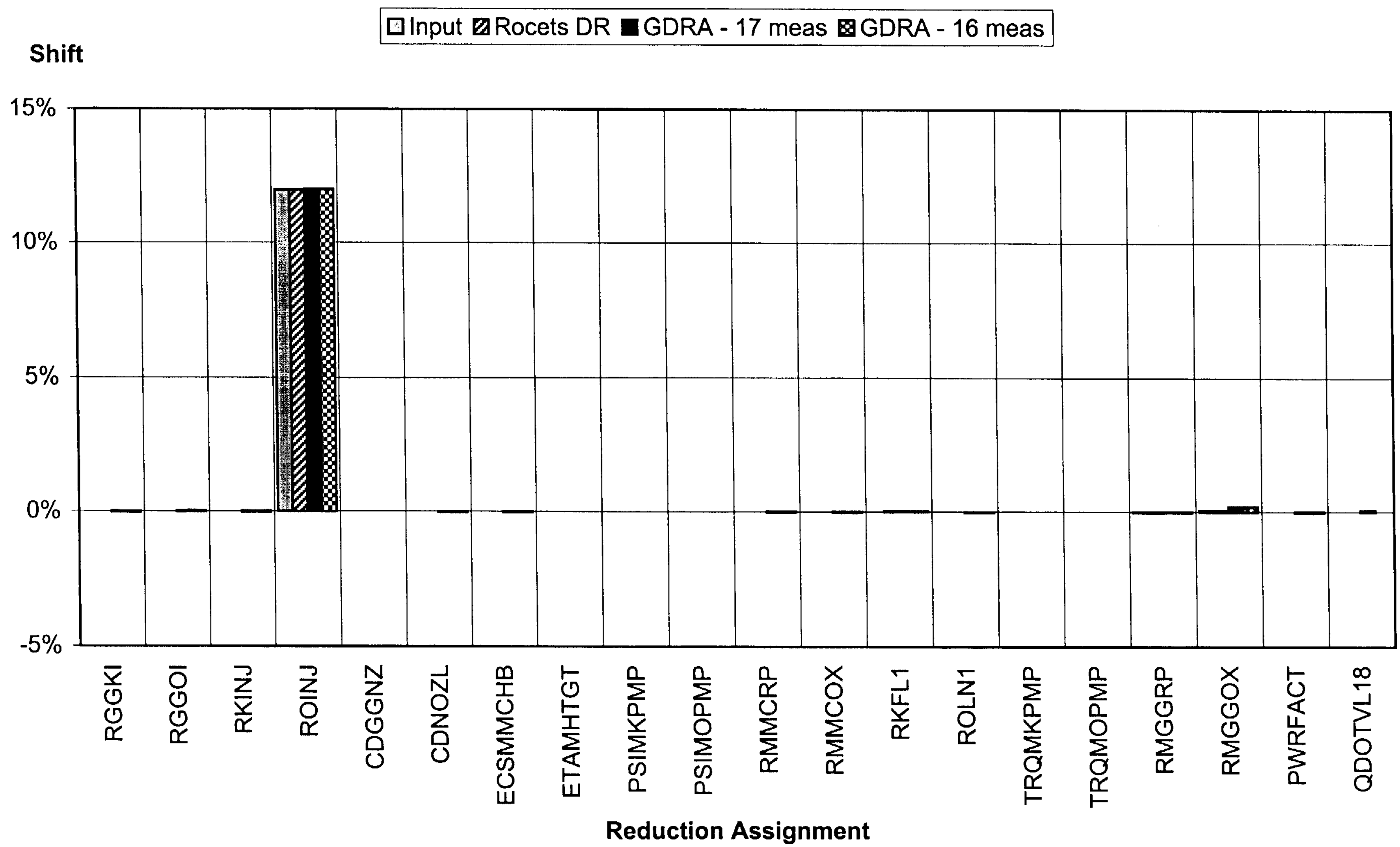


Figure E11 PSIMKPMP single source anomaly allocation

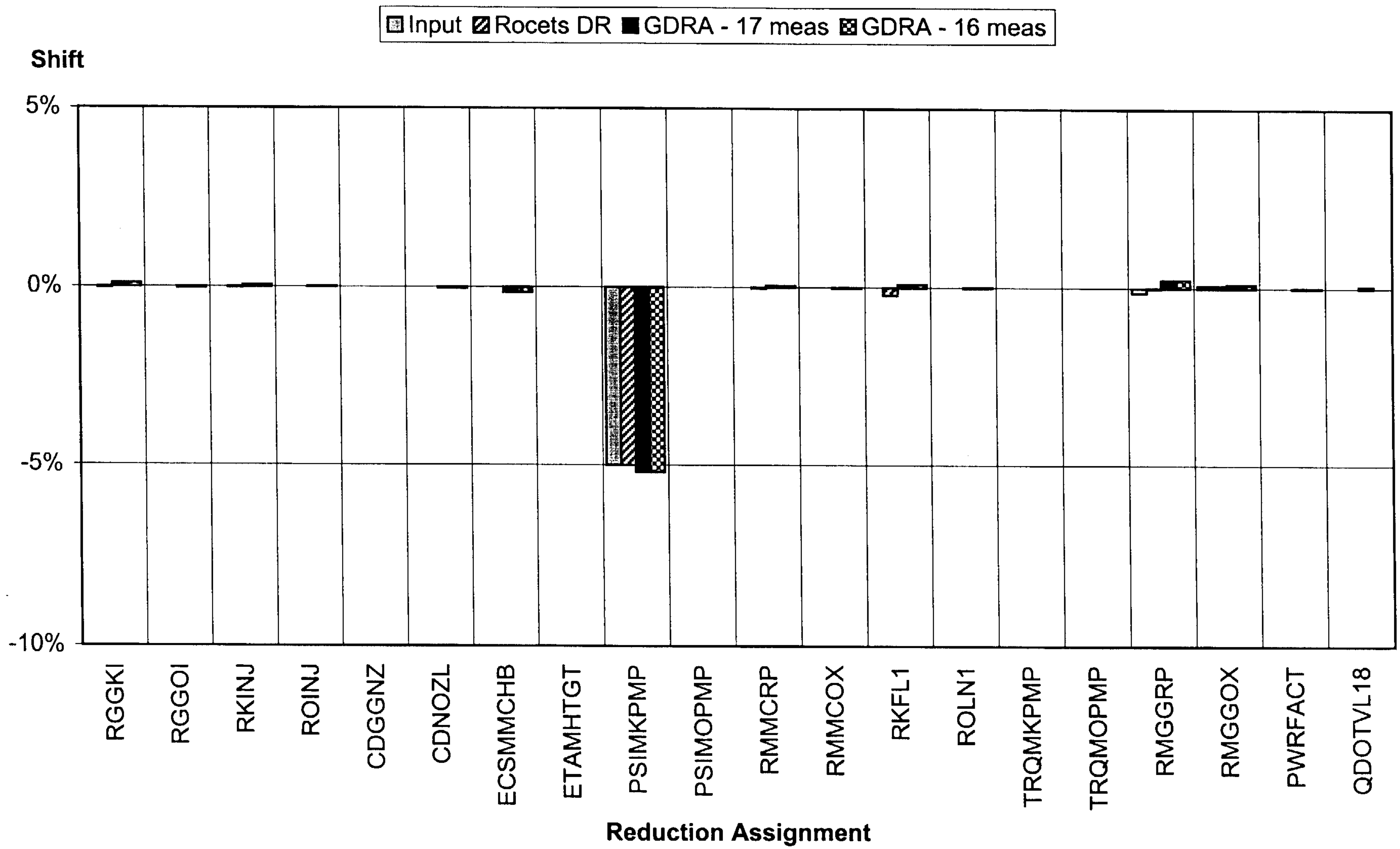


Figure E12 PSIMOPMP single source anomaly allocation

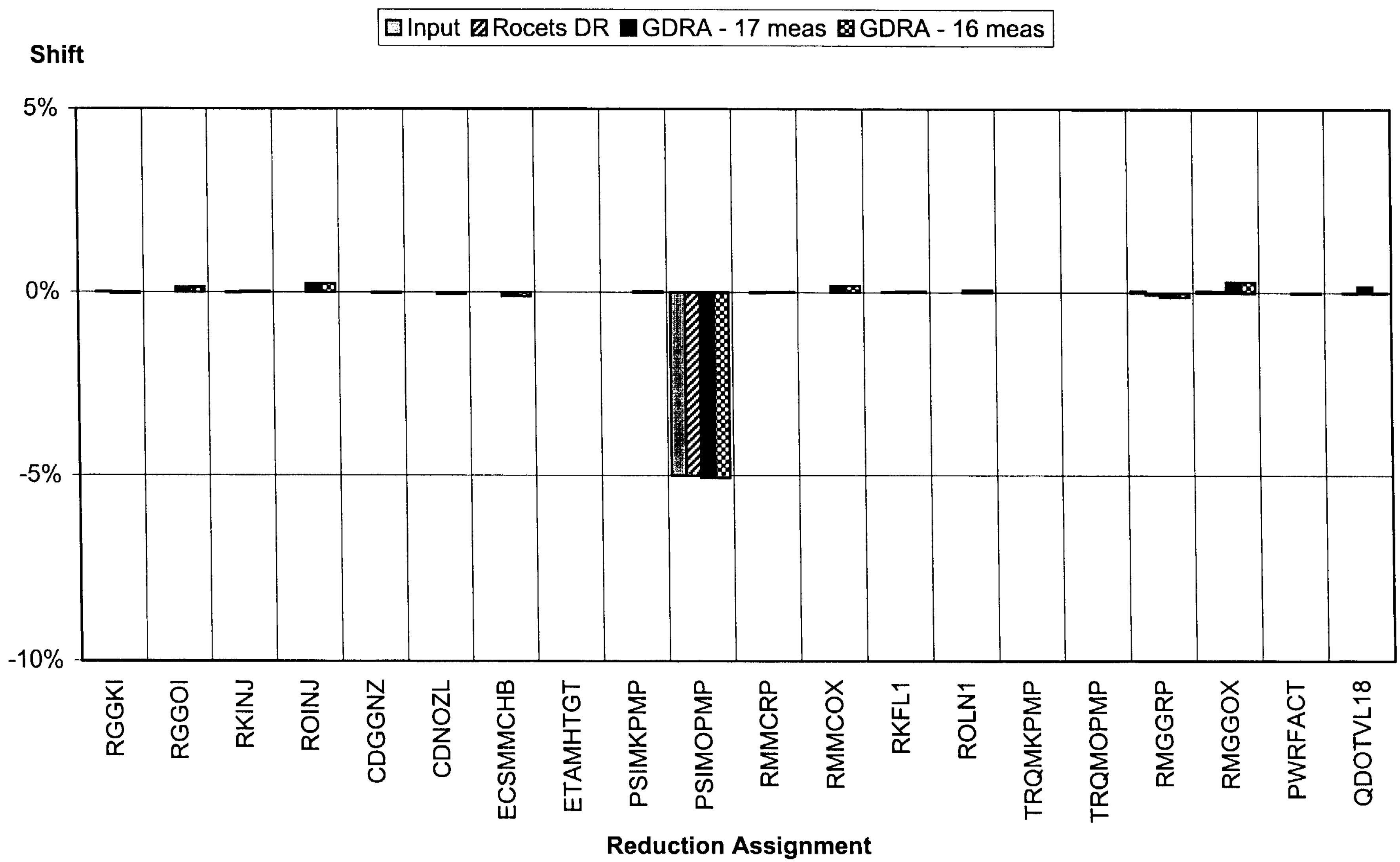


Figure E13 TRQMKPMP single source anomaly allocation

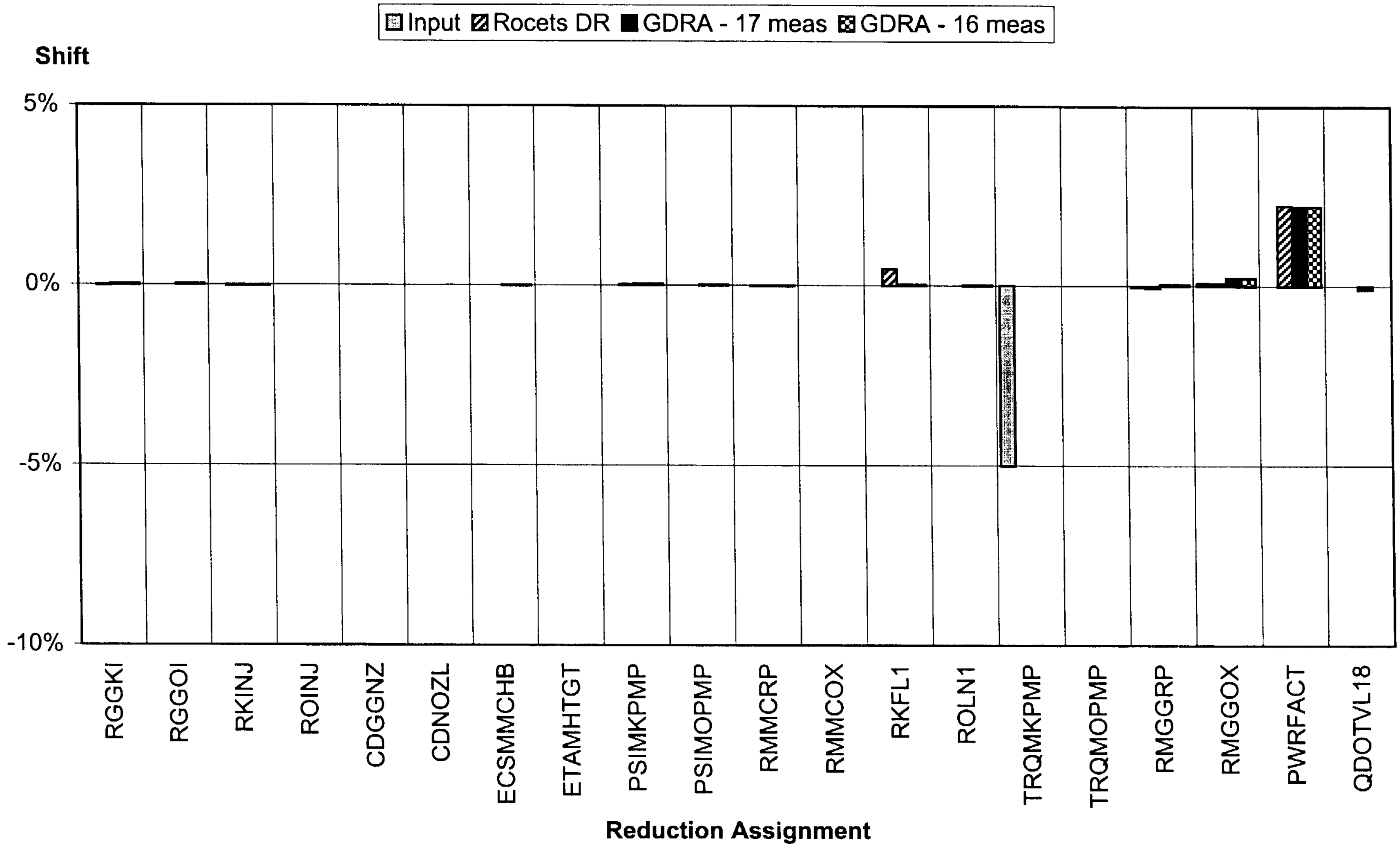


Figure E14 TRQMOPMP single source anomaly allocation

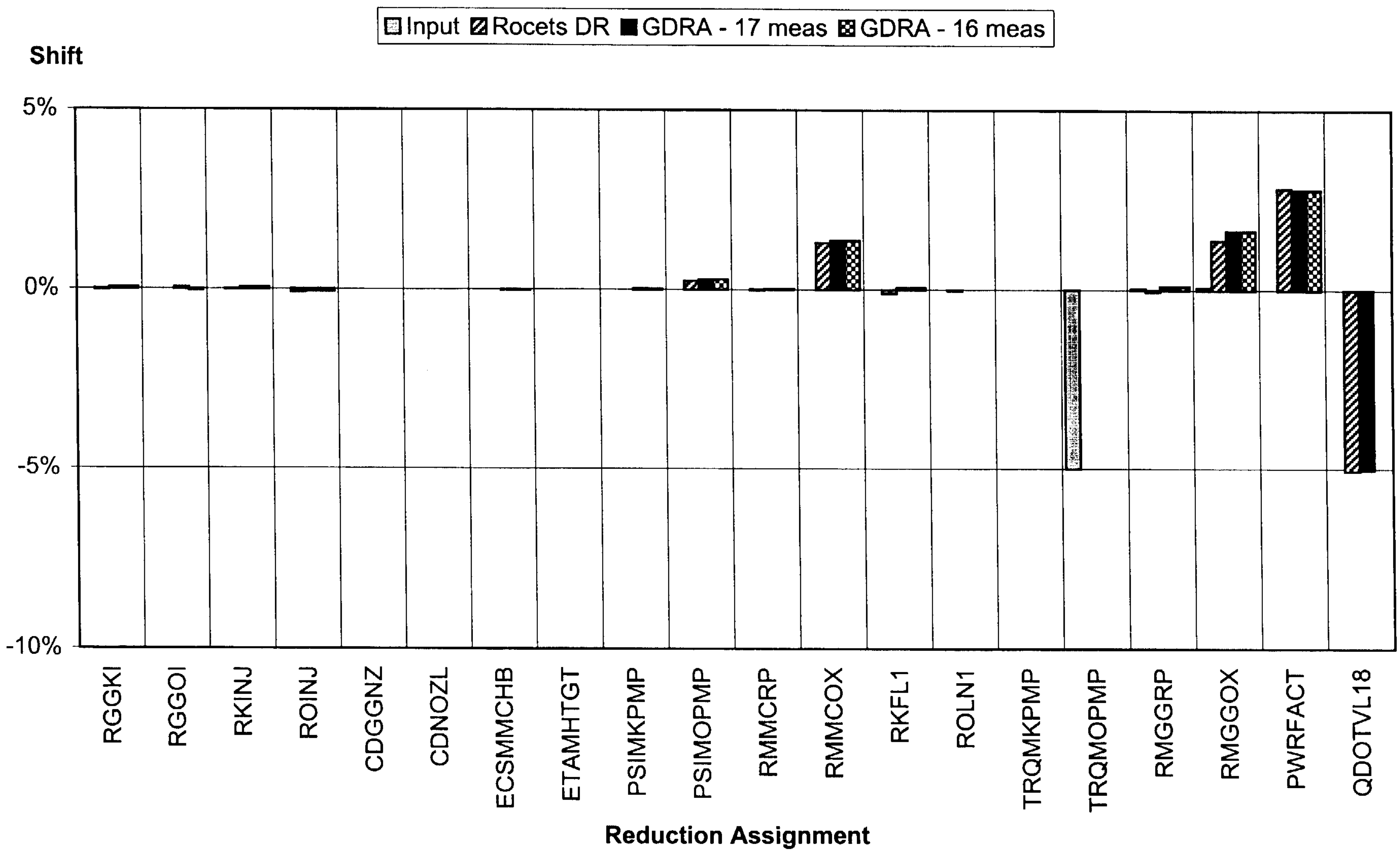


Figure E15 CDGGNZ single source anomaly allocation

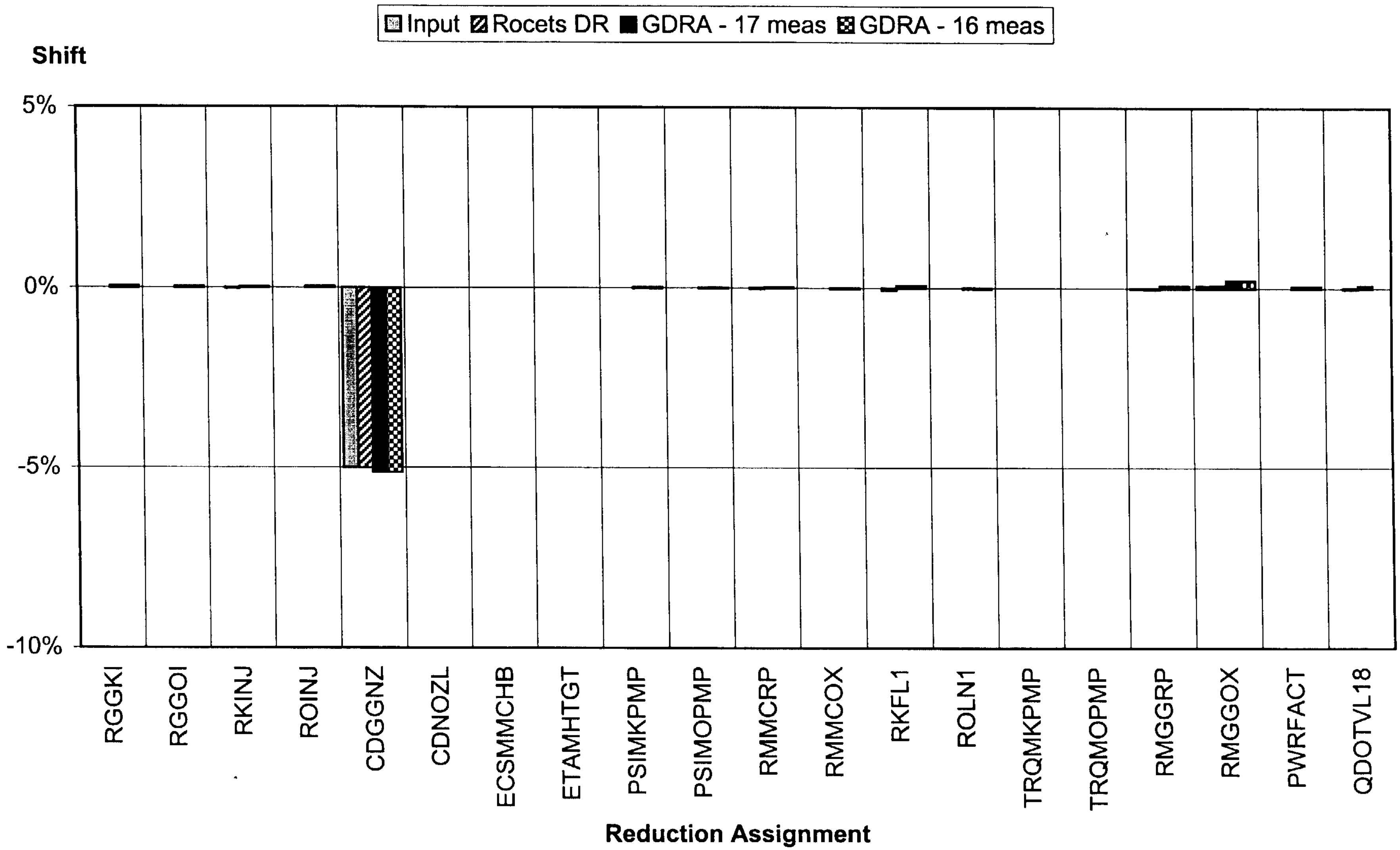


Figure E16 ETAMHTGT single source anomaly allocation

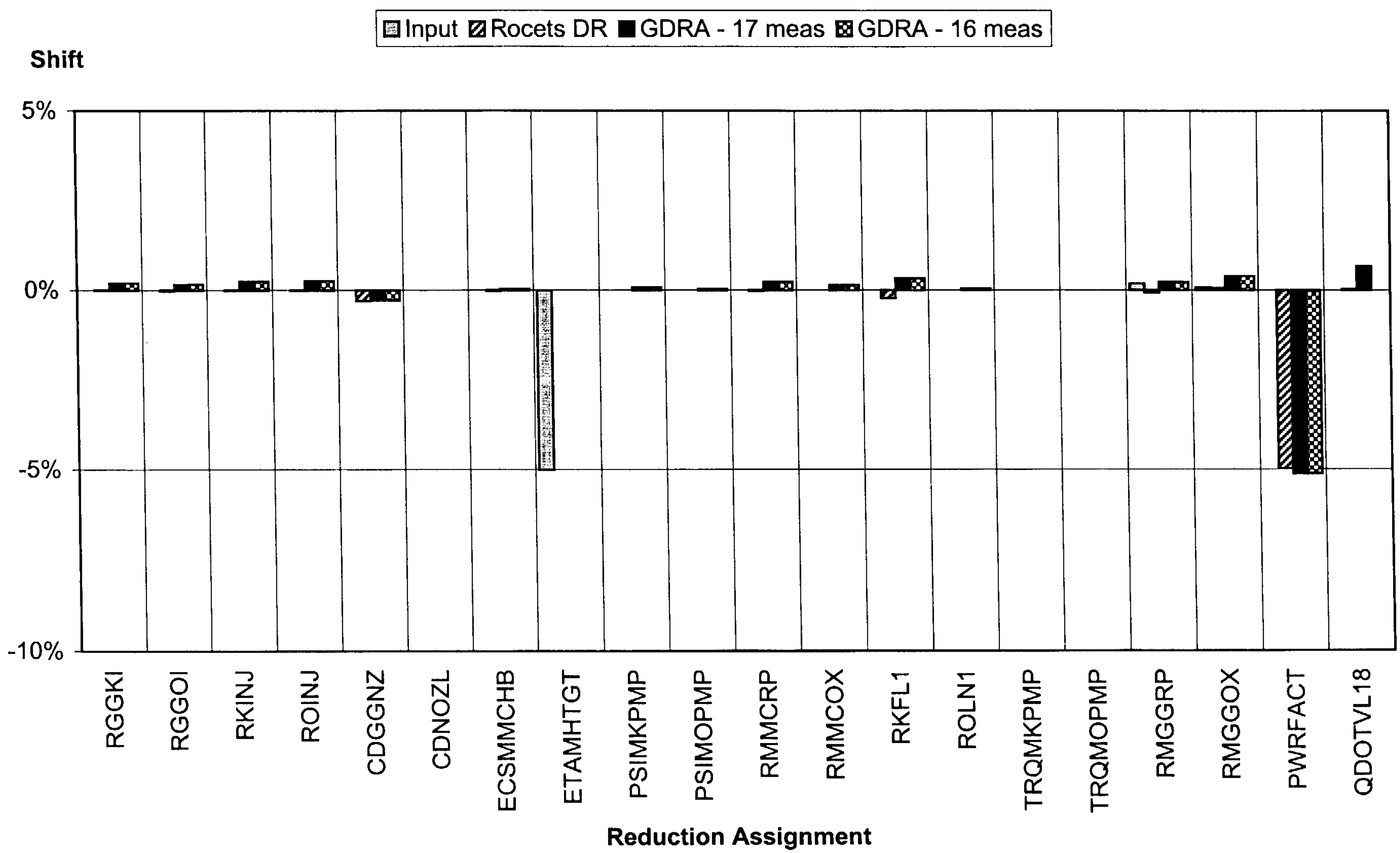


Figure E17 PWRFACT single source anomaly allocation

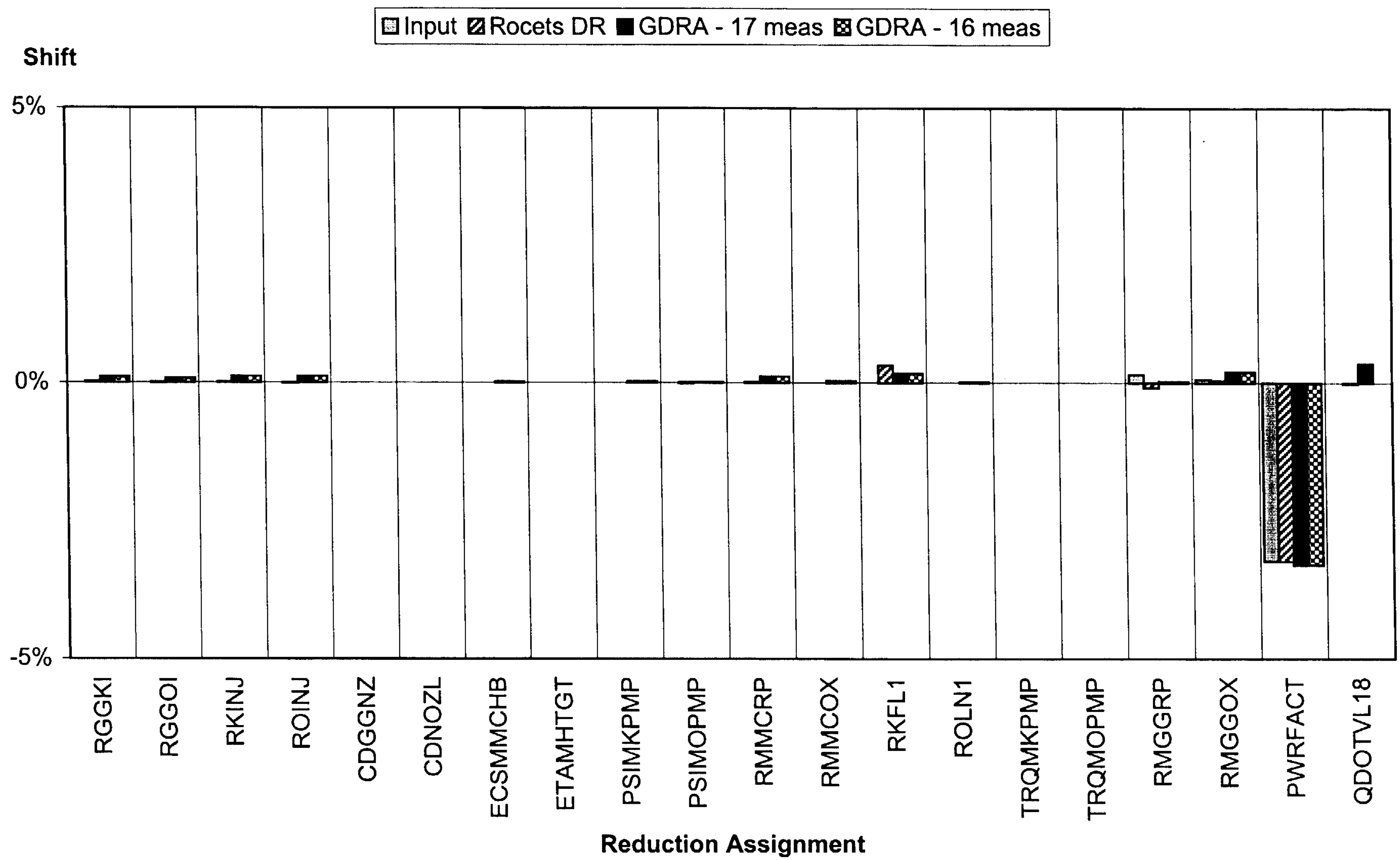


Figure E18 CDNOZL single source anomaly allocation

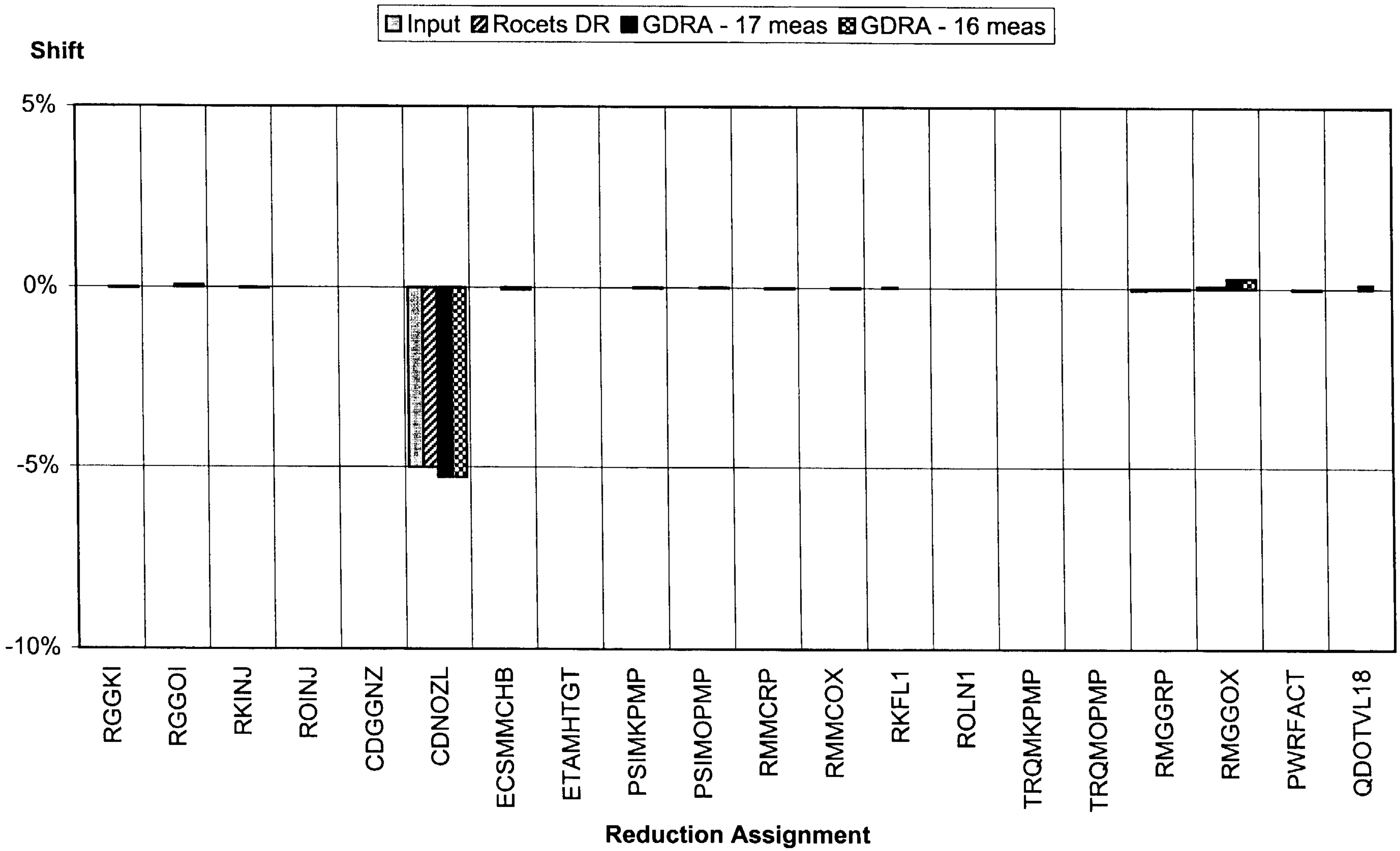


Figure E19 ECSMMCHB single source anomaly allocation

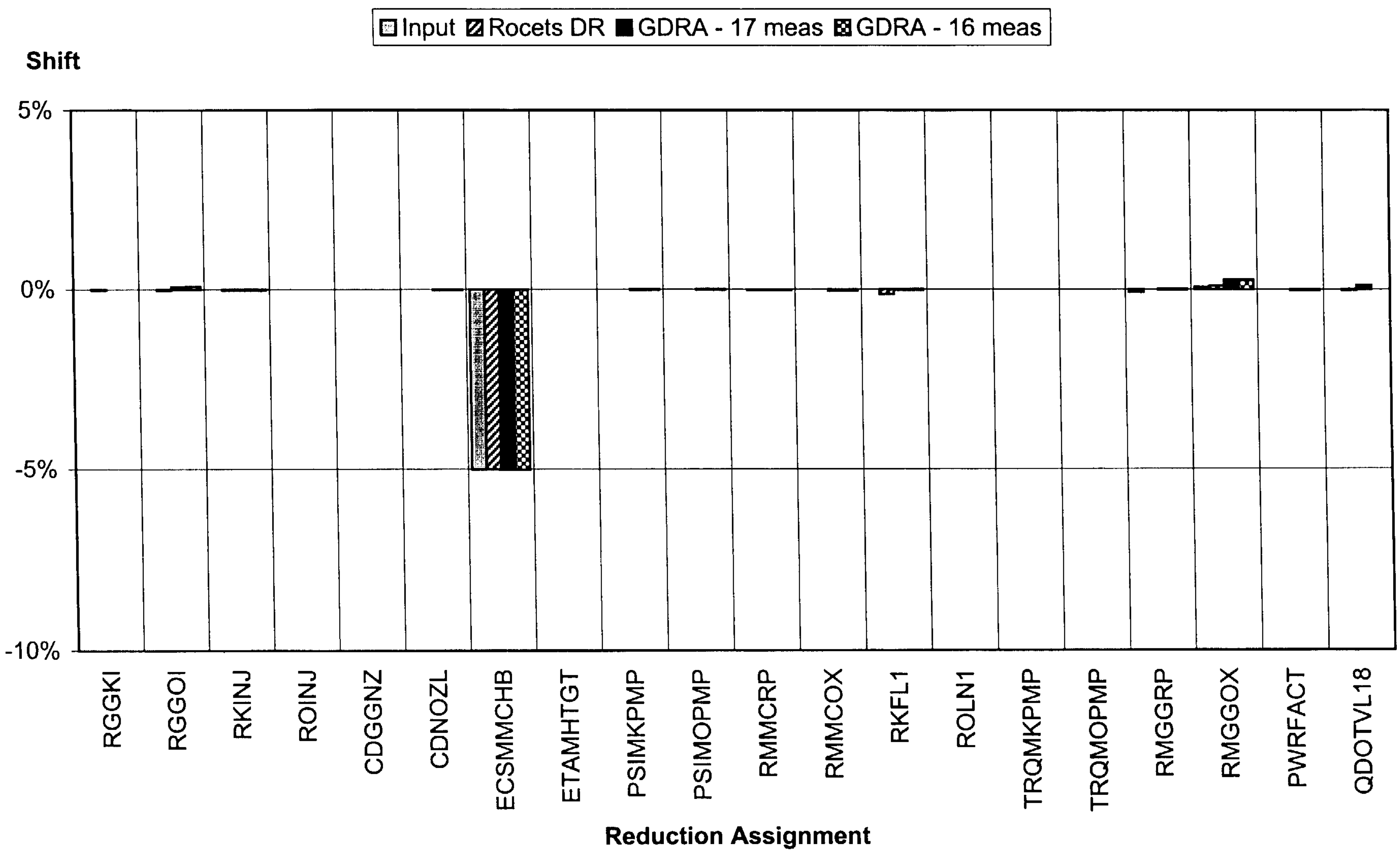
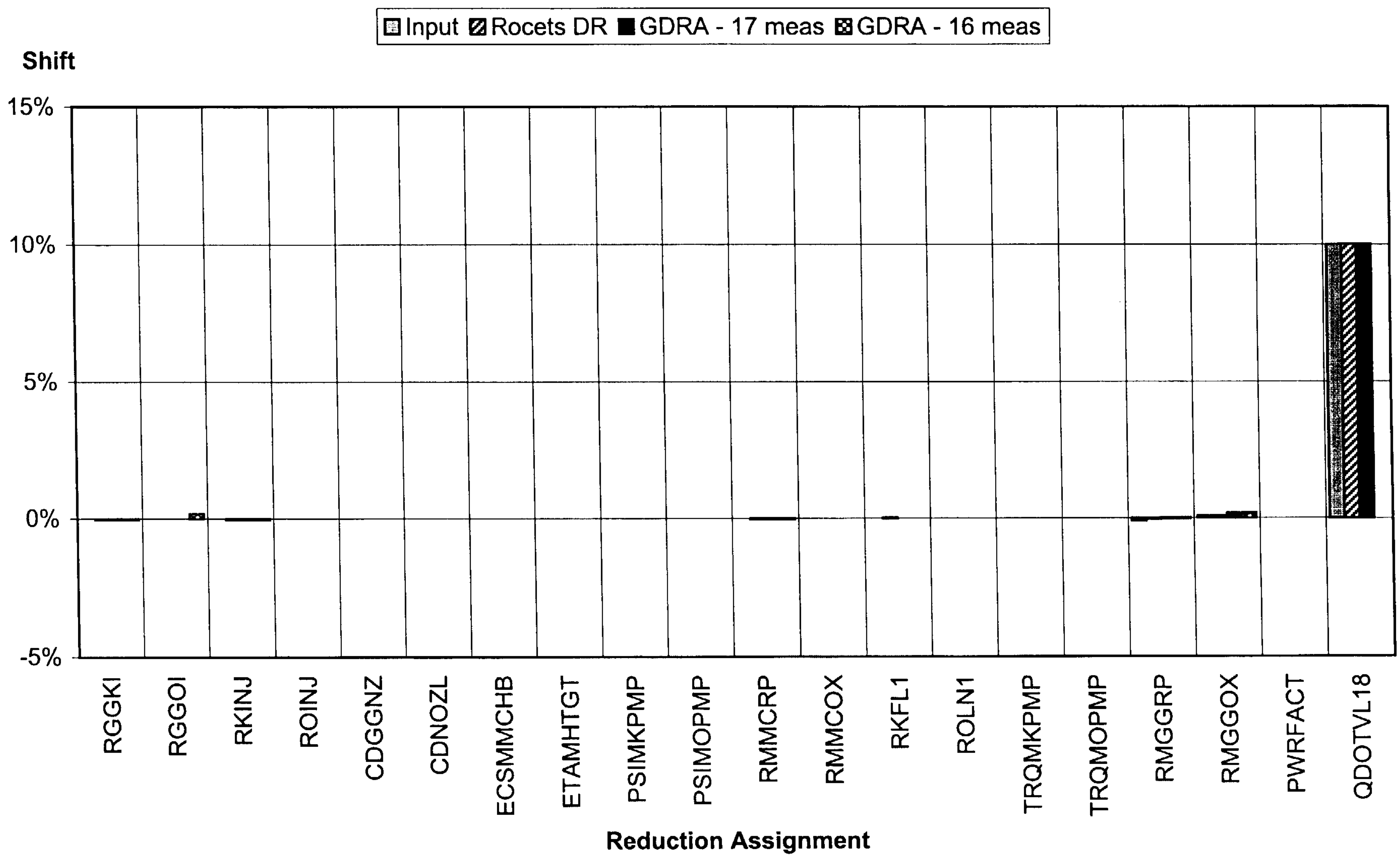


Figure E20 QDOTVL18 single source anomaly allocation



Appendix F

MC-1 engine
Comparison of standard ROCETS DR andGDRA using only flight measurements

Figure F1 Reduction results with flight measurement set R3MCRP

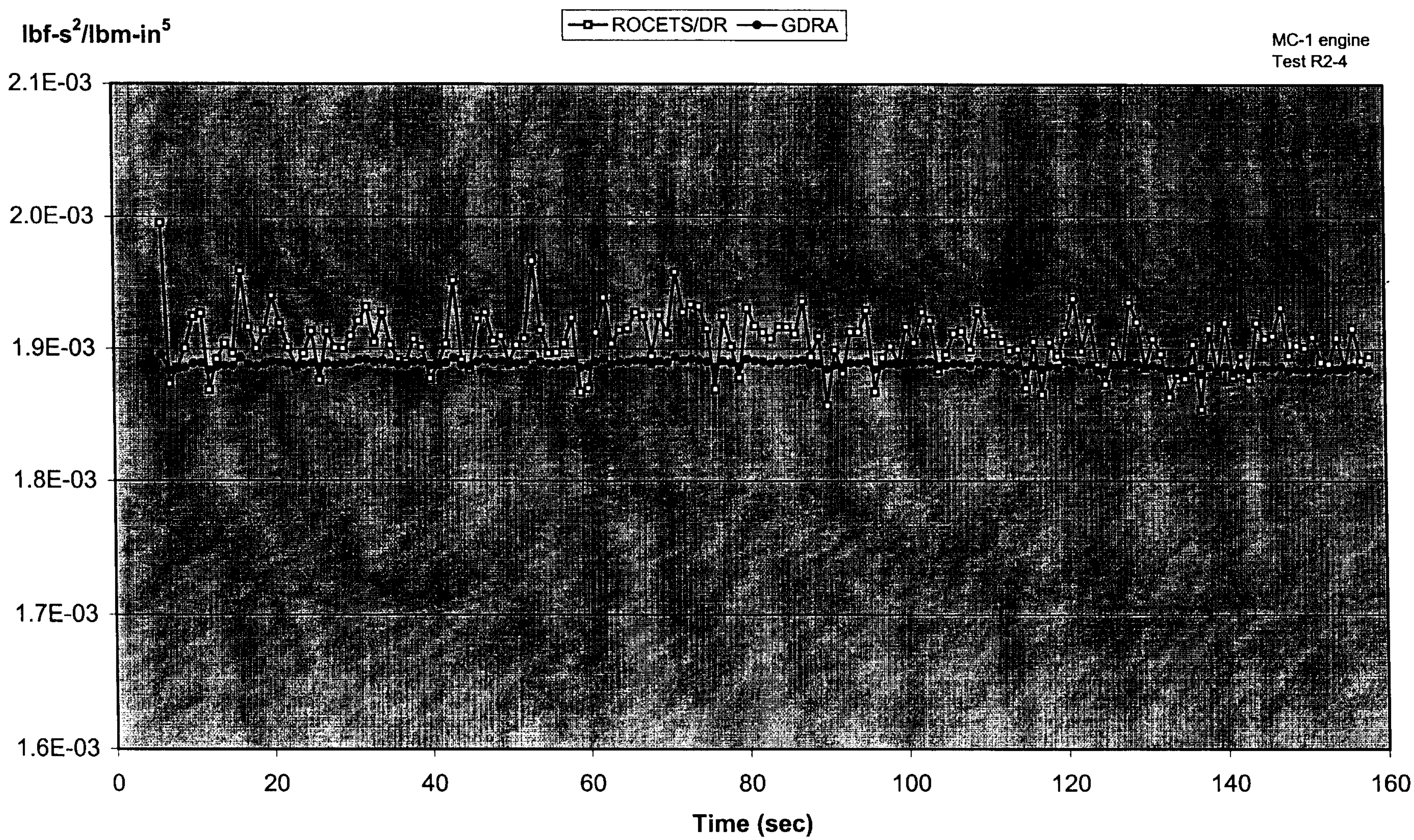


Figure F2 Reduction results with flight measurement set R3MCOX

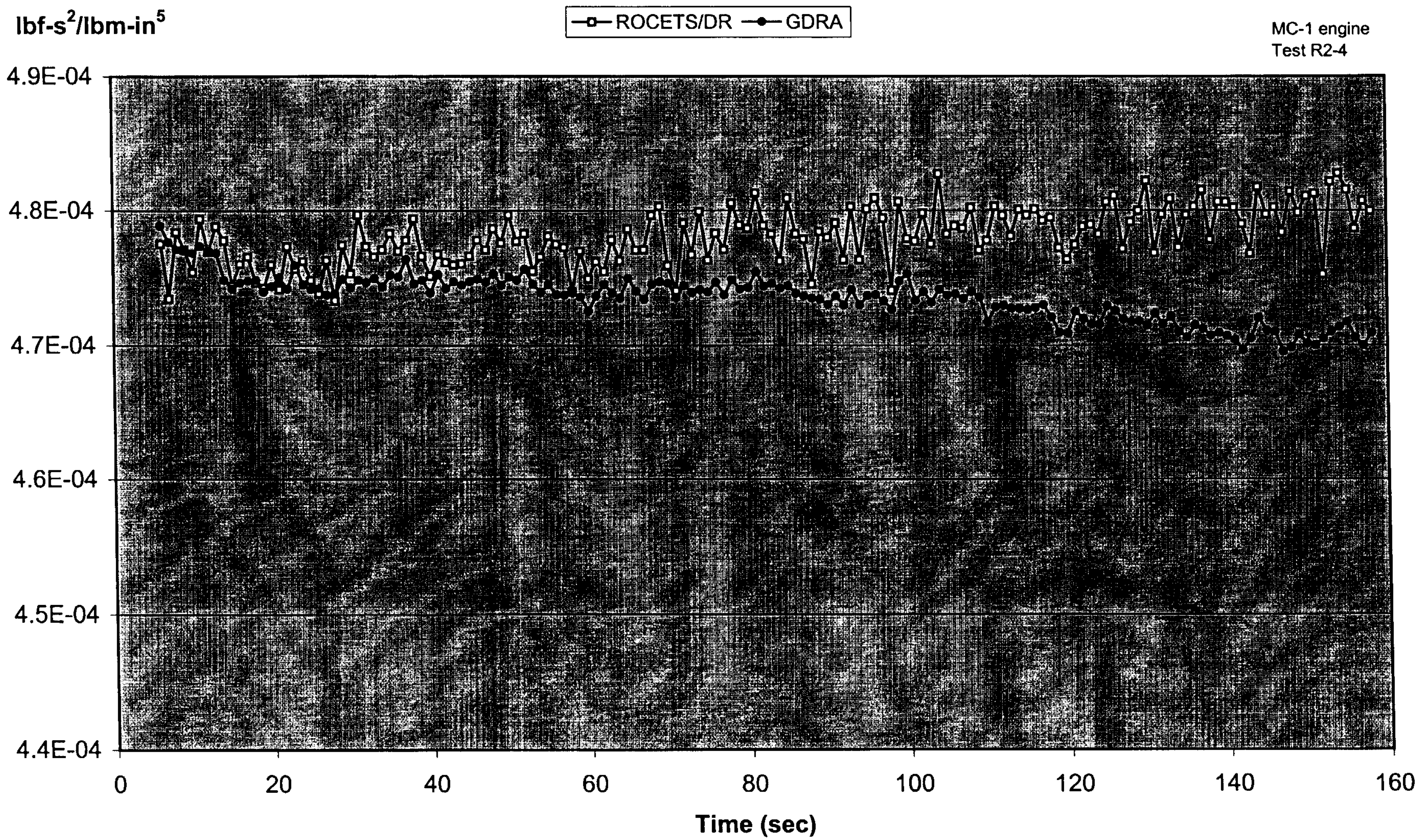


Figure F3 Reduction results with flight measurement set R3GGRP

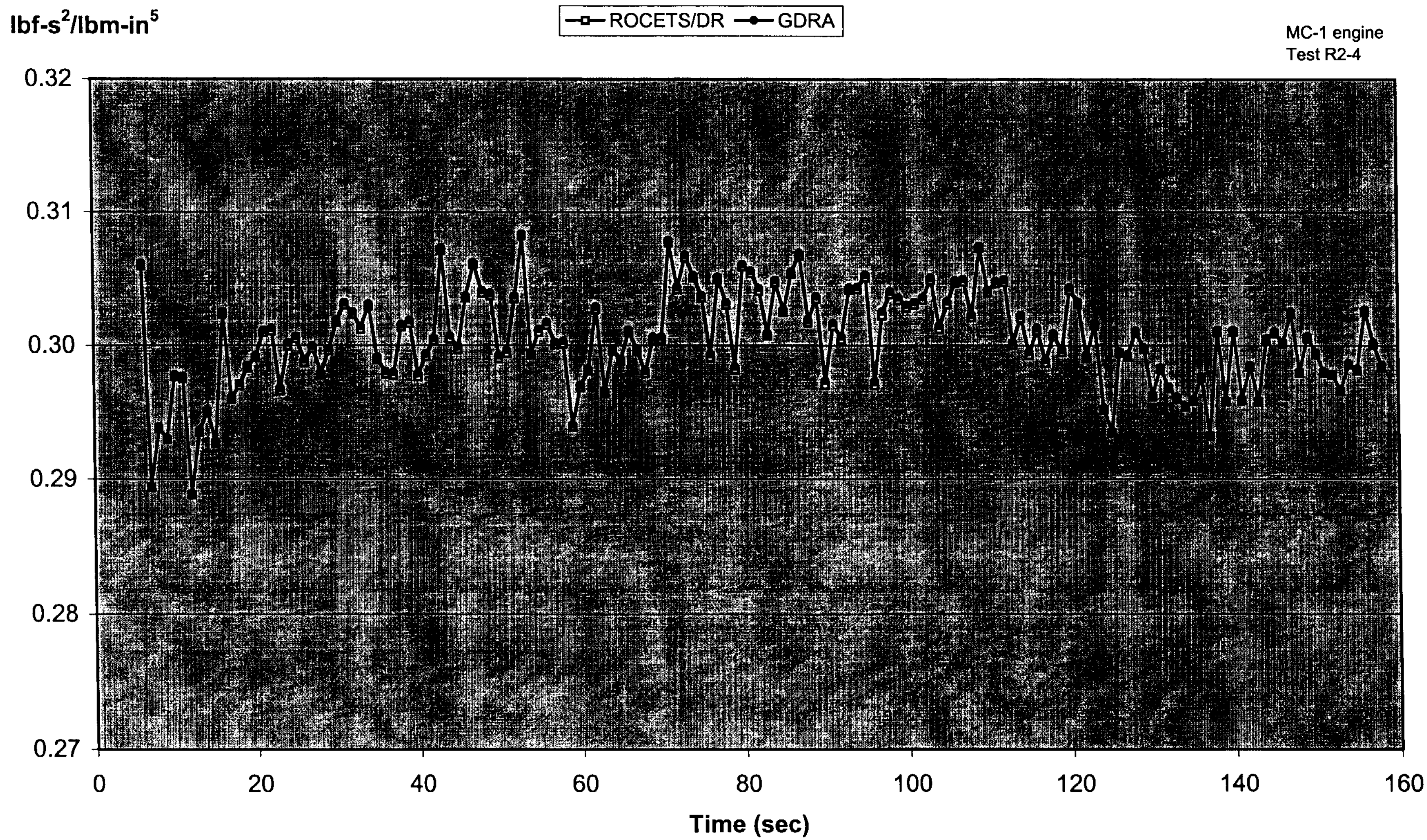


Figure F4 Reduction results with flight measurement set R3GGOX

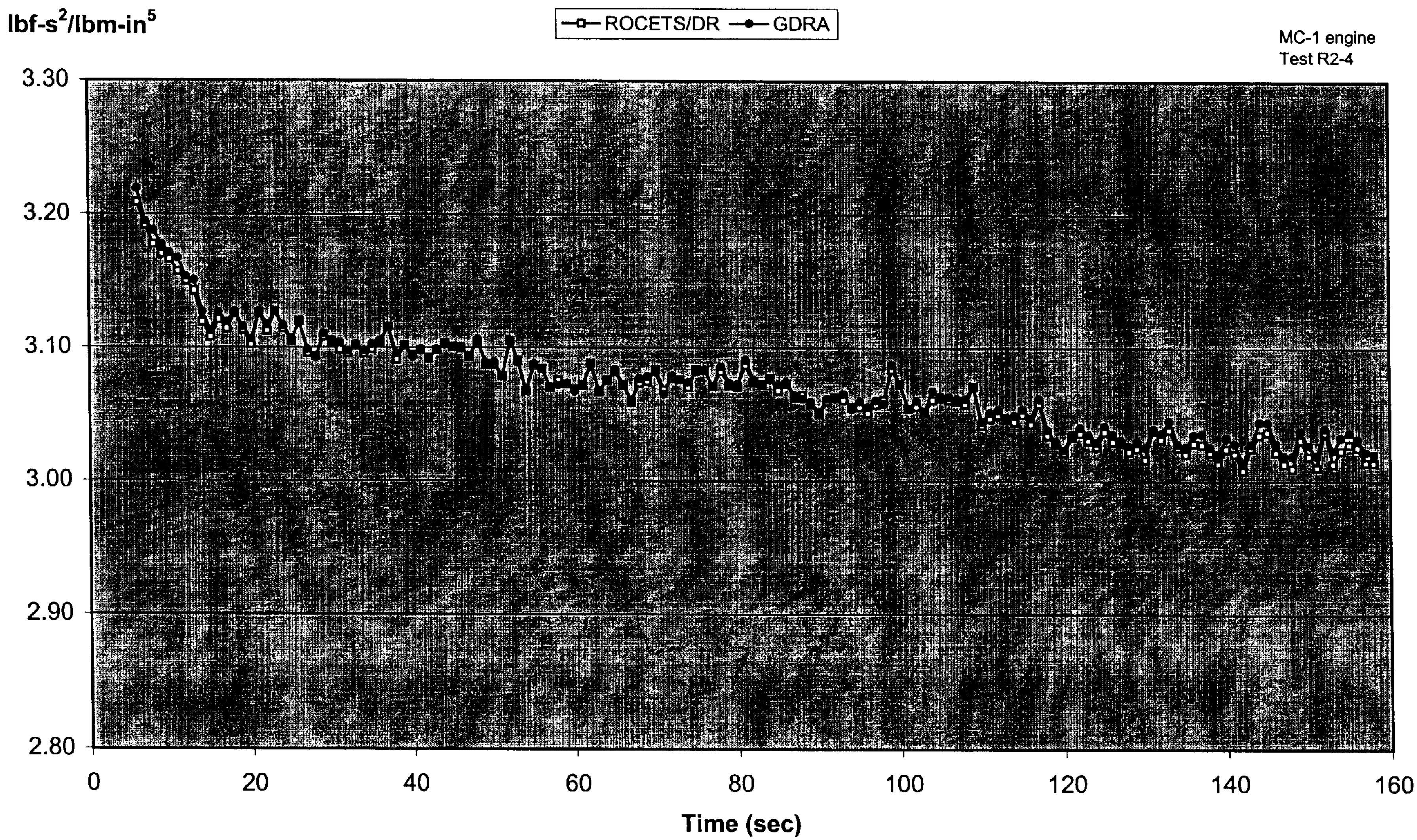


Figure F5 Reduction results with flight measurement set PSIMKPMP

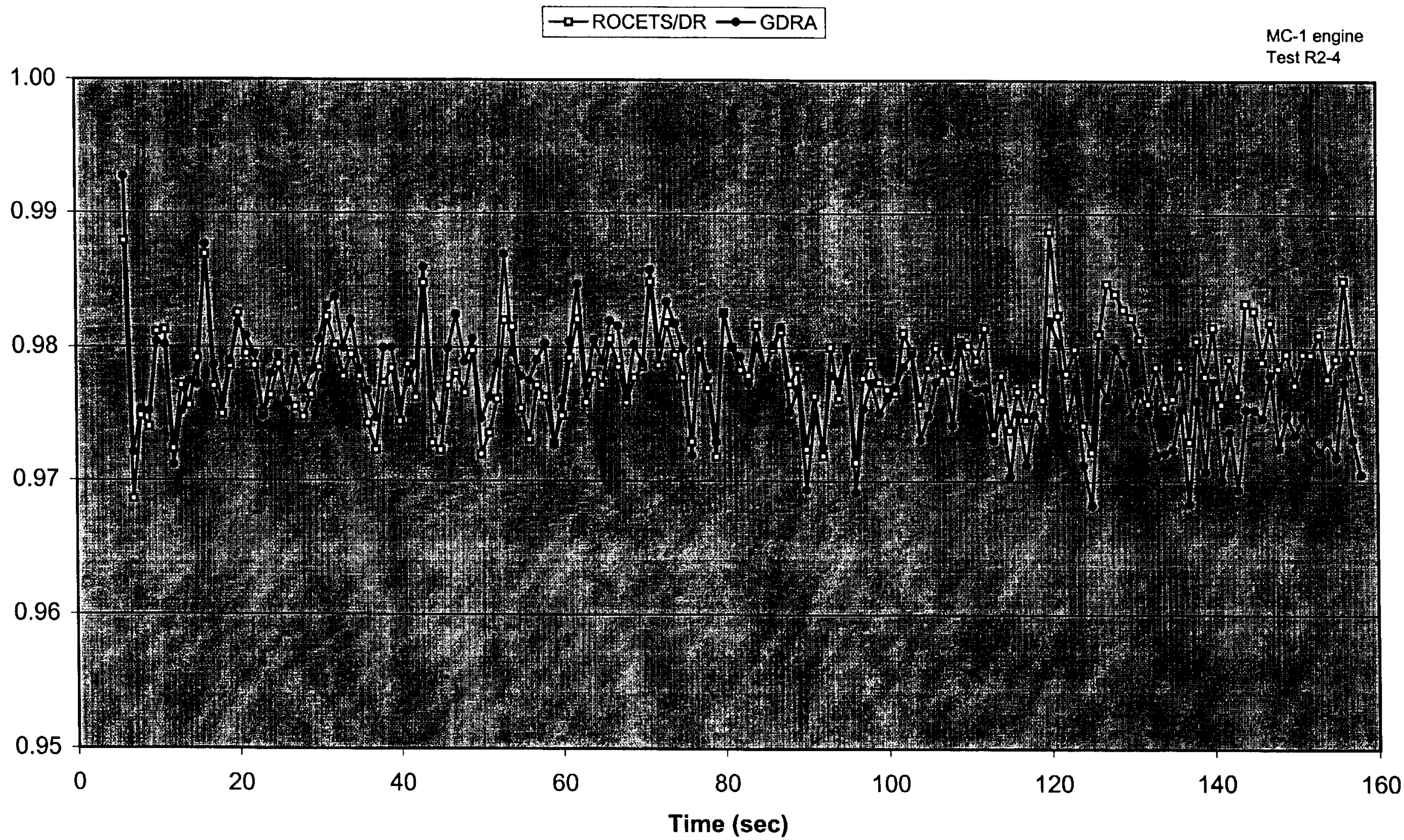


Figure F6 Reduction results with flight measurement set PSIMOPMP

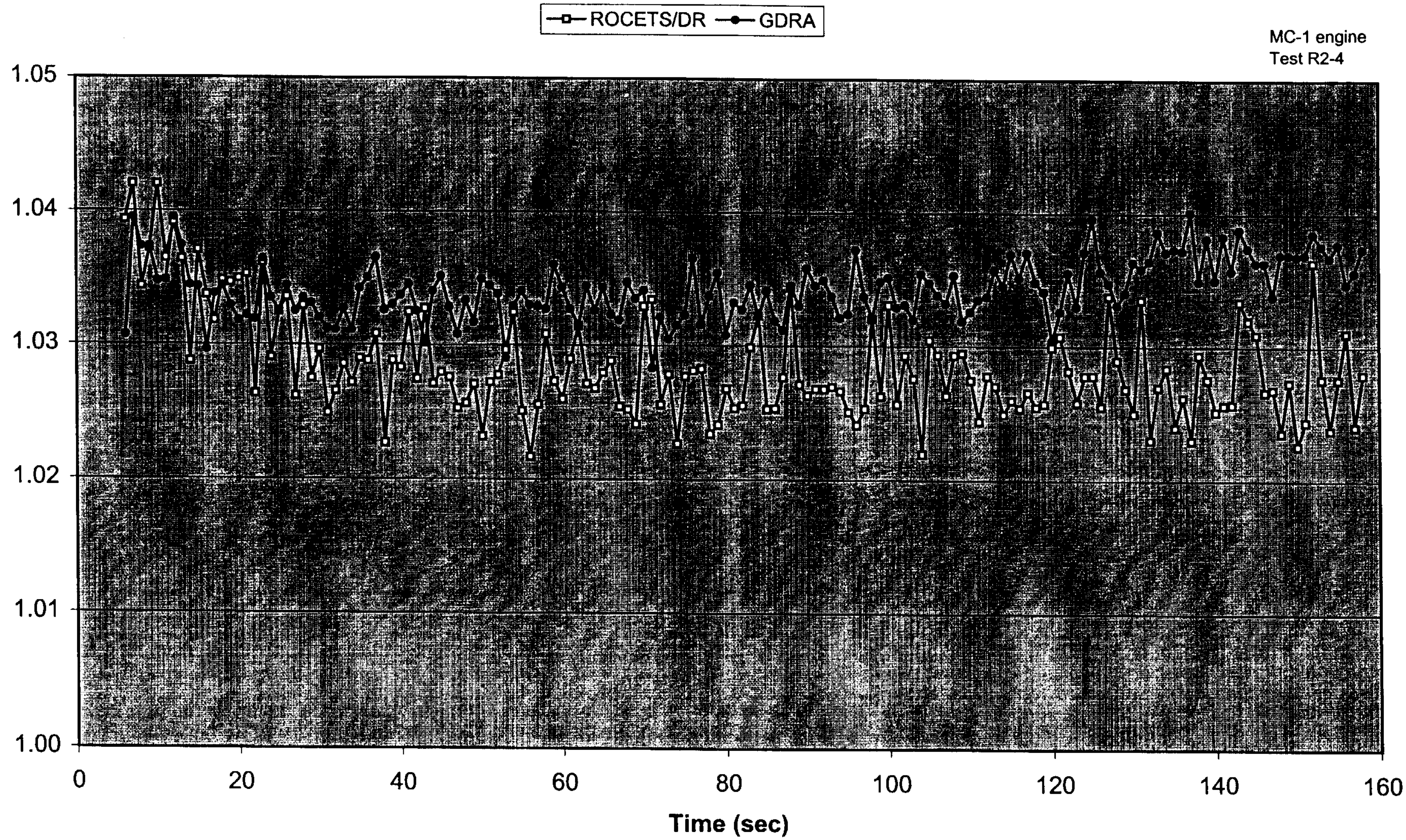


Figure F7   Reduction results with flight measurement set PWRFACT

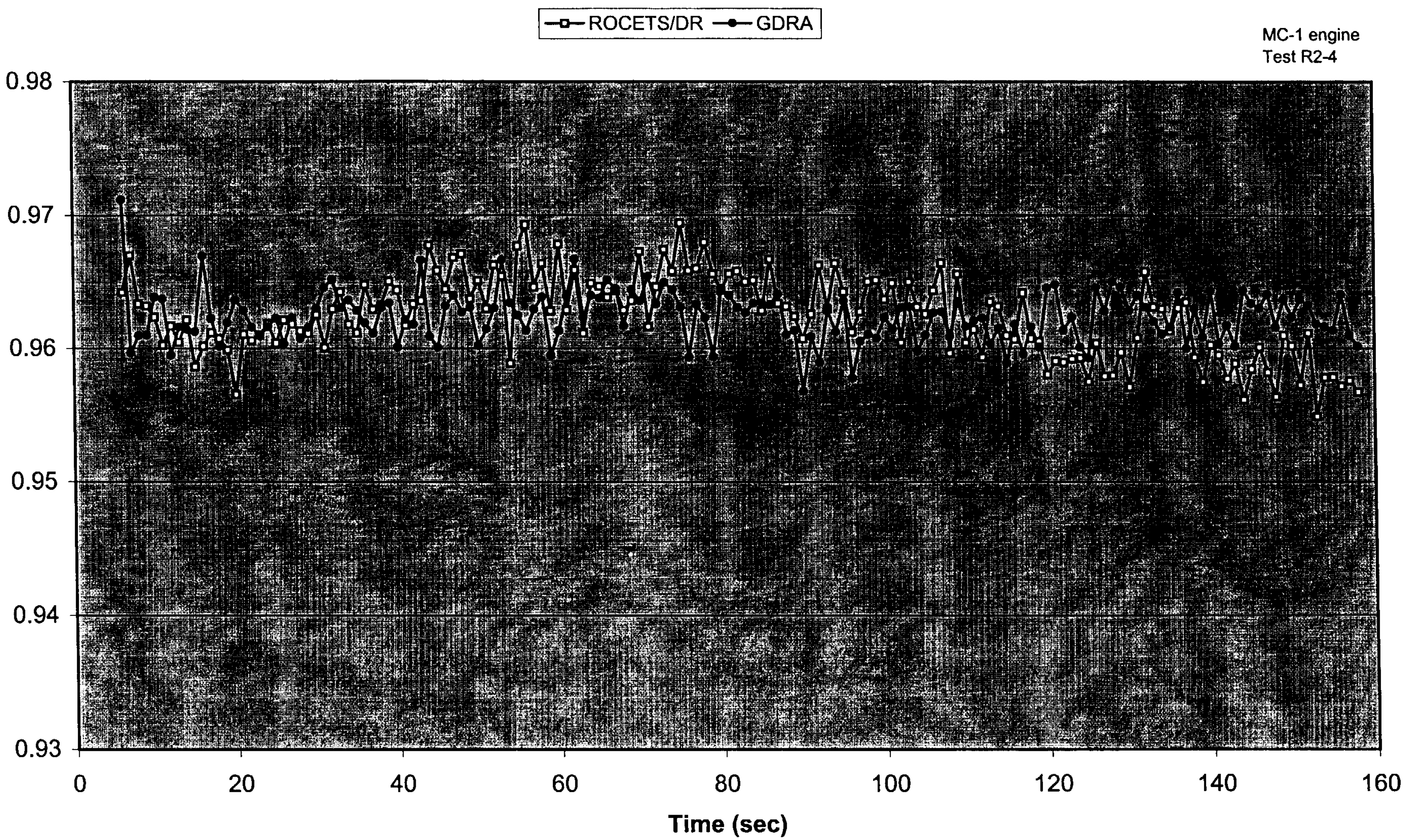


Figure F8 Reduction results with flight measurement set ECSMMCHB

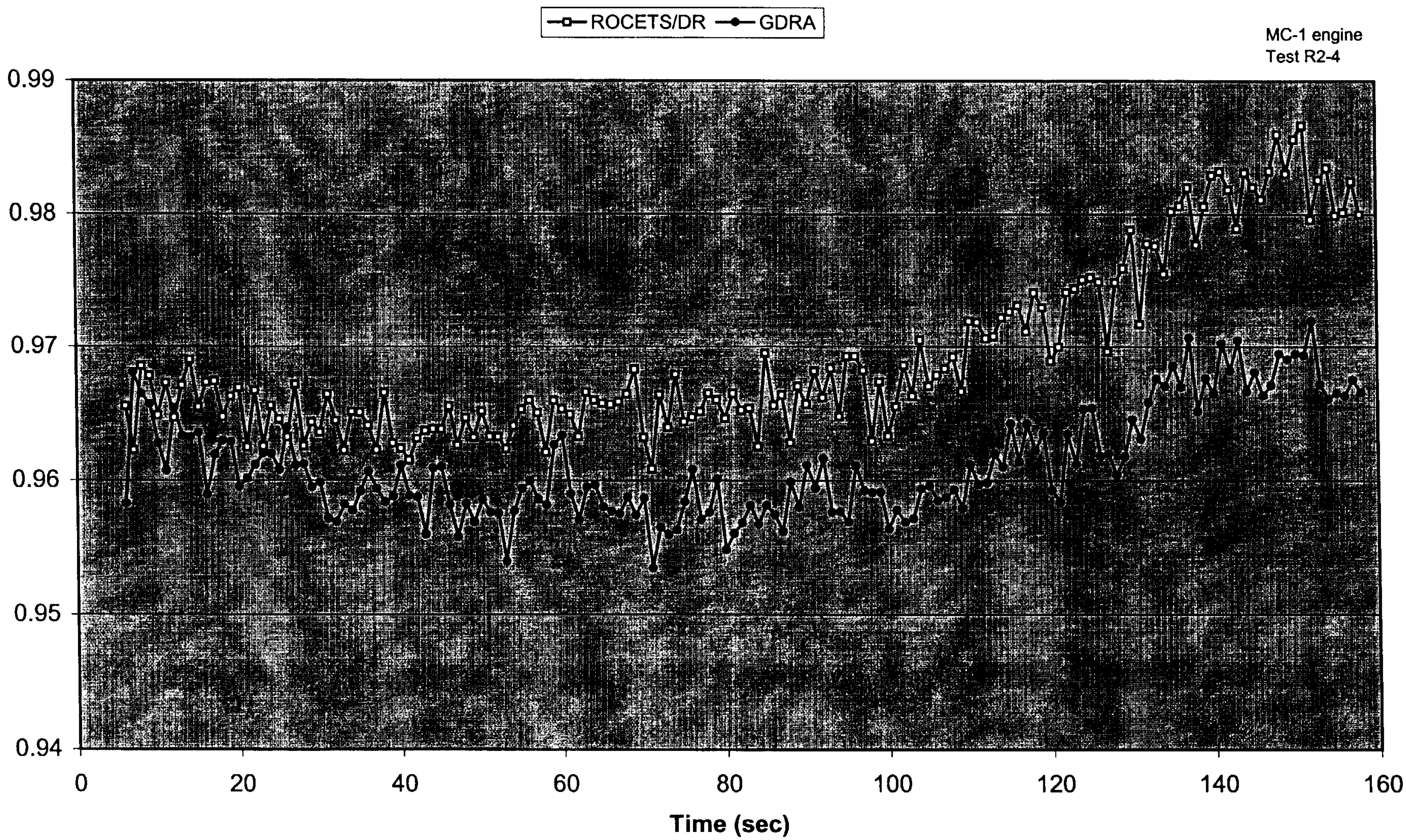


Figure F9 Reduction results with flight measurement set QDOTVL18

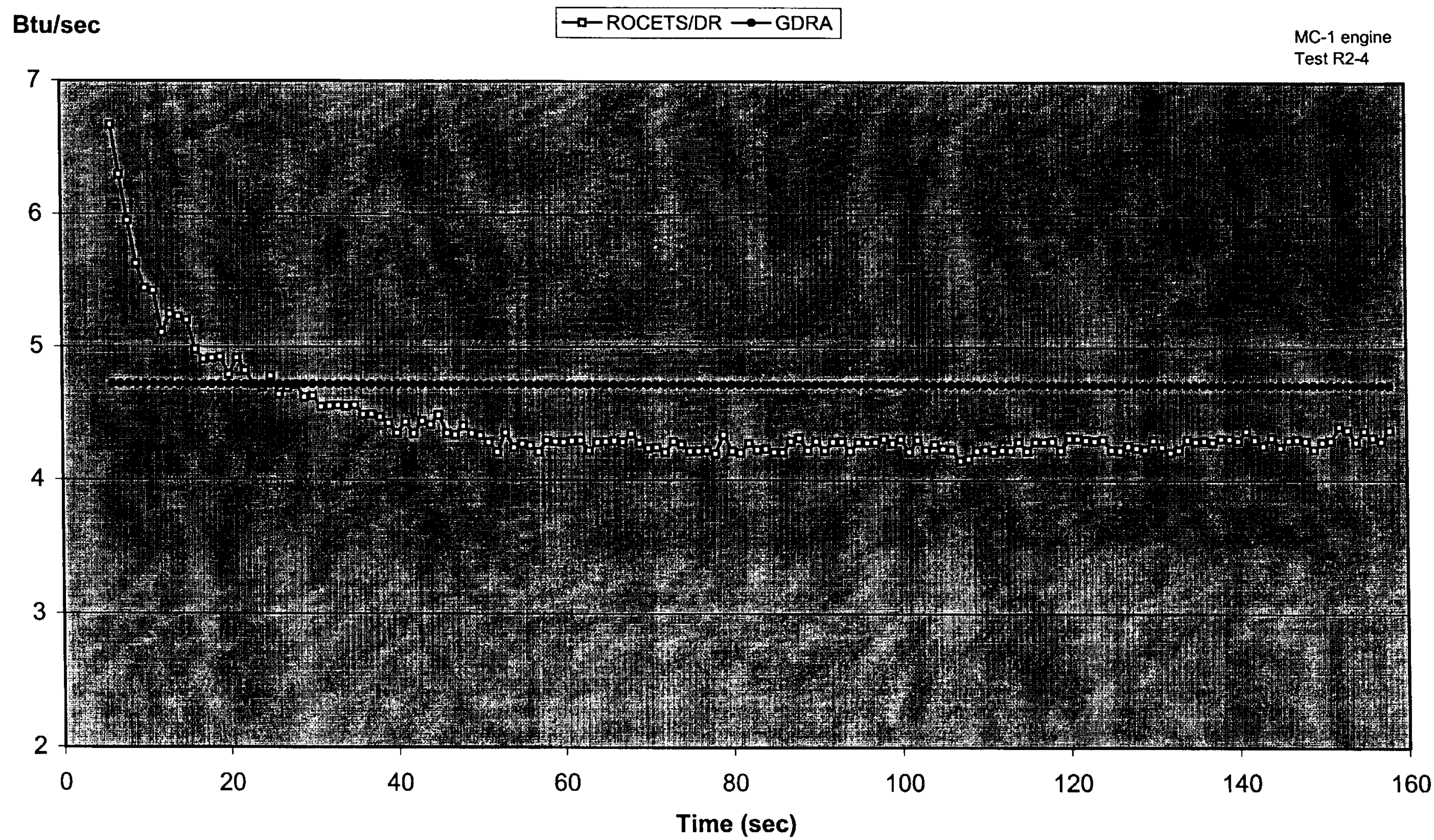


Figure F10 Reduction results with flight measurement set and 20-23 second avg flows
R3MCRP

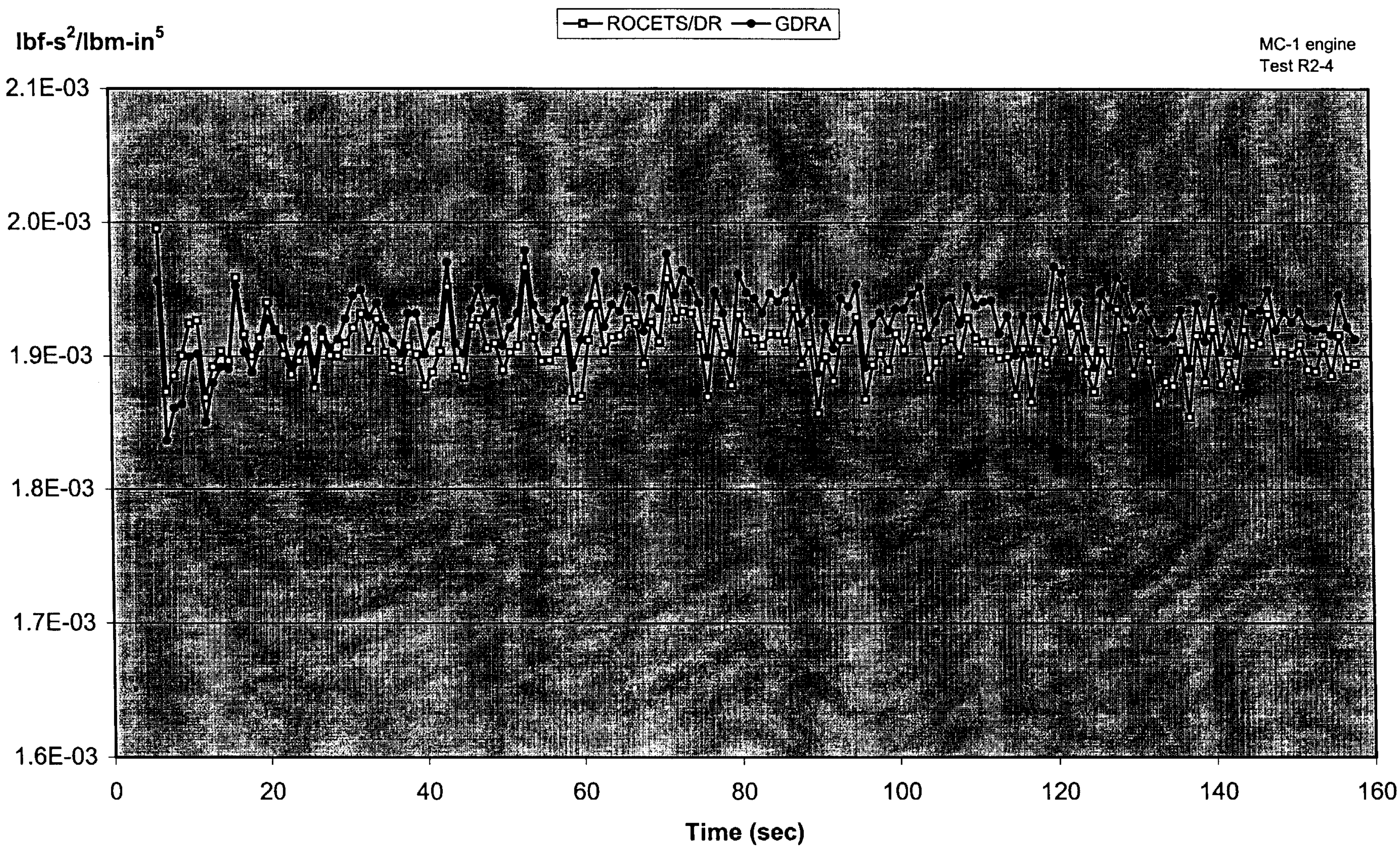


Figure F11 Reduction results with flight measurement set and 20-23 second avg flows
R3MCOX

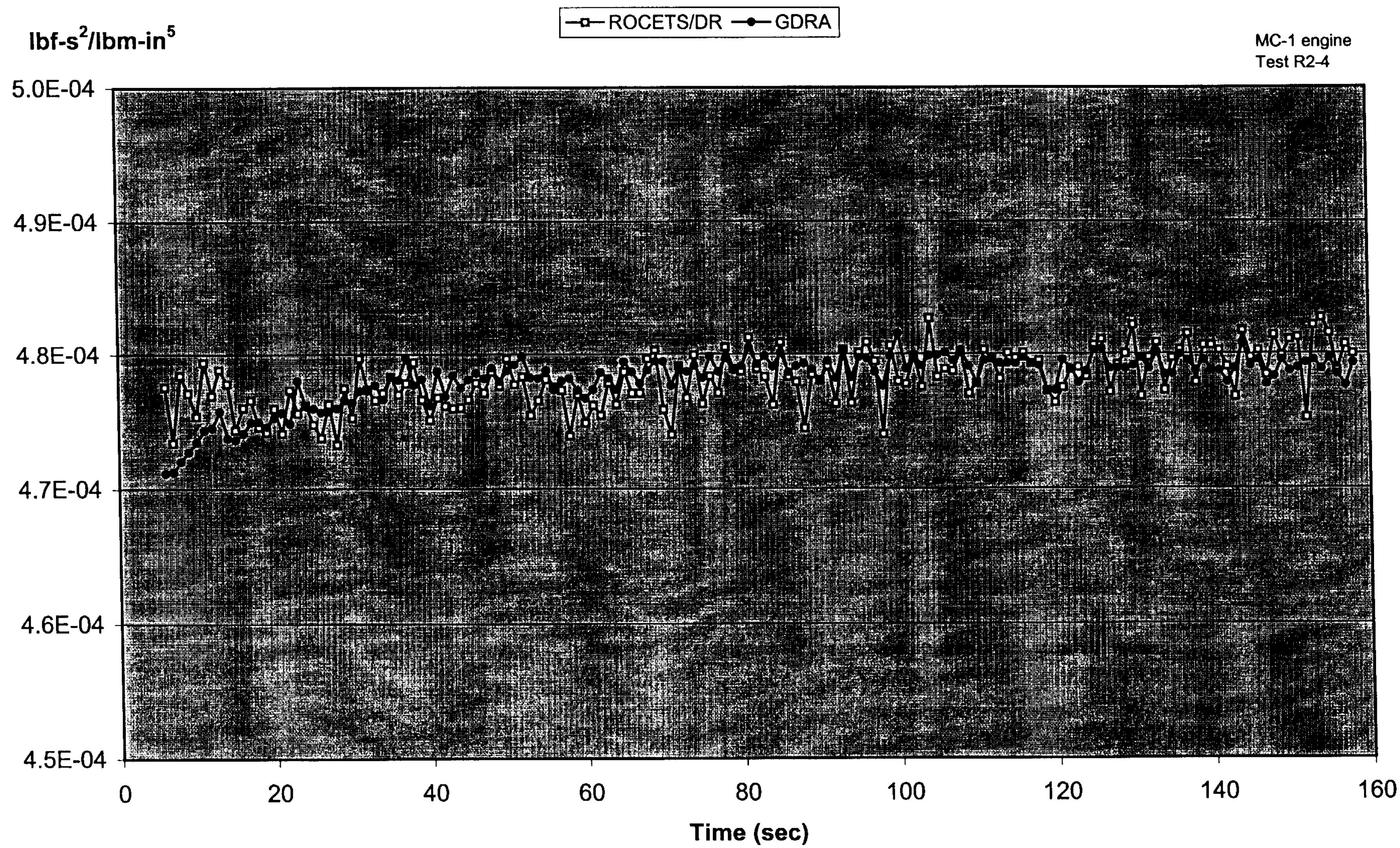


Figure F12 Reduction results with flight measurement set and 20-23 second avg flows
R3GGRP

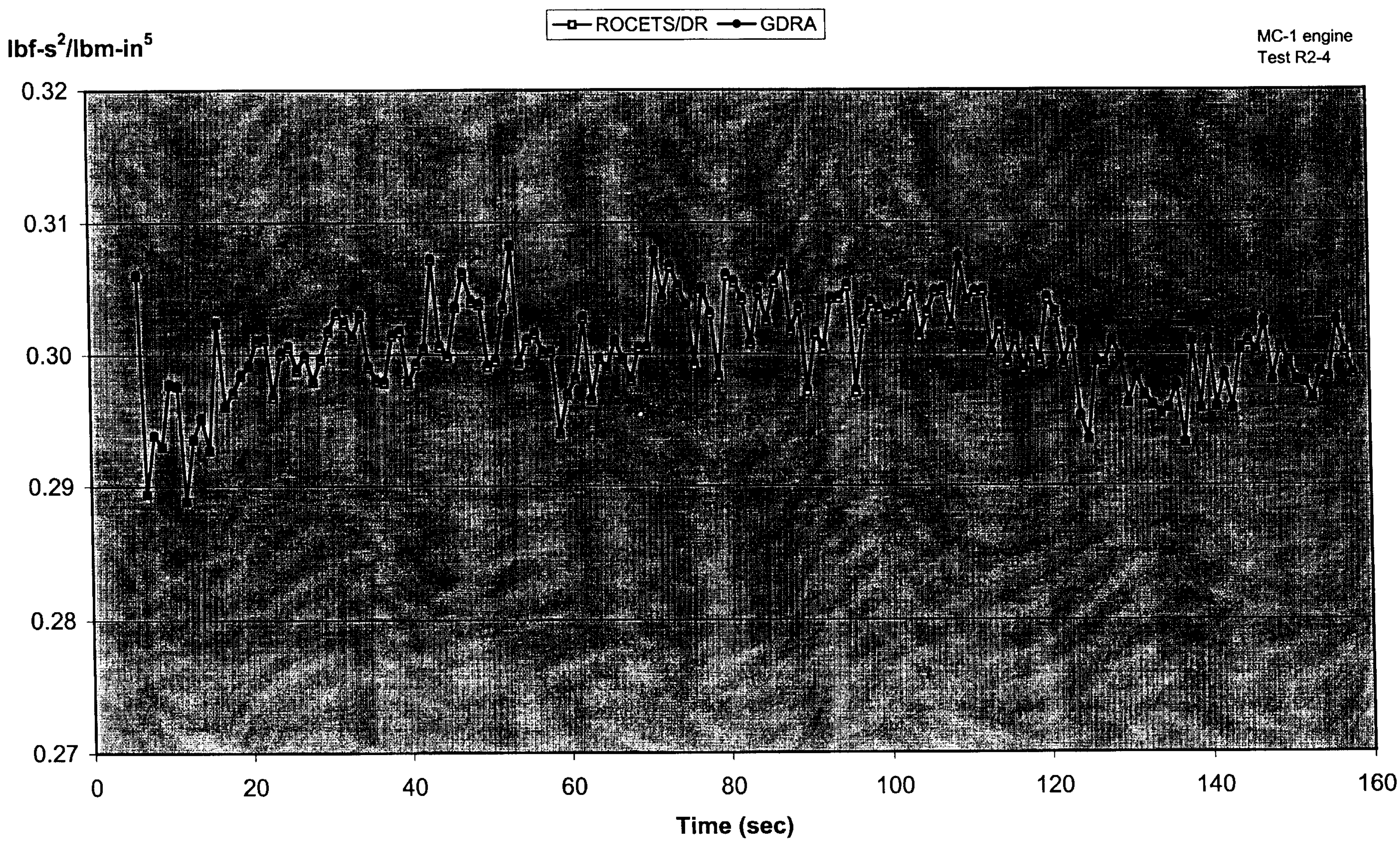


Figure F13 Reduction results with flight measurement set and 20-23 second avg flows R3GGOX

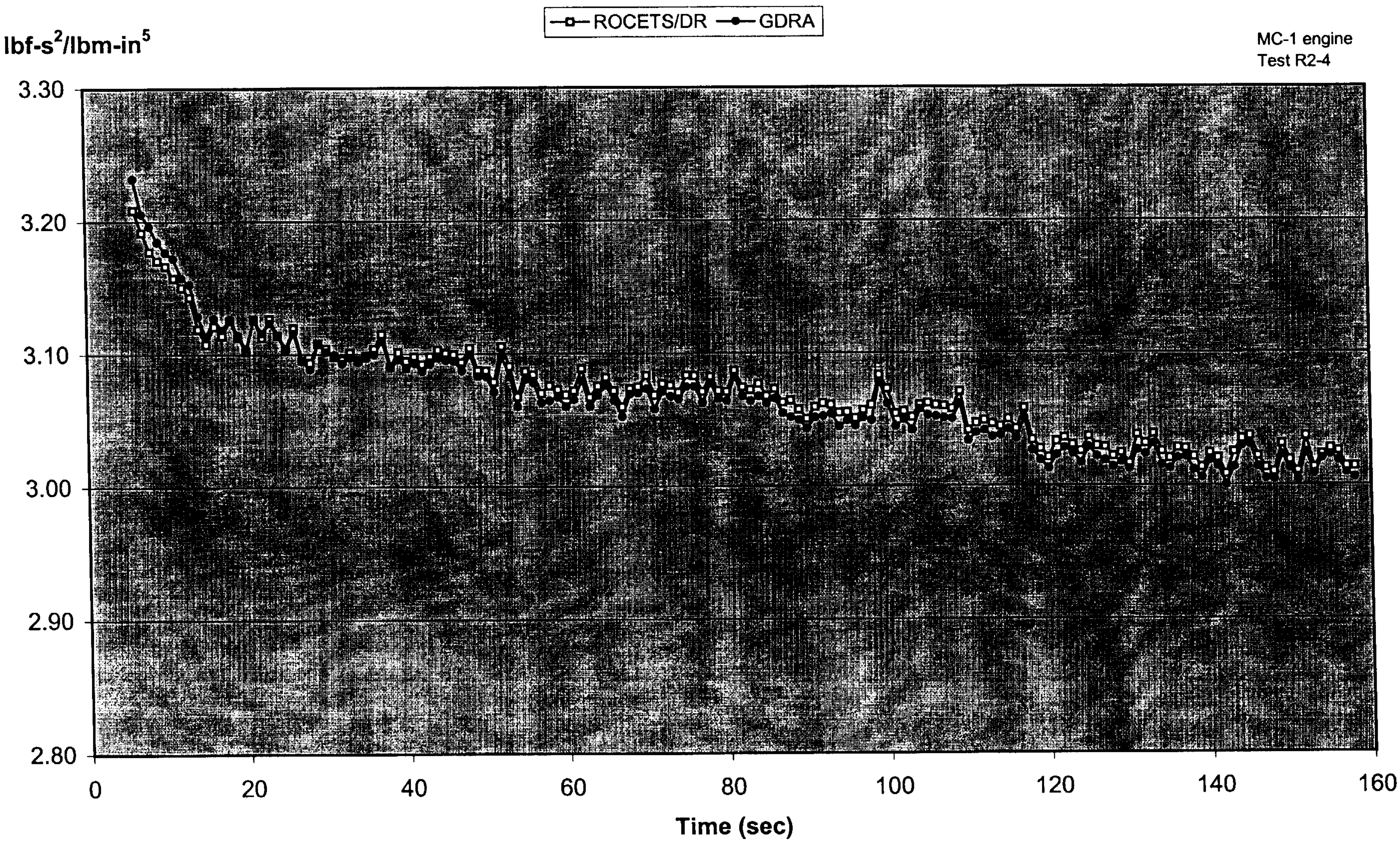


Figure F14 Reduction results with flight measurement set and 20-23 second avg flows
PSIMKPMP

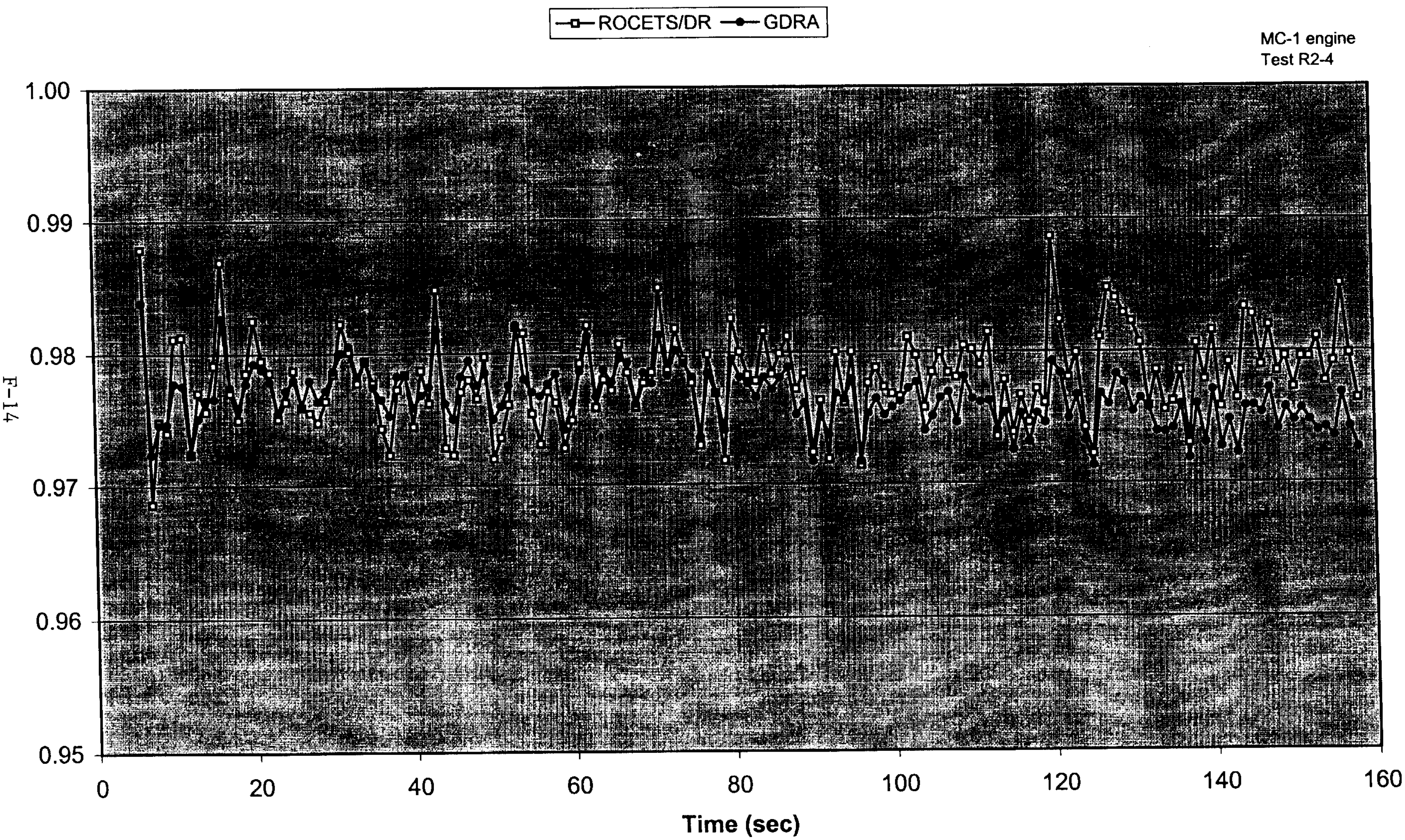


Figure F15 Reduction results with flight measurement set and 20-23 second avg flows
PSIMOPMP

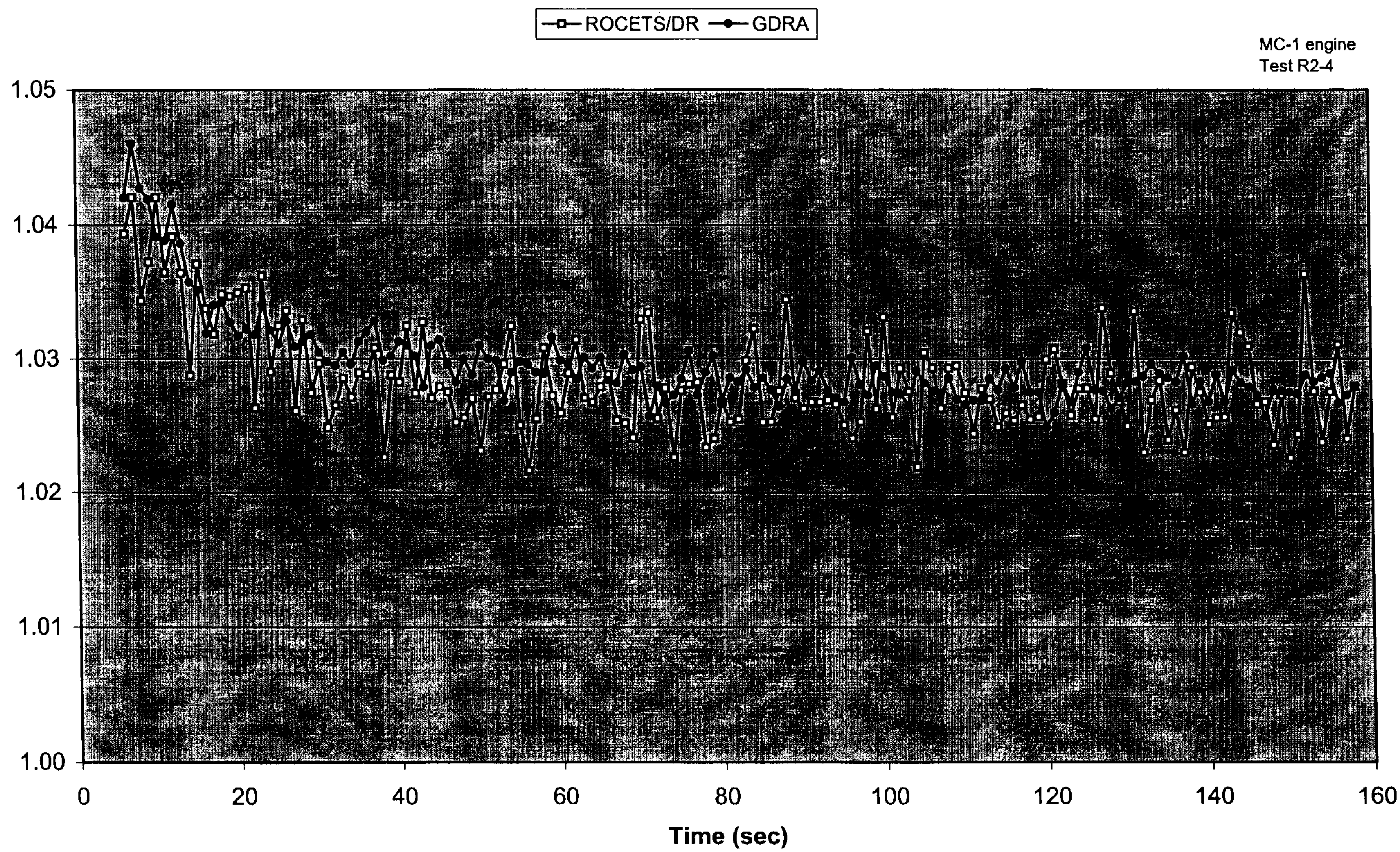


Figure F16 Reduction results with flight measurement set and 20-23 second avg flows
PWRFACT

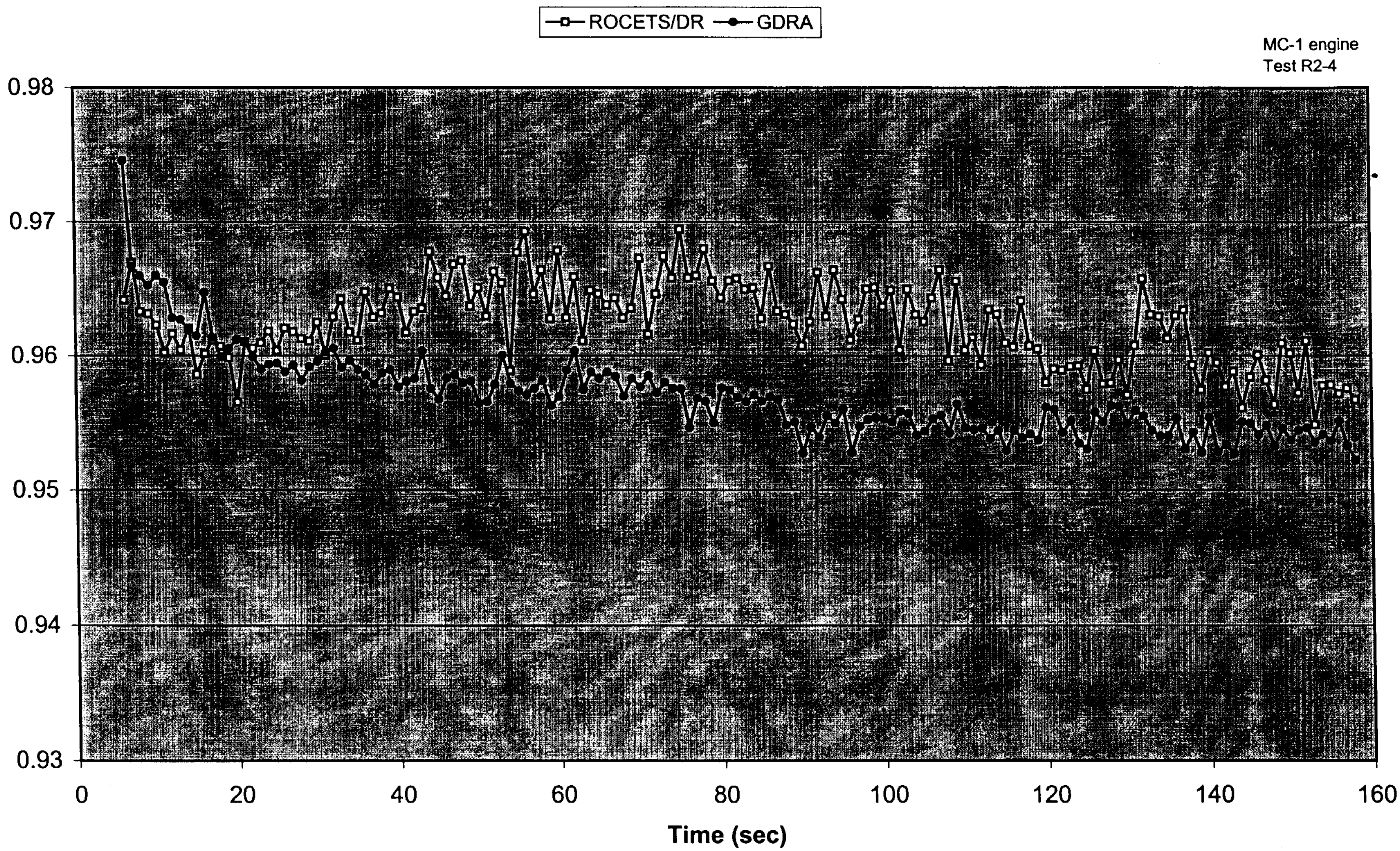


Figure F17   Reduction results with flight measurement set and 20-23 second avg flows
ECSMMCHB

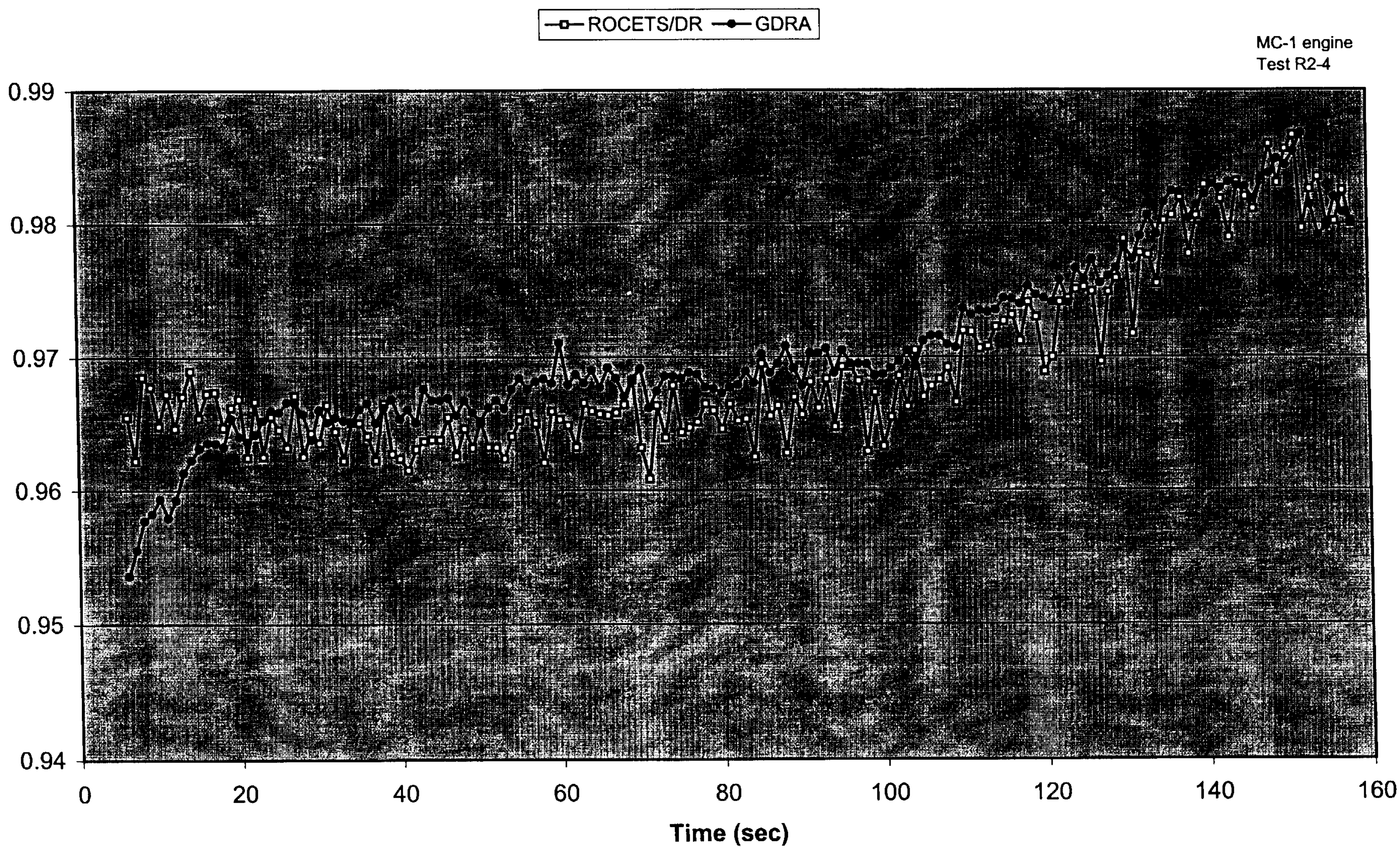
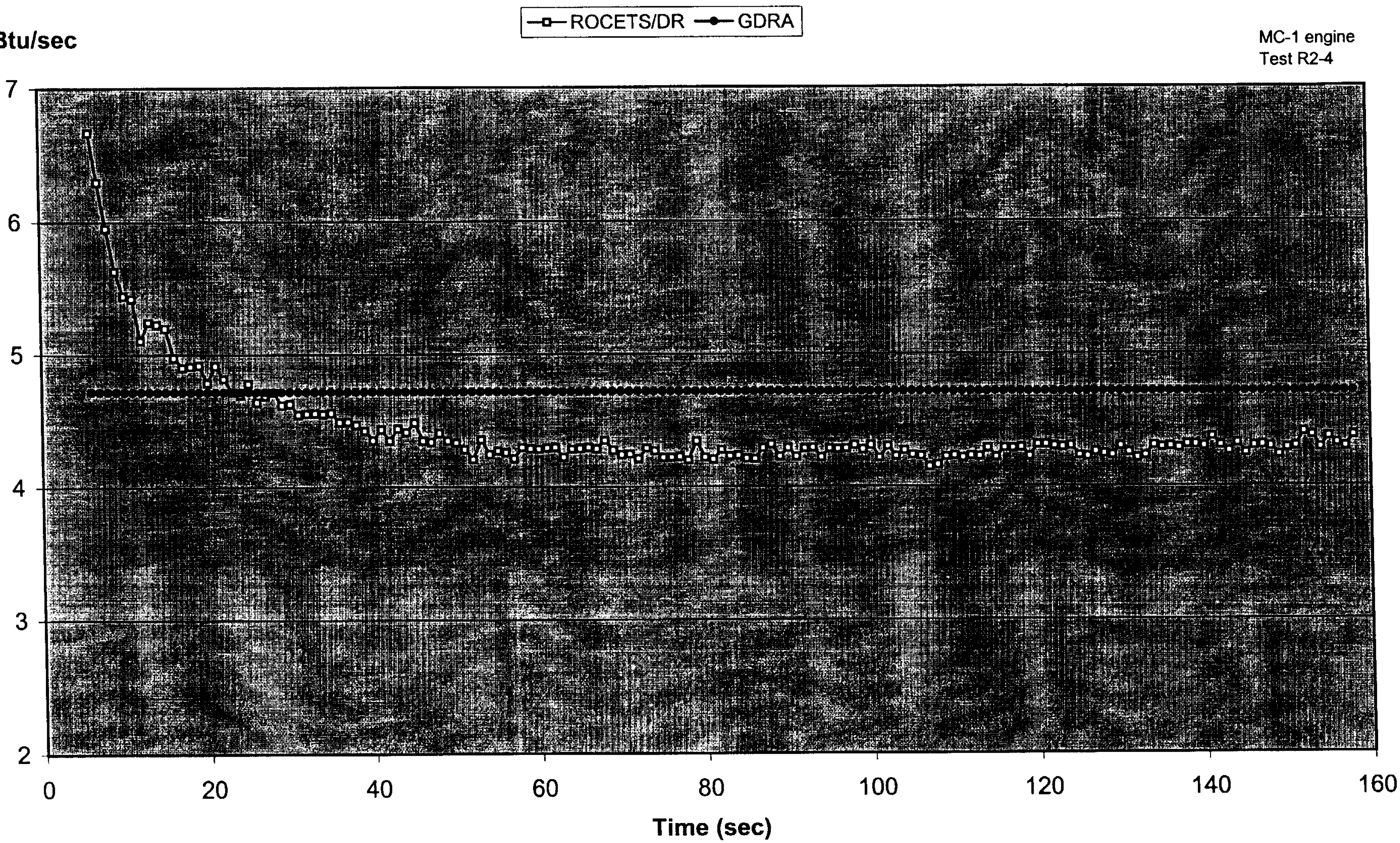


Figure F18 Reduction results with flight measurement set and 20-23 second avg flows QDOTVL18



Appendix G

MC-1 engine
R2 and R3 test series
Information for data reduction

Table G1 Description of MC-1 engine test sequence used as study data source

SEQ	TEST NUMBER	TEST DATE	DURATION PLANNED	DURATION ACTUAL	DATA FILE NUMBER	TEST OBJECTIVES	Engine	Nozzle	ORIFICE SIZES GGRP	GGOX	MRP	MOX	GGNZ	ORIFICE SET
16	R2-1	29-Jul-00	24.000	24.004	35	Calibration Baseline	Eng 3	15:1	0.500	0.260	1.572	2.230	3.170	5
17	R2-2	10-Aug-00	24.000	24.008	39	LOX Inlet Pressure Ramp	Eng 3	15:1	0.500	0.260	1.572	2.230	3.170	5
19	R2-3a	17-Aug-00	24.000	24.005	41	Engine Calibration (OF Change #1) (Possible OBV leakage negating calibration attempt.)	Eng 3	15:1	0.420	0.275	1.350	2.230	3.170	6
20	R2-3b	31-Aug-00	24.000	24.007	43	Engine Calibration (OF Change #1, Repeat)	Eng 3	15:1	0.420	0.275	1.350	2.230	3.170	6
21	R2-4	8-Sep-00	159.000	159.000	45	FULL DURATION	Eng 3	15:1	0.400	0.290	1.340	2.230	3.170	7
22	R3-1a	25-Oct-00	24.000	24.000	51	Establish baseline and evaluate post-test data to determine orifices needed for calibration.	Eng 5	30:1	0.420	0.260	1.350	2.230	3.170	8
25	R3-2b	4-Dec-00	24.000	24.000	61	Evaluate Engine Calibration	Eng 5	30:1	0.400	0.290	1.340	2.230	3.170	7

Table G2 Parameters for MC-1 engine reduction study

MC-1 TEST SEQUENCE MEASUREMENTS

Subsystem	Variable Name	Variable Description
Inlet	PSVL10	LOX inlet pressure
	TTVL10	LOX inlet temperature
	PSRPFV	RP inlet pressure
	TTRPFV	RP inlet temperature
LOX	PSOXDS	LOX pump discharge pressure
	PSVL13	LOX orifice discharge pressure
	PTVL14	LOX dome pressure
	PSVL15	GGOV inlet pressure
	PTVL18	LOX GG inlet pressure
	TTVL14	LOX dome temperature
	TTVL18	LOX GG inlet temperature
	WOXTOTL	LOX flow
RP (Fuel)	PSVL00	RP pump inlet pressure
	PSVL01	RP pump discharge pressure
	PTVL05	Fuel manifold pressure
	PTVL09	GG RP inlet pressure
	TTVL05	Fuel manifold temperature
	WRPTOTL	RP flow
GG/Turbine	PTHTGI	GG pressure
	PTVL22	Turbine discharge pressure
	TTHTGI	Turbine inlet temperature
	TTHTGD	Turbine discharge temperature
MCC/Nozzle	PTMCHY	MCC pressure
Other	SNSHFT	Turbopump shaft speed
	FT15A	Vacuum thrust
shading indicates measurement not used in standard DR		

MC-1 HARDWARE DESCRIPTIONS

Component	Variable Name	Component Description
MCC		main combustion chamber
MFV		main fuel valve
MOV		main oxidizer valve
GG		gas generator
GGFV		gas generator fuel valve
GGOV		gas generator oxidizer valve
Type	**Parameter**	**Parameter Description**
Lines	RCALMF	Main fuel line calibration resistance
	RCALMO	Main LOX line calibration resistance
	RKFL1	Fuel pump inlet line resistance
	ROLN1	LOX pump inlet line resistance
Valves	XMGGKO	GGFV area multiplier
	XMGGOO	GGOV area multiplier
	XMMCKO	MFV area multiplier
	XMMGOO	MOV area multiplier
Injectors	CDGGKI	GG fuel injector discharge coefficient
	CDGGOI	GG oxidizer injector discharge coefficient
	CDKINJ	MCC fuel injector discharge coefficient
	CDOINJ	MCC LOX injector discharge coefficient
Pumps	PSIMKPMP	Fuel pump head coefficient multiplier
	PSIMOPMP	LOX pump head coefficient multiplier
	TRQMKPMP	Fuel pump torque multiplier
	TRQMOPMP	LOX pump torque multiplier
GG/Turbine	CDGGNZ	GG exhaust duct orifice discharge coef
	ETAMHTGT	Turbine efficiency multiplier
Trubopump	FRICFACT	Turbopump shaft friction parameter
MCC/Nozzle	CDNOZL	Nozzle discharge coefficient
	ECSMMCHB	MCC C* efficiency multiplier
Other	QDOTVL18	GG LOX flow heat transfer
shading indicates parameter not used in standard DR		

Table G3 Baseline values for MC-1 engine measurement variables

Subsystem	Variable Name	Engine	3	3	3	3	3	5	5
		Orifice Set	5	5	6	6	7	8	7
		MC-1 Test No	R2-1	R2-2	R2-3a	R2-3b	R2-4	R3-1a	R3-2b
		Units							
Inlet	PSVL10	psia	47	47	47	47	47	47	47
	TTVL10	deg R	164.5	164.5	164.5	164.5	164.5	164.5	164.5
	PRSPRV	psia	43	43	43	43	43	43	43
	TTRPFV	deg R	505	505	505	505	505	505	505
LOX	PSOXDS	psia	735.96	735.96	725.22	725.22	750.52	710.02	739.61
	PSVL13	psia	765.31	765.31	754.73	754.73	779.99	736.12	765.54
	PTVL14	psia	756.07	756.07	744.82	744.82	767.42	724.90	755.66
	PSVL15	psia	785.06	785.06	774.97	774.97	801.62	758.69	790.43
	PTVL18	psia	700.38	700.38	683.53	683.53	722.84	666.77	713.82
	TTVL14	deg R	167.75	167.75	167.77	167.77	167.97	167.57	167.86
	TTVL18	deg R	175.35	175.35	175.44	175.44	175.51	175.35	175.53
	WOXTOTL	lb/s	137.71	137.71	138.60	138.60	141.86	136.49	141.29
RP (Fuel)	PSVL00	psia	36.953	36.953	37.303	37.303	37.102	37.344	37.237
	PSVL01	psia	817.33	817.33	855.30	855.30	886.04	833.91	875.68
	PTVL05	psia	761.46	761.46	736.26	736.26	759.20	714.11	744.62
	PTVL09	psia	731.38	731.38	721.88	721.88	734.49	696.15	725.24
	TTVL05	deg R	513.46	513.46	513.86	513.86	514.28	513.66	514.22
	WRPTOTL	lb/s	69.871	69.871	65.945	65.945	67.748	63.227	65.915
GG/Turbine	PTHTGI	psia	554.00	554.00	549.53	549.53	568.59	533.93	560.29
	PTVL22	psia	78.774	78.774	77.520	77.520	79.001	77.972	81.133
	TTHTGI	deg R	1542.6	1542.6	1542.0	1542.0	1600.3	1533.4	1607.7
	TTHTGD	deg R	1390.0	1390.0	1389.0	1389.0	1433.0	1385.4	1442.7
MCC/Nozzle	PTMCHY	psia	645.62	645.62	627.10	627.10	649.86	625.22	646.84
Other	SNSHFT	rpm	18382	18382	18390	18390	18839	18028	18654
	FT15A	lb	46696	46696	46142	46142	47301	46288	48207

Table G4 Baseline values for MC-1 engine hardware parameters

Component	Variable Name	Units							
		Engine	3	3	3	3	3	5	5
		Orifice Set	5	5	6	6	7	8	7
		MC-1 Test No	R2-1	R2-2	R2-3a	R2-3b	R2-4	R3-1a	R3-2b
Lines	RCALMF	$lbf\text{-}s^2/lbm\text{-}in^5$	9.2721E-03	9.2721E-03	9.0988E-03	9.0988E-03	9.0462E-03	9.1968E-03	9.1375E-03
	RCALMO	$lbf\text{-}s^2/lbm\text{-}in^5$	9.7323E-04	9.7323E-04	9.7336E-04	9.7336E-04	9.7464E-04	9.7986E-04	9.8177E-04
	RKFL1	$lbf\text{-}s^2/lbm\text{-}in^5$	2.6701E-05	2.6701E-05	2.8791E-05	2.8791E-05	2.8069E-05	3.1865E-05	2.9281E-05
	ROLN1	$lbf\text{-}s^2/lbm\text{-}in^5$	1.0123E-04	1.0123E-04	1.0242E-04	1.0242E-04	1.0705E-04	1.0610E-04	1.0155E-04
Valves	XMGGKO	none	1.98884	1.98884	1.58894	1.58894	1.50258	1.48744	1.45768
	XMGGOO	none	1.04932	1.04932	0.86265	0.86265	0.88393	0.94156	0.88478
	XMMCKO	none	1	1	1	1	1	1	1
	XMMCOO	none	1	1	1	1	1	1	1
Injectors	CDGGKI	none	0.54786	0.54786	0.55176	0.55176	0.55021	0.55772	0.54068
	CDGGOI	none	0.70282	0.70282	0.73173	0.73173	0.70981	0.71219	0.70188
	CDKINJ	none	0.81972	0.81972	0.79169	0.79169	0.81671	0.83940	0.83975
	CDOINJ	none	0.74981	0.74981	0.73115	0.73115	0.74874	0.78249	0.77519
Pumps	PSIMKPMP	none	0.96658	0.96658	0.98478	0.98478	0.97507	0.98886	0.97501
	PSIMOPMP	none	1.05700	1.05700	1.04857	1.04857	1.03617	1.06951	1.04626
	TRQMKPMP	none	1	1	1	1	1	1	1
	TRQMOPMP	none	1	1	1	1	1	1	1
GG/Turbine	CDGGNZ	none	0.79622	0.79622	0.80241	0.80241	0.81232	0.77630	0.78028
	ETAMHTGT	none	1	1	1	1	1	1	1
Turbopump	FRICFACT	none	0.03365	0.03365	0.03108	0.03108	0.03901	0.03579	0.03555
MCC/Nozzle	CDNOZL	none	0.97775	0.97775	0.99648	0.99648	0.97675	1	1
	ECSMMCHB	none	0.94666	0.94666	0.94960	0.94960	0.94017	0.97559	0.96998
Other	QDOTVL18	Btu/sec	4.57350	4.57350	4.56995	4.56995	4.71635	4.50382	4.74871

Table G5 Revised hardware parameter list for MC-1 engine reduction study

MC-1 HARDWARE PARAMETERS		
Component	**Variable Name**	**Variable Description**
Lines Valves Orifices	RMMCRP	Main fuel line resistance series
	RMMCOX	Main LOX line resistance series
	RKFL1	Fuel pump inlet line resistance
	ROLN1	LOX pump inlet line resistance
	RMGGRP	GG fuel line resistance series
	RMGGOX	GG LOX line resistance series
Injectors	RGGKI	GG fuel injector resistance
	RGGOI	GG oxidizer injector resistance
	RKINJ	MCC fuel injector resistance
	ROINJ	MCC LOX injector resistance
Pumps	PSIMKPMP	Fuel pump head coefficient multiplier
	PSIMOPMP	LOX pump head coefficient multiplier
	TRQMKPMP	Fuel pump torque multiplier
	TRQMOPMP	LOX pump torque multiplier
GG/Turbine	CDGGNZ	GG exhaust duct orifice discharge coef
	ETAMHTGT	Turbine efficiency multiplier
Trubopump	PWRFACT	Turbopump power factor
MCC/Nozzle	CDNOZL	Nozzle discharge coefficient
	ECSMMCHB	MCC C* efficiency multiplier
Other	QDOTVL18	GG LOX flow heat transfer

Table G6 Flight parameter list for MC-1 engine reduction study

MC-1 FLIGHT MEASUREMENTS

Subsystem	Variable Name	Variable Description
Inlet	PSVL10	LOX inlet pressure
	TTVL10	LOX inlet temperature
	PSRPFV	RP inlet pressure
	TTRPFV	RP inlet temperature
LOX	PSOXDS	LOX pump discharge pressure
RP (fuel)	PSVL01	RP pump discharge pressure
GG/Turbine	PTHTGI	GG pressure
	TTHTGI	Turbine inlet temperature
MCC/Nozzle	PTMCHY	MCC chamber pressure

FLIGHT MC-1 HARDWARE PARAMETERS

Type Component	Variable Name	Variable Description
Lines Valves Orifices Injectors	R3MCRP	Fuel pump discharge to MCC effective resis
	R3MCOX	Ox pump discharge to MCC effective resistance
	R3GGRP	Fuel pump discharge to GG effective resistance
	R3GGOX	Oxidizer pump discharge to GG effective resis
Pumps	PSIMKPMP	Fuel pump head coefficient multiplier
	PSIMOPMP	LOX pump head coefficient multiplier
	TRQMKPMP	Fuel pump torque multiplier
	TRQMOPMP	LOX pump torque multiplier
GG/Turbine	ETAMHTGT	Turbine efficiency multiplier
Trubopump	PWRFACT	Turbopump power factor
MCC/Nozzle	ECSMMCHB	MCC C* efficiency multiplier
Other	QDOTVL18	GG Lox flow heat transfer

Appendix H

MC-1 engine
R2 and R3 test series data

Table H1 MC-1 engine - test R2-1 one second average data

Variable Measured	Units	Time (sec) measured from engine start (sec)																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	41.8	42.0	41.8	41.8	41.7	41.7	41.5	41.5	41.4	41.3	41.4	41.6	41.4	41.3	41.4	41.2	41.2	41.1
TTVL10	deg R	164.3	163.8	163.7	163.8	164.0	163.9	163.6	163.1	162.8	162.6	162.4	162.4	162.4	162.3	162.2	162.2	162.2	162.2
PRSPRV	psia	49.5	50.4	50.2	49.8	49.7	49.4	49.1	48.9	48.7	48.5	48.2	48.0	47.8	47.6	47.3	47.1	46.9	46.8
TTRPFV	deg R	549.2	550.9	551.4	551.6	551.8	551.9	552.0	552.2	552.3	552.4	552.5	552.6	552.6	552.7	552.8	552.8	552.9	553.0
PSOXDS	psia	734.0	736.7	739.3	740.6	740.0	740.1	743.5	743.8	745.5	745.5	748.0	746.9	747.7	748.7	749.7	750.0	749.9	752.3
PSVL13	psia	756.7	759.2	761.6	763.1	762.5	763.2	766.2	767.4	769.8	769.5	772.6	771.6	772.3	773.8	774.8	776.0	776.3	777.1
PTVL14	psia	747.9	750.3	752.3	754.0	753.3	753.6	756.8	757.9	760.5	759.9	763.2	762.2	762.7	764.2	765.2	766.3	766.5	767.5
PSVL15	psia	746.0	748.4	750.8	752.6	751.7	752.4	755.2	756.4	758.8	758.5	761.7	760.5	760.9	762.6	763.5	764.4	764.7	765.5
PTVL18	psia	694.3	698.3	701.3	703.0	702.2	702.7	704.7	704.7	706.7	705.4	708.1	706.2	706.8	708.2	709.2	709.1	710.1	710.6
TTVL14	deg R	175.6	174.6	173.9	173.9	173.7	173.6	173.6	172.6	172.1	171.9	171.7	171.4	171.6	171.3	171.1	171.0	171.0	171.0
TTVL18	deg R	178.4	177.1	176.3	175.9	175.8	175.5	175.2	174.8	174.2	173.9	173.7	173.5	173.3	173.3	173.2	173.1	173.1	173.0
WOXTOTL	lbm/sec	138.7	138.4	139.0	139.1	138.9	138.9	140.3	139.8	139.6	140.9	140.5	139.6	141.0	140.0	140.6	141.1	141.2	140.7
PSVL00	psia	43.4	44.6	44.2	43.9	43.8	43.6	43.2	43.2	42.7	42.7	42.2	42.3	42	41.7	41.5	41.3	41.1	40.8
PSVL01	psia	809.7	808.1	811.2	814.4	813.8	815.4	812.1	812.2	818.3	813.7	821.6	816.1	819.1	822.2	825.6	823.6	822.4	823.1
PTVL05	psia	755.8	757.7	759.2	759.4	758.6	759.1	761.1	761.9	763.7	763.3	766	764.5	764.4	765.7	766.6	767.4	767.3	767.7
PTVL09	psia	724.1	726.0	727.3	728.9	728.2	729.8	731.1	731.5	733.3	732.8	735.2	734.1	734.2	735.0	736.0	737.1	737.3	737.4
TTVL05	deg R	551.3	553.2	554.1	554.5	554.8	554.9	555.2	555.3	555.5	555.6	555.6	555.8	555.8	556.0	556.0	556.1	556.2	556.2
WRPTOTL	lbm/sec	68.0	68.3	68.4	68.3	68.3	68.4	68.4	68.4	68.4	68.6	68.6	68.7	68.6	68.6	68.7	68.8	68.7	68.8
PTHTGI	psia	548.5	549.8	551.3	552.9	552.5	553.4	554.6	555.1	556.4	555.9	558.3	557.4	558.1	558.7	559.7	558.9	559.9	560.4
PTVL22	psia	77.7	78.3	78.5	78.6	78.6	78.8	79	78.9	79.2	79.2	79.6	79.4	79.4	79.6	79.5	79.6	79.7	79.6
TTHTGI	deg R	1531	1536	1543	1545	1543	1544	1550	1552	1556	1558	1562	1561	1560	1563	1563	1565	1568	1566
TTHTGD	deg R	1189	1194	1200	1202	1202	1204	1208	1209	1212	1214	1216	1216	1216	1218	1218	1222	1224	1223
PTMCHY	psia	642.1	643.8	645.2	645.7	644.9	645.1	647.2	647.9	649.4	648.8	650.8	649.9	650.1	651.0	651.7	652.3	652.1	652.8
SNSHFT	rpm	18483	18500	18500	18500	18500	18504	18572	18554	18592	18600	18600	18600	18588	18600	18600	18608	18642	18600
FT15A	lbf	46916	47067	47129	47174	47071	47082	47224	47274	47371	47318	47489	47358	47364	47406	47466	47512	47462	47520

Table H2 MC-1 engine - test R2-2 one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	42.1	42.1	42.1	41.9	42.0	42.9	44.1	45.4	46.1	48.1	49.4	51.0	53.2	54.1	55.4	55.4	55.5	55.2
TTVL10	deg R	165.2	164.7	164.3	164.1	164.0	163.9	163.8	163.6	163.4	163.2	163.1	163.1	163.0	163.0	162.9	163.0	163.0	163.0
PRSPRV	psia	38.9	38.7	38.5	38.5	38.5	38.6	38.5	38.5	38.5	38.5	38.5	38.4	38.5	38.4	38.4	38.4	38.4	38.4
TTRPFV	deg R	547.2	546.1	546.0	545.9	545.9	545.8	545.8	545.8	545.7	545.7	545.7	545.7	545.7	545.6	545.6	545.6	545.6	545.6
PSOXDS	psia	737.1	740.0	741.4	741.7	743.2	747.1	752.8	755.6	758.6	757.1	760.3	760.1	760.8	763.3	764.5	764.0	764.7	765.1
PSVL13	psia	756.4	758.7	760.1	760.2	762.2	766.6	773.5	776.5	780.3	778.7	781.5	783.0	782.5	784.9	786.1	786.5	786.3	787.4
PTVL14	psia	747.2	748.8	750.1	750.1	752.4	756.7	763.5	766.2	770.4	768.6	771.4	772.9	772.5	775.1	776.3	776.3	776.2	777.3
PSVL15	psia	745.8	748.0	749.1	749.5	751.5	755.7	762.4	765.3	769.1	767.3	770.6	771.5	770.9	773.1	774.2	774.7	774.3	775.3
PTVL18	psia	686.9	689.3	690.8	691.0	693.4	696.5	703.1	705.9	709.3	708.0	710.5	712.3	712.6	714.7	715.3	714.8	715.2	717.7
TTVL14	deg R	177.5	176.5	175.8	176.3	176.2	176.4	176.7	176.2	177.5	176.6	177.7	177.1	176.3	177.1	177.0	176.0	175.7	176.1
TTVL18	deg R	179.4	178.2	177.2	176.5	175.9	175.7	175.4	175.2	174.8	174.6	174.4	174.2	174.0	174.0	173.9	173.8	173.8	173.7
WOXTOTL	lbm/sec	138.6	139.2	138.8	139.4	139.1	140.0	141.6	142.3	142.9	142.6	143.2	142.7	142.8	143.7	143.1	143.1	143.2	143.4
PSVL00	psia	33.2	32.9	32.7	32.8	32.9	33	32.7	32.8	32.8	32.8	32.7	32.7	32.6	32.7	32.7	32.7	32.7	32.6
PSVL01	psia	806.3	805	808.2	808	806.1	815.4	816.8	820.1	823.1	816.9	822.6	820.6	825	825.6	826.8	824.9	822.6	828.4
PTVL05	psia	752.1	752.7	753.9	753.4	755.4	758.4	762.4	764	767.3	765.7	768.2	768.7	768.8	770.8	771	769.9	770.9	772.2
PTVL09	psia	723.0	723.7	724.6	725.2	726.3	728.7	733.7	735.7	738.1	737.8	738.9	739.0	739.7	741.5	741.9	742.3	742.2	743.6
TTVL05	deg R	550.7	549.1	548.9	548.9	548.8	548.8	548.9	548.9	548.9	548.8	548.8	548.8	548.8	548.8	548.8	548.8	548.8	548.8
WRPTOTL	lbm/sec	67.3	67.2	67.4	67.4	67.4	67.6	67.6	67.7	67.8	67.8	68.0	68.0	68.0	68.3	68.2	68.1	68.1	68.5
PTHTGI	psia	548.8	550.1	551.4	550.9	552.1	553.9	558.2	560.1	562.1	561.4	563.2	563.5	563.2	564.6	565.1	566.1	565.6	566.1
PTVL22	psia	77.8	78.1	78.4	78.5	78.7	79.1	79.5	79.7	79.9	79.8	80.1	80.2	80.2	80.5	80.4	80.3	80.3	80.4
TTHTGI	deg R	1543	1541	1547	1545	1550	1555	1558	1561	1565	1563	1568	1570	1569	1570	1572	1569	1568	1572
TTHTGD	deg R	1361	1363	1372	1374	1382	1388	1393	1396	1400	1400	1405	1408	1407	1411	1413	1410	1410	1415
PTMCHY	psia	640.7	641.8	642.5	642.0	643.4	646.1	650.4	652.0	654.6	653.1	655.0	655.6	655.4	657.0	657.4	657.4	657.0	657.9
SNSHFT	rpm	18456	18456	18456	18456	18500	18556	18606	18606	18618	18612	18635	18660	18641	18744	18704	18726	18732	18739
FT15A	lbf	46647	46712	46778	46733	46789	47047	47424	47533	47759	47645	47788	47845	47793	47915	47960	47927	47891	47974

Table H3 MC-1 engine - test R2-3a one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	40.9	40.6	40.7	40.8	40.7	40.9	40.7	40.7	40.4	40.5	40.4	40.4	40.4	40.3	40.4	40.1	40.2	40.2
TTVL10	deg R	164.5	164.0	163.9	164.1	164.2	164.0	163.8	163.2	162.7	162.6	162.5	162.4	162.3	162.2	162.2	162.2	162.1	162.1
PRSPRV	psia	39.1	39.1	39.1	39.1	39.1	39.0	39.0	39.0	39.1	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
TTRPFV	deg R	548.8	548.6	548.6	548.6	548.6	548.6	548.6	548.7	548.7	548.7	548.7	548.7	548.7	548.7	548.7	548.7	548.7	548.7
PSOXDS	psia	725.4	728.4	731.0	730.4	730.7	732.5	732.5	734.8	736.6	737.1	736.4	737.4	738.5	738.3	739.3	740.5	739.9	740.2
PSVL13	psia	748.3	751.3	753.5	752.4	752.8	754.7	754.9	757.3	759.3	760.9	759.6	761.2	762.3	762.2	763.3	764.8	764.0	764.9
PTVL14	psia	738.5	741.3	743.4	742.3	742.5	744.6	744.9	747.3	749.4	750.9	749.7	751.3	752.3	752.1	753.2	754.5	753.5	754.6
PSVL15	psia	734.7	737.8	740.0	739.1	739.3	741.0	741.4	743.9	745.8	747.5	746.0	747.7	748.3	748.6	749.4	750.8	749.8	750.9
PTVL18	psia	675.7	679.3	681.1	680.1	681.0	682.9	683.4	685.4	687.2	689.1	686.4	687.4	688.9	688.7	689.7	691.5	690.7	692.2
TTVL14	deg R	175.3	174.2	173.7	173.2	173.4	173.1	172.9	172.2	171.5	171.5	171.0	170.9	170.7	170.5	170.5	170.3	170.4	170.3
TTVL18	deg R	178.9	177.5	176.7	176.3	176.1	175.9	175.5	175.0	174.3	173.9	173.8	173.7	173.5	173.4	173.2	173.0	173.1	173.0
WOXTOTL	lbm/sec	139.7	140.2	140.3	140.2	140.2	141.0	141.0	141.1	141.2	141.2	141.1	140.7	141.9	141.0	141.9	141.4	142.7	141.7
PSVL00	psia	33.7	33.7	33.8	33.7	33.7	33.8	33.6	33.6	33.5	33.6	33.7	33.5	33.4	33.6	33.6	33.6	33.6	33.4
PSVL01	psia	842.2	848.6	848.7	846.8	845	852.6	844.2	856.4	853.3	857.6	853	849.1	858.1	850.7	855	858.3	859.9	856.5
PTVL05	psia	730.8	732.4	734	732	732.4	734.4	734.5	735.4	736.7	737.8	736.6	738.2	738.2	738.7	738.9	740	738.9	739.5
PTVL09	psia	713.7	715.7	717.2	716.8	716.6	717.7	717.7	719.8	720.8	722.3	721.3	721.5	723.1	723.2	724.0	725.3	724.5	725.1
TTVL05	deg R	551.6	551.4	551.5	551.6	551.6	551.6	551.7	551.8	551.8	551.8	551.9	551.9	551.9	551.9	552.0	552.0	552.0	552.0
WRPTOTL	lbm/sec	63.9	64.2	64.1	64.2	64.2	64.3	64.4	64.2	64.3	64.5	64.5	64.6	64.5	64.5	64.7	64.7	64.6	64.7
PTHTGI	psia	544.5	546.6	548.1	547.8	548.0	549.2	549.3	550.3	551.7	552.9	551.8	552.2	553.2	553.3	554.0	555.0	554.3	555.0
PTVL22	psia	76.5	77.1	77.5	77.5	77.6	77.7	77.8	77.8	78	78.2	78	78.2	78.2	78.1	78.2	78.4	78.2	78.2
TTHTGI	deg R	1551	1552	1554	1554	1555	1557	1558	1560	1562	1564	1562	1564	1566	1565	1565	1566	1567	1569
TTHTGD	deg R	1368	1375	1380	1382	1385	1389	1392	1394	1397	1400	1400	1403	1405	1405	1406	1408	1409	1411
PTMCHY	psia	624.8	626.3	627.3	626.1	626.2	627.4	627.3	628.6	630.0	630.9	629.8	630.7	631.4	631.3	631.6	632.7	631.7	632.2
SNSHFT	rpm	18456	18456	18462	18456	18456	18512	18534	18562	18600	18606	18594	18606	18606	18600	18606	18606	18606	18606
FT15A	lbf	46423	46511	46608	46443	46454	46481	46487	46546	46656	46709	46639	46706	46718	46688	46713	46777	46751	46738

Table H4 MC-1 engine - test R2-3b one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	41.1	41.3	41.1	40.9	41.0	40.9	40.8	40.8	40.8	40.7	40.6	40.7	40.7	40.5	40.6	40.6	40.6	40.5
TTVL10	deg R	165.0	164.8	164.5	164.2	164.0	163.8	163.7	163.4	163.1	163.0	162.8	162.7	162.7	162.6	162.6	162.6	162.6	162.6
PRSPRV	psia	38.9	38.9	38.8	38.8	38.8	38.8	38.8	38.7	38.7	38.8	38.8	38.8	38.7	38.7	38.7	38.7	38.7	38.7
TTRPFV	deg R	529.0	529.2	529.3	529.3	529.4	529.4	529.5	529.5	529.5	529.5	529.5	529.6	529.6	529.6	529.6	529.6	529.7	529.7
PSOXDS	psia	729.6	732.7	734.0	736.4	735.3	738.0	739.0	739.3	741.5	740.9	741.3	742.3	741.8	744.0	744.7	744.4	746.2	746.1
PSVL13	psia	751.8	754.2	755.4	757.8	757.6	759.7	761.1	762.1	763.7	763.9	764.6	765.3	764.9	768.1	768.9	768.4	769.8	769.9
PTVL14	psia	740.9	743.1	744.5	746.6	746.3	748.6	749.9	750.8	752.3	752.5	753.2	753.9	753.6	756.5	757.1	757.0	758.4	758.4
PSVL15	psia	740.4	742.7	743.9	746.1	746.0	748.2	749.4	750.3	752.0	752.1	752.8	753.6	752.9	755.7	756.7	756.1	757.6	757.6
PTVL18	psia	691.7	693.5	694.8	697.2	694.5	696.0	697.0	697.6	699.3	699.0	699.9	699.2	699.4	702.0	703.3	702.8	704.6	704.2
TTVL14	deg R	175.4	174.9	174.6	173.9	173.3	172.9	172.9	172.6	172.0	171.7	171.5	171.4	171.0	171.2	171.1	171.0	170.9	171.0
TTVL18	deg R	178.6	177.7	177.0	176.3	176.0	175.6	175.1	174.7	174.4	174.2	173.9	173.9	173.5	173.4	173.2	173.3	173.1	173.0
WOXTOTL	lbm/sec	138.7	139.3	139.4	139.9	139.6	139.9	140.2	141.0	140.5	140.7	140.9	141.0	140.6	140.8	141.2	140.9	141.1	141.3
PSVL00	psia	33.2	33.1	33.3	33	32.9	32.9	33	32.9	32.9	32.9	32.9	32.8	32.9	32.7	32.8	32.7	32.8	32.9
PSVL01	psia	852.6	851.2	857	855.3	857.7	855.9	861	857.6	862.6	860.5	861.4	860.8	861.6	863.5	870.7	867.8	864.9	866.3
PTVL05	psia	734.9	737.5	738.4	739.3	738	739.7	740.7	740.9	741.8	741.9	742.3	741.7	741.7	743.4	744.9	743.9	745.4	745.7
PTVL09	psia	723.5	724.1	725.1	726.3	725.2	726.6	727.9	729.4	730.4	729.7	730.7	730.5	730.0	732.7	734.1	732.4	734.5	733.8
TTVL05	deg R	532.2	532.4	532.7	532.7	532.8	533.0	533.0	533.1	533.1	533.1	533.2	533.2	533.2	533.2	533.3	533.3	533.4	533.4
WRPTOTL	lbm/sec	64.5	64.7	64.8	64.9	64.7	64.6	64.7	64.9	64.9	65.1	65.1	65.1	65.1	65.0	65.3	65.2	65.4	65.4
PTHTGI	psia	549.9	551.7	552.1	553.1	553.3	555.2	555.5	556.0	556.9	556.7	557.1	557.0	556.9	557.9	559.3	558.3	559.2	559.2
PTVL22	psia	76.9	77.6	77.9	78.2	78.2	78.2	78.3	78.5	78.5	78.5	78.5	78.5	78.4	78.7	78.7	78.6	78.8	78.8
TTHTGI	deg R	1541	1541	1545	1548	1550	1549	1551	1554	1557	1558	1559	1560	1559	1564	1564	1563	1567	1568
TTHTGD	deg R	1360	1364	1370	1377	1379	1381	1384	1387	1392	1393	1395	1397	1397	1403	1404	1403	1408	1410
PTMCHY	psia	633.6	635.0	635.3	636.6	636.0	637.2	638.2	638.2	639.1	639.1	639.3	639.4	639.1	641.0	641.6	641.0	642.0	642.1
SNSHFT	rpm	18486	18499	18517	18555	18533	18558	18569	18577	18603	18591	18602	18618	18593	18635	18649	18630	18672	18673
FT15A	lbf	46190	46344	46322	46400	46300	46437	46485	46540	46677	46662	46651	46625	46603	46732	46775	46683	46842	46797

Table H5 MC-1 engine - test R2-4 one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	39.8	39.7	39.7	39.6	39.6	39.5	39.5	39.5	39.3	39.3	39.2	39.2	39.1	39.2	39.2	39.2	39.1	39.2
TTVL10	deg R	165.3	164.7	164.3	164.1	164.0	163.9	163.9	163.6	163.3	163.1	163.1	163.0	162.9	162.9	162.9	162.8	162.8	162.8
PRSPRV	psia	38.6	38.6	38.6	38.6	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.4	38.5	38.5	38.6	38.5
TTRPFV	deg R	540.9	540.8	540.8	540.8	540.8	540.8	540.9	540.9	540.9	540.9	540.9	540.9	540.9	540.9	540.9	540.9	540.9	540.9
PSOXDS	psia	745.3	747.7	750.2	751.2	752.4	752.1	753.0	755.4	755.6	756.4	756.9	757.5	757.6	758.7	758.1	758.3	758.3	760.4
PSVL13	psia	776.9	779.9	782.7	783.5	784.3	783.2	783.6	784.9	785.8	786.0	786.2	786.4	785.7	787.0	785.8	785.5	785.7	786.3
PTVL14	psia	758.0	760.2	762.5	763.6	764.8	764.4	765.5	767.4	768.8	769.9	770.5	771.3	771.2	772.6	772.1	772.2	772.5	773.4
PSVL15	psia	756.2	758.6	761.2	762.1	763.3	762.9	764.0	765.9	767.2	768.3	769.0	769.3	769.1	770.8	770.1	770.0	770.3	771.1
PTVL18	psia	714.4	716.9	718.9	719.5	721.1	720.5	721.9	723.9	724.8	725.6	726.0	726.6	726.3	727.9	727.5	726.8	727.8	728.5
TTVL14	deg R	176.2	175.3	174.0	173.4	173.5	173.2	172.9	172.5	172.4	171.8	171.7	171.5	171.3	171.3	171.2	171.1	170.9	170.7
TTVL18	deg R	179.3	178.1	177.2	176.5	176.1	176.0	175.5	175.4	175.1	174.8	174.5	174.3	174.2	174.2	174.0	174.1	174.0	173.8
WOXTOTL	lbm/sec	141.8	142.9	141.8	142.3	142.9	142.1	142.8	142.6	142.4	143.2	142.9	143.0	143.5	143.5	143.2	143.8	142.8	144.0
PSVL00	psia	32.9	32.9	33	32.9	32.9	32.9	33.1	33	32.9	33	33	33	32.9	32.9	32.8	32.9	32.8	32.7
PSVL01	psia	885.6	871.7	876.2	876.8	882	881.4	875.7	880.7	882.8	883	891.2	885.1	883.2	886.8	888.4	887.3	887	884.9
PTVL05	psia	750.9	753	755.7	754.9	755.9	755	756.5	757.5	758	758.7	759.4	758.9	759	760.7	759.4	759.3	759.8	760.2
PTVL09	psia	725.5	726.9	728.1	728.7	730.1	729.5	730.4	731.7	732.5	733.5	733.8	733.8	733.3	735.7	735.1	734.3	734.5	735.7
TTVL05	deg R	544.1	544.2	544.2	544.2	544.4	544.3	544.5	544.5	544.5	544.6	544.6	544.6	544.6	544.7	544.6	544.7	544.7	544.7
WRPTOTL	lbm/sec	65.9	65.9	66.1	66.0	66.1	66.1	66.2	66.3	66.3	66.3	66.4	66.3	66.3	66.4	66.4	66.4	66.6	66.6
PTHTGI	psia	562.6	564.3	565.5	566.3	567.1	567.0	568.1	569.2	569.9	570.8	570.5	571.0	570.5	571.6	571.7	570.8	571.1	572.0
PTVL22	psia	78.1	78.6	78.9	79.1	79.3	79.2	79.2	79.4	79.4	79.4	79.4	79.5	79.4	79.5	79.4	79.3	79.3	79.4
TTHTGI	deg R	1604	1606	1610	1610	1612	1613	1611	1615	1616	1615	1616	1618	1621	1621	1620	1622	1623	1623
TTHTGD	deg R	1411	1417	1423	1426	1430	1431	1432	1436	1438	1438	1441	1444	1446	1448	1447	1451	1453	1452
PTMCHY	psia	645.4	646.6	648.0	648.3	649.0	648.1	648.9	650.2	650.8	651.3	651.6	651.6	651.5	652.8	651.9	651.7	652.1	652.7
SNSHFT	rpm	18873	18898	18899	18902	18903	18896	18918	18933	18965	18942	18956	18974	18974	18983	18962	18985	19000	19005
FT15A	lbf	47283	47415	47533	47505	47536	47507	47491	47645	47687	47683	47719	47665	47653	47745	47699	47652	47630	47669

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
PSVL10	psia	39.1	39.2	39.1	39.1	39.2	39.2	39.2	39.2	39.2	39.2	39.1	39.2	39.2	39.3	39.3	39.2	39.3	39.3
TTVL10	deg R	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8
PRSPRV	psia	38.4	38.5	38.4	38.4	38.5	38.5	38.4	38.5	38.4	38.4	38.4	38.4	38.4	38.5	38.4	38.3	38.4	38.4
TTRPFV	deg R	540.9	540.9	540.9	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.0	541.1	541.1
PSOXDS	psia	760.0	759.8	760.2	760.1	759.7	758.8	760.1	759.9	760.1	760.2	759.6	761.0	761.2	761.1	760.8	761.4	759.6	761.2
PSVL13	psia	786.6	786.7	786.5	786.8	786.3	784.5	786.6	785.5	785.9	786.0	785.6	786.6	787.1	786.0	786.5	787.2	785.9	786.7
PTVL14	psia	773.6	774.2	774.6	774.6	774.3	772.6	774.8	773.8	774.5	774.4	774.2	775.1	775.7	774.6	775.3	775.6	774.4	775.3
PSVL15	psia	771.5	771.7	771.9	772.4	771.9	770.2	772.5	771.7	772.0	772.2	771.7	772.7	773.4	772.2	773.0	773.3	772.2	772.9
PTVL18	psia	729.2	729.2	729.1	730.0	729.5	727.6	729.6	729.1	729.9	729.9	729.2	730.0	730.8	729.1	730.9	731.1	729.5	730.5
TTVL14	deg R	170.8	171.0	170.7	170.9	170.9	170.7	170.8	170.6	170.6	170.4	170.6	170.4	170.5	170.4	170.6	170.5	170.5	170.3
TTVL18	deg R	173.8	173.9	173.7	173.8	173.8	173.7	173.7	173.6	173.6	173.6	173.6	173.6	173.5	173.5	173.5	173.4	173.3	173.4
WOXTOTL	lbm/sec	143.4	143.7	143.9	143.3	144.1	143.2	143.7	142.8	143.4	143.7	143.3	143.4	143.7	143.9	143.0	143.8	143.7	143.9
PSVL00	psia	32.7	32.6	32.9	32.8	32.8	32.8	32.8	32.8	32.8	32.7	32.8	32.7	32.8	32.9	32.7	32.6	32.7	32.7
PSVL01	psia	887.5	888.7	886.1	889.1	887	886.6	889.9	891.5	892.2	889.6	890.8	889	887.9	886.1	890.5	890.9	886.2	888.7
PTVL05	psia	761	760.8	761.8	761.4	761	759.6	761.8	760.8	760.6	761.5	760.8	762	762.4	760.7	762.1	763.4	761.2	761.8
PTVL09	psia	735.9	736.4	735.7	737.3	737.7	735.2	736.8	736.5	737.7	736.4	736.4	737.5	737.5	736.6	737.8	737.1	737.6	737.6
TTVL05	deg R	544.7	544.7	544.8	544.8	544.8	544.8	544.8	544.8	544.9	544.8	544.8	544.8	544.8	544.8	544.9	544.8	544.8	544.8
WRPTOTL	lbm/sec	66.7	66.7	66.8	66.6	66.6	66.7	66.8	66.8	66.8	66.9	66.8	66.8	66.8	66.8	66.8	66.9	66.9	67.0
PTHTGI	psia	572.1	572.4	572.1	572.9	572.9	571.7	572.6	572.6	573.0	572.8	572.6	573.3	573.3	572.8	573.4	573.5	572.8	573.5
PTVL22	psia	79.4	79.5	79.5	79.4	79.5	79.3	79.5	79.4	79.5	79.7	79.6	79.6	79.8	79.5	79.7	79.9	79.8	79.8
TTHTGI	deg R	1624	1624	1624	1624	1624	1624	1625	1624	1623	1625	1625	1624	1624	1625	1626	1626	1625	1626
TTHTGD	deg R	1455	1454	1456	1456	1457	1457	1459	1458	1458	1461	1461	1461	1461	1463	1464	1464	1463	1465
PTMCHY	psia	653.2	653.1	653.6	653.5	653.0	651.8	653.2	652.6	652.8	652.7	652.6	653.2	653.5	652.6	653.3	653.7	652.8	653.2
SNSHFT	rpm	19024	19011	19017	19040	19027	19014	19033	19023	19041	19042	19029	19031	19048	19042	19054	19055	19038	19032
FT15A	lbf	47716	47705	47691	47686	47666	47580	47702	47618	47533	47623	47582	47631	47671	47563	47544	47593	47561	47590

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
PSVL10	psia	39.2	39.1	39.2	39.1	39.2	39.1	39.1	39.2	39.1	39.1	39.2	39.1	39.1	39.2	39.1	39.1	39.2	39.2
TTVL10	deg R	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8
PRSPRV	psia	38.4	38.4	38.4	38.5	38.3	38.5	38.4	38.4	38.5	38.4	38.3	38.5	38.4	38.4	38.4	38.4	38.5	38.3
TTRPFV	deg R	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.1	541.2
PSOXDS	psia	759.7	762.0	761.1	761.4	761.7	760.7	761.8	760.7	760.7	761.5	762.2	761.0	761.8	762.7	761.5	762.1	762.3	761.7
PSVL13	psia	785.6	787.5	787.2	787.0	787.0	786.2	787.2	786.2	785.9	787.0	787.0	786.9	787.5	788.2	787.5	787.9	788.0	787.6
PTVL14	psia	774.3	776.0	776.0	775.4	775.8	774.8	775.8	774.9	774.4	775.8	775.8	775.4	776.3	776.9	775.9	776.9	776.4	776.0
PSVL15	psia	771.8	773.8	773.3	773.2	773.4	772.4	773.6	772.5	772.0	773.5	773.3	773.1	774.3	774.6	773.8	774.3	774.4	773.8
PTVL18	psia	729.6	731.5	730.3	730.2	730.8	730.0	730.4	730.2	729.8	731.0	730.5	730.1	731.6	732.2	731.1	732.3	732.1	731.5
TTVL14	deg R	170.5	170.4	170.4	170.5	170.4	170.4	170.4	170.3	170.3	170.3	170.2	170.2	170.4	170.3	170.3	170.2	170.2	170.2
TTVL18	deg R	173.3	173.4	173.4	173.5	173.3	173.3	173.4	173.3	173.3	173.2	173.1	173.3	173.1	173.2	173.2	173.1	173.2	173.2
WOXTOTL	lbm/sec	143.6	144.0	143.8	143.8	143.6	143.7	143.5	143.5	143.2	143.8	143.8	144.1	143.8	143.6	143.4	143.6	144.5	143.5
PSVL00	psia	32.7	32.7	32.7	32.6	32.6	32.8	32.4	32.9	32.6	32.7	32.8	32.8	32.8	32.7	32.5	32.7	32.6	32.7
PSVL01	psia	888.6	896.3	888.2	887.3	891.5	892.9	890.9	891.5	887	889.2	891.1	896.5	892	891.3	890.2	892	892.9	886.4
PTVL05	psia	760.5	762.7	761.8	761.9	762.5	761.7	762.4	761.3	760.5	761.7	762.5	761.8	763	763.7	763.1	763.1	762.7	762.9
PTVL09	psia	736.4	738.0	737.5	737.5	737.9	737.4	738.1	737.8	737.5	738.3	738.4	738.5	739.1	739.2	738.3	739.2	738.9	738.9
TTVL05	deg R	544.9	544.8	544.9	544.9	544.8	544.9	544.9	545.0	544.9	545.0	544.9	544.9	544.9	545.0	544.9	544.9	544.9	545.0
WRPTOTL	lbm/sec	66.8	66.9	66.8	66.8	66.8	66.9	66.8	66.9	66.8	66.7	66.9	66.7	66.9	67.0	66.9	67.0	66.8	66.8
PTHTGI	psia	572.9	573.9	573.2	573.4	573.6	573.3	573.4	573.5	573.5	574.4	573.7	573.7	575.1	574.7	574.1	575.1	575.2	574.8
PTVL22	psia	79.7	80.2	80.2	80.1	80.1	80.1	80.3	80.1	80.1	79.9	80.2	80.1	80	80.5	80.5	80.2	80.2	80.1
TTHTGI	deg R	1626	1628	1628	1629	1629	1629	1630	1629	1628	1628	1630	1628	1626	1629	1629	1627	1626	1625
TTHTGD	deg R	1465	1468	1468	1470	1469	1470	1471	1470	1470	1470	1472	1470	1469	1472	1473	1471	1470	1470
PTMCHY	psia	652.6	654.2	653.7	653.7	653.8	653.0	653.7	653.1	652.7	653.3	653.7	653.3	654.1	654.7	654.2	654.5	654.6	654.4
SNSHFT	rpm	19041	19043	19064	19062	19056	19070	19067	19047	19061	19068	19069	19061	19033	19082	19087	19075	19081	19054
FT15A	lbf	47493	47662	47610	47564	47582	47539	47613	47513	47451	47544	47542	47521	47566	47599	47547	47535	47569	47484

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77
PSVL10	psia	39.2	39.1	39.2	39.1	39.1	39.2	39.2	39.2	39.1	39.1	39.2	39.1	39.2	39.2	39.1	39.1	39.2	39.2
TTVL10	deg R	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8	162.8
PRSPRV	psia	38.4	38.4	38.4	38.4	38.5	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
TTRPFV	deg R	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2	541.2
PSOXDS	psia	763.3	761.6	762.7	762.1	762.3	762.5	763.0	762.1	761.8	762.9	763.4	760.7	762.2	762.7	762.9	762.4	763.5	762.8
PSVL13	psia	789.6	787.2	788.0	787.5	788.3	787.7	788.5	788.5	787.5	788.5	789.2	786.7	788.2	789.0	788.6	788.2	788.9	788.7
PTVL14	psia	778.8	775.9	776.9	776.0	776.9	776.3	777.1	776.9	775.8	777.0	777.8	775.3	776.7	777.2	776.9	776.7	777.3	777.2
PSVL15	psia	776.2	773.5	774.6	773.7	774.4	773.9	774.7	774.8	773.8	774.6	775.2	772.6	774.5	774.9	774.5	774.3	775.3	774.8
PTVL18	psia	733.5	731.4	731.7	731.7	731.7	731.7	732.3	732.6	731.3	731.7	732.9	730.6	731.4	732.3	732.0	731.7	732.0	732.1
TTVL14	deg R	170.2	170.3	170.3	170.3	170.2	170.2	170.3	170.2	170.2	170.1	170.2	170.2	170.3	170.2	170.2	170.2	170.2	170.2
TTVL18	deg R	173.2	173.2	173.2	173.1	173.2	173.2	173.2	173.2	173.3	173.2	173.1	173.1	173.1	173.2	173.2	173.1	173.1	173.1
WOXTOTL	lbm/sec	143.9	143.7	144.2	143.5	143.7	143.6	143.8	143.6	143.2	143.2	144.3	144.3	143.4	143.9	143.2	143.9	143.8	143.8
PSVL00	psia	32.5	32.8	32.6	32.7	32.6	32.7	32.6	32.8	32.7	32.6	32.6	32.8	32.6	32.6	32.5	32.5	32.5	32.7
PSVL01	psia	890.9	891.9	895.8	890.2	892.9	891.5	894.7	893.8	889.3	893.2	892.7	896.3	893.2	896.2	895.2	893	888.3	894.4
PTVL05	psia	765.4	761.5	763.1	762.5	763.3	761.7	763.5	763.2	762	763	763.3	760.9	762.1	763.3	762.7	763.1	763.7	762.5
PTVL09	psia	740.6	739.3	738.7	738.4	738.6	739.0	739.8	740.0	739.0	738.5	739.9	738.3	738.9	739.8	739.3	738.7	739.3	739.6
TTVL05	deg R	545.0	544.9	544.9	544.9	544.9	544.9	544.9	545.0	545.0	544.9	544.9	544.9	544.9	544.9	545.0	544.9	545.0	545.0
WRPTOTL	lbm/sec	67.1	66.8	66.9	66.9	66.9	66.8	66.9	66.9	67.0	66.9	66.9	66.9	66.8	67.0	66.9	67.0	67.0	66.9
PTHTGI	psia	575.9	574.9	574.9	575.3	575.1	574.9	575.6	575.6	574.7	575.3	575.4	574.4	574.7	575.1	575.3	574.7	575.2	575.3
PTVL22	psia	80.5	80	80.2	79.9	80.1	80.3	80.3	80.2	80.2	80.2	80.9	80.3	80.6	80.9	80.7	81	80.8	81
TTHTGI	deg R	1627	1623	1625	1625	1625	1625	1626	1625	1627	1627	1628	1630	1631	1631	1631	1630	1632	1632
TTHTGD	deg R	1472	1470	1471	1471	1471	1472	1473	1472	1473	1474	1475	1477	1477	1478	1478	1477	1479	1478
PTMCHY	psia	656.3	654.3	654.8	654.4	655.0	654.2	655.1	654.6	653.8	654.6	655.1	653.3	654.1	654.8	654.8	654.7	655.0	654.9
SNSHFT	rpm	19095	19051	19066	19059	19072	19060	19068	19075	19056	19072	19066	19042	19065	19077	19083	19076	19077	19070
FT15A	lbf	47700	47475	47573	47471	47510	47516	47568	47515	47438	47514	47561	47388	47502	47586	47522	47528	47551	47521

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start 78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
PSVL10	psia	39.2	39.2	39.1	39.1	39.1	39.2	39.2	39.1	39.1	39.1	39.1	39.2	39.2	39.3	39.1	39.2	39.1	39.2
TTVL10	deg R	162.8	162.8	162.8	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9
PRSPRV	psia	38.4	38.3	38.5	38.3	38.4	38.4	38.4	38.4	38.5	38.4	38.4	38.5	38.4	38.4	38.4	38.4	38.4	38.4
TTRPFV	deg R	541.2	541.2	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3
PSOXDS	psia	762.7	762.2	762.1	762.9	762.4	763.3	762.4	764.2	762.7	763.3	764.2	763.0	761.8	764.0	763.4	764.6	762.5	764.2
PSVL13	psia	787.8	788.1	787.7	787.8	788.0	788.8	788.3	789.7	788.3	789.2	790.2	788.8	787.7	789.7	789.7	790.4	788.7	789.8
PTVL14	psia	776.2	776.5	776.1	776.4	776.3	777.2	776.7	777.9	776.9	777.4	778.5	777.2	776.2	778.2	777.8	778.6	777.1	778.6
PSVL15	psia	774.06	774.1	773.9	774.0	774.2	774.9	774.1	775.9	774.5	775.4	776.2	774.9	774.0	775.7	775.6	776.4	774.7	776.1
PTVL18	psia	731.4	731.2	731.3	730.9	731.4	732.2	731.1	732.8	731.7	732.4	733.1	732.3	731.5	732.9	732.6	733.0	732.1	733.2
TTVL14	deg R	170.17	170.2	170.1	170.0	170.2	170.1	170.1	170.1	170.0	170.1	170.1	170.1	170.1	170.1	170.1	170.1	170.1	170.1
TTVL18	deg R	173.1	173.3	173.1	173.2	173.3	173.2	173.2	173.2	173.2	173.3	173.3	173.2	173.3	173.2	173.3	173.3	173.2	173.3
WOXTOTL	lbm/sec	143.2	143.4	143.5	143.2	143.5	143.8	144.1	143.2	143.5	143.7	144.6	143.5	143.4	143.5	143.9	143.4	143.9	143.3
PSVL00	psia	32.6	32.6	32.6	32.6	32.7	32.7	32.5	32.8	32.6	32.6	32.5	32.5	32.6	32.6	32.6	32.6	32.6	32.7
PSVL01	psia	891.7	887.8	895.1	893.7	893.2	892.3	893.8	894.2	894.4	896.4	892.6	892.9	886.2	892.2	890	894.9	893.1	896.1
PTVL05	psia	762.4	762.2	762.3	762.9	762.3	763.2	762.2	764.2	763.7	763.7	764.5	763.1	762.3	763.6	764.2	764.4	762.9	763.6
PTVL09	psia	739.1	738.4	738.3	738.3	739.0	739.7	738.8	739.9	739.1	739.7	740.2	739.9	738.7	740.2	739.6	740.1	740.0	740.8
TTVL05	deg R	545	544.9	545.0	545.0	544.9	545.0	545.0	545.0	545.1	545.0	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1
WRPTOTL	lbm/sec	67	67.0	67.0	67.0	66.9	66.9	66.9	66.9	67.1	67.0	67.0	66.9	66.9	66.9	67.0	67.0	66.9	67.0
PTHTGI	psia	574.7	574.9	574.9	574.7	575.0	575.7	575.0	576.2	575.2	575.9	576.5	575.9	575.5	576.4	576.0	576.6	575.8	576.6
PTVL22	psia	81	80.6	80.7	80.8	80.7	80.9	80.9	80.7	80.9	80.8	80.8	80.9	80.6	80.9	81	81.1	81.1	81.2
TTHTGI	deg R	1631.2	1631	1631	1632	1632	1630	1632	1631	1632	1634	1634	1634	1634	1634	1634	1634	1635	1634
TTHTGD	deg R	1477.9	1478	1479	1479	1478	1477	1479	1479	1480	1481	1481	1480	1480	1481	1481	1481	1481	1480
PTMCHY	psia	654.3	654.2	654.0	654.3	654.4	655.0	654.5	655.8	655.0	655.4	656.2	655.2	654.4	655.9	655.9	656.1	655.0	656.0
SNSHFT	rpm	19075	19075	19061	19069	19077	19068	19058	19080	19081	19079	19082	19070	19062	19080	19096	19080	19089	19085
FT15A	lbf	47465	47437	47406	47439	47503	47524	47479	47542	47443	47517	47528	47460	47357	47478	47479	47537	47377	47483

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113
PSVL10	psia	39.1	39.2	39.2	39.2	39.1	39.1	39.2	39.1	39.2	39.1	39.1	39.2	39.2	39.2	39.3	39.2	39.2	39.1
TTVL10	deg R	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	162.9	163.0	163.0	163.0	163.0	163.0	163.0	163.0	163.0
PRSPRV	psia	38.4	38.4	38.4	38.4	38.4	38.3	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4	38.4
TTRPFV	deg R	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.3	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4
PSOXDS	psia	763.6	763.1	762.6	763.2	764.0	763.0	763.8	763.9	763.6	764.8	764.9	764.6	764.6	763.9	765.1	765.6	765.9	765.6
PSVL13	psia	789.2	789.4	788.9	788.6	788.7	788.6	789.3	789.9	788.8	790.1	790.1	790.3	789.5	789.2	791.4	791.2	791.3	791.4
PTVL14	psia	777.8	777.7	777.5	776.8	777.0	777.0	777.7	778.2	777.2	778.5	778.6	778.7	778.3	777.6	780.0	779.4	779.8	779.5
PSVL15	psia	775.2	775.25	775.2	774.4	774.9	774.5	775.1	775.9	774.9	776.3	776.1	776.3	775.7	775.1	777.3	777.2	777.5	777.3
PTVL18	psia	732.5	731.9	731.7	730.8	731.9	732.0	732.1	733.1	731.8	733.0	733.2	733.3	732.6	731.8	734.2	734.0	733.9	734.2
TTVL14	deg R	170.1	170.09	170.1	170.1	170.1	170.1	170.1	170.1	170.2	170.1	170.2	170.2	170.1	170.2	170.2	170.2	170.1	170.2
TTVL18	deg R	173.3	173.3	173.3	173.3	173.3	173.2	173.3	173.2	173.3	173.2	173.3	173.2	173.2	173.3	173.3	173.3	173.3	173.3
WOXTOTL	lbm/sec	143.1	143.2	144.3	143.2	144.3	143.7	143.4	143.8	142.7	143.8	143.7	143.6	143.4	143.9	143.4	143.2	143.4	143.7
PSVL00	psia	32.6	32.7	32.7	32.6	32.6	32.5	32.8	32.8	32.5	32.6	32.6	32.7	32.9	32.6	32.7	32.5	32.5	32.6
PSVL01	psia	887.7	891.8	892.9	890.8	892.7	893	894.6	895.9	890.4	893.2	895.4	895.6	892.7	896.3	896.1	896.2	896.5	893.2
PTVL05	psia	762.5	762.8	762.7	762.2	761.9	763.4	762.6	764.4	763.2	764.3	764.1	764.7	764	763.8	766.4	765.7	765.9	765.5
PTVL09	psia	739.6	739.3	739.7	738.5	739.7	739.2	740.2	740.2	739.3	740.1	740.3	740.7	740.8	739.8	741.2	741.5	741.3	742.0
TTVL05	deg R	545.1	545.03	545.1	545.0	545.0	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1	545.1
WRPTOTL	lbm/sec	66.9	67	67.0	67.0	66.9	67.0	66.8	67.0	67.0	67.0	67.0	67.0	66.9	66.9	67.0	67.0	67.1	66.9
PTHTGI	psia	576.4	575.9	575.7	574.9	576.0	576.1	576.4	576.7	575.9	576.7	576.9	576.8	576.8	576.0	577.7	577.7	577.8	577.9
PTVL22	psia	80.8	81	81.1	81.1	80.9	80.9	81	81.2	81.1	81.2	81.4	81.4	81	81.2	81.2	81.1	81	81.2
TTHTGI	deg R	1634	1634	1634	1634	1634	1634	1633	1634	1635	1636	1635	1635	1635	1635	1636	1637	1637	1635
TTHTGD	deg R	1481	1480.5	1481	1481	1481	1482	1481	1483	1482	1483	1482	1482	1482	1482	1483	1484	1484	1482
PTMCHY	psia	655.4	655.4	655.4	654.9	654.9	655.2	655.5	656.0	655.3	656.5	656.7	656.7	656.3	656.2	658.0	657.7	657.9	657.8
SNSHFT	rpm	19078	19070	19070	19064	19076	19091	19057	19089	19074	19077	19085	19099	19068	19085	19084	19101	19089	19107
FT15A	lbf	47429	47408	47341	47331	47308	47383	47381	47354	47258	47396	47351	47385	47311	47303	47390	47390	47359	47343

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131
PSVL10	psia	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.2	39.3	39.2	39.2	39.2	39.1	39.2	39.3	39.2	39.3	39.2
TTVL10	deg R	163.0	163.0	163	163.0	163.0	163.0	163.0	163.0	163.0	163.0	163.0	163.1	163.1	163.1	163.1	163.1	163.1	163.1
PRSPRV	psia	38.4	38.4	38.4	38.4	38.3	38.4	38.4	38.4	38.4	38.4	38.4	38.5	38.3	38.4	38.4	38.4	38.3	38.4
TTRPFV	deg R	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.4	541.5	541.5	541.5	541.5	541.5
PSOXDS	psia	765.7	766.3	766.4	766.0	766.7	765.4	765.2	766.1	766.9	765.3	767.3	767.4	768.3	766.5	766.8	767.2	768.3	768.0
PSVL13	psia	791.4	791.8	791.7	791.3	792.7	791.8	791.3	791.3	792.4	791.0	793.2	792.1	793.4	792.2	792.2	792.8	793.6	793.2
PTVL14	psia	779.9	780.1	780.3	779.7	781.1	780.2	779.8	779.8	781.1	779.3	781.7	780.7	782.1	780.7	780.8	781.1	782.3	781.5
PSVL15	psia	777.6	777.8	777.73	777.4	778.8	777.7	777.4	777.1	778.4	777.0	779.3	777.8	779.5	778.3	778.4	778.8	779.4	779.2
PTVL18	psia	734.1	734.1	734.6	733.7	735.2	734.5	734.4	734.4	734.6	733.6	736.0	734.9	736.2	735.1	735.5	735.8	736.9	735.9
TTVL14	deg R	170.2	170.3	170.29	170.2	170.2	170.3	170.3	170.2	170.2	170.2	170.3	170.3	170.3	170.3	170.2	170.2	170.3	170.3
TTVL18	deg R	173.4	173.3	173.4	173.4	173.4	173.3	173.4	173.4	173.4	173.4	173.4	173.4	173.4	173.4	173.4	173.4	173.5	173.4
WOXTOTL	lbm/sec	143.2	143.3	143.3	143.4	143.3	143.4	143.6	143.9	143.4	143.1	143.5	143.3	143.2	143.8	143.3	143.1	142.6	144.1
PSVL00	psia	32.6	32.8	32.7	32.7	32.6	32.7	32.6	32.8	32.7	32.7	32.6	32.5	32.5	32.5	32.8	32.6	32.6	32.6
PSVL01	psia	895	891.9	895.4	891.7	895.9	894.2	900	899.2	895.3	896.4	893.6	891.3	899.1	896.8	899.9	899.2	897.3	898
PTVL05	psia	765.7	766.3	765.3	765.4	766.3	766.3	765.7	765.3	766.4	765.6	767.2	766.2	767.7	766.1	766	767.1	769	767.1
PTVL09	psia	742.4	742.2	742.1	741.6	742.3	742.4	742.3	742.3	742.4	742.2	743.1	742.0	743.7	743.1	743.1	743.2	744.2	743.7
TTVL05	deg R	545.2	545.2	545.15	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.2	545.3	545.2	545.3
WRPTOTL	lbm/sec	67.0	67.0	66.9	67.1	66.9	66.9	67.4	66.8	66.9	66.8	66.9	66.8	67.1	67.3	66.9	67.0	67.1	67.0
PTHTGI	psia	577.9	578.0	578.4	577.6	578.9	578.5	578.7	578.8	579.0	578.3	579.7	579.4	580.2	579.3	579.7	579.8	580.6	579.9
PTVL22	psia	81.4	81.1	81	81.3	81.2	81.1	81	80.9	81.1	81.1	81.1	80.8	81.1	81.2	81.2	81.3	81.3	81.2
TTHTGI	deg R	1635	1636	1634.7	1634	1635	1634	1633	1633	1634	1633	1632	1632	1632	1632	1631	1631	1631	1631
TTHTGD	deg R	1483	1484	1482.4	1482	1483	1482	1481	1482	1482	1481	1481	1482	1481	1481	1481	1481	1481	1480
PTMCHY	psia	657.9	658.5	658.4	658.2	659.0	658.6	658.4	658.2	659.3	658.2	659.8	659.3	660.2	659.1	659.4	659.8	660.8	660.2
SNSHFT	rpm	19099	19101	19106	19099	19108	19100	19078	19094	19094	19084	19106	19102	19121	19076	19088	19098	19095	19105
FT15A	lbf	47318	47339	47333	47316	47381	47300	47275	47257	47343	47206	47279	47218	47314	47247	47264	47285	47333	47240

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149
PSVL10	psia	39.2	39.3	39.3	39.2	39.2	39.3	39.2	39.3	39.2	39.3	39.3	39.3	39.2	39.4	39.3	39.3	39.3	39.3
TTVL10	deg R	163.1	163.1	163.1	163.1	163.1	163.1	163.1	163.1	163.1	163.1	163.1	163.2	163.2	163.2	163.2	163.2	163.2	163.2
PRSPRV	psia	38.3	38.4	38.4	38.3	38.4	38.3	38.5	38.4	38.3	38.5	38.4	38.4	38.4	38.4	38.4	38.4	38.5	38.3
TTRPFV	deg R	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.5	541.6	541.6	541.6	541.6	541.6
PSOXDS	psia	768.7	770.3	768.6	770.1	771.3	771.1	769.5	770.5	770.6	771.1	770.5	771.1	771.8	771.0	770.6	770.7	771.2	772.5
PSVL13	psia	794.6	795.3	794.0	795.9	796.7	796.3	795.0	795.6	795.8	796.6	796.2	796.5	796.5	796.4	795.6	796.6	796.9	797.7
PTVL14	psia	783.0	783.8	782.4	784.5	785.2	784.8	783.4	784.2	784.3	785.1	784.8	785.0	785.2	784.9	784.1	785.1	785.3	786.2
PSVL15	psia	780.5	781.2	779.9	781.93	782.8	782.4	781.2	781.8	781.8	782.9	782.3	782.5	782.7	782.4	781.9	782.7	782.9	783.6
PTVL18	psia	737.1	737.6	737.1	738.4	739.0	739.0	737.5	738.4	738.5	739.1	738.8	739.2	738.7	738.3	738.5	739.0	739.3	740.1
TTVL14	deg R	170.3	170.3	170.3	170.3	170.3	170.3	170.3	170.4	170.4	170.4	170.4	170.5	170.4	170.5	170.5	170.4	170.4	170.4
TTVL18	deg R	173.4	173.4	173.5	173.5	173.5	173.5	173.5	173.5	173.5	173.6	173.5	173.5	173.6	173.5	173.6	173.6	173.6	173.5
WOXTOTL	lbm/sec	143.2	143.2	143.7	143.1	143.3	142.9	143.6	143.1	142.9	143.0	143.1	143.9	143.1	143.2	143.2	143.2	142.6	143.3
PSVL00	psia	32.4	32.5	32.6	32.6	32.6	32.5	32.5	32.7	32.6	32.5	32.7	32.5	32.7	32.7	32.7	32.5	32.6	32.7
PSVL01	psia	897.6	896.8	895.8	897.6	900.6	895.2	900.3	897.2	901.9	897.2	899.8	897	901.5	900.8	900.5	903.4	899.8	902.2
PTVL05	psia	768.5	769.9	768.9	771.2	771	771.8	769.4	769.9	770.8	770.9	770.6	771.1	770.2	770.8	770	771.1	771.1	772.7
PTVL09	psia	744.8	745.9	744.4	745.4	746.7	744.8	744.5	745.4	745.3	745.3	746.1	746.2	747.0	746.0	745.9	746.1	746.7	747.1
TTVL05	deg R	545.2	545.2	545.2	545.25	545.3	545.3	545.3	545.3	545.3	545.3	545.3	545.4	545.4	545.3	545.4	545.4	545.4	545.3
WRPTOTL	lbm/sec	66.9	67.3	67.0	67.1	67.0	67.1	66.9	67.0	66.9	66.9	67.0	66.8	66.8	66.9	66.9	66.8	66.9	67.0
PTHTGI	psia	580.4	580.9	580.6	581.5	581.9	581.7	581.1	581.9	581.5	581.9	582.1	582.0	581.8	581.3	581.7	582.1	582.4	582.4
PTVL22	psia	81.6	81.8	81.6	81.5	81.8	81.9	81.6	81.7	81.8	81.8	81.6	81.8	81.8	81.9	81.8	81.7	81.6	81.9
TTHTGI	deg R	1631	1633	1632	1633	1632	1633	1636	1635	1634	1635	1636	1636	1635	1635	1636	1636	1636	1636
TTHTGD	deg R	1480	1482	1481	1482.2	1481	1483	1484	1482	1482	1484	1484	1484	1483	1483	1484	1484	1484	1484
PTMCHY	psia	661.3	662.3	661.4	662.9	663.4	663.4	662.2	662.8	663.3	663.8	663.6	663.9	663.7	663.7	663.1	664.1	664.3	665.0
SNSHFT	rpm	19141	19126	19125	19142	19145	19146	19122	19119	19128	19132	19132	19125	19104	19108	19136	19135	19134	19151
FT15A	lbf	47364	47419	47314	47415	47415	47412	47295	47351	47327	47354	47322	47327	47296	47281	47206	47262	47245	47349

Table H5 MC-1 engine - test R2-4 one second average data (continued)

Variable Measured	Units	Time (sec) measured from engine start																	
		150	151	152	153	154	155	156	157	158									
PSVL10	psia	39.3	39.3	39.3	39.4	39.3	39.4	39.4	39.4	39.4									
TTVL10	deg R	163.2	163.2	163.2	163.2	163.3	163.3	163.3	163.3	163.3									
PRSPRV	psia	38.4	38.4	38.5	38.4	38.4	38.4	38.4	38.4	38.4									
TTRPFV	deg R	541.6	541.6	541.6	541.6	541.6	541.6	541.6	541.6	541.6									
PSOXDS	psia	771.8	772.5	773.6	770.3	768.4	769.2	770.0	768.9	769.3									
PSVL13	psia	797.1	797.8	798.5	795.1	793.5	793.8	795.3	794.9	794.7									
PTVL14	psia	785.7	786.5	787.2	783.7	781.9	782.2	784.0	783.4	783.4									
PSVL15	psia	783.1	783.5	784.5	781.6	779.72	779.7	781.7	780.8	780.7									
PTVL18	psia	739.6	740.1	740.4	738.2	736.4	736.9	738.2	737.6	737.3									
TTVL14	deg R	170.5	170.5	170.5	170.5	170.53	170.6	170.5	170.5	170.6									
TTVL18	deg R	173.6	173.6	173.7	173.7	173.7	173.8	173.7	173.7	173.8									
WOXTOTL	lbm/sec	142.8	142.8	144.4	142.7	142.4	142.9	143.3	142.6	143.2									
PSVL00	psia	32.5	32.7	32.5	32.8	32.7	32.5	32.5	32.6	32.6									
PSVL01	psia	900.9	902.4	901.7	898.2	897.1	896.9	902.1	898.4	896.9									
PTVL05	psia	771.9	772.4	773.1	770.1	767.7	768.7	770.7	770.1	768.5									
PTVL09	psia	747.3	747.6	748.2	745.5	744.2	744.8	745.1	744.7	744.8									
TTVL05	deg R	545.4	545.4	545.4	545.4	545.33	545.3	545.3	545.3	545.4									
WRPTOTL	lbm/sec	66.9	66.9	67.1	67.0	66.7	66.9	67.0	67.0	66.7									
PTHTGI	psia	582.4	583.2	583.0	581.8	580.4	580.7	581.3	581.0	581.3									
PTVL22	psia	81.8	81.6	81.9	81.6	81.6	81.6	81.7	81.7	81.6									
TTHTGI	deg R	1637	1634	1635	1634	1634.6	1635	1636	1637	1638									
TTHTGD	deg R	1484	1482	1483	1483	######	1484	1484	1485	1485									
PTMCHY	psia	664.7	665.3	666.2	662.8	661.4	661.8	663.2	662.5	662.1									
SNSHFT	rpm	19155	19148	19149	19102	19105	19107	19108	19116	19120									
FT15A	lbf	47282	47309	47364	47328	47237	47287	47341	47319	47338									

Table H6 MC-1 engine - test R3-1a one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	43.4	43.2	43.0	43.1	43.3	43.0	43.1	42.9	43.1	42.9	42.8	43.0	43.1	42.9	42.9	42.8	42.8	42.8
TTVL10	deg R	164.8	164.4	164.3	164.3	164.2	163.9	163.6	163.1	162.7	162.5	162.3	162.2	162.1	162.1	162.1	162.0	162.0	162.0
PRSPRV	psia	40.5	40.4	40.5	40.5	40.4	40.4	40.5	40.5	40.5	40.4	40.5	40.5	40.4	40.5	40.4	40.4	40.5	40.5
TTRPFV	deg R	525.2	525.5	525.7	525.7	525.8	525.8	525.8	525.8	525.9	525.9	525.9	525.9	526.0	526.0	526.0	526.0	526.0	526.1
PSOXDS	psia	703.4	707.0	709.6	710.0	710.9	713.4	713.9	713.9	715.7	716.4	718.5	717.6	718.7	720.1	721.1	722.1	721.8	721.8
PSVL13	psia	727.5	730.6	733.3	733.1	733.6	736.2	736.4	736.8	738.1	738.4	740.6	739.0	740.2	741.7	743.0	743.4	742.8	742.9
PTVL14	psia	713.1	715.6	718.1	718.3	718.8	721.9	722.4	723.2	724.5	725.5	727.7	726.5	727.9	729.7	731.0	731.8	731.4	731.4
PSVL15	psia	714.5	717.4	720.2	720.1	720.8	723.8	724.2	724.8	726.5	727.0	729.5	728.1	729.3	731.2	732.7	733.3	732.8	733.2
PTVL18	psia	655.2	658.5	660.6	660.2	660.5	664.2	664.2	664.9	666.7	666.9	669.4	668.3	669.6	671.6	672.2	673.4	672.9	672.7
TTVL14	deg R	175.4	174.1	173.7	173.5	173.2	172.7	172.5	172.0	171.2	170.9	170.9	170.5	170.5	170.2	170.4	170.2	170.1	170.0
TTVL18	deg R	178.9	177.6	176.8	176.4	176.1	175.6	175.2	174.9	174.1	173.8	173.5	173.3	173.1	173.0	173.0	172.8	172.7	172.8
WOXTOTL	lbm/sec	136.6	137.0	137.5	137.8	137.5	138.0	137.9	138.8	138.2	138.3	138.6	138.4	138.3	139.0	138.5	138.8	139.0	138.6
PSVL00	psia	35.1	35.1	35.1	35.3	34.9	35.1	35	35	34.9	34.9	35	35	35	35.1	34.9	34.8	34.9	34.9
PSVL01	psia	823.9	823.3	826.1	823	823.2	829.2	829.5	827.1	833.9	833.6	831.3	834.1	829.3	836.7	832.3	838.2	835.8	835.8
PTVL05	psia	705.4	707.7	709.4	709.2	710.2	712.3	712	712.4	713.8	713.7	715.3	714.2	715.7	716.7	717.5	718.5	717.4	717.2
PTVL09	psia	687.2	689.8	691.2	691.3	690.8	693.7	694.4	694.4	695.0	694.8	696.4	696.4	697.4	698.3	699.1	699.9	699.0	699.1
TTVL05	deg R	528.3	528.7	529.0	529.1	529.2	529.3	529.3	529.4	529.4	529.5	529.5	529.6	529.6	529.7	529.7	529.7	529.7	529.8
WRPTOTL	lbm/sec	62.3	62.4	62.3	62.4	62.4	62.6	62.6	62.3	62.4	62.5	62.4	62.5	62.6	62.7	62.6	62.8	62.7	62.6
PTHTGI	psia	526.8	529.2	530.6	530.5	530.3	533.1	532.9	533.6	534.7	534.2	535.7	535.2	536.1	537.1	537.2	538.3	538.0	537.9
PTVL22	psia	74.7	75.5	76.1	76.6	76.9	77.3	77.6	77.7	77.8	78.1	78.3	78.2	78.3	78.5	78.7	78.7	78.6	78.5
TTHTGI	deg R	1522	1529	1532	1535	1538	1540	1541	1540	1541	1542	1545	1545	1545	1547	1549	1549	1549	1549
TTHTGD	deg R	1324	1334	1340	1346	1351	1355	1358	1359	1362	1366	1369	1370	1373	1375	1379	1379	1380	1381
PTMCHY	psia	618.1	620.1	621.7	621.6	622.0	624.1	624.4	624.6	625.8	626.1	627.5	626.5	627.6	628.7	629.6	630.1	629.3	629.2
SNSHFT	rpm	18007	18021	18055	18067	18077	18081	18102	18082	18083	18085	18102	18099	18105	18136	18133	18146	18137	18146
FT15A	lbf	39485	39650	39781	39732	39718	39858	39846	39840	39956	39952	40025	39925	39998	40080	40166	40128	40085	40048

Table H7 MC-1 engine - test R3-2b one second average data

Variable Measured	Units	Time (sec) measured from engine start																	
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
PSVL10	psia	41.3	41.3	41.5	41.5	41.4	41.4	41.4	41.1	41.1	41.0	41.0	41.0	41.0	41.0	41.0	41.0	40.9	40.9
TTVL10	deg R	165.2	164.8	164.8	164.9	164.7	164.3	163.9	163.2	162.9	162.7	162.5	162.4	162.4	162.3	162.3	162.3	162.2	162.2
PRSPRV	psia	39.9	39.8	39.9	39.8	39.9	39.9	39.8	39.8	39.9	39.9	39.9	39.8	39.8	39.8	39.8	39.8	39.8	39.7
TTRPFV	deg R	527.2	527.2	527.2	527.3	527.3	527.3	527.3	527.3	527.3	527.3	527.3	527.3	527.4	527.4	527.4	527.4	527.4	527.4
PSOXDS	psia	734.8	737.5	737.2	737.8	737.9	739.4	740.3	743.0	744.1	744.8	744.9	746.0	747.4	748.7	748.2	748.6	748.5	750.4
PSVL13	psia	755.8	758.3	756.8	757.6	758.1	759.7	761.1	763.3	764.9	765.5	766.4	767.4	768.3	769.2	769.1	769.4	770.1	771.4
PTVL14	psia	744.9	747.4	746.0	747.0	747.1	748.9	750.4	752.8	754.3	755.0	756.0	756.8	757.9	758.8	759.0	759.3	760.0	761.3
PSVL15	psia	745.8	748.3	747.4	747.8	748.1	749.9	751.3	753.5	755.1	755.8	756.8	757.7	758.9	759.5	759.5	759.8	760.4	761.7
PTVL18	psia	704.7	706.9	705.9	706.5	706.9	708.7	709.7	712.1	713.5	714.0	715.1	716.3	716.9	718.1	717.7	718.3	718.2	719.3
TTVL14	deg R	176.3	175.4	175.0	175.0	174.7	174.0	173.8	172.9	172.2	171.9	171.8	171.6	171.4	171.3	171.1	171.2	170.9	170.9
TTVL18	deg R	177.3	176.6	176.3	176.2	176.1	175.8	175.4	174.8	174.3	174.0	173.8	173.7	173.5	173.5	173.4	173.4	173.3	173.2
WOXTOTL	lbm/sec	140.6	140.9	140.8	140.7	140.9	141.7	141.6	142.0	142.4	142.9	142.5	142.7	142.8	143.1	143.2	142.6	142.5	143.2
PSVL00	psia	34	34	34	34.1	34	34.1	34.2	34.2	34.1	34.1	34	34.1	33.9	34.1	34.1	33.9	34	34
PSVL01	psia	874.4	871	871.2	866.2	876.4	875.8	873.2	871.9	873.2	872	875.3	874.3	877.5	878.5	885	875.9	876.7	876.4
PTVL05	psia	737.8	739.4	737.9	738	738.3	739.9	740.1	740.6	742.1	741.6	742.7	743.5	744.3	744.8	745	744.6	745	746.8
PTVL09	psia	718.0	719.4	718.6	718.6	719.2	720.4	721.1	722.4	722.8	723.5	723.9	724.4	725.5	726.1	726.7	726.4	726.5	727.5
TTVL05	deg R	530.3	530.5	530.6	530.8	530.8	530.9	530.9	530.9	531.0	531.0	531.1	531.1	531.1	531.2	531.2	531.2	531.2	531.3
WRPTOTL	lbm/sec	64.8	65.0	64.8	64.6	64.9	64.8	64.8	64.6	64.8	64.8	64.8	64.9	65.2	64.9	65.2	65.0	65.1	65.3
PTHTGI	psia	555.3	555.7	556.0	556.1	556.5	557.7	558.5	559.9	560.4	561.0	561.7	562.3	562.6	563.4	563.3	563.5	563.5	563.9
PTVL22	psia	77.6	78.5	78.7	78.9	79.2	79.5	79.7	79.9	80.5	80.6	80.8	80.9	81.2	81.3	81.4	81.4	81.5	81.6
TTHTGI	deg R	1603	1609	1608	1607	1610	1612	1612	1613	1618	1618	1618	1619	1622	1622	1623	1623	1623	1624
TTHTGD	deg R	1390	1399	1400	1401	1405	1409	1411	1413	1420	1420	1423	1425	1430	1431	1433	1435	1435	1439
PTMCHY	psia	641.6	643.3	642.1	642.2	642.4	643.5	644.1	645.3	646.0	646.2	646.8	647.6	648.2	648.7	648.8	648.6	649.3	650.1
SNSHFT	rpm	18657	18673	18635	18626	18646	18652	18644	18655	18688	18694	18690	18698	18723	18719	18747	18724	18724	18775
FT15A	lbf	41381	41474	41348	41359	41323	41370	41414	41494	41585	41566	41612	41634	41671	41695	41683	41651	41669	41745

1	39.4
2	163.3
3	38.4
4	541.6

Table H8 MC-1 Engine - R2 series tests - general observations

Subsystem	Figure	Measured Variable	R2 Series Avg Rise (% base)	Test to Test Avg Abs(Diff) (% base)		Other Observations
				(R2-2 - R2-1)	(R2-3b - R2-3a)	
INLET	B1	PSVL10	6.10%	14.05%	0.58%	unique R2-2 ramp up sequence
	B2	TTVL10	-1.42%	0.35%	0.23%	
	B3	PSRPFV	-1.98%	23.36%	0.62%	R2-1 >> all other tests
	B4	TTRPFV	0.09%	1.24%	3.80%	
INTERNAL						
LOX	B5	PSOXDS	2.37%	1.32%	0.67%	
	B6	PSVL13	2.46%	0.93%	0.59%	
	B7	PTVL14	2.65%	0.93%	0.43%	
	B8	PSVL15	2.48%	0.89%	0.81%	
	B9	PTVL18	2.41%	0.85%	1.91%	
	B10	TTVL14	-2.21%	2.42%	0.27%	R2-2 anomaly behavior
	B11	TTVL18	-2.81%	0.36%	0.09%	
	B12	WOXTOTL	1.98%	1.29%	0.49%	
RP (fuel)	B13	PSVL00	-2.48%	26.79%	1.86%	Inlet effect, R2-1>> all other tests
	B14	PSVL01	1.84%	0.46%	0.99%	Data groups by orifice set
	B15	PTVL05	1.58%	0.47%	0.70%	
	B16	PTVL09	1.83%	0.55%	1.24%	
	B17	TTVL05	0.19%	1.20%	3.65%	
	B18	WRPTOTL	1.14%	1.00%	0.87%	
GG/Turbine	B19	PTHTGI	2.04%	0.70%	0.89%	
	B20	PTVL22	1.97%	0.67%	0.62%	
	B21	TTHTGI	1.65%	0.43%	0.34%	
	B22	TTHTGD	2.99%	13.30%	0.43%	R2-1 anomaly behavior
MCC/Nozzle	B23	PTMCHY	1.61%	0.61%	1.48%	
Other	B24	SNSHFT	1.03%	0.33%	0.21%	
	B25	FT15A	1.41%	0.76%	0.19%	
Total Internal				21	21	
Number with						
%Diff < 1%				14	16	
1% < %Diff < 2%				4	4	
%Diff > 2%				3	1	

Table H9 MC-1 Engine - R2 series tests - observations adjusted to std input

Subsystem	Figure	Measured Variable	R2 Series Avg Rise (% base)	Test to Test Avg Abs(Diff) (% base)		Other Observations
				(R2-2 - R2-1)	(R2-3b - R2-3a)	
INLET	B1	PSVL10	N/A	0	0	
	B2	TTVL10	N/A	0	0	
	B3	PSRPFV	N/A	0	0	
	B4	TTRPFV	N/A	0	0	
INTERNAL						
LOX	B5	PSOXDS	0.37%	0.88%	1.41%	
	B6	PSVL13	1.17%	0.33%	1.22%	
	B7	PTVL14	1.37%	0.32%	1.05%	
	B8	PSVL15	1.15%	0.32%	1.48%	
	B9	PTVL18	1.16%	0.60%	2.50%	
	B10	TTVL14	-0.79%	2.07%	0.13%	R2-2 anomaly behavior
	B11	TTVL18	-1.43%	0.06%	0.19%	
	B12	WOXTOTL	0.50%	0.59%	0.48%	
RP (fuel)	B13	PSVL00	-0.14%	0.31%	1.09%	
	B14	PSVL01	0.96%	0.41%	1.19%	Data groups by orifice set
	B15	PTVL05	0.62%	0.22%	1.00%	
	B16	PTVL09	0.88%	0.25%	1.53%	
	B17	TTVL05	0.08%	0.06%	0.07%	
	B18	WRPTOTL	1.03%	0.52%	0.28%	Data groups by orifice set
GG/Turbine	B19	PTHTGI	0.95%	0.29%	1.34%	
	B20	PTVL22	0.91%	0.28%	1.02%	
	B21	TTHTGI	1.11%	0.19%	0.31%	
	B22	TTHTGD	2.52%	12.96%	0.18%	R2-1 anomaly behavior
MCC/Nozzle	B23	PTMCHY	0.52%	0.25%	1.89%	
Other	B24	SNSHFT	0.58%	0.15%	0.69%	
	B25	FT15A	-0.06%	0.40%	0.51%	
Total Internal				21	21	
Number with						
%Diff < 1%				19	9	
1% < %Diff < 2%				0	11	
%Diff > 2%				2	1	

Appendix I

MC-1 engine
GDR prediction comparisons

Table I1 Comparison of GDRA and ROCETS/DR results

Hardware Parameter	R2-1 Avg % Dev	R2-1 Max % Dev	R2-2 Avg % Dev	R2-2 Max % Dev	R2-3a Avg % Dev	R2-3a Max % Dev	R2-3b Avg % Dev	R2-3b Max % Dev	R2-4 Avg % Dev	R2-4 Max % Dev	R3-1a Avg % Dev	R3-1a Max % Dev	R3-2b Avg % Dev	R3-2b Max % Dev
RCALMF	0.010	0.021	0.009	0.026	0.015	0.034	0.017	0.045	0.016	0.062	0.015	0.051	0.022	0.068
RCALMO	0.027	0.058	0.101	0.147	0.011	0.027	0.008	0.037	0.017	0.039	0.017	0.031	0.010	0.019
RKFL1	1.226	2.496	0.170	0.595	0.148	0.543	0.216	0.522	0.149	0.581	0.131	0.437	0.191	0.479
ROLN1	0.010	0.022	0.037	0.087	0.415	0.432	0.350	0.409	0.052	0.189	0.065	0.133	0.013	0.022
XMGGKO	1.158	3.300	1.428	4.835	0.153	0.365	0.133	0.542	0.099	0.482	0.087	0.231	0.057	0.309
XMGGOO	0.090	0.320	1.530	2.725	0.301	0.688	0.179	0.322	0.068	0.352	0.167	0.430	0.191	0.606
CDGGKI	0.008	0.018	0.008	0.026	0.020	0.026	0.005	0.010	0.030	0.042	0.004	0.009	0.035	0.048
CDGGOI	0.017	0.042	0.041	0.128	0.014	0.026	0.143	0.227	0.039	0.068	0.008	0.021	0.008	0.019
CDKINJ	0.061	0.186	0.068	0.198	0.040	0.191	0.121	0.289	0.053	0.188	0.053	0.183	0.074	0.194
CDOINJ	0.039	0.139	0.055	0.118	0.054	0.113	0.189	0.396	0.012	0.115	0.052	0.131	0.049	0.140
PSIMKPMP	0.040	0.132	0.059	0.131	0.040	0.107	0.036	0.092	0.044	0.106	0.021	0.073	0.034	0.094
PSIMOPMP	0.010	0.035	0.021	0.032	0.013	0.024	0.015	0.029	0.010	0.045	0.005	0.012	0.004	0.011
CDGGNZ	0.001	0.007	0.002	0.005	0.001	0.007	0.002	0.011	0.017	0.046	0.018	0.133	0.032	0.163
FRICFACT	0.593	2.411	0.664	1.681	0.120	0.397	0.225	0.618	0.201	0.889	0.221	0.806	0.254	0.900
CDNOZL	0.008	0.024	0.031	0.070	0.042	0.065	0.046	0.079	0.030	0.096	0.000	0.000	0.000	0.000
ECSMMCHB	0.067	0.125	0.238	0.330	0.125	0.192	0.080	0.127	0.059	0.153	0.045	0.105	0.046	0.092
QDOTVL18	0.062	0.275	0.087	0.241	0.085	0.158	0.131	0.264	0.321	0.567	0.107	0.417	0.103	0.198
Hdwe in DR	17	17	17	17	17	17	17	17	17	17	16	16	16	16
with														
Dev < 0.5%	14	14	14	13	17	15	17	14	17	14	16	15	16	14
.5%<Dev<1%	1	0	1	1	0	2	0	3	0	3	0	1	0	2
1%<Dev<2%	2	0	2	1	0	0	0	0	0	0	0	0	0	0
Dev > 2%	0	3	0	2	0	0	0	0	0	0	0	0	0	0

gray indicates hardware parameter not used in reduction analyses

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I2 Comparison of GDRA (linear) and GDRC(2nd order) results

Hardware Parameter	GDRA (linear) R2-1 Avg % Dev	GDRA (linear) R2-1 Max % Dev	GDRA (linear) R2-2 Avg % Dev	GDRA (linear) R2-2 Max % Dev	GDRC (2nd order) R2-1 Avg % Dev	GDRC (2nd order) R2-1 Max % Dev	GDRC (2nd order) R2-2 Avg % Dev	GDRC (2nd order) R2-2 Max % Dev
RCALMF	0.010	0.021	0.009	0.026	0.012	0.029	0.010	0.024
RCALMO	0.027	0.058	0.101	0.147	0.022	0.052	0.089	0.139
RKFL1	1.226	2.496	0.170	0.595	1.675	4.130	0.403	1.147
ROLN1	0.010	0.022	0.037	0.087	0.013	0.027	0.025	0.067
XMGGKO	1.158	3.300	1.428	4.835	4.376	14.865	3.129	11.325
XMGGOO	0.090	0.320	1.530	2.725	0.064	0.119	0.697	0.876
CDGGKI	0.008	0.018	0.008	0.026	0.112	0.362	0.091	0.187
CDGGOI	0.017	0.042	0.041	0.128	0.014	0.033	0.042	0.068
CDKINJ	0.061	0.186	0.068	0.198	0.090	0.238	0.068	0.190
CDOINJ	0.039	0.139	0.055	0.118	0.040	0.078	0.044	0.082
PSIMKPMP	0.040	0.132	0.059	0.131	0.042	0.104	0.066	0.161
PSIMOPMP	0.010	0.035	0.021	0.032	0.012	0.044	0.018	0.040
CDGGNZ	0.001	0.007	0.002	0.005	0.001	0.007	0.003	0.009
FRICFACT	0.593	2.411	0.664	1.681	0.496	1.379	1.536	2.387
CDNOZL	0.008	0.024	0.031	0.070	0.011	0.032	0.034	0.063
ECSMMCHB	0.067	0.125	0.238	0.330	0.051	0.147	0.142	0.245
QDOTVL18	0.062	0.275	0.087	0.241	0.069	0.142	0.150	0.276
Hdwe in DR with	17	17	17	17	17	17	17	17
Dev < 0.5%	14	14	14	13	15	14	14	13
.5%<Dev<1%	1	0	1	1	0	0	1	1
1%<Dev<2%	2	0	2	1	1	1	1	1
Dev > 2%	0	3	0	2	1	2	1	2

gray indicates hardware parameter not used in DR

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I3 Comparison of GDRA and ROCETS/DR results using modified hardware set

Hardware Parameter	R2-1 Avg % Dev	R2-1 Max % Dev	R2-2 Avg % Dev	R2-2 Max % Dev	R2-3a Avg % Dev	R2-3a Max % Dev	R2-3b Avg % Dev	R2-3b Max % Dev	R2-4 Avg % Dev	R2-4 Max % Dev	R3-1a Avg % Dev	R3-1a Max % Dev	R3-2b Avg % Dev	R3-2b Max % Dev
RMMCRP	0.119	0.360	0.139	0.442	0.118	0.331	0.149	0.365	0.115	0.422	0.110	0.369	0.170	0.489
RMMCOX	0.042	0.140	0.731	1.095	0.096	0.209	0.094	0.182	0.136	0.305	0.119	0.231	0.079	0.142
RKFL1	1.239	2.483	0.171	0.587	0.226	0.626	0.227	0.517	0.143	0.577	0.130	0.447	0.197	0.532
ROLN1	0.006	0.030	0.037	0.087	0.049	0.089	0.004	0.016	0.051	0.189	0.065	0.133	0.013	0.022
RMGGRP	0.154	0.615	0.294	0.549	0.183	0.280	0.092	0.229	0.064	0.169	0.055	0.084	0.056	0.219
RMGGOO	0.046	0.290	0.659	1.048	0.156	0.505	0.098	0.178	0.093	0.295	0.095	0.228	0.071	0.198
RGGKI	0.036	0.073	0.031	0.083	0.034	0.066	0.046	0.114	0.056	0.092	0.010	0.036	0.011	0.030
RGGOI	0.019	0.081	0.142	0.249	0.070	0.128	0.019	0.038	0.150	0.359	0.014	0.034	0.017	0.035
RKINJ	0.092	0.325	0.126	0.376	0.189	0.526	0.135	0.387	0.106	0.358	0.105	0.361	0.134	0.347
ROINJ	0.044	0.149	0.071	0.155	0.061	0.147	0.015	0.069	0.024	0.075	0.035	0.094	0.016	0.050
PSIMKPMP	0.028	0.086	0.059	0.129	0.021	0.078	0.026	0.076	0.043	0.104	0.021	0.071	0.030	0.084
PSIMOPMP	0.010	0.025	0.015	0.025	0.007	0.019	0.004	0.010	0.010	0.045	0.004	0.012	0.003	0.008
CDGGNZ	0.002	0.012	0.002	0.006	0.003	0.011	0.002	0.021	0.017	0.046	0.018	0.133	0.031	0.162
PWRFACT	0.023	0.092	0.018	0.033	0.008	0.016	0.005	0.013	0.009	0.032	0.009	0.032	0.011	0.047
CDNOZL	0.008	0.028	0.031	0.069	0.106	0.140	0.021	0.036	0.029	0.096	0.000	0.000	0.000	0.000
ECSMMCHB	0.017	0.046	0.232	0.328	0.155	0.207	0.081	0.124	0.059	0.153	0.046	0.110	0.047	0.091
QDOTVL18	0.081	0.597	0.086	0.223	0.277	0.741	0.103	0.362	0.402	0.661	0.060	0.329	0.067	0.171
Hdwe in DR with	17	17	17	17	17	17	17	17	17	17	16	16	16	16
Dev < 0.5%	16	14	15	13	17	13	17	16	17	15	16	16	16	15
.5%<Dev<1%	0	2	2	2	0	4	0	1	0	2	0	0	0	1
1%<Dev<2%	1	0	0	2	0	0	0	0	0	0	0	0	0	0
Dev > 2%	0	1	0	0	0	0	0	0	0	0	0	0	0	0

gray indicates hardware parameter not used in reduction analyses

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I4 Sensor elimination study results

Sensor Lost	nominal sensor suite	PSOXDS	PSVL13	PTVL14	PSVL18	TTVL18	WOXTOTL	PSVL00	PSVL01	PTVL05
Hdwe Parameter	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**	**% Dev**
RMMCRP	0.115	0.116	0.116	0.115	0.115	0.115	0.114	0.115	2.763	1.262
RMMCOX	0.136	1.555	2.179	0.135	0.137	0.136	0.141	0.136	0.136	0.136
RKFL1	0.143	0.143	0.143	0.143	0.143	0.143	0.144	3.106	0.142	0.142
ROLN1	0.051	0.051	2.501	3.146	0.051	0.051	0.501	0.051	0.051	0.051
RMGGRP	0.064	0.064	0.064	0.063	0.065	0.064	0.059	0.064	3.882	0.062
RMGGOX	0.093	1.623	0.093	0.092	2.716	0.093	1.035	0.093	0.094	0.093
RGGKI	0.056	0.056	0.056	0.056	0.055	0.056	0.053	0.057	0.053	0.057
RGGOI	0.150	0.296	0.150	0.149	1.158	0.296	0.277	0.150	0.149	0.150
RKINJ	0.106	0.106	0.106	0.105	0.105	0.106	0.104	0.106	0.121	1.562
ROINJ	0.024	0.027	0.024	1.349	0.024	0.024	1.765	0.024	0.023	0.024
PSIMKPMP	0.043	0.043	0.043	0.043	0.043	0.043	0.042	0.034	0.467	0.042
PSIMOPMP	0.010	0.098	0.010	0.009	0.010	0.010	0.880	0.010	0.009	0.010
CDGGNZ	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
PWRFACT	0.009	0.009	0.009	0.009	0.009	0.009	0.130	0.009	0.008	0.009
CDNOZL	0.029	0.029	0.029	0.029	0.029	0.029	0.058	0.029	0.028	0.029
ECSMMCHB	0.059	0.060	0.059	0.060	0.059	0.059	0.754	0.059	0.055	0.058
QDOTVL18	0.402	9.361	0.402	0.403	0.339	9.361	9.362	0.402	0.402	0.402
Sensor Lost		PSOXDS	PSVL13	PTVL14	PSVL18	TTVL18	WOXTOTL	PSVL00	PSVL01	PTVL05
Measurements Eliminated	TTVL14 TTHTGD TTVL05 PSVL15	TTVL14 TTVL05 TTHTGD TTVL18 PSVL15	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL05 TTVL14 TTHTGD PSVL15 TTVL18	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL14 TTVL05 PSVL15 TTHTGD	TTVL14 TTVL05 PSVL15 TTHTGD
Number Meas Used	**17**	**15**	**16**	**16**	**16**	**16**	**15**	**16**	**16**	**16**
Number Hdwe										
Dev < 0.5%	17	14	15	15	15	16	11	16	15	15
.5%<Dev<1%	0	0	0	0	0	0	3	0	0	0
1%<Dev<2%	0	2	0	2	1	0	2	0	0	2
Dev > 2%	0	1	2	0	1	1	1	1	2	0

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I4 Sensor elimination study results (continued)

Sensor Lost	nominal sensor suite	PSVL09	WRPTOTL	PTHTGI	PTVL22	TTHTGI	PTMCHY	SNSHFT	FI15A
Hdwe Parameter	% Dev	% Dev	% Dev	% Dev	% Dev	% Dev	% Dev	% Dev	% Dev
RMMCRP	0.115	0.116	0.826	0.113	0.113	0.186	0.116	0.116	0.116
RMMCOX	0.136	0.135	0.136	0.136	0.143	0.125	0.136	0.152	0.135
RKFL1	0.143	0.144	1.152	0.143	0.147	0.139	0.143	0.142	0.143
ROLN1	0.051	0.051	0.051	0.051	0.051	0.052	0.051	0.051	0.051
RMGGRP	0.064	3.137	0.068	0.495	0.060	3.212	0.064	0.064	0.064
RMGGOX	0.093	0.093	0.093	0.462	0.092	0.634	0.093	0.107	0.091
RGGKI	0.056	1.874	0.054	0.794	0.057	1.813	0.056	0.055	0.056
RGGOI	0.150	0.150	0.150	0.942	0.148	0.274	0.150	0.296	0.144
RKINJ	0.106	0.106	0.901	0.112	0.102	0.215	0.506	0.106	0.106
ROINJ	0.024	0.023	0.024	0.026	0.032	0.013	0.428	0.024	0.024
PSIMKPMP	0.043	0.043	0.188	0.043	0.043	0.042	0.043	0.208	0.042
PSIMOPMP	0.010	0.009	0.010	0.010	0.010	0.010	0.010	0.217	0.009
CDGGNZ	0.017	0.017	0.017	0.151	0.934	0.025	0.017	0.018	0.017
PWRFACT	0.009	0.009	0.029	0.230	0.490	0.579	0.009	0.208	0.008
CDNOZL	0.029	0.029	0.065	0.029	0.027	0.039	0.113	0.029	0.992
ECSMMCHB	0.059	0.059	0.097	0.059	0.054	0.047	0.070	0.059	0.976
QDOTVL18	0.402	0.399	0.403	0.424	0.443	0.204	0.402	9.361	0.412
Sensor Lost		PSVL09	WRPTOTL	PTHTGI	PTVL22	TTHTGI	PTMCHY	SNSHFT	FI15A
Measurements Eliminated	TTVL14 TTHTGD TTVL05 PSVL15	TTVL14 TTVL05 PSVL15 TTHTGD	TTHTGD TTVL14 PSVL15 TTVL05	TTVL14 TTVL05 PSVL15 TTHTGD	TTHTGD TTVL14 TTVL05 PSVL15 *forced elimination*	TTHTGD TTVL05 TTVL14 PSVL15	TTVL14 TTVL05 PSVL15 TTHTGD	TTHTGD TTVL05 PSVL15 TTVL14 TTVL18	TTVL14 TTHTGD TTVL05 PSVL15
Number Meas Used	17	16	16	16	16	16	16	15	16
Number Hdwe									
Dev < 0.5%	17	15	14	15	16	13	16	16	15
.5%<Dev<1%	0	0	2	2	1	2	1	0	2
1%<Dev<2%	0	1	1	0	0	1	0	0	0
Dev > 2%	0	1	0	0	0	1	0	1	0

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I5 Comparison of GDRA and ROCETS/DR results using flight measurements only

	Test R2-4 Flight Measurements Only			Test R2-4 Flight Measurements and 20-23 sec Avg Flows		
Hardware Parameters	Avg Dev (%)	Max Dev (%)	Std Dev (%)	Avg Dev (%)	Max Dev (%)	Std Dev (%)
R3MCOX	0.986	2.406	0.629	0.303	1.336	0.259
R3MCRP	1.100	5.015	0.786	1.277	2.896	0.463
R3GGOX	0.107	0.332	0.087	0.230	0.725	0.103
R3GGRP	0.059	0.106	0.015	0.070	0.116	0.015
PWRFACT	0.294	0.856	0.211	0.612	1.273	0.317
ECSMMCHB	0.845	1.765	0.404	0.286	1.237	0.222
PSIMKPMP	0.270	0.893	0.205	0.240	0.952	0.193
PSIMOPMP	0.617	1.672	0.363	0.287	0.810	0.181
QDOTVL18	9.375	29.312	3.821	9.375	29.309	3.821
Hdwe in DR with	9			9		
Dev < 0.5%	4			6		
.5%<Dev<1%	3			1		
1%<Dev<2%	1			1		
Dev > 2%	1			1		

% Dev - average percent absolute deviation from standard ROCETS data reduction results

Table I6 Subset selection examples with MC-1 engine parameters

Flight Measures		Subset Selection							
Manual Selection		Auto Selection 1		Auto Selection 2		Auto Selection 3		Auto Selection 4	
Meas	Hdwe	Meas	Hdwe	Meas	Hdwe	Meas	Hdwe	Meas	Hdwe
PSOXDS		PSOXDS		PSOXDS		PSOXDS	CDGGNZ	PSOXDS	RGGKI
PSVL01		TTHTGI		PSVL01		PSVL01	ECSMMCHB	PTVL01	ECSMMCHB
PTMCHY		WRPTOTL		PTMCHY		PTMCHY	PSIMKPMP	PTMCHY	PSIMKPMP
PTHTGI		WOXTOTL		PTVL22		PTVL22	PSIMOPMP	TTHTGI	PSIMOPMP
TTHTGI		PTVL22		SNSHFT		SNSHFT	PWRFACT	SNSHFT	PWRFACT
		User Eliminated		User Eliminated		User Eliminated		User Eliminated	
		Meas	Hdwe	Meas	Hdwe	Meas	Hdwe	Meas	Hdwe
		FT15A	CDNOZL	FT15A	CDNOZL	FT15A	CDNOZL	FT15A	CDGGNZ
			ETAMHTGT	WRPTOTL	ETAMHTGT	WRPTOTL	ETAMHTGT	WRPTOTL	CDNOZL
			TRQMKPMP	WOXTOTL	TRQMKPMP	WOXTOTL	TRQMKPMP	WOXTOTL	ETAMHTGT
			TRQMOPMP		TRQMOPMP		TRQMOPMP		TRQMKPMP
									TRQMOPMP
		Auto-Elimination		Auto-Elimination		Auto-Elimination		Auto-Elimination	
		Meas	Hdwe	Meas	Hdwe	Meas	Hdwe	Meas	Hdwe
		sequential	(none)	sequential	(none)	alt sequence	alt sequence	alt sequence	alt sequence