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Response Models for the F101, TF33, and F107 Turbofan Engines to Dust Environments

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Technical Report

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13. ABSTRACT *(Maximum 200 words)*

This report describes the contributions made by Calspan to the development of P–EARL, a computer code designed to evaluate route selection for aircraft operation in adverse dusty environments. Calspan's contributions documented in this report consisted of creating algorithms to describe the responses of several gas turbine propulsion systems of interest (F101, TF33, and F107 engines) to adverse dusty environments. The dust environments discussed in this report include materials labeled as the most probable blend and blend #2.

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SUMMARY

This report describes the contributions made by Calspan to the development of P-EARL (Prototype-Environments and Aircraft Responses modeL), a computer code designed to evaluate route selection for aircraft operation in adverse environments. P-EARL is being developed by SAIC (Science Applications International Corporation) and by KAMAN SCIENCES under direction from DNA (Defense Nuclear Agency). Calspan's contributions documented in this report consisted of creating algorithms to describe the response of several gas turbine propulsion systems of interest (F101, TF33, and F107 engines) to adverse dusty environments.

The understanding of the operational behavior and limitations of gas turbine engines in adverse environments has been an area of keen interest in the gas turbine community for many years. The scenarios postulated for the formulation of the engine response algorithms described here are related to the post-nuclear environment as opposed to the small arms survivability events which are of most interest to the tri-service studies (Thompson 1981 and Sullivan 1983). When viewed from a post-nuclear point of view, many of the effects are categorized as short term while others are long term. Examples of short-term environmental effects on aircraft are electromagnetic pulse, overpressure, initial nuclear radiation and thermal radiation. The longer term effects include residual nuclear radiation and lofted dust. It is important to note that lofted dust does not require the discharge of a nuclear device. Parts of the world experience sand storms which in many ways create the same conditions as lofted dust.

Potential engine damage and crew or electronic component damage caused by ingestion of dust-laden air is a serious consideration during operation of aircraft in dust environments. Several different mechanisms can be active in altering engine performance during or after exposure to such an environment. Encountering a particle-laden environment falls into the category of unanticipated performance degradation and may be manifested in one or more of the following ways: (1) deposition of material on hot section components, (2) erosion of compressor blading, (3) blockage of cooling holes and paths, and (4) contamination and/or blockage of the oil system. As far as the crew is concerned, compressor bleed air which contains the ingested dust is passed directly into the cabin where the crew would inhale the dust particles. This contaminated bleed air is also used to cool electronic components.

Calspan has a history of ongoing research in the area of gas turbine propulsion and has contributed to the understanding of the aforementioned engine failure modes and for a definition of the characteristics of the dust passing through the environmental control system (ECS). Experimental facilities and techniques have been developed at Calspan to investigate these phenomena. At the center of these facilities is the Large Engine Research Cell (LERC) where one can

subject operational engines to adverse environments without endangering either an aircraft or a flight crew, and a hot section test system (HSTS) in which one can investigate in depth the behavior of candidate environments prior to testing a full-up engine.

PREFACE

The work described in this report was performed by the Calspan Advanced Technology Center. The work was performed under subcontract from SAIC, McLean, Va., authorization No. 29-930031- 73. The SAIC monitor was Mr. Peter Versteegen. The SAIC prime contract was from the Defense Nuclear Agency and the technical monitor for that effort was Lt. Col. Jerry Miatech. Lt. Col. Miatech also provided technical monitoring of this effort. The work was performed during the period 1 June 1992 to 30 December 1992.

All of the material contained in this report was provided simultaneously to Peter Versteegen (SAIC) and to Tom Stagliano (Kaman Sciences) for use in their P-EARL development.

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ______________ BY ____________ TO GET

TO GET ______________ BY ____________ DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	giga bacqueral (CBq)*
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	t°_{K} = (t°f+459.67)/1.8	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.875 414 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (raiation dose absorbed)	1.000 000	Gray (Gy)**
kilotons	4.183	tarajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbf avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N-m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter (kg-m^2) (kg-m^2)
pound-mass/foot	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	Gray (Gy)**
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shaka	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22 X E -1	kilo pascal (kPa)

* The bacqueral (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI sunit of absorbed radaition.

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SECTION 1

THE RESPONSE OF A YF101 TURBOFAN ENGINE TO DUST ENVIRONMENTS

1.1 DESCRIPTION OF THE RESPONSE.

1.1.1 Overview.

The YF101 engine is one of the more modern engines that has been tested by Calspan for its response to a dust-laden environment. The YF101 engine is the pre-production version of the F101, but the operating conditions for the two engines are essentially the same. It has, therefore, been possible to use the YF series of engines (which were available) to obtain the fundamental data necessary to construct a response model for the production engine. From this point on, the Y in the engine designation will, in general, be dropped. The engine is operated by setting the power lever angle (PLA) to an appropriate power setting and leaving it there. An engine control system then takes over the task of maintaining the engine at the desired power setting. The F101 engine has a relatively sophisticated engine control system which regulates many of the engine parameters including core speed (N2) and fuel flow based on readings from various sensors within the engine.

The response of the engine to dust environments is integral with the response of the engine control system to the changing conditions within the engine. The F101 engine response is a function of the type of dust to which it is exposed. The engine response model, therefore, is dust specific.

Experiments conducted by Calspan [Baran et al, 1992 (YF101)] suggest that the damage modes for the F101 engine are a combination of compressor blade erosion and material deposition on the high pressure turbine components. The two dust blends that have been evaluated under the present effort are labeled as the 'most probable blend' and blend #2, both of which are defined in Baran et al., 1992 (YF101). One effect of the dust environment on the engine control system is to reduce the core speed while PLA is held constant. Another effect is an increased demand on fuel flow which in turn increases engine temperature. The magnitude of both responses were found to be dependent on the dust concentration and the dust blend. The net response results in a loss in aircraft range due to the increased demand on fuel and a reduction in engine operability since the engine is more susceptible to surge after sufficient dust ingestion.

1.1.2 Principal Variables.

The principal variables that affect the response of the engine to the dust environment are in order of importance as follows:

- The power lever angle (PLA), i.e. TIT (Turbine inlet temperature)

- The type of dust in the environment
- The dust concentration
- The total dust mass ingested by the engine

1.1.3 Criteria.

There are two principal criteria to address in evaluating the response of the engine:

(1) Can the engine be operated by the flight crew?

Our laboratory experience indicates that by the time the F101 engine surges, it has been severely damaged and may be unable to generate significant thrust. The engine response model indicates to the user when the engine is in danger of surging. This is done by evaluating the amount of CDP increase above the pre-dust CDP value at the corresponding core speed.

(2) Does the loss in engine capability impact the aircraft performance enough to prevent accomplishment of the mission objectives?

In order to assess this criterion, the aircraft response, mission objectives, selected flight path, and dust environments must be defined. The F101 engine response model provides the contribution of the engine to the accomplishment of the mission objectives. The coupled engine response and aircraft response need to be evaluated against the mission objectives to address this question.

1.2 FORMULATION.

This section describes the formulation of the F101 engine response model to dust environments. The formulation involves all the principal variables mentioned in Section 1.1.2. The parameter which the pilot has direct control over is the PLA, and therefore this is a primary input to the engine response model. The PLA sets the nominal core speed for the engine, which is the primary controlling parameter for the engine parameters of interest, which are: airflow, compressor discharge pressure (CDP), fuel flow, and thrust.

1.2.1 Basis.

The basis of the F101 engine response model is a series of experiments performed by Calspan during the period from 18 November 1991 to 16 March 1992 involving a YF101-100 turbofan engine, and is part of a long history of research by Calspan in dust exposure effects on airbreathing propulsion systems. The experiments were sponsored by the Defense Nuclear Agency (DNA) under RDT&E RMSS CODE B342085466 N99QMXAJ00002 H2590D and were performed at Edwards AFB, California (6510 CRS Propulsion Branch). The details of the test facility can be found in Baran et al., 1992 (YF101). The engine was operated at a power setting of military power and dust concentrations ranging from 45 to 450 mg/m^3. A dust laden air stream was drawn into the engine while the engine variables available from the controller were monitored and recorded. The experimental data set consists of five pre-dust exposure matrix points to establish the nominal behavior of the engine prior to dust exposure and 12 additional matrix points with dust exposure. Each dust exposure matrix point (run) provided a profile of dust concentration of a specific dust blend (either the 'most probable blend' or blend #2). The matrix of dust exposure runs involved varying the dust blend and/or the dust concentration profile.

1.2.2 Model.

The F101 dust response model consists of an algorithm by which dust effects are evaluated for a controlling engine parameter (core speed (N2) has been selected) and assessing the impact of the compensation of those effects on other engine parameters such as thrust, fuel flow, and CDP. The algorithm is presented in this section as well as in Appendix A, which has a more complete description of the F101 engine response model.

The following is a definition of expressions used:

- t = time from take-off
- $(\,)_i$ = pertaining to the current dust environment i
- $(\,)_n$ = pertaining to the prior dust environment n
- t_n = time duration of dust environment n
- c_n = dust concentration of dust environment n
- $\tau_i(t)$ = time into dust environment i at time t $(t_{i-1} \le \tau_i(t) \le t)$
- $N_{2nominal}(PLA)$ = the nominal core speed for a power setting, PLA
- $P_{nominal}(N_2(t))$ = the nominal behavior of an engine parameter, P, of interest (i.e., thrust, fuel flow,...) based on core speed
- $N_2(t)$ = core speed response to dust exposure
- $P_i(t)$ = response of P to dust exposure during i
- $\Delta N_{2i}(t,c)$ = change in core speed during i (function of dust conc.)
- $\Delta P_i(t)$ = cumulative dust effects on P during i
- $\frac{d}{dt}[\Delta N_2(c)]$ = rate of change of core speed (function of dust conc.)

- $\frac{d}{dc}\left(\frac{d}{dt}(\Delta P)\right)$ = rate of cumulative dust effects on P per unit dust conc.
- $\sum_{n=1}^{(i-1)} \Delta N_{2n}(t_n, c_n)$ = history of change in core speed during events prior to i
- $\sum_{n=1}^{(i-1)} \Delta P_n(t_n)$ = history of cumulative dust effects on P prior to i

The F101 engine response algorithm is given below in Figure 1-1.

The data obtained in the experiments of Baran et al., 1992 (YF101) reflect the combined effects of compressor blade erosion and material deposition on internal engine components. Prior experiments conducted at Calspan (Kim et al, 1992) have shown that dust material deposition is a strong function of the turbine inlet temperature (TIT) and the type of dust material. Material deposition occurs when the TIT exceeds a threshold temperature for that dust blend. The threshold temperature is approximately 2000°F. When operated in a dust environment at sufficiently elevated engine temperatures, the condition of the F101 engine will change due to compressor blade erosion and material deposition damage modes. Operation of the engine in dust environments at temperatures below the threshold temperature renders the engine susceptible mainly to compressor blade erosion. The experiments of Baran et al., 1992 (YF101) were conducted at turbine inlet temperatures exceeding 2000°F. The F101 response model is based on those results, and therefore is applicable for conditions above the material deposition threshold temperature. This corresponds to power lever angle (PLA) settings above 65°.

There are two ways in which dust environments affect the response of an engine parameter. The first is that the dust environment changes the core speed, typically, a decrease. The core speed responds differently depending on the particular dust environment and is correlated to dust concentration. When exposed to the 'most probable blends', the core speed response was significantly different once the engine ingested more than 72 kg of dust and therefore the core speed response model for the 'most probable blends' requires the accumulated mass of dust ingested by the engine to be calculated (see Appendix A). When the core speed changes, so do the other engine parameters, by virtue of the core speed dependent nominal behavior. The nominal behavior is defined to be the response of the engine parameter measured prior to any dust exposure.

When exposed to a dust environment, parameters such as fuel flow and CDP exhibited a progressive departure from their nominal behavior. This was due to the combined effects of compressor degradation and dust material deposition in the hot sections of the engine [Baran et al, 1992 (YF101)] and is the second way in which dust exposure affects the engine response. It is independent of the changes in core speed. When the effect of continually decreasing core speed was taken into account, the departure of each parameter was collapsed to a linear

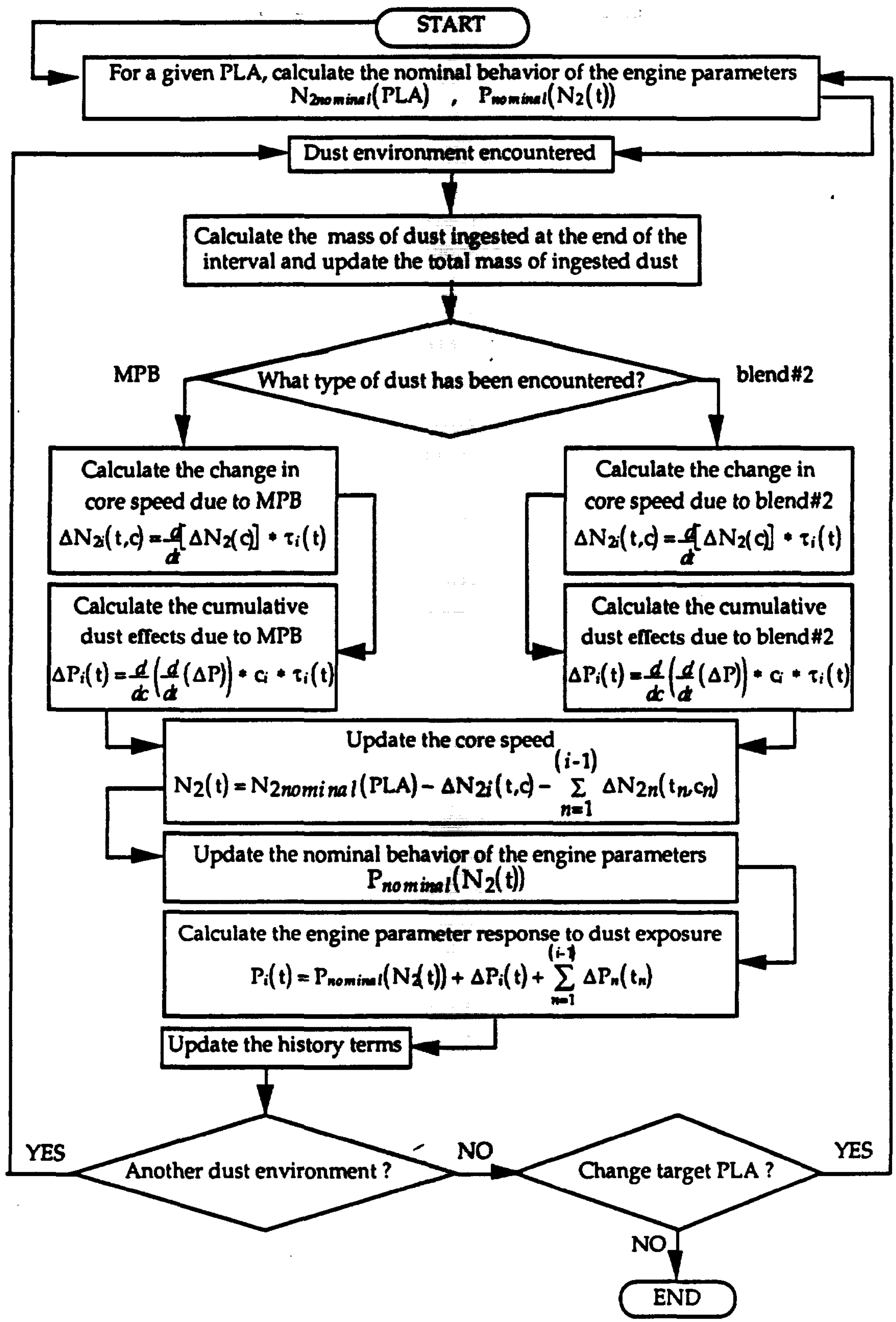

Figure 1-1. F101 engine response algorithm.

relation with dust concentration. The cumulative dust effect on the engine parameter was then modeled as the rate of change of that engine parameter with respect to time and dust concentration. The rates of cumulative dust effect for each parameter of interest also are dust blend dependent.

The engine is progressively worn and the performance worsens by continued dust exposure. The F101 engine response algorithm takes the worn condition of the engine into account by two terms which track the history of dust effects. One history term is for the core speed response and another is for the cumulative dust effect on the specific engine parameter. The response of an engine parameter to a dust environment is the sum of the core speed driven nominal behavior and the cumulative dust effects on that parameter due to the current dust environment and all prior dust environments.

The validity of the dust effects on core speed as well as the cumulative dust effects on CDP, fuel flow, and thrust are limited to the range of dust concentrations given in Appendix A. Implicit in the correlations of Appendix A is the condition that all dust effects go to zero for dust concentrations approaching zero. Extrapolation beyond the listed ranges of dust concentration is not recommended. The nominal behavior of each engine parameter of interest is limited to a range of core speed within which the response is considered valid. This range encompasses all core speeds measured during the course of the F101 experiments and is also presented in Appendix A.

1.2.3 Error Estimate.

The error for parameters is the sum of the error for the nominal behavior of the engine parameter and the error for the cumulative dust effect contribution. The cumulative dust effect term is a function of dust blend, as is the error in that term. The error estimate was made for engine operating conditions between cruise (PLA=73°) and military power (PLA=80°) up to the point of engine surge for both dust blends. For the 'most probable blends', the error in CDP is ±4% and the error in fuel flow is ±6%. For blend #2, the error in CDP is ±7% and the error in fuel flow is 9%. The thrust was a calculated quantity. The thrust calculation is estimated to be accurate to within ±13% for the 'most probable blend' environments and ±16% for blend #2 environments.

1.3 SAMPLE PROBLEMS.

1.3.1 Problems Statements.

There are six sample problems for the F101 engine response model. The format of each problem is similar:

An F101 engine encounters N consecutive environments. The engine operates at a power setting corresponding to a power lever angle, PLA, throughout its flight path and the reference ambient conditions are constant at 14.7 psia and 59°F. What is the response of the engine prior to encountering any environment (i.e. nominal behavior) and at the conclusion of each environment encounter? Engine parameters of interest include: airflow (lbm/sec), the integrated (accumulated) mass of dust ingested by the engine (kg), core speed (rpm), compressor discharge pressure (psig), fuel flow (lbm/hr), and thrust without the pressure contribution term (lbf). Also, at what point will the engine surge? Engine surge has been observed to occur when the compressor discharge pressure (CDP) during dust exposure differs form the nominal CDP by about 54 psi. The nominal CDP behavior is solely a function of the engine core speed. The type of dust encountered in a given interval is defined by: 0 - clear air, 1 - the most probable blend, 2 - blend #2.

The first five problems have been constructed in the following way: An engine operating point was chosen. Problems 1-3 each have a constant dust concentration throughout a common flight time. The dust concentration is varied parametrically from one problem to the next. Within each of the three problems, the discretization of the flight time is varied to assess the time step independence of the engine response model. Problem 4 has a variation in the engine power setting from one of the first three problems to isolate the effect of engine power setting on the engine response model. Problem 5 has a varied profile of dust type, dust concentration, and encounter durations for the nominal engine power setting.

A sixth problem was constructed to evaluate the effect of dust blend on the response model. Problem 6 is identical to Problem 1 except that the dust blend was changed from blend #2 to the 'most probable blend'.

Problem #1:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=80°. The total flight time is 60 minutes. The dust environment consists solely of blend #2. The dust concentration is constant throughout the flight at a value of 100 mg/m³. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters

#	dust blend	dust concentration (mg/m³)	duration(min.)
1	2	100	6
2	2	100	6
3	2	100	6
4	2	100	6
5	2	100	6
6	2	100	6
7	2	100	6
8	2	100	6
9	2	100	6
10	2	100	6

Part (2): N = 5 dust encounters

#	dust blend	dust concentration (mg/m³)	duration(min.)
1	2	100	12
2	2	100	12
3	2	100	12
4	2	100	12
5	2	100	12

Part (3): N = 3 dust encounters

#	dust blend	dust concentration (mg/m³)	duration(min.)
1	2	100	20
2	2	100	20
3	2	100	20

Part (4): N = 1 dust encounter

#	dust blend	dust concentration (mg/m³)	duration(min.)
1	2	100	60

Problem #2:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=80°. The total flight time is 60 minutes. The dust environment consists solely of blend #2. The dust concentration is constant throughout the flight at a value of 295 mg/m³. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #3:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=80°. The total flight time is 60 minutes. The dust environment consists solely of blend #2. The dust concentration is constant throughout the flight at a value of 200 mg/m³. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #4:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=60°. The total flight time is 60 minutes. The dust environment consists solely of blend #2. The dust concentration is constant throughout the flight at a value of 295 mg/m³. Consider the flight as being made up of 10 equally spaced successive dust encounters similar to problem 2, part 1.

Problem #5:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=80°. The dust environment is varied, as are the dust concentrations and encounter durations as follows:

#	dust blend	dust concentration (mg/m³)	duration(min.)
1	1	50	7
2	1	100	3
3	1	50	7
4	1	250	5
5	1	50	13
6	2	50	7
7	2	150	3
8	2	50	7
9	2	250	5
10	2	50	13

Problem #6:

What is the engine response for the following conditions? The engine operates at a power setting of PLA=80°. The total flight time is 60 minutes. The dust environment consists solely of the 'most probable blend'. The dust concentration is a constant 100 mg/m³ throughout the flight. Consider the flight as being made up of N equally spaced successive dust encounters:

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	100	6
2	1	100	6
3	1	100	6
4	1	100	6
5	1	100	6
6	1	100	6
7	1	100	6
8	1	100	6
9	1	100	6
10	1	100	6

1.3.2 Solutions.

A code was written at Calspan which incorporates the engine response algorithm and associated correlations of Appendix A. The purpose of this undertaking was to provide SAIC and KAMAN SCIENCES with the solutions to the aforementioned sample problems. The Calspan solutions to the F101 sample problems are presented in Appendix A. The source code for the Calspan version of the F101 engine response model is presented in Appendix A.

SECTION 2

THE RESPONSE OF A TF33 TURBOFAN ENGINE TO DUST ENVIRONMENTS

2.1 DESCRIPTION OF THE RESPONSE.

2.1.1 Overview.

The TF33 engine (B52-H, C135, C141, E3) is a relatively old and forgiving engine when compared to engines such as the F100 or the F101. For the B52 application, the engine is generally operated to maintain a given engine pressure ratio (EPR). The engine is affected by dust environments. Dust ingestion results in progressive compressor flowpath degradation. Because the engine operates at relatively low turbine inlet temperatures, deposition of material on the hot section components does not generally occur. At a constant throttle setting, the compressor degradation results in a progressive loss of EPR. A pilot would then have to advance the throttle to maintain the target EPR. Associated with the increased throttle setting is an increased fuel flow which then results in an elevated exhaust gas temperature (EGT). The engine core speed (N2) is also increased. There is a limitation to how much one can advance the throttle to compensate for compressor degradation. One such limitation is on core speed. Having reached the overspeed limit of 104%, the EPR loss can no longer be accounted for and the engine's maximum thrust capability is reduced. Another physical limitation is the possibility of deformation of turbine and/or compressor blades and ensuing engine component failure resulting from continued engine operation beyond the temperature limit of 1040°F. The primary adverse effects resulting from the dust environment are a loss in aircraft range as a result of the increased fuel flow and a reduction in engine operability since the engine is susceptible to surge after a sufficient amount of compressor blade erosion has occurred.

2.1.2 Principal Variables.

The principal variables that affect the response of a TF33 engine to a dusty environment are in order of importance:

- The target EPR
- The accumulated mass of dust ingested by the engine
- The dust concentration

2.1.3 Criteria.

There are two principal criteria to address in evaluating the response of the engine:

(1) Can the engine be operated by the flight crew?

For the TF33 engine, two situations arise that render the engine difficult to control and perhaps inoperable: (a) Engine surge without the crew being able to take proper corrective action, and (b) Exceeding the operating limits of the engine. The TF33 engine response model indicates when the engine is either in danger of surging or when it has surged. The operational limits of the modeled engine parameters are defined in the TF33 engine response model through the limits of the pre-dust behavior correlations. If the operational limits of the engine are exceeded, there is a strong possibility of engine failure.

(2) Does the loss in engine performance impact the aircraft performance enough to prevent the accomplishment of the mission objectives?

In order to assess this criterion, the aircraft response, mission objectives, selected flight path, and dust environments must be defined. The TF33 engine response model provides the contribution of the engine to the accomplishment of the mission objectives. The coupled engine response and aircraft response needs to be evaluated against the mission objectives to address this question.

2.2 FORMULATION.

This section describes the formulation of the TF33 engine response model to dust environments in terms of the target EPR, the accumulated dust mass, and the local dust concentration. The type of dust blend is not a variable in the TF33 engine response model but was included in the sample problem because in general, other turbofan engines have a dependence of engine response to dust type. A general approach to the turbofan response problem was undertaken.

2.2.1 Basis.

The basis of the TF33 engine response model is a series of experiments performed by Calspan during the periods from 1 April 1984 to 1 September 1985 and from 1 February 1986 to 1 April 1986 involving, in total, three TF33-P-11A turbofan engines, and is part of a long history of research at Calspan in dust exposure effects on airbreathing engine response. The experiments were sponsored by the Defense Nuclear Agency (DNA) under RDT&E RMSS CODE B342085466 N99QMXAJ00002 H2590D and were performed in Calspan's Large Engine Research Center (LERC). The details of the test facility can be found in Dunn et al., 1986. The data with a common link to the other two engines to be treated in PEARL (YF101 and F107) are those of the third TF33 engine tested at Calspan. The dust blend used for this particular engine contained black scoria which was also used in one of the YF101 and F107 blends. The other two TF33 engines were subjected to an environment made up of Warren AFB soil and Mt. St. Helens ash. The experiments involving the third TF33 engine are described in Dunn et al., Oct. 1992, and the experiments involving the other two TF33 engines are described in Dunn et al., Jan. 1986, and Dunn et al., July 1986. These data were used to formulate the TF33 engine response model. Specifically, there were five dust exposure runs performed using dust blend #2 and three pre-dust exposure runs which defined the dust response of the engine. As noted above, the other two TF33 engines were exposed to a different dust blend, blend #1. The primary damage mechanism eventually leading to engine surge for the TF33 is compressor blade erosion. The experience at Calspan is that this damage mechanism is independent of the compressor blade material and dust cloud constituents for the dust environments considered. Therefore, the correlation of engine surge events to the dust environment was made using data from all three engines tested. Engine power settings ranged from cruise to military power and dust concentrations ranged from 120 to 900 mg/m^3. A dust laden air stream was drawn into the engine while various engine measurements were monitored and recorded.

2.2.2 Model.

The TF33 dust response model consists of an algorithm by which dust effects are evaluated based on maintaining constant EPR and assessing the impact that maintaining EPR has on other engine parameters such as EGT, fuel flow, and core speed (N2). The algorithm is presented in this section as well as in Appendix B, which has a more complete description of the TF33 engine response model.

The following expressions are defined:

- $EPR(t)$ = EPR response after overspeed limit reached ($EPR(t) = EPR_o(t)$ for $N_2 < N_{2lim}$)
- $EPR_o(t)$ = target EPR at time, t
- $\Delta EPR_i(t)$ = decrease in EPR at constant throttle for interval i (throttle adjustment compensates for decrease in EPR for $N_2 < N_{2lim}$ but no further compensation for decrease in EPR possible for $N_2 \geqq N_{2lim}$)
- $\sum_{n=0}^{i} \Delta EPR_n(t)$ = sum of decreases in EPR at constant throttle through interval i after overspeed limit reached $\left(\sum_{n=0}^{i} \Delta EPR_n(t) = 0 \text{ for } N_2 < N_{2_{\text{lim}}}\right)$
- $P_{1nominal}(EPR(t))$ = the nominal behavior for airflow and thrust (changes in $P_{1nominal}$ prior to overspeed are due only to changes in the target EPR setting while changes at the overspeed condition are also due to dust effects)

- $P_{2nominal}(EPR_o(t), \Delta P_{2i})$ = the nominal behavior for fuel flow, EGT, and N_2 (changes in $P_{2nominal}$ prior to overspeed are due either to changes in the target EPR setting or compensation for dust effects while changes at the overspeed condition are only due to a reduction in the target EPR)
- $P_{2i}(t)$ = fuel flow, EGT, and N_2 response to dust effects
- $\Delta P_{2i}(\Delta EPR_i(t))$ = increment in parameter P_2 as a result of throttle increase in order to maintain $EPR_o(t)$

The TF33 engine response algorithm is given below in Figure 2-1.

The engine response to dust for a given engine parameter resulting from the algorithm must be within the range specified by the pre-dust behavior for that parameter (specified in Appendix B1). Data regarding engine nominal performance are not to be extrapolated due to the operational limitations of the engine. In all experiments performed at Calspan, the engine was operated within those limitations.

Dust effects on EPR at constant throttle are supported by test data at the cruise (target EPR=1.30) and military power (target EPR=1.785) settings. A linear relationship between the slope of the correlation for accumulated dust greater than 142 kg (313 lbm) with target EPR is recommended. The model is considered valid between these two settings. There is no physical reason why one should not extrapolate to power settings below cruise power. The effect of EPR decrease will lessen with decreasing target EPR and approach zero at a target EPR of one. At an EPR of one, the engine is generating little thrust. Due to the limited amount of data at varied power settings investigated to date, extrapolation of data for any given target EPR beyond the maximum amount of accumulated dust, 388kg (855 lbm) is not recommended.

2.2.3 Error Estimate.

The error for parameters measured directly during the TF33 experiments and subsequently incorporated in the engine response model are estimated to be: airflow (±2%), exhaust gas temperature (±3%), fuel flow (±4%), and core speed (±1%). The TF33 thrust model was based on measurements readily available on the engine. The calculation of thrust incorporated in the TF33 engine response model has an estimated error of ±10%.

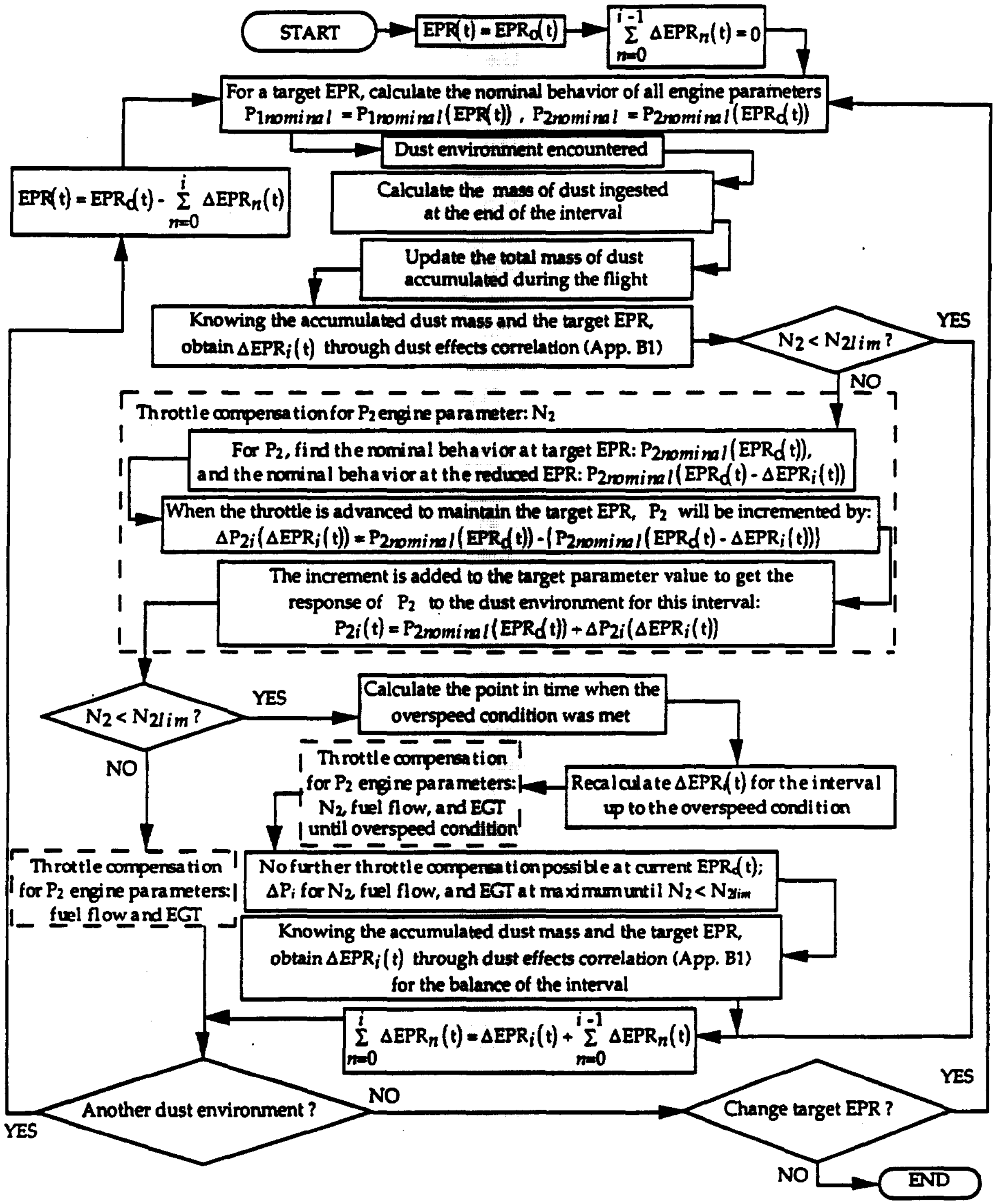

Figure 2-1. TF33 engine response algorithm.

2.3 SAMPLE PROBLEMS.

2.3.1 Problems Statements.

There are five sample problems for the TF33 engine response model. The format of each problem is similar:

A TF33 engine encounters N consecutive environments. The engine operates at a power setting corresponding to a target EPR throughout its flight path and the ambient reference conditions are constant at 14.7 psia and 59°F. What is the response of the engine prior to encountering any environment (i.e. nominal behavior) and at the conclusion of each environment encounter? Engine parameters of interest include: airflow (lbm/sec), the integrated (accumulated) mass of dust ingested by the engine (kg), exhaust gas temperature (F), fuel flow (lbm/hr), core speed (%), compressor discharge pressure (psig), thrust without the pressure contribution term (lbf), and the surge figure of merit. At what point along the flight path will the engine first be susceptible to surge? Also, at what point will the engine be most likely to surge? The TF33 engines tested at Calspan have been observed to surge after ingesting a total of between 313 kg and 586 kg of dust. At what point in the flight path will the engine exceed its overspeed and overtemp limits? The TF33 overspeed and overtemp limits are 104% and 1040°F respectively. The type of dust encountered in a given interval is defined by: 0 - clear air, 1 - the most probable blend, 2 - blend #2.

The five problems have been constructed in the following way: An engine operating point was chosen. Problems 1-3 each have a constant dust concentration throughout a common flight time. The dust concentration is varied parametrically from one problem to the next. Within each of the three problems, the discretization of the flight time is varied to assess the time step independence of the engine response model. Problem 4 has a variation in the engine power setting from one of the first three problems to isolate the effect of engine power setting on the engine response model. Problem 5 has a varied profile of dust type, dust concentration, and encounter durations for the nominal engine power setting.

Problem #1:

What is the engine response for the following conditions? The engine operates at a throttle setting which produces an EPR of 1.70. The total flight time is 60 minutes. The dust environment consists solely of the most probable blend. The dust concentration is constant throughout the flight at a value of 500 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	500	6

2	1	500	6
3	1	500	6
4	1	500	6
5	1	500	6
6	1	500	6
7	1	500	6
8	1	500	6
9	1	500	6
10	1	500	6

Part (2): N = 5 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	500	12
2	1	500	12
3	1	500	12
4	1	500	12
5	1	500	12

Part (3): N = 3 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	500	20
2	1	500	20
3	1	500	20

Part (4): N = 1 dust encounter

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	500	60

Problem #2:

What is the engine response for the following conditions? The engine operates at a throttle setting which produces an EPR of 1.70. The total flight time is 60 minutes. The dust environment consists solely of the most probable blend. The dust concentration is constant throughout the flight at a value of 900 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #3:

What is the engine response for the following conditions? The engine operates at a throttle setting which produces an EPR of 1.70. The total flight time is 60 minutes. The dust environment consists solely of the most probable blend. The dust concentration is constant throughout the flight at a value of 300 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #4:

What is the engine response for the following conditions? The engine operates at a throttle setting which produces an EPR of 1.30. The total flight time is 60 minutes. The dust environment consists solely of the most probable blend. The dust concentration is constant throughout the flight at a value of 900 mg/m^3. Consider the flight as being made up of 10 equally spaced successive dust encounters similar to problem 2, part 1.

Problem #5:

What is the engine response for the following conditions? The engine operates at a throttle setting which produces an EPR of 1.70. The dust environment is varied, as are the dust concentrations and encounter durations as follows:

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	50	60
2	0	0	5
3	2	100	10
4	2	300	10
5	2	900	30
6	2	300	10
7	2	100	10
8	0	0	5
9	1	500	60
10	1	50	240

2.3.2 Solutions.

A code was written at Calspan which incorporates the engine response algorithm and associated correlations of Appendix B. The purpose of this undertaking was to provide SAIC and KAMAN SCIENCES with the solutions to the aforementioned sample problems. The Calspan solutions to the TF33 sample problems are presented in

Appendix B. The source code for the Calspan version of the TF33 engine response model is presented in Appendix B.

SECTION 3
THE RESPONSE OF AN F107 TURBOFAN ENGINE TO DUST ENVIRONMENTS

3.1 DESCRIPTION OF THE RESPONSE.

3.1.1 Overview.

The F107 engine is currently used in ALCM and SLCM applications and is the predecessor to the more advanced F112 engine now entering cruise missile inventories. It is a low thrust class by comparison to the F101 and TF33 engines, which also are of interest in P-EARL. For the cruise missile application, the control system maintains the engine at constant core speed for a specific setting. The engine behavior is affected by dust environments. Dust ingestion results in a progressive contamination of the oil lubrication system which causes a decrease in oil pressure and ultimately results in catastrophic failure of the engine. Although there was significant dust material deposition on hot-section engine components, compressor degradation, and combustor burn through, the most immediate effect of the dust environment was the oil contamination problem. Consequently, the thrust, airflow, and range of the engine would not have been affected within the time scale for failure due to oil lubrication system contamination.

3.1.2 Principal Variables.

The principal variables that affect the response of an F107 engine are in order of importance:

- The accumulated mass of dust ingested by the engine
- The dust concentration
- The type of dust in the environment
- The core speed

3.1.3 Criteria.

There are two principal criteria to address in evaluating the response of this particular engine:

(1) Can the engine operate?

The F107 engine will be rendered inoperable after the bearings seize from a lack of proper oil lubrication. Complete loss of engine operation is certain and catastrophic failure of the engine is likely. The engine response model indicates when the engine is in danger of seizing. This is done by evaluating whether the oil supply pressure has fallen below the minimum value recommended by the manufacturer (25 psig). More will be said about this in Section 3.2.2. The F107 engine response model accomplishes this objective.

(2) Does the loss in engine performance impact the missile performance enough to prevent the accomplishment of the mission objectives?

Unlike the F101 and TF33 engine responses, the F107 oil problem occurs so quickly that deposition and erosion don't have time to become the primary problem areas. It should be noted that the F107 engine life was extended by repeatedly changing the oil filter and oil (which would not be possible in flight) and in this way the operational life was extended and deposition and erosion did become problems. The mission objectives will be met as long as the engine is functional. When the engine fails, the mission is terminated.

3.2 FORMULATION.

This section describes the formulation of the F107 engine response model to dust environments. The formulation involves all of the aforementioned principal variables. The core speed is the parameter which controls the engine parameters of interest, which are: thrust, airflow, and oil pressure.

3.2.1 Basis.

The basis of the F107 engine response model is a series of experiments performed by Calspan during the period from 30 September 1991 to 10 October 1991 involving a F107-WR-102 turbofan engine, and is part of a long history of research by Calspan in dust exposure effects on airbreathing engine response. The experiments were sponsored by the Defense Nuclear Agency (DNA) under RDT&E RMSS CODE B342085466 N99QMXAJ00002 H2590D and were performed in Calspan's Large Engine Research Center (LERC). The details of the test facility can be found in Baran et al., 1992 (F107). The engine was typically run at maximum continuous rated thrust, corresponding to a core speed of approximately 62,000 rpm. At this operating condition, the engine was capable of generating a calculated turbine inlet temperature (TIT) of 1880 °F, which is hot enough to produce dust material deposition for blend #2 but not for the 'most probable' blends as described in Kim et al., 1992. A dust laden air stream was drawn into the engine while various engine measurements were monitored and recorded. The 'most probable' blend and blend #2 were the types of dust used in the experiments and the dust concentrations ranged from 84 to 6120 mg/m^3. The experimental data nominally consisted of five pre-dust exposure runs to establish the nominal behavior of the engine prior to dust exposure and eight dust exposure runs. Each dust exposure run provided a profile of varied dust concentrations. The dust exposure runs typically varied the dust blend and/or the dust concentration profile.

3.2.2 Model.

The F107 dust response model consists of an algorithm which calculates the oil pressure loss for a given dust environment and indicates when the oil pressure is below the recommended minimum value of 25 psig. The engine thrust and airflow are also presented and are calculated using experimentally measured quantities. The desired thrust setting for the engine is achieved by specifying the core speed.

The following expressions are defined:

- t = time from take-off
- $(\,)_i$ = pertaining to the current dust environment i
- $(\,)_n$ = pertaining to the prior dust environment n
- t_n = time duration of dust environment n
- c_n = dust concentration of dust environment n
- $\tau_i(t)$ = time into dust environment i at time t $(t_{i-1} \leq \tau_i(t) \leq t)$
- $N_2(t)$ = core speed for a desired thrust setting
- $P_{1nominal}(N_2(t))$ = the nominal behavior of an engine parameter, P_1, of interest (i.e., thrust and airflow) based on core speed
- $P_{2nominal}(N_2(t), \Delta P_{2i})$ = the nominal behavior of an engine parameter, P_2, of interest (i.e., oil pressure) based on core speed
- $P_{1i}(t)$ = response of P_1 to dust exposure during i
- $P_{2i}(t)$ = response of P_2 to dust exposure during i
- $\Delta P_{2i}(t)$ = oil pressure loss during i
- $\frac{d}{dt}(P_2)$ = rate of oil pressure loss
- $\sum_{n=1}^{(i-1)} \Delta P_{2n}(t_n)$ = history of change in core speed during events prior to i

The F107 engine response algorithm is given below in Figure 3-1.

The engine parameters exhibit their nominal behavior until a dust environment is encountered. After the dust encounter, the amount of dust is calculated and by knowing the dust type and dust concentration, the dust effects correlation of Appendix C define the rate of oil pressure loss over the duration of the dust encounter which then gives the oil pressure loss. The dust effects correlation reflects the observation that until a critical mass of dust has been ingested,

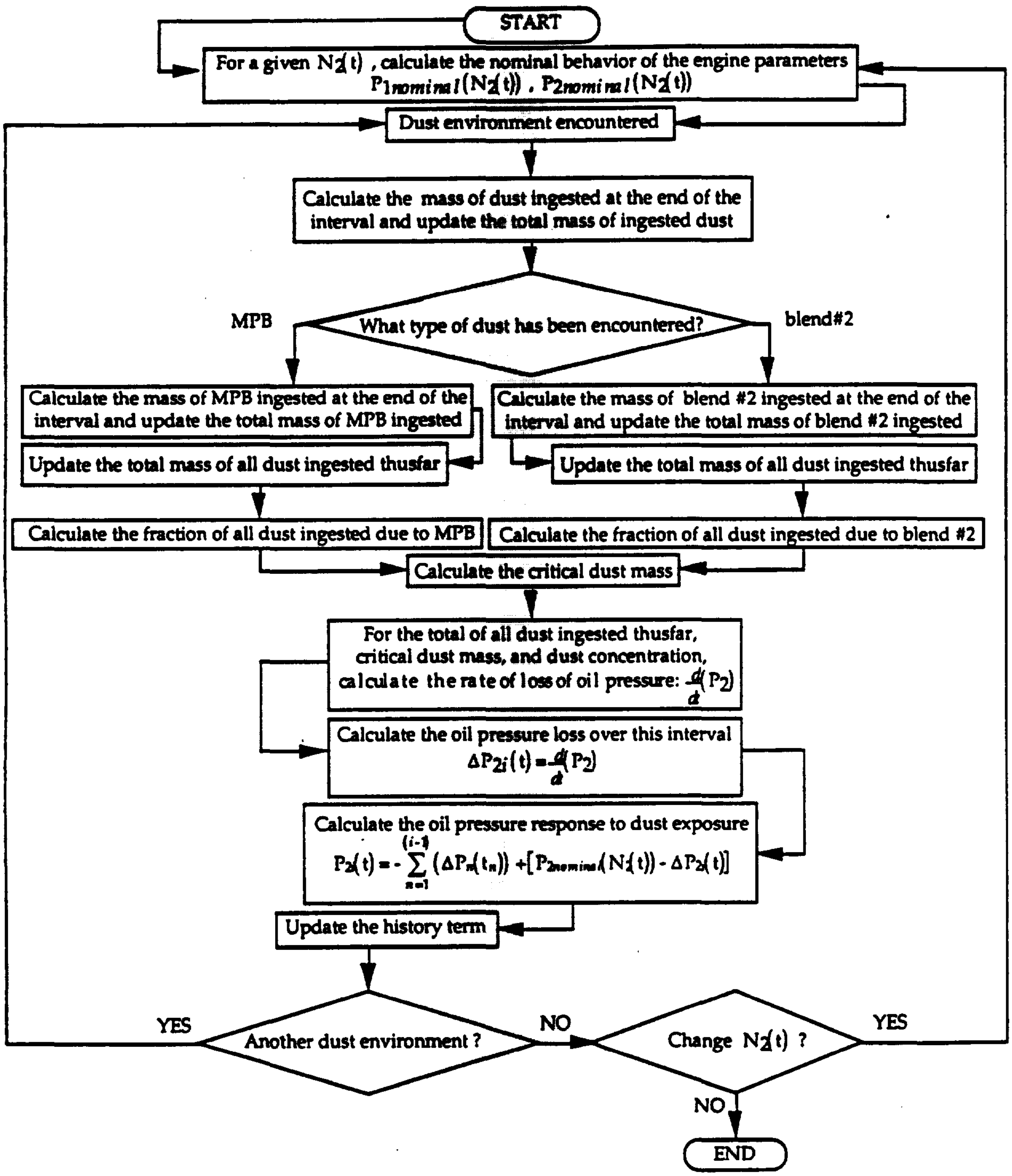

Figure 3–1. F107 engine response algorithm.

the oil pressure loss rates are fairly modest compared to those after the engine ingests the critical dust mass. The critical dust mass is dust blend dependent. This loss in oil pressure is continually updated with each subsequent dust encounter. The engine is in danger of failure at any time after the oil pressure falls below 25 psig. The manufacturer is very cautious about continuing to operate the engine with oil pressure less than 25 psig. During the measurement program described here, the engine was operated at Calspan for a very brief period of time with oil pressure in the 18 psig range. No engines were run to destruction so an absolute lower bound pressure and time at that pressure are unknown. Thrust and airflow for the engine are solely a function of the core speed input.

The algorithm takes into account the possibility of varying the core speed as well as encountering multiple dust types during the course of the mission. The core speed is unaffected by the dust environment and will remain constant unless directed to do so. The multiple dust environments are handled by changing the critical dust mass to reflect the contribution of both dust blends to the accumulated mass of all dust ingested and is described in detail in Appendix C.

The oil pressure loss rate correlation to dust environment is valid for the range of dust concentrations presented in Appendix C. The dust effects can be assumed to go to zero for dust concentrations approaching zero. Extrapolation beyond the highest dust concentration for either branch of the correlation is not recommended. The nominal behavior of each engine parameter of interest is limited to a range of core speeds within which the response is considered valid. This range encompasses all core speeds measured during the course of the F107 experiments and is also presented in Appendix C.

3.2.3 Error Estimate.

The error for the oil pressure response is estimated to be $\pm 9\%$, and is a combination of the uncertainties in the nominal behavior and the dust effects correlation. The airflow is estimated to be accurate to $\pm 2\%$. The calculation of thrust incorporated in the F107 engine response model has an estimated error of $\pm 10\%$.

3.3 SAMPLE PROBLEMS.

3.3.1 Problems Statements.

There are six sample problems for the F107 engine response model. The format of each problem is similar:

The first five problems have been constructed in the following way: An engine operating point was chosen. Problems 1-3 each have a constant dust concentration throughout a common flight time. The dust concentration is varied parametrically from one problem to the next. Within each of the three problems, the discretization of the flight time is varied to assess the time step independence of the engine response model. Problem 4 has a variation in the core speed setting from one of the first three problems to isolate the effect of core speed setting on the engine response model. Problem 5 has a varied profile of dust type, dust concentration, and encounter duration for the nominal core speed setting.

A sixth problem was constructed to evaluate the effect of dust blend on the response model. Problem 6 is identical to Problem 1 except that the dust blend was changed from blend #2 to the 'most probable blend'.

Problem #1:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=62,000 rpm. The total flight time is 12 minutes. The dust environment consists solely of blend 2. The dust concentration is constant throughout the flight at a level of 500 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	2	500	1.2
2	2	500	1.2
3	2	500	1.2
4	2	500	1.2
5	2	500	1.2
1.2	2	500	1.2
7	2	500	1.2
8	2	500	1.2
9	2	500	1.2
10	2	500	1.2

Part (2): N = 5 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	2	500	2.4
2	2	500	2.4
3	2	500	2.4
4	2	500	2.4
5	2	500	2.4

Part (3): N = 3 dust encounters

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	2	500	4
2	2	500	4
3	2	500	4

Part (4): N = 1 dust encounter

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	2	500	12

Problem #2:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=62,000 rpm. The total flight time is 12 minutes. The dust environment consists solely of blend 2. The dust concentration is constant throughout the flight at a level of 6000 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #3:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=62,000 rpm. The total flight time is 12 minutes. The dust environment consists solely of blend 2. The dust concentration is constant throughout the flight at a level of 2000 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

Part (1): N = 10 dust encounters
Part (2): N = 5 dust encounters
Part (3): N = 3 dust encounters
Part (4): N = 1 dust encounter

Problem #4:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=58,000 rpm. The total flight time is 12 minutes. The dust environment consists solely of blend 2. The dust concentration is constant throughout the flight at a level of 6000 mg/m^3. Consider the flight as being made up of 10 equally spaced successive dust encounters similar to problem 2, part 1.

Problem #5:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=62,000 rpm. The dust environment is varied, as are the dust concentrations and encounter duration as follows:

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	100	10
2	0	0	2
3	2	200	10

4	2	500	5
5	2	200	10
6	0	0	2
7	1	1000	5
8	1	2000	2
9	1	1000	5
10	2	100	20

Problem #6:

What is the engine response for the following conditions. The engine operates at a core speed setting of N2=58,000 rpm. The total flight time is 12 minutes. The dust environment consists solely of the 'most probable'. The dust concentration is constant throughout the flight at a level of 6000 mg/m^3. Consider the flight as being made up of N equally spaced successive dust encounters as follows:

#	dust blend	dust concentration (mg/m^3)	duration(min.)
1	1	6000	1.2
2	1	6000	1.2
3	1	6000	1.2
4	1	6000	1.2
5	1	6000	1.2
6	1	6000	1.2
7	1	6000	1.2
8	1	6000	1.2
9	1	6000	1.2
10	1	6000	1.2

3.3.2 Solutions.

A code was written at Calspan which incorporates the engine response algorithm and associated correlations of Appendix C. The purpose of this undertaking was to provide SAIC and KAMAN SCIENCES with the solutions to the aforementioned sample problems. The Calspan solutions to the F107 sample problems are presented in Appendix C. The source code for the Calspan version of the F107 engine response model is presented in Appendix C.

SECTION 4

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APPENDIX A
F101 ENGINE RESPONSE MODEL

This appendix contains the detailed information required for the F101 engine response model. It consists of:

- Observations made during the YF101 experiments and the engine surge criterion for the F101
- The general representation of a sample environment
- The general form of the F101 engine response model
- Speed correlation
- Nominal behavior of core speed
- Dust effects on core speed
- Dust effects model
- Nominal behavior of engine parameters of interest
- Cumulative dust effects on CDP, fuel flow, and thrust
- The F101 engine response algorithm

OBSERVATIONS & ENGINE SURGE CRITERION

- ENGINE DAMAGE DUE TO A COMBINATION OF COMPRESSOR BLADE WEAR AND DUST MATERIAL DEPOSITION ON THE HOT SECTIONS OF THE ENGINE.

- ENGINE RESPONSE IS DEPENDENT ON DUST TYPE AND DUST CONCENTRATION.

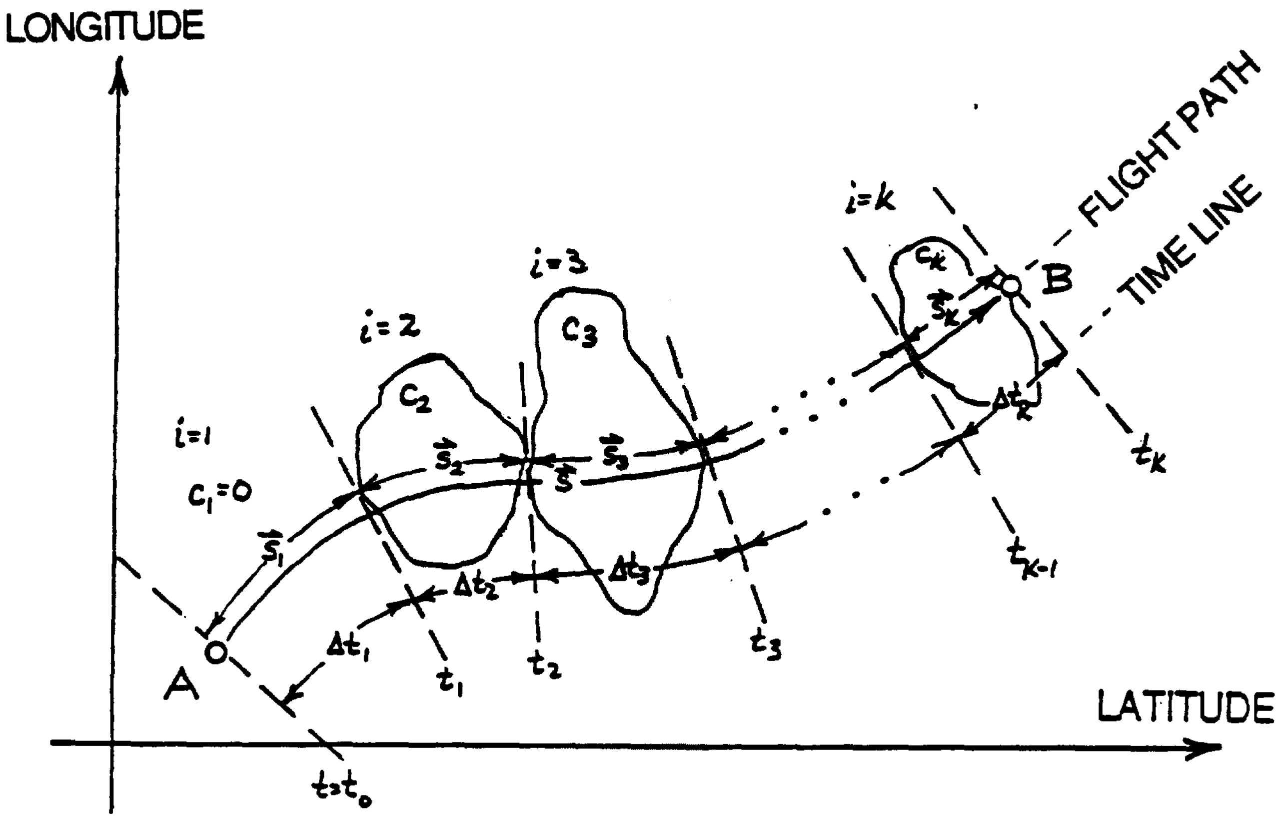
- CORE SPEED IS REDUCED AS A FUNCTION OF DUST INGESTION.

- THE FOLLOWING ENGINE PARAMETERS WERE OBSERVED TO PROGRESSIVELY DEPART FROM THEIR NOMINAL BEHAVIOR:

    - COMPRESSOR DISCHARGE PRESSURE
    - FUEL FLOW
    - THRUST
    - EXHAUST GAS TEMPERATURE
    - PYROMETER TEMPERATURE

- ENGINE SURGED WHEN THE DEPARTURE OF COMPRESSOR DISCHARGE PRESSURE FROM IT'S NOMINAL BEHAVIOR EXCEEDED 54 PSI.

- CONSIDER A PIECEWISE REPRESENTATION OF AN INTENDED FLIGHT PATH, $\vec{s}$, BASED ON DISCRETE REGIONS, i, OF LOCALLY CONSTANT DUST CONCENTRATION, c_i.

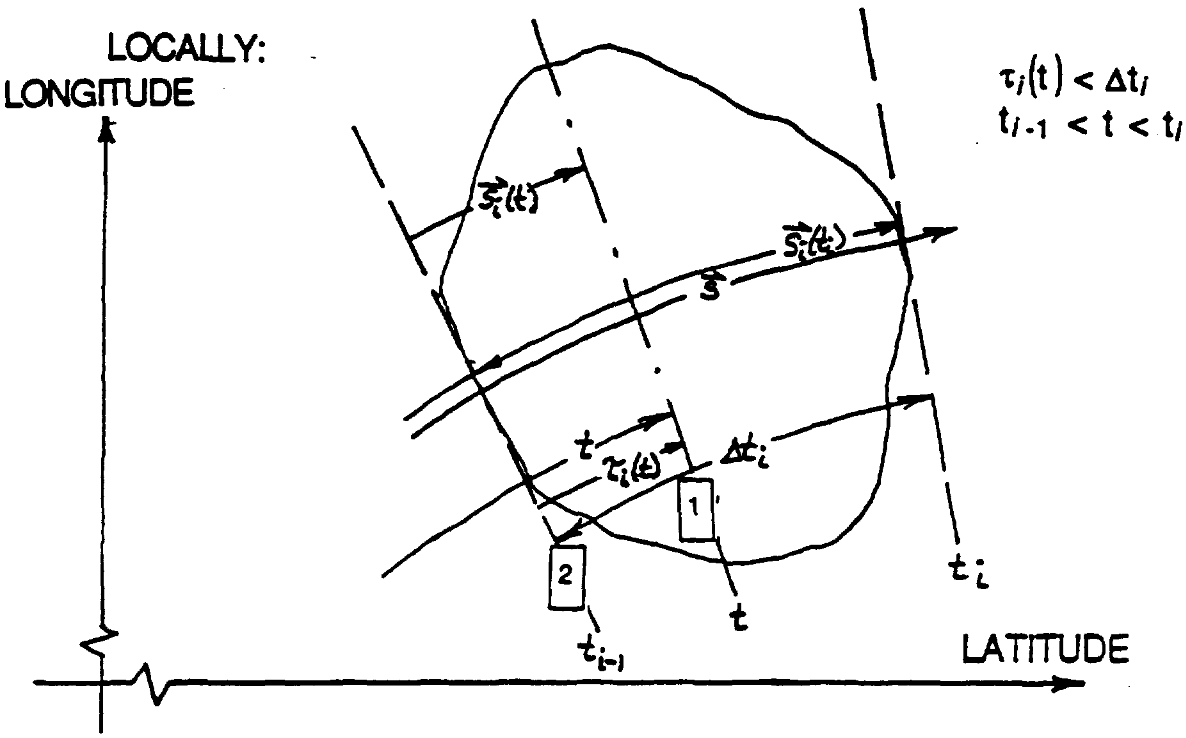


where,

$\vec{s}$ = flight path from A to B
t = time from origin
k = total # of discrete environments along $\vec{s}$
i = index for current environment encounter
n = dummy index for prior environment encounters

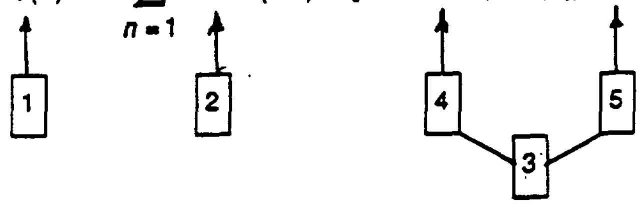
t_i = time at conclusion of encounter i
Δt_i = time duration of encounter i
$\tau_i(t)$ = elapsed time within encounter i
c_i = dust concentration (constant throughout i)
$\vec{s}_i$ = path traversed through encounter i

Figure A-1. Sample environment.



GENERAL FORM:

$$P_i(t) = \sum_{n=1}^{(i-1)} \Delta P_n(t_n) + [P_{nominal}(N_2(t)) + \Delta P_i(t)]$$



where,

1 PARAMETER WITH DUST EFFECTS DURING ENCOUNTER *i*

2 ACCUMULATED DUST EFFECTS TO DATE (not a function of time)

3 INCREMENT IN DUST EFFECTS ON P DURING *i* (a function of time)

4 DUST EFFECTS DUE SOLELY TO CHANGES IN ENGINE SPEED

5 CUMULATIVE DUST EFFECTS

Figure A-2. General form of parameter response.

SPEED CORRELATION

[1] POLYNOMIAL FUNCTION OF PLA

[3] HISTORY OF DUST EFFECTS

$$N_2(t) = N_{2_{nominal}}(PLA) - \Delta N_{2_i}(t, c) - \sum_{n=1}^{(i-1)} \Delta N_{2_n}(t_n, c_n)$$

[2] DUST EFFECTS IN CURRENT CLOUD

where,

$$\Delta N_{2_i}(t, c) = \frac{d}{dt}[\Delta N_2(c)] * \tau_i(t)$$

POLYNOMIAL FUNCTION OF CONCENTRATION

$N_2(t)$ INPUT INTO ALL OTHER ENGINE PARAMETER MODELS

[1] THROTTLE SETTING DETERMINES THE ENGINE SPEED

[2] MODIFICATIONS ARE MADE TO ENGINE SPEED BASED ON OBSERVED DUST EFFECTS ON ENGINE SPEED

[3] HISTORY TERM OF DUST EXPOSURE (CONSIDER DUST EFFECTS TO BE FULLY CUMULATIVE)

Table A-1. Engine core speed pre-dust curve fits – nominal behavior.

$$N2 = a0 + a1 \cdot PLA + a2 \cdot PLA^2 + a3 \cdot PLA^3 + a4 \cdot PLA^4 + a5 \cdot PLA^5 + a6 \cdot PLA^6 + a7 \cdot PLA^7 + a8 \cdot PLA^8 + a9 \cdot PLA^9$$

where: N2 = engine core speed
PLA = power lever angle

parameter	units	PLA lower bound (-)	PLA upper bound (-)	---------polynomial coefficients (3 significant figures)---------- a0 / a6	a1 / a7	a2 / a8	a3 / a9	a4	a5
N2	rpm	16.5	30	+1.04E+04	+1.81E-01				
		30	80	+1.03E+04	+2.21E+02	-2.13E+01	+6.96E-01	-8.80E-03	+3.88E-05

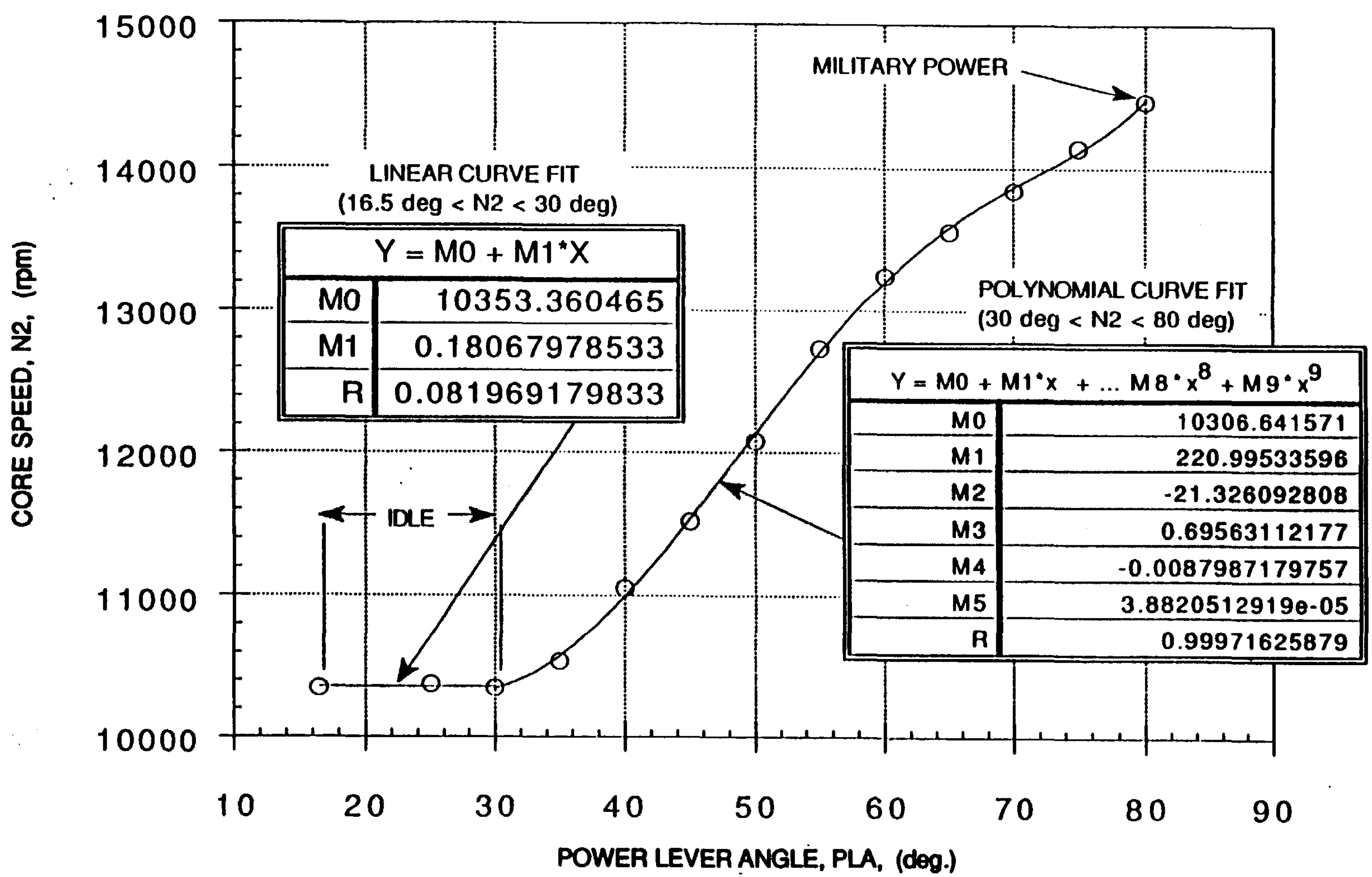


Figure A-3. Core speed pre-dust nominal behavior.

Table A-2. Dust effects curve fits on engine core speed.

$$\frac{d}{dt}[\Delta N_2(c)] = a0 + a1*c + a2*c\text{^}2 + a3*c\text{^}3 + a4*c\text{^}4 + a5*c\text{^}5 + a6*c\text{^}6 + a7*c\text{^}7 + a8*c\text{^}8 + a9*c\text{^}9$$

where: $\frac{d}{dt}[\Delta N_2(c)]$ = rate of engine speed decrease

c = dust concentration

parameter	units	c lower bound (-)	c upper bound (-)	---------polynomial a0 / a6	coefficients a1 / a7	(3 a2 / a8	significant a3 / a9	figures)---------- a4	a5
MOST PROBABLE BLEND (accumulated dust mass < 72 kg)									
	rpm/min	0	72	+0.00E+00	+3.11E-02				
		72	293	+2.24E+00					
MOST PROBABLE BLEND (accumulated dust mass > 72 kg)									
	rpm/min	0	282	+4.16E-01	+6.27E-02				
BLEND #2									
	rpm/min	0	295	-2.31E-02	+1.96E-01	-1.95E-03	+6.96E-06		

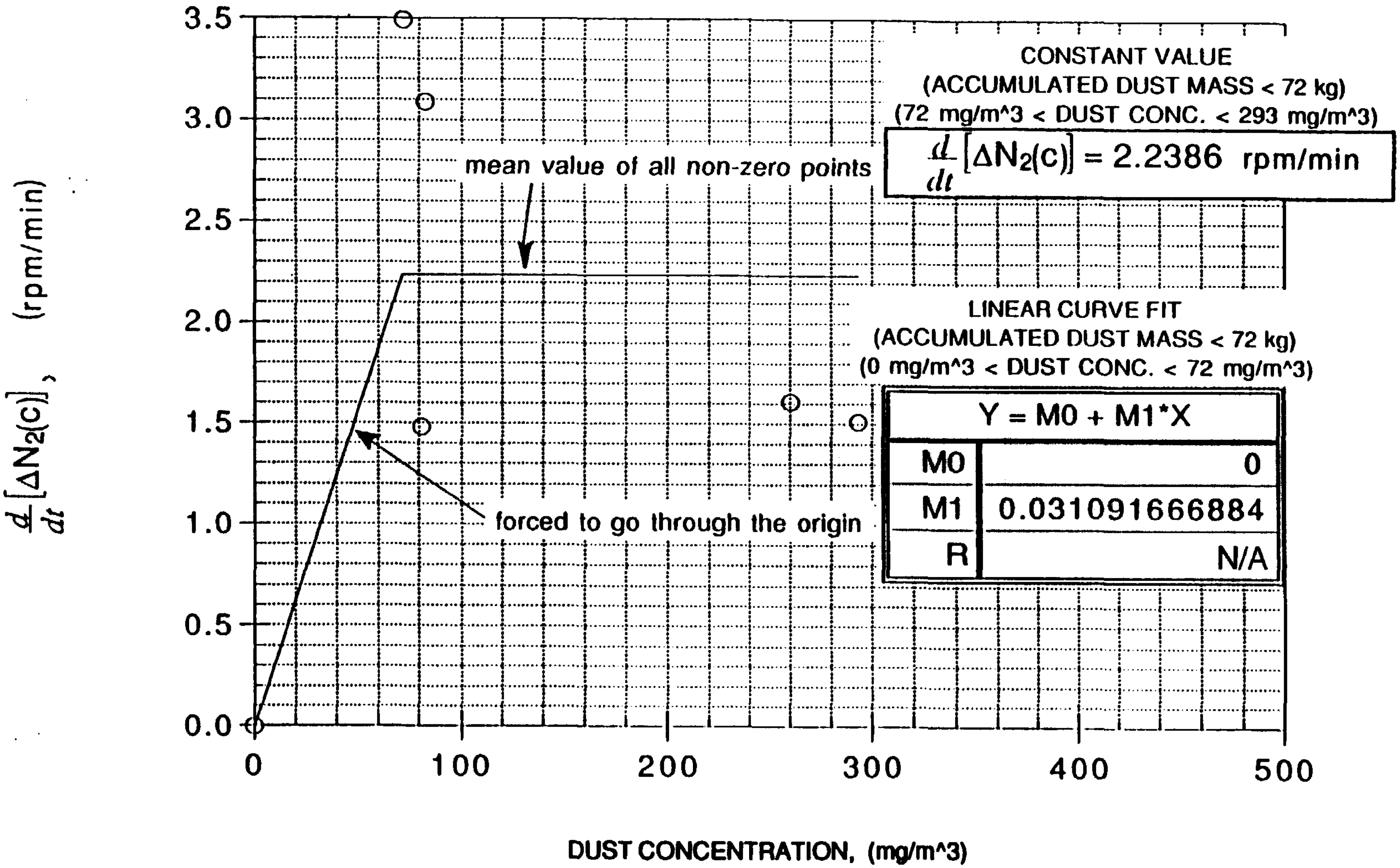


Figure A-4. Modelling of most probable blend effects on core speed for an accumulated dust mass <72 kg.

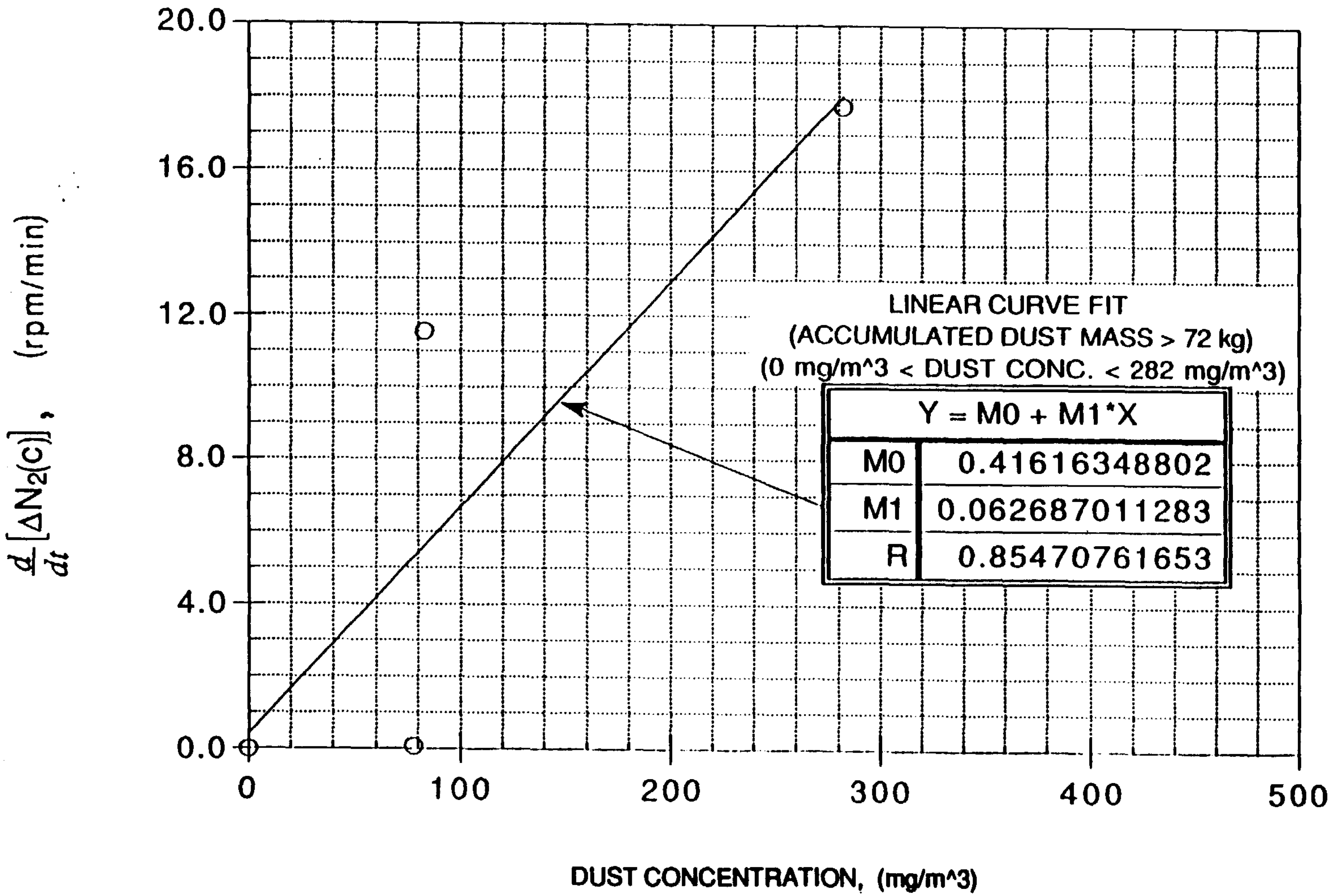


Figure A-5. Modelling of most probable blend effects on core speed for an accumulated dust mass >72 kg.

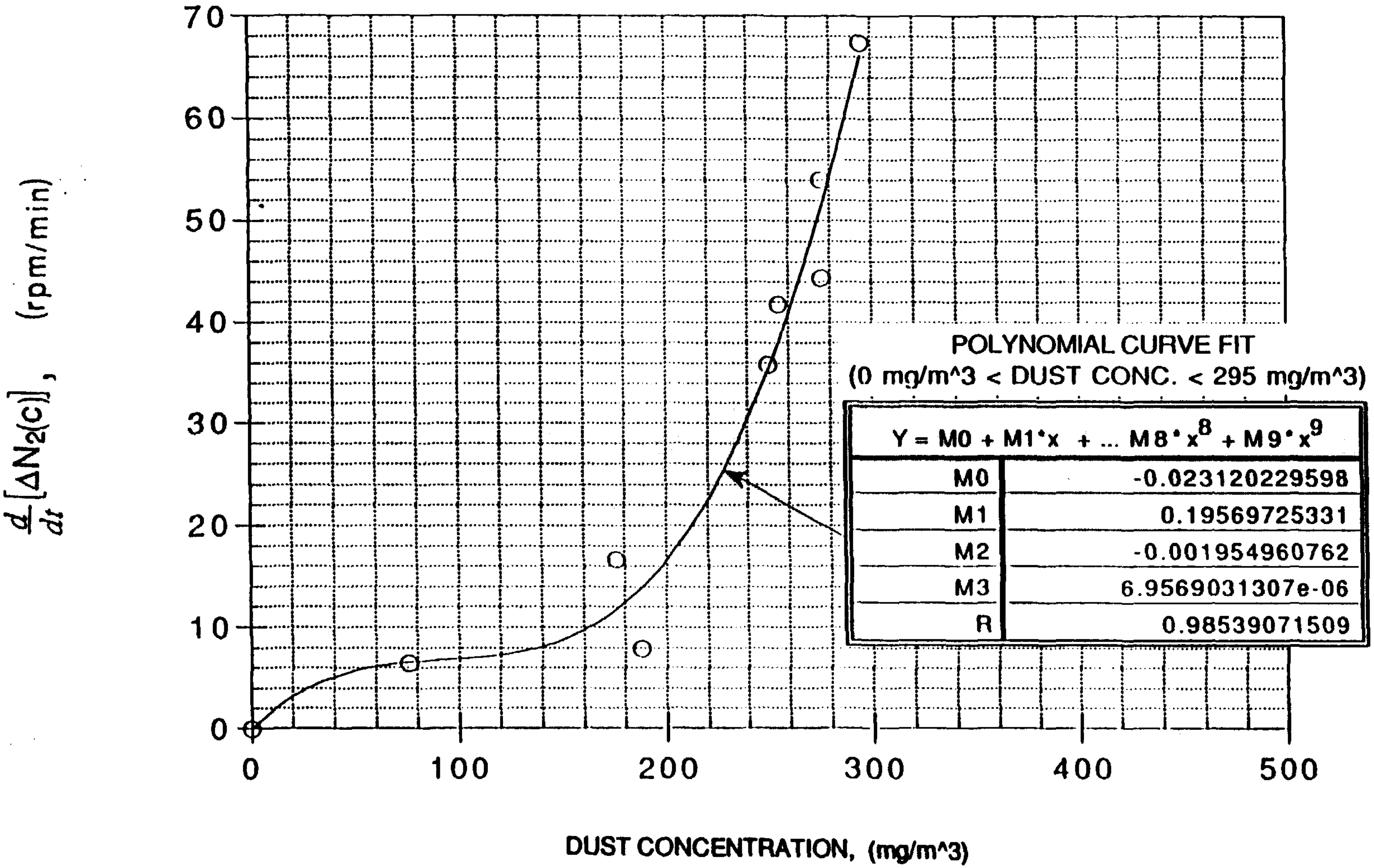


Figure A-6. Modelling of blend #2 effects on core speed.

DUST EFFECTS MODEL

PARAMETER VALUE MUST:

- REFLECT PRE-DUST PERFORMANCE
- REFLECT EFFECTS OF CHANGING ENGINE SPEED
- REFLECT CURRENT DUST CONCENTRATION
- REFLECT CUMULATIVE INGESTED DUST

$$P_i(t) = \sum_{n=1}^{(i-1)} \Delta P_n(t_n) + \frac{d}{dc}\left(\frac{d}{dt}(\Delta P)\right) * c_i \tau_i(t) + P_{nominal}(N(t))$$

RATE OF CUMULATIVE DUST EFFECTS

DUST CONCENTRATION

DUST EXPOSURE TIME

ENGINE SPEED (DUST EFFECTS & THROTTLE)

PRE-DUST BEHAVIOR

[3] INCREMENT IN DUST EFFECTS ON P DURING *i* (a function of time)

[2] ACCUMULATED DUST EFFECTS TO DATE (not a function of time)

[1] PARAMETER WITH DUST EFFECTS DURING ENCOUNTER *i*

Table A-3. Pre-dust curve fits - nominal behavior.

$$P = a0 + a1*N2 + a2*N2\text{^}2 + a3*N2\text{^}3 + a4*N2\text{^}4 + a5*N2\text{^}5 + a6*N2\text{^}6 + a7*N2\text{^}7 + a8*N2\text{^}8 + a9*N2\text{^}$$

where: P = parameter
N2 = engine core speed

parameter	units	N2 lower bound (-)	N2 upper bound (-)	polynomial coefficients (3 significant figures) a0 / a6	a1 / a7	a2 / a8	a3 / a9	a4	a5
AIRFLOW	lbm/sec	10348	15000	+4.41E+05	-1.74E+02	+2.73E-02	-2.14E-06	+8.32E-11	-1.29E-15
CDP	psig	10348	15000	+5.28E+04	-2.04E+01	+3.16E-03	-2.44E-07	+9.44E-12	-1.46E-16
FUEL FLOW	Pph	10348	15000	-4.98E+04	+1.52E+01	-9.05E-04	-1.08E-07	+1.34E-11	-3.69E-16
THRUST	lbf	10543	13246	-9.02E+07	+3.82E+04	-6.45E+00	+5.43E-04	-2.28E-04	+3.82E-14
		13246	15000	-2.65E+07	+5.60E+03	-2.42E-01	-2.25E-05	+2.23E-09	-5.20E-14

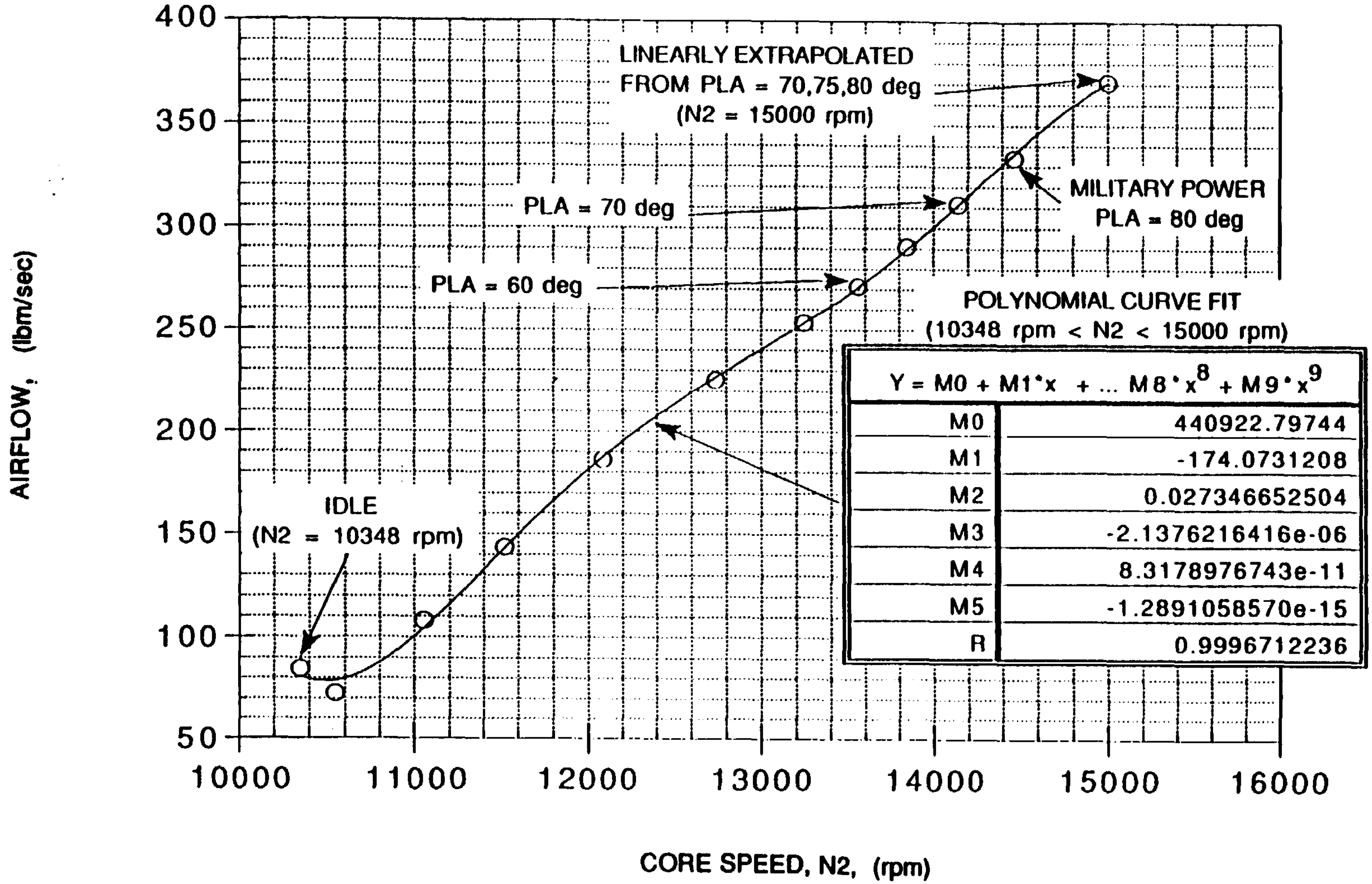


Figure A-7. Airflow pre-dust nominal behavior.

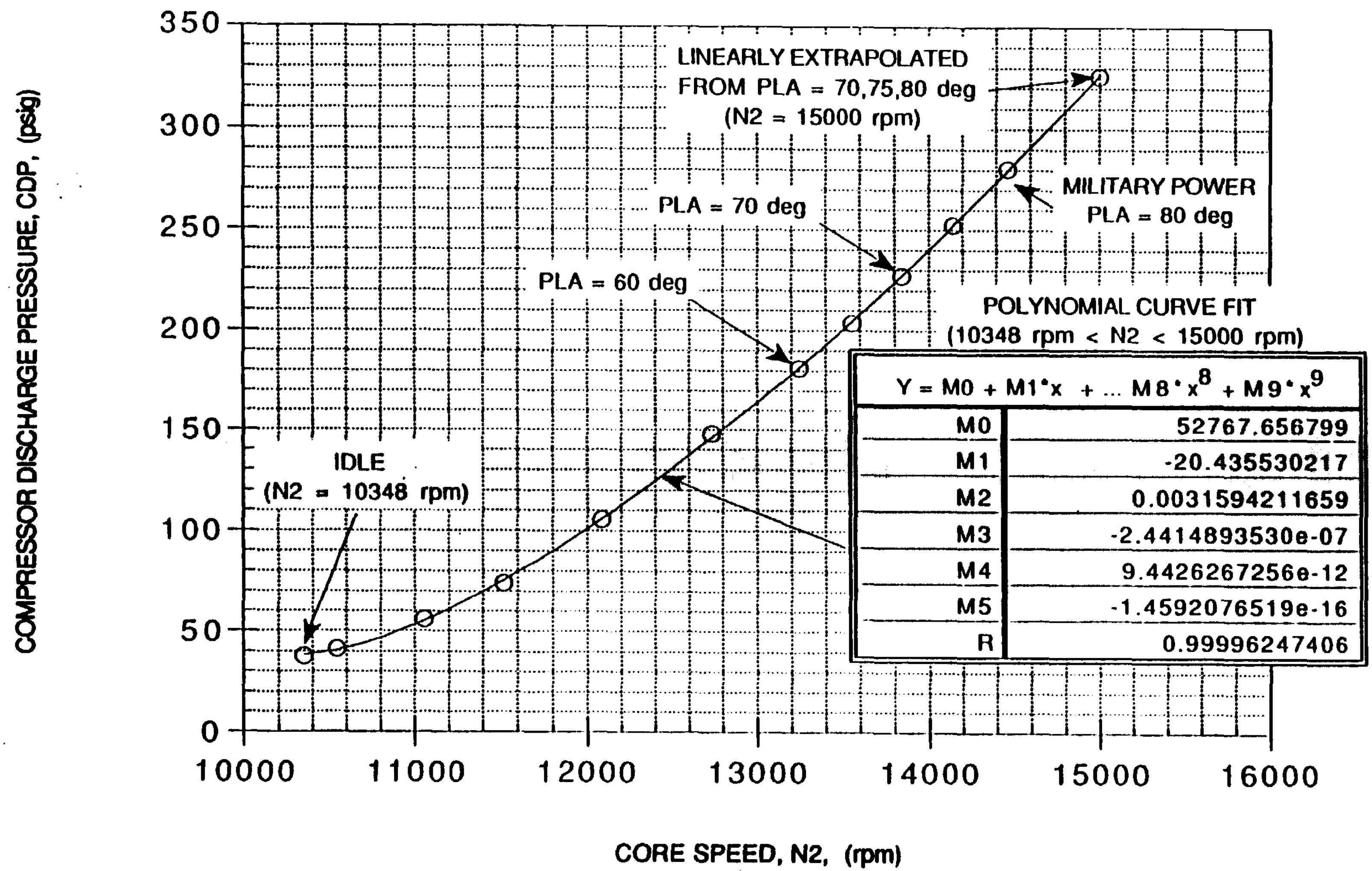


Figure A-8. CDP pre-dust nominal behavior.

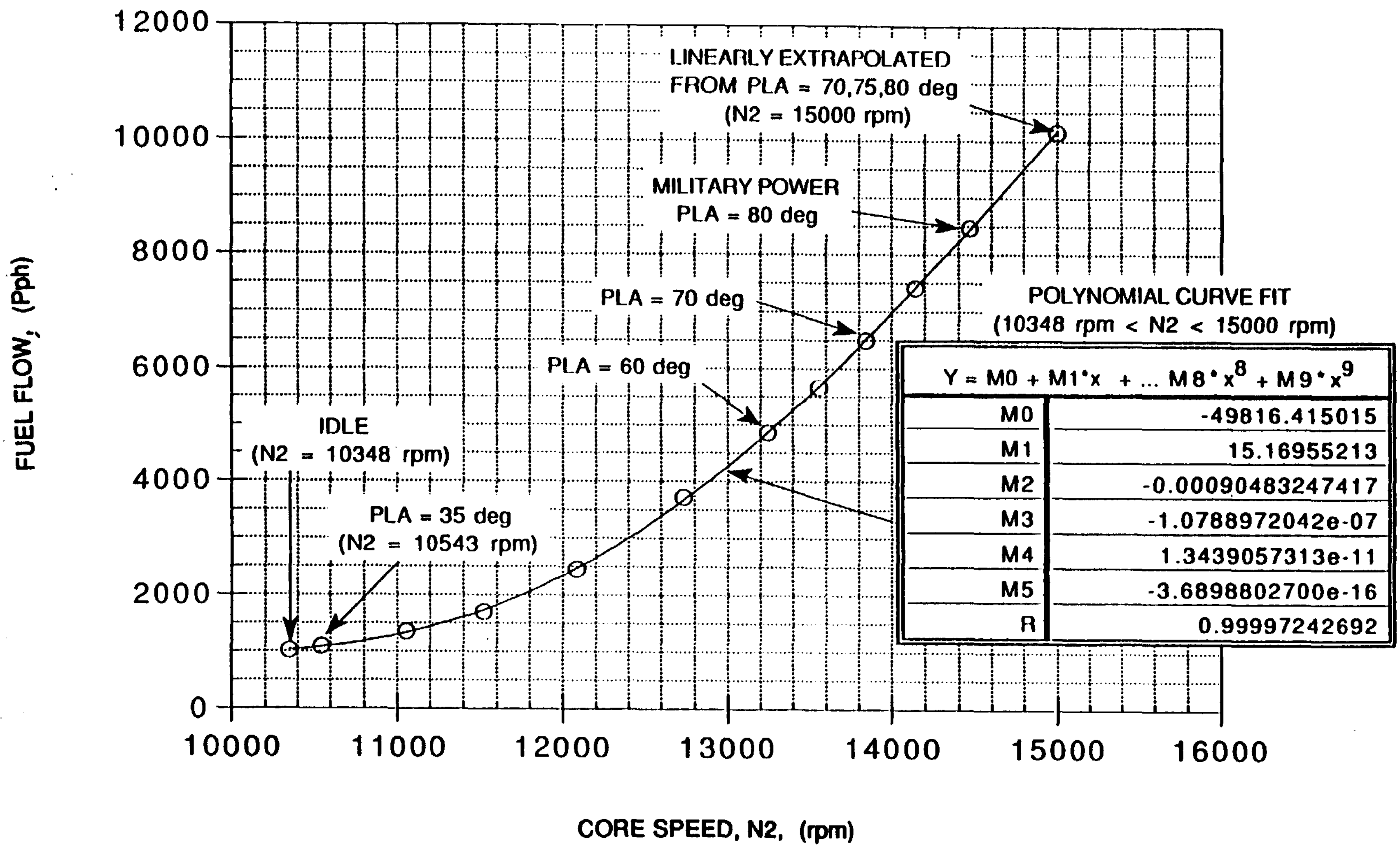


Figure A-9. Fuel flow pre-dust nominal behavior.

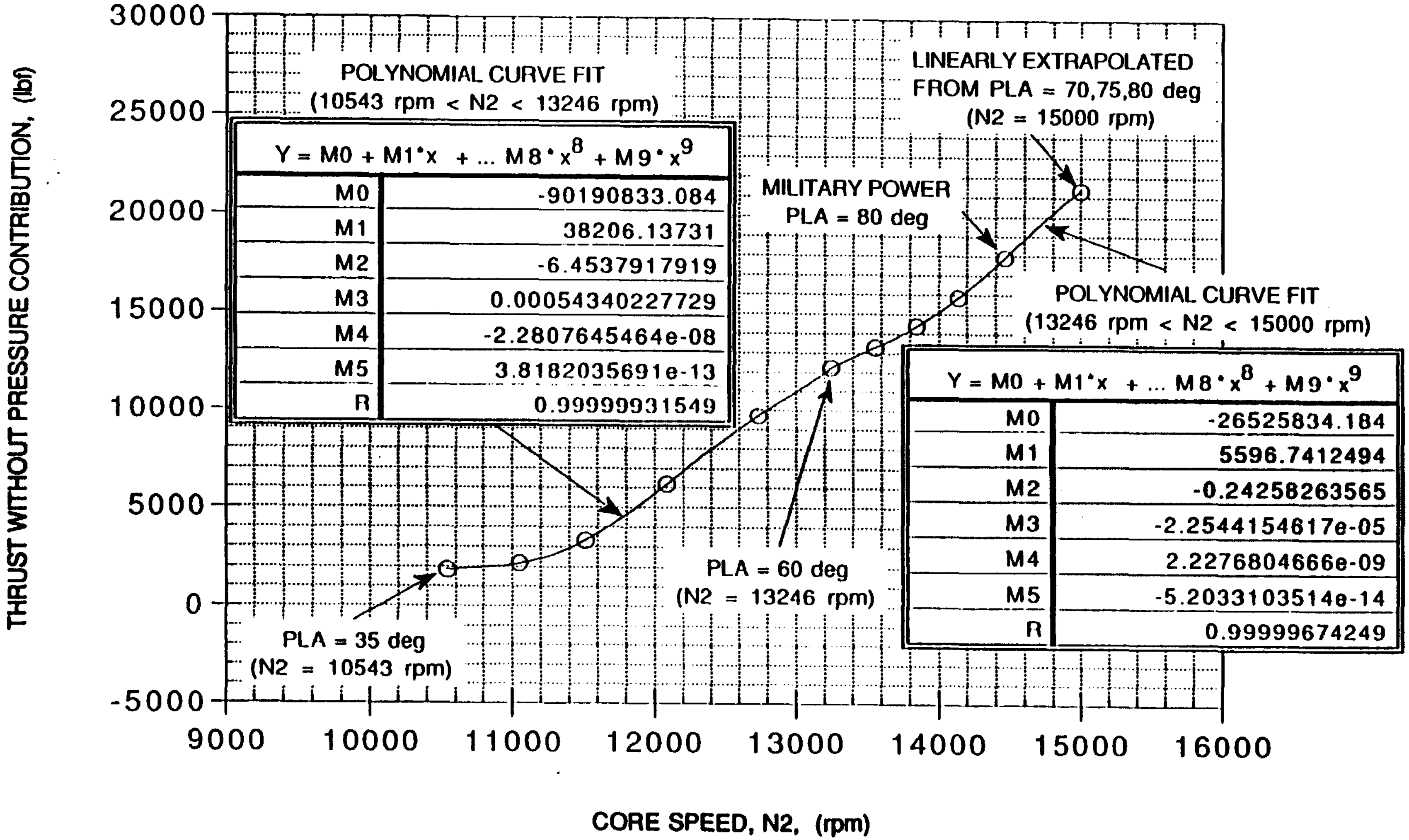


Figure A-10. Thrust pre-dust nominal behavior.

Table A-4. Cumulative dust effects.

$$\frac{d}{dc}\left(\frac{d}{dt}(\Delta \mathrm{PARAMETER})\right),\quad (\Delta\mathrm{PARAMETER/min})/(\mathrm{mg/m^{\wedge}3})$$

PARAMETER	MOST PROBABLE BLENDS	BLEND#2
CDP	9.36E-03	1.59E-02
FUEL FLOW	1.22E-01	3.32E-01
THRUST	1.41E-01	3.33E-01

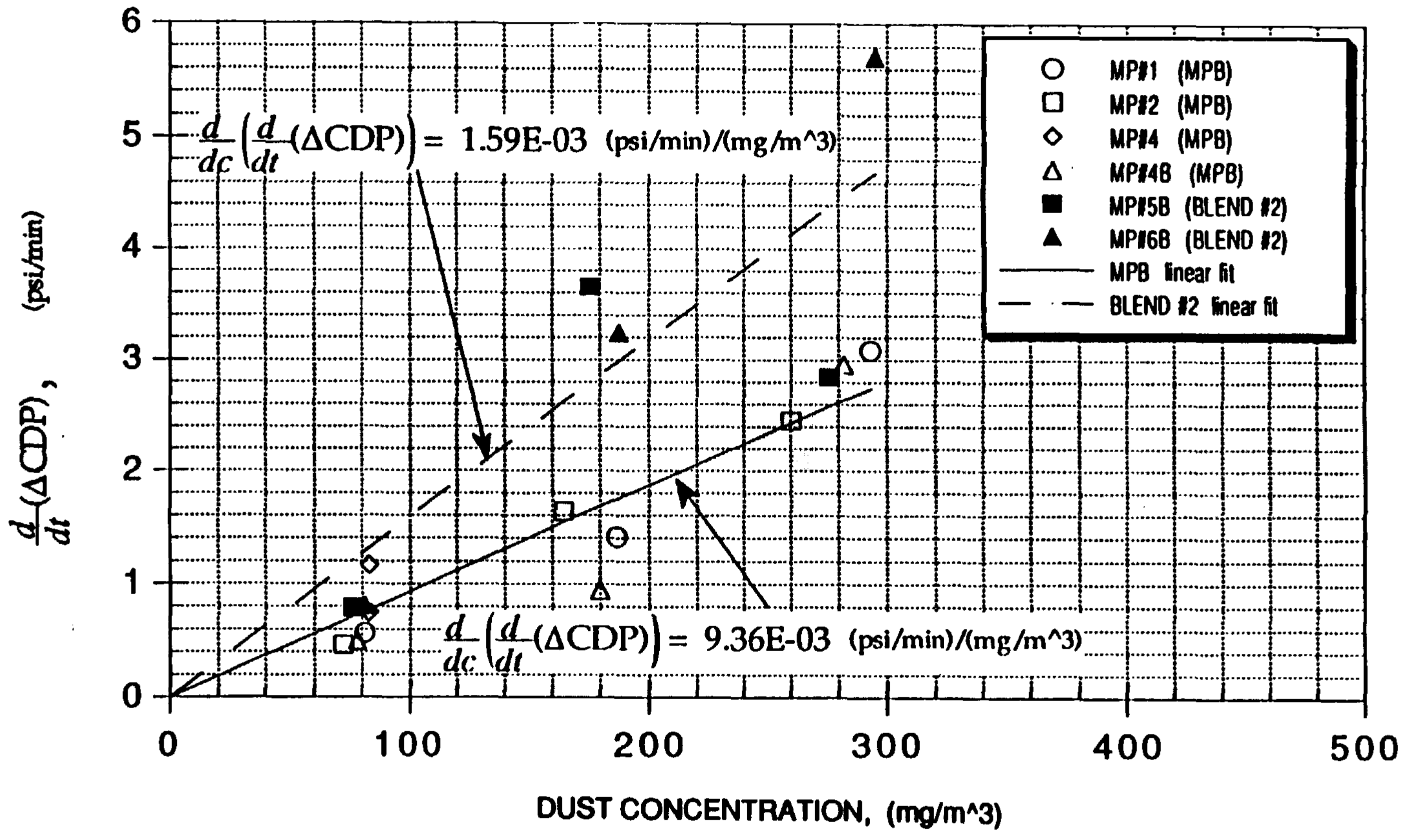


Figure A-11. Cumulative dust effects on compressor discharge pressure.

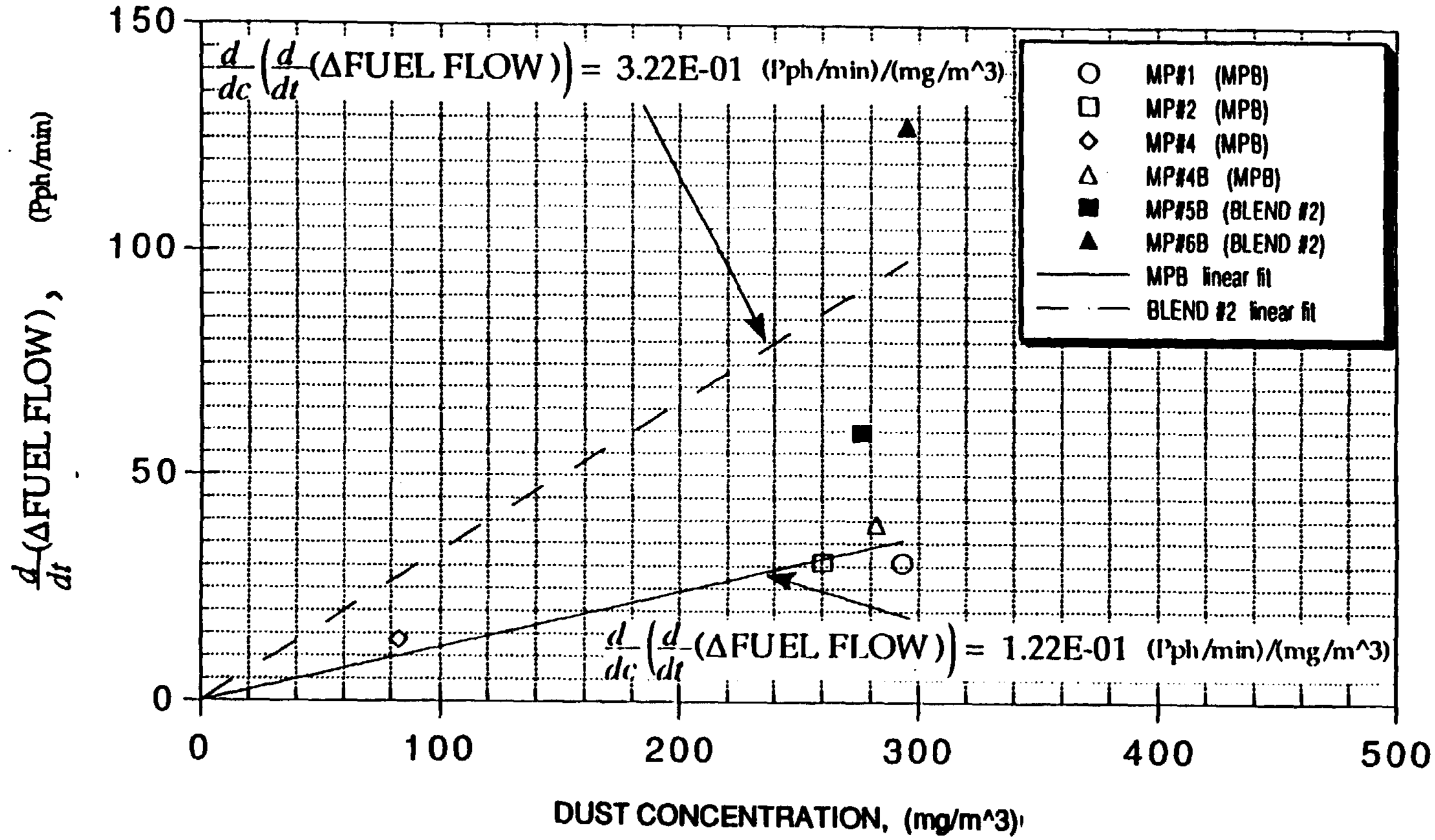


Figure A-12. Cumulative dust effects on fuel flow.

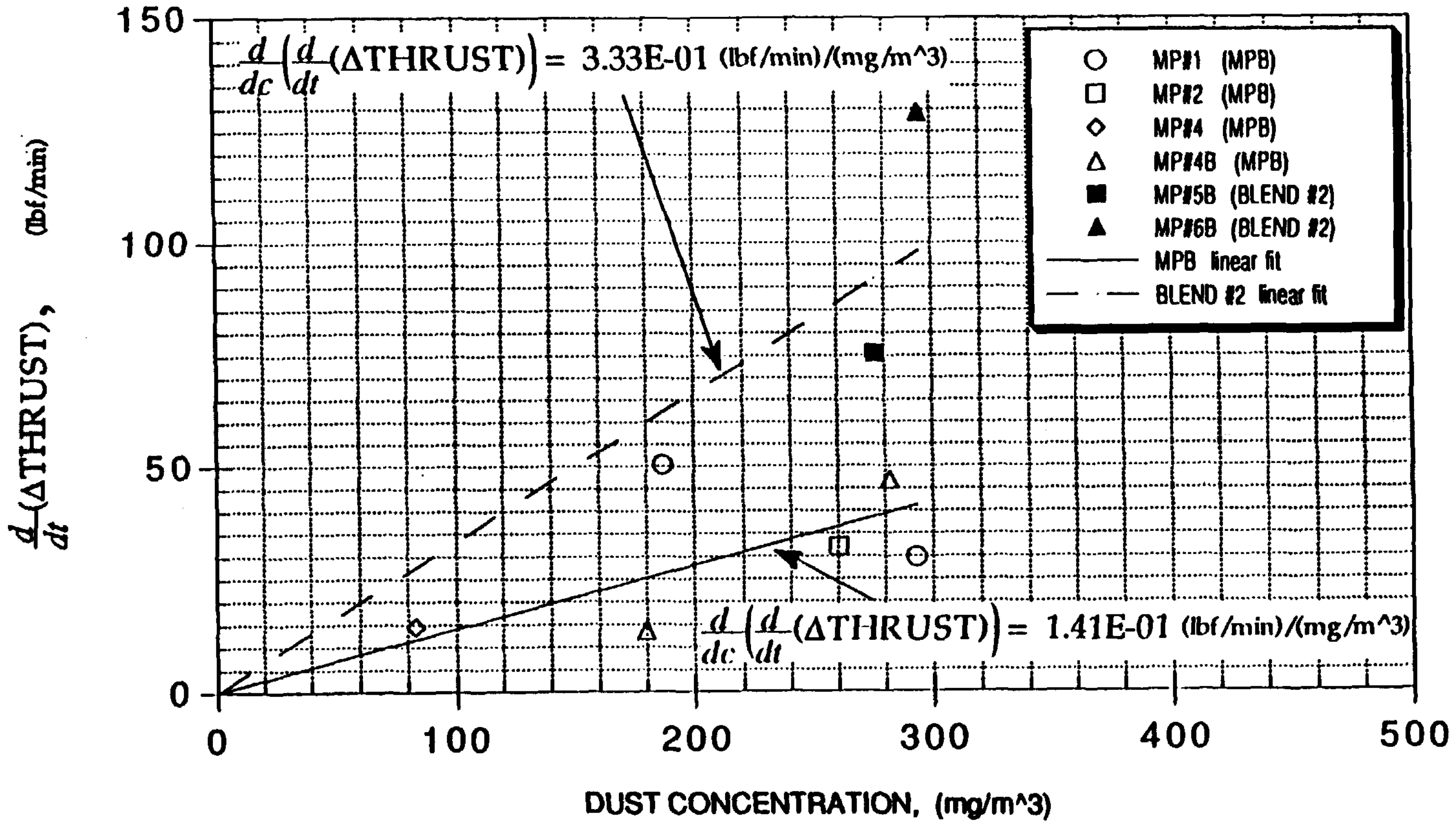


Figure A-13. Cumulative dust effects on thrust.

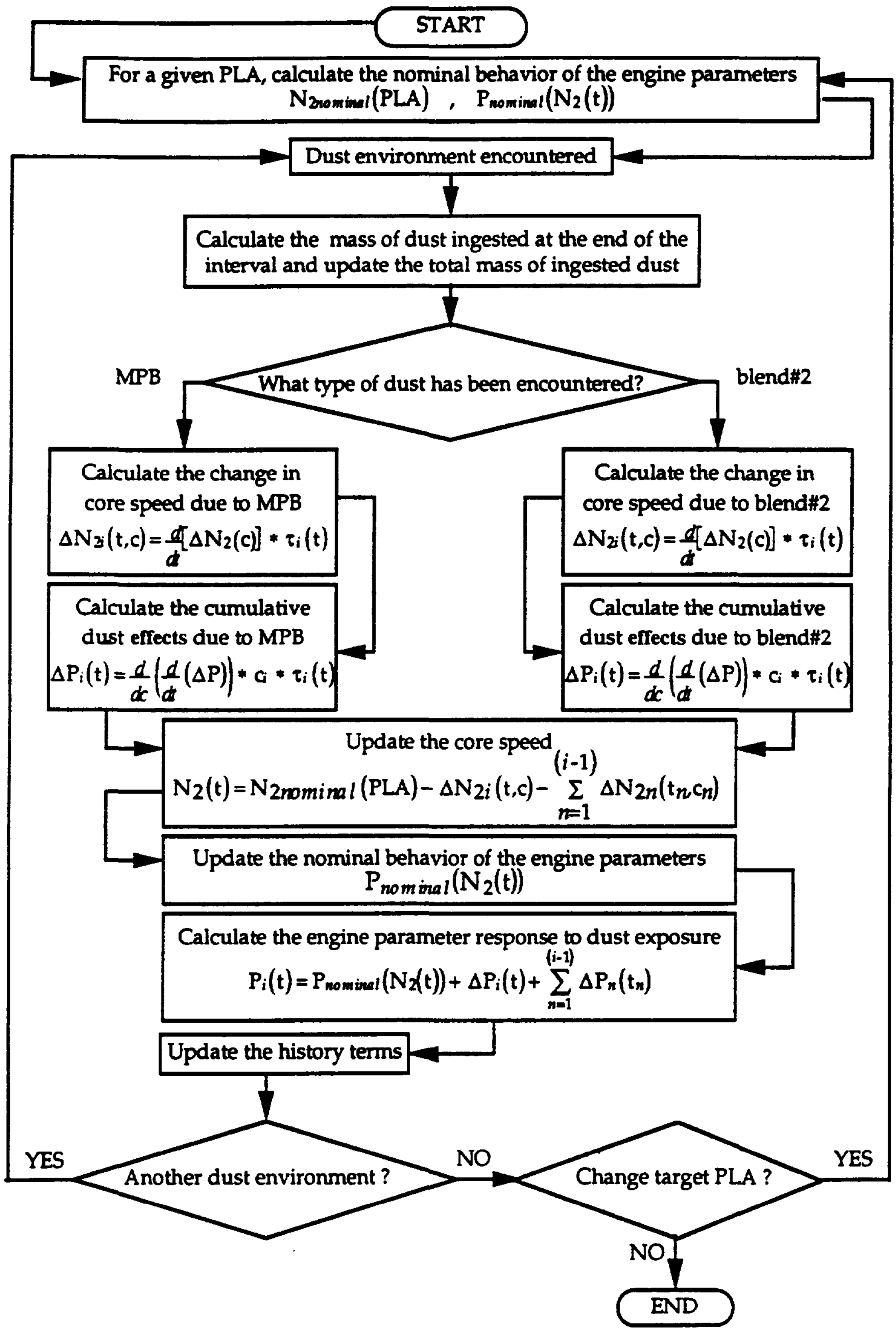


Figure A-14. F101 engine response algorithm.

Solutions for the F101 Sample Problems

This appendix contains the Calspan solutions for the set of sample problems for the F101 engine response model. The solutions were generated by the Calspan version of the F101 engine response model, named F101.f, whose source listing is presented in later in this appendix. The solutions are labelled as:

f101.out(a)(b)

where: (a) = the problem #
(b) = the part # (for problems 1-3)

PEARL - F101 response model

inputs :

PLA (deg) [16.5-80] => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) [1-10] => 10
blend [1=mpb,2=blend2] , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 1.000E+02 6.000E+00
ienc= 2 => 2 1.000E+02 6.000E+00
ienc= 3 => 2 1.000E+02 6.000E+00
ienc= 4 => 2 1.000E+02 6.000E+00
ienc= 5 => 2 1.000E+02 6.000E+00
ienc= 6 => 2 1.000E+02 6.000E+00
ienc= 7 => 2 1.000E+02 6.000E+00
ienc= 8 => 2 1.000E+02 6.000E+00
ienc= 9 => 2 1.000E+02 6.000E+00
ienc= 10 => 2 1.000E+02 6.000E+00

debug mode [0=off,1=on] => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	100.0	6.0	333.6	4.486E+00	14432.3	286.5	8531.2	17893.9
2	2	100.0	6.0	330.4	8.930E+00	14390.5	292.4	8597.6	17811.8
3	2	100.0	6.0	327.1	1.333E+01	14348.8	298.4	8664.5	17734.8
4	2	100.0	6.0	323.9	1.769E+01	14307.1	304.3	8731.8	17663.8
5	2	100.0	6.0	320.7	2.200E+01	14265.4	310.3	8799.8	17599.4
*** engine surge at 4.0 minutes into the 6-th encounter									
6	2	100.0	6.0	317.5	2.628E+01	14223.6	316.3	8868.4	17542.2
7	2	100.0	6.0	314.3	3.050E+01	14181.9	322.3	8937.6	17492.9
8	2	100.0	6.0	311.1	3.469E+01	14140.2	328.4	9007.5	17451.8
9	2	100.0	6.0	308.0	3.884E+01	14098.5	334.4	9078.1	17419.2
10	2	100.0	6.0	304.9	4.294E+01	14056.7	340.5	9149.5	17395.4

PEARL - F101 response model

inputs :

```
PLA (deg)  (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 5
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 1.000E+02 1.200E+01
ienc= 2 => 2 1.000E+02 1.200E+01
ienc= 3 => 2 1.000E+02 1.200E+01
ienc= 4 => 2 1.000E+02 1.200E+01
ienc= 5 => 2 1.000E+02 1.200E+01

debug mode (0=off,1=on) => 0
```

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	100.0	12.0	330.4	8.973E+00	14390.5	292.4	8597.6	17811.8
2	2	100.0	12.0	323.9	1.777E+01	14307.1	304.3	8731.8	17663.8
*** engine surge at 10.0 minutes into the 3-rd encounter									
3	2	100.0	12.0	317.5	2.640E+01	14223.6	316.3	8868.4	17542.2
4	2	100.0	12.0	311.1	3.486E+01	14140.2	328.4	9007.5	17451.8
5	2	100.0	12.0	304.9	4.315E+01	14056.7	340.5	9149.5	17395.4

PEARL - F101 response model

inputs :

PLA (deg) {16.5-80} => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

iencı= 1 => 2 1.000E+02 2.000E+01
ienc= 2 => 2 1.000E+02 2.000E+01
ienc= 3 => 2 1.000E+02 2.000E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	100.0	20.0	326.0	1.495E+01	14334.9	300.4	8686.9	17710.5
*** engine surge at 14.0 minutes into the 2-nd encounter									
2	2	100.0	20.0	315.3	2.943E+01	14195.8	320.3	8914.4	17508.5
3	2	100.0	20.0	304.9	4.344E+01	14056.7	340.5	9149.5	17395.4

```
PEARL - F101 response model

inputs :

PLA (deg)  (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 1
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 1.000E+02 6.000E+01

debug mode (0=off,1=on) => 0

calculation begun

 i blend dust conc time int AIR FLOW  ACC DUST   N2       CDP   FUEL FLOW  THRUST
         (mg/m^3)    (min)  (lbm/sec)   (kg)    (rpm)    (psig) (lbm/hr)   (lbf)
+--+----+---------+---------+--------+---------+--------+--------+--------+--------
  0  0       0.0       0.0     336.8 0.000E+00 14474.0   280.5    8465.3  17980.1
*** engine surge at    34.0 minutes into the  1-st encounter
  1  2     100.0      60.0     304.9 4.486E+01 14056.7   340.5    9149.5  17395.4
```

PEARL - F101 response model

inputs :

PLA (deg) (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.950E+02 6.000E+00
ienc= 2 => 2 2.950E+02 6.000E+00
ienc= 3 => 2 2.950E+02 6.000E+00
ienc= 4 => 2 2.950E+02 6.000E+00
ienc= 5 => 2 2.950E+02 6.000E+00
ienc= 6 => 2 2.950E+02 6.000E+00
ienc= 7 => 2 2.950E+02 6.000E+00
ienc= 8 => 2 2.950E+02 6.000E+00
ienc= 9 => 2 2.950E+02 6.000E+00
ienc= 10 => 2 2.950E+02 6.000E+00

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	295.0	6.0	306.4	1.323E+01	14076.9	274.9	7806.8	16093.8
*** engine surge at 5.5 minutes into the 2-nd encounter									
2	2	295.0	6.0	278.8	2.527E+01	13679.8	270.9	7218.5	14933.1
3	2	295.0	6.0	255.5	3.623E+01	13282.8	268.8	6727.7	14167.1
4	2	295.0	6.0	234.6	4.627E+01	12885.7	268.9	6354.6	12821.5
5	2	295.0	6.0	213.2	5.549E+01	12488.7	271.1	6113.0	11418.7
6	2	295.0	6.0	188.1	6.387E+01	12091.6	275.2	6010.2	9773.5
7	2	295.0	6.0	157.9	7.126E+01	11694.5	281.5	6048.2	8244.4
8	2	295.0	6.0	124.4	7.747E+01	11297.5	290.5	6223.2	7354.4
9	2	295.0	6.0	93.8	8.236E+01	10900.4	303.2	6527.1	7339.2
10	2	295.0	6.0	78.7	8.604E+01	10503.3	321.5	6946.9	5894.1

PEARL - F101 response model

inputs :

PLA (deg) {16.5-80} => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 5
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

iencm 1 => 2 2.950E+02 1.200E+01
iencm 2 => 2 2.950E+02 1.200E+01
iencm 3 => 2 2.950E+02 1.200E+01
iencm 4 => 2 2.950E+02 1.200E+01
iencm 5 => 2 2.950E+02 1.200E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
*** engine surge at 11.5 minutes into the 1-st encounter									
1	2	295.0	12.0	278.8	2.647E+01	13679.8	270.9	7218.5	14933.1
2	2	295.0	12.0	234.6	4.838E+01	12885.7	268.9	6354.6	12821.5
3	2	295.0	12.0	188.1	6.682E+01	12091.6	275.2	6010.2	9773.5
4	2	295.0	12.0	124.4	8.161E+01	11297.5	290.5	6223.2	7354.4
5	2	295.0	12.0	78.7	9.139E+01	10503.3	321.5	6946.9	5894.1

```
PEARL - F101 response model

inputs :

PLA (deg)  (16.5-80) =>  8.000E+01
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) (1-10) =>  3
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  2.950E+02  2.000E+01
ienc=  2 =>  2  2.950E+02  2.000E+01
ienc=  3 =>  2  2.950E+02  2.000E+01

debug mode (0=off,1=on) => 0

calculation begun

 i blend dust conc time int AIR FLOW  ACC DUST   N2       CDP   FUEL FLOW  THRUST
        (mg/m^3)    (min)  (lbm/sec)   (kg)     (rpm)    (psig) (lbm/hr)   (lbf)
+--+----+---------+---------+--------+--------+--------+--------+--------+--------
  0  0       0.0       0.0    336.8  0.000E+00  14474.0   280.5   8465.3  17980.1
*** engine surge at    11.5 minutes into the  1-st encounter
  1  2     295.0      20.0    248.4  4.412E+01  13150.4   268.6   6589.5  13711.1
  2  2     295.0      20.0    168.5  7.665E+01  11826.9   279.2   6020.0   8707.4
  3  2     295.0      20.0     78.7  9.873E+01  10503.3   321.5   6946.9   5894.1
```

PEARL - F101 response model

inputs :

PLA (deg) {16.5-80} => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.950E+02 6.000E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
*** engine surge at 11.5 minutes into the 1-st encounter									
1	2	295.0	60.0	78.7	1.323E+02	10503.3	321.5	6946.9	5894.1

```
PEARL - F101 response model

inputs :

PLA (deg)  (16.5-80) =>  8.000E+01
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  2.000E+02  6.000E+00
ienc=  2 =>  2  2.000E+02  6.000E+00
ienc=  3 =>  2  2.000E+02  6.000E+00
ienc=  4 =>  2  2.000E+02  6.000E+00
ienc=  5 =>  2  2.000E+02  6.000E+00
ienc=  6 =>  2  2.000E+02  6.000E+00
ienc=  7 =>  2  2.000E+02  6.000E+00
ienc=  8 =>  2  2.000E+02  6.000E+00
ienc=  9 =>  2  2.000E+02  6.000E+00
ienc= 10 =>  2  2.000E+02  6.000E+00

debug mode (0=off,1=on) => 0

calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	200.0	6.0	329.1	8.973E+00	14374.5	291.0	8546.8	17705.1
2	2	200.0	6.0	321.4	1.774E+01	14275.1	301.6	8631.2	17460.6
*** engine surge at 5.0 minutes into the 3-rd encounter									
3	2	200.0	6.0	313.8	2.631E+01	14175.7	312.3	8718.9	17256.5
4	2	200.0	6.0	306.3	3.467E+01	14076.2	323.0	8810.7	17099.1
5	2	200.0	6.0	299.0	4.283E+01	13976.8	333.9	8906.8	16991.4
6	2	200.0	6.0	292.0	5.079E+01	13877.3	344.8	9007.9	16933.1
7	2	200.0	6.0	285.2	5.857E+01	13777.9	355.9	9114.3	16920.3
8	2	200.0	6.0	278.7	6.617E+01	13678.5	367.1	9226.5	16946.1
9	2	200.0	6.0	272.5	7.360E+01	13579.0	378.4	9344.9	17000.5
10	2	200.0	6.0	266.6	8.086E+01	13479.6	389.9	9469.7	17070.0

PEARL - F101 response model

inputs :

PLA (deg) (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 5
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

iencm 1 => 2 2.000E+02 1.200E+01
iencm 2 => 2 2.000E+02 1.200E+01
iencm 3 => 2 2.000E+02 1.200E+01
iencm 4 => 2 2.000E+02 1.200E+01
iencm 5 => 2 2.000E+02 1.200E+01

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	2	200.0	12.0	321.4	1.795E+01	14275.1	301.6	8631.2	17460.6
*** engine surge at 5.0 minutes into the 2-nd encounter									
2	2	200.0	12.0	306.3	3.507E+01	14076.2	323.0	8810.7	17099.1
3	2	200.0	12.0	292.0	5.140E+01	13877.3	344.8	9007.9	16933.1
4	2	200.0	12.0	278.7	6.696E+01	13678.5	367.1	9226.5	16946.1
5	2	200.0	12.0	266.6	8.181E+01	13479.6	389.9	9469.7	17070.0

```
PEARL - F101 response model

inputs :

PLA (deg)  (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 3
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.000E+02 2.000E+01
ienc= 2 => 2 2.000E+02 2.000E+01
ienc= 3 => 2 2.000E+02 2.000E+01

debug mode (0=off,1=on) => 0

calculation begun

 i blend dust conc time int AIR FLOW  ACC DUST   N2       CDP   FUEL FLOW  THRUST
         (mg/m^3)    (min)  (lbm/sec)   (kg)     (rpm)   (psig) (lbm/hr)   (lbf)
+--+----+---------+---------+--------+--------+--------+--------+--------+--------
 0  0       0.0       0.0     336.8  0.000E+00 14474.0   280.5   8465.3  17980.1
*** engine surge at    17.0 minutes into the  1-st encounter
 1  2     200.0      20.0     311.3  2.991E+01 14142.5   315.8   8749.1  17198.6
 2  2     200.0      20.0     287.5  5.755E+01 13811.1   352.2   9078.2  16919.8
 3  2     200.0      20.0     266.6  8.308E+01 13479.6   389.9   9469.7  17070.0
```

```
PEARL - F101 response model

inputs :

PLA (deg)  [16.5-80] => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) [1-10] => 1
blend [1=mpb,2=blend2] , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.000E+02 6.000E+01

debug mode [0=off,1=on] => 0

calculation begun

 i blend dust conc time int AIR FLOW  ACC DUST   N2       CDP   FUEL FLOW  THRUST
        (mg/m^3)     (min)  (lbm/sec)   (kg)     (rpm)    (psig) (lbm/hr)   (lbf)
+--+----+---------+---------+--------+---------+--------+--------+--------+--------
  0  0      0.0       0.0    336.8  0.000E+00 14474.0   280.5    8465.3  17980.1
*** engine surge at     17.0 minutes into the  1-st encounter
  1  2    200.0      60.0    266.6  8.973E+01 13479.6   389.9    9469.7  17070.0
```

PEARL - F101 response model

inputs :

PLA (deg) {16.5-80} => 6.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.950E+02 6.000E+00
ienc= 2 => 2 2.950E+02 6.000E+00
ienc= 3 => 2 2.950E+02 6.000E+00
ienc= 4 => 2 2.950E+02 6.000E+00
ienc= 5 => 2 2.950E+02 6.000E+00
ienc= 6 => 2 2.950E+02 6.000E+00
ienc= 7 => 2 2.950E+02 6.000E+00
ienc= 8 => 2 2.950E+02 6.000E+00
ienc= 9 => 2 2.950E+02 6.000E+00
ienc= 10 => 2 2.950E+02 6.000E+00

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	251.2	0.000E+00	13204.2	178.7	4764.8	12029.5
1	2	295.0	6.0	230.5	9.873E+00	12807.1	179.2	4416.8	10678.3
*** engine surge at 5.5 minutes into the 2-nd encounter									
2	2	295.0	6.0	208.6	1.893E+01	12410.1	181.8	4202.3	9222.0
3	2	295.0	6.0	182.5	2.713E+01	12013.0	186.3	4127.4	7559.7
4	2	295.0	6.0	151.4	3.430E+01	11615.9	193.1	4192.9	6118.2
5	2	295.0	6.0	117.8	4.025E+01	11218.9	202.7	4394.3	5399.6
6	2	295.0	6.0	89.1	4.488E+01	10821.8	216.3	4722.2	5529.2
7	2	295.0	6.0	79.1	4.838E+01	10424.7	235.9	5163.2	4125.9
8	2	295.0	6.0	0.0	5.149E+01	10027.7	225.1	4701.1	4715.3
9	2	295.0	6.0	0.0	5.149E+01	9630.6	253.3	5288.8	5304.7
10	2	295.0	6.0	0.0	5.149E+01	9233.6	281.4	5876.4	5894.1

PEARL - F101 response model

inputs :

PLA (deg) (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 5.000E+01 7.000E+00
ienc= 2 => 1 1.500E+02 3.000E+00
ienc= 3 => 1 5.000E+01 7.000E+00
ienc= 4 => 1 2.500E+02 5.000E+00
ienc= 5 => 1 5.000E+01 1.300E+01
ienc= 6 => 2 5.000E+01 7.000E+00
ienc= 7 => 2 1.500E+02 3.000E+00
ienc= 8 => 2 5.000E+01 7.000E+00
ienc= 9 => 2 2.500E+02 5.000E+00
ienc= 10 => 2 5.000E+01 1.300E+01

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	1	50.0	7.0	335.9	2.617E+00	14463.1	282.9	8473.2	17954.5
2	1	150.0	3.0	335.4	5.973E+00	14456.4	286.5	8506.6	17971.8
3	1	50.0	7.0	334.6	8.580E+00	14445.5	288.8	8514.6	17946.6
4	1	250.0	5.0	333.7	1.787E+01	14434.3	299.6	8631.4	18046.5
5	1	50.0	13.0	332.2	2.268E+01	14414.1	303.9	8646.3	18000.9
6	2	50.0	7.0	329.1	2.526E+01	14373.9	306.0	8634.6	17847.8
7	2	150.0	3.0	327.0	2.855E+01	14347.4	310.9	8700.1	17822.7
8	2	50.0	7.0	323.9	3.109E+01	14307.2	313.0	8689.3	17678.4
*** engine surge at 1.8 minutes into the 9-th encounter									
9	2	250.0	5.0	310.4	4.008E+01	14130.1	317.9	8551.7	17025.8
10	2	50.0	13.0	304.8	4.456E+01	14055.4	322.0	8538.2	16836.3

PEARL - F101 response model

inputs :

PLA (deg) (16.5-80) => 8.000E+01
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

```
ienc=  1 =>  1  1.000E+02  6.000E+00
ienc=  2 =>  1  1.000E+02  6.000E+00
ienc=  3 =>  1  1.000E+02  6.000E+00
ienc=  4 =>  1  1.000E+02  6.000E+00
ienc=  5 =>  1  1.000E+02  6.000E+00
ienc=  6 =>  1  1.000E+02  6.000E+00
ienc=  7 =>  1  1.000E+02  6.000E+00
ienc=  8 =>  1  1.000E+02  6.000E+00
ienc=  9 =>  1  1.000E+02  6.000E+00
ienc= 10 =>  1  1.000E+02  6.000E+00
```

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	N2 (rpm)	CDP (psig)	FUEL FLOW (lbm/hr)	THRUST (lbf)
0	0	0.0	0.0	336.8	0.000E+00	14474.0	280.5	8465.3	17980.1
1	1	100.0	6.0	335.7	4.486E+00	14460.5	285.0	8495.5	17972.2
2	1	100.0	6.0	334.7	8.959E+00	14447.1	289.5	8525.8	17964.7
3	1	100.0	6.0	333.7	1.342E+01	14433.7	293.9	8556.2	17957.6
4	1	100.0	6.0	332.6	1.786E+01	14420.3	298.4	8586.6	17951.0
5	1	100.0	6.0	331.6	2.229E+01	14406.8	302.8	8617.0	17944.7
6	1	100.0	6.0	330.6	2.671E+01	14393.4	307.3	8647.5	17939.0
7	1	100.0	6.0	329.5	3.112E+01	14380.0	311.7	8678.0	17933.8
8	1	100.0	6.0	328.5	3.551E+01	14366.5	316.2	8708.6	17929.1
9	1	100.0	6.0	327.5	3.988E+01	14353.1	320.7	8739.2	17925.0
*** engine surge at 3.7 minutes into the 10-th encounter									
10	1	100.0	6.0	326.4	4.424E+01	14339.7	325.1	8769.9	17921.5

Source Code Listings for the Calspan Version of the F101 Engine Response Model

This appendix contains the sorce code listings for the Calspan version of the F101 engine response model.

The main program :

- f101.f

Associated subprograms:

- fair.f
- fcdpnom.f
- ffuelnom.f
- fthrustnom.f
- fxn2nom.f
- fxn2rate.f

```
c
c     f101.f is a code which evaluates the aircraft responses model
c      developed for DNA through SAIC and KAMAN under W/A # L0380500
c      during the period 06/01/92 thru 10/31/92.
c
c     engine parameters:
c
c        xn1     - fan speed (rpm)
c        xn2     - core speed (rpm)
c
c      (fan speed correlation)
c
c        xigv    - fan inlet variable guide vane angle (deg.)
c        ps14    - fan discharge static pressure (psig)
c        pt25    - fan discharge total pressure (psig)
c        xoil1   - oil pressure [xn1 correlation] (psig)
c
c      (core speed correlation)
c
c        thrust  - thrust (lbf)
c        air     - airflow (lbm/sec)
c        vgv     - compressor inlet variable guide vane angle (deg.)
c        cdp     - compressor discharge pressure (psig)
c        pyro    - pyrometer temperature (F)
c        egt     - exhaust gas temperature (F)
c        fuel    - fuel flow (Pph)
c        xoil2   - oil pressure [xn2 correlation] (psig)
c
c       (subscripts)
c
c        ()nom   - nominal value
c        ()del   - (in/de)crement over current interval
c        ()sum   - sum of (in/de)crements over previous intervals
c
c       (prescripts)
c        f()     - function which generates the value of the variable
c
      implicit integer*4(i-n),real*8(a-h,o-z)
      dimension ib(10),c(10),delt(10)
c
      data const/1.699e-06/
      data cdprate1,cdprate2/9.36e-03,1.59e-02/
      data fuelrate1,fuelrate2/1.22e-01,3.32e-01/
      data thrustrate1,thrustrate2/1.41e-01,3.33e-01/
c
      open(7,file='f101.out',status='unknown')
c
      write(*,*)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'PEARL - F101 response model'
      write(*,*)
      write(*,*)
      write(*,'(a)') 'inputs :'
      write(*,*)
      write(*,100)
```

```
 100  format('PLA (deg)  {16.5-80} => ',$)
      read(*,*) pla
      write(7,*)
      write(7,*)
      write(7,*)
      write(7,'(a)') 'PEARL - F101 response model'
      write(7,*)
      write(7,*)
      write(7,'(a)') 'inputs :'
      write(7,*)
      write(7,200) pla
 200  format('PLA (deg)  {16.5-80} => ',1pe10.3)
      write(*,101)
 101  format('ambient pressure (psia) => ',$)
      read(*,*) pamb
      write(7,201) pamb
 201  format('ambient pressure (psia) => ',1pe10.3)
      write(*,102)
 102  format('ambient temperature (F) => ',$)
      read(*,*) tamb
      write(7,202) tamb
 202  format('ambient temperature (F) => ',1pe10.3)
      write(*,*)
      write(7,*)
      write(*,103)
 103  format('# of encounters (-) {1-10} => ',$)
      read(*,*) nenc
      write(7,203) nenc
 203  format('# of encounters (-) {1-10} => ',i2)
      write(*,104)
 104  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(*,*)
      write(7,204)
 204  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(7,*)
      do 1 ienc=1,nenc
       write(*,105) ienc
 105   format('ienc= ',i2,' => ',$)
       read(*,*) ib(ienc),c(ienc),delt(ienc)
       write(7,205) ienc,ib(ienc),c(ienc),delt(ienc)
 205   format('ienc= ',i2,' => ',i2,1x,1pe10.3,1x,1pe10.3)
 1    continue
      write(*,*)
      write(*,150)
 150  format('debug mode (0=off,1=on) => ',$)
      read(*,*) ibug
      write(7,*)
      write(7,250) ibug
 250  format('debug mode (0=off,1=on) => ',i1)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'calculation begun'
      write(*,*)
      write(*,*)
```

```
      write(7,*)
      write(7,*)
      write(7,'(a)') 'calculation begun'
      write(7,*)
      write(7,*)
c
c     initialize all engine parameters to zero
c
      ienc=0
      none=0
      dust=0.
      icdpflag=0
      cdplim=54.
      accdust=0.
      xn2nom=0.
      xn2del=0.
      xn2sum=0.
      cdpnom=0.
      cdpdel=0.
      cdpsum=0.
      fuelnom=0.
      fueldel=0.
      fuelsum=0.
      thrustnom=0.
      thrustdel=0.
      thrustsum=0.
c
c     calculate the ambient density (lbm/sec)
c
      rhoamb=144.*pamb/(53.3*(tamb+460.))
c
c     calculate the engine parameters
c
c     nominal clear air engine parameter values
c
      xn2nom=FXN2NOM(pla)
      xn2=xn2nom
      air=FAIR(xn2)
      cdpnom=FCDPNOM(xn2)
      cdp=cdpnom
      fuelnom=FFUELNOM(xn2)
      fuel=fuelnom
      thrustnom=FTHRUSTNOM(xn2)
      thrust=thrustnom
c
c     write the header
c
      write(7,500)
 500  format(' i ','blend',' dust conc',' time int '
     &,'AIR FLOW ',' ACC DUST','   N2    ','   CDP   '
     &,'FUEL FLOW','  THRUST ')
      write(7,501)
 501  format('   ','     ',' (mg/m^3) ','   (min)  '
     &,'(lbm/sec)','   (kg)  ','  (rpm)  ','  (psig) '
     &,'(lbm/hr) ','  (lbf)  ')
      write(7,502)
```

```
 502  format('+--','+----','+---------','+---------'
     &,'+--------','+--------','+--------','+--------'
     &,'+--------','+--------')
      write(7,550) ienc,none,none,none
     &,air,accdust,xn2,cdp,fuel,thrust
c
c     loop over all encounters
c
      do 2 ienc=1,nenc
      if(ibug.eq.1) write(7,300) ienc
 300  format('ienc = ',i2)
      if(ibug.eq.1) write(7,301) ienc,ib(ienc)
 301  format('ib(',i2,') = ',i2)
      if(ibug.eq.1) write(7,302) ienc,c(ienc)
 302  format('c(',i2,') = ',1pe10.3)
      if(ibug.eq.1) write(7,303) ienc,delt(ienc)
 303  format('delt(',i2,') = ',1pe10.3)
c
c     calculate the airflow, injested dust over this interval, and the
c      total accumulated dust (based on conditions at the start of the
c      encounter)
c
      air=FAIR(xn2)
      q=air/rhoamb
      dust=const*q*c(ienc)*delt(ienc)
      accdust=dust+accdust
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,304) xn2
 304  format('xn2(initial) = ',1pe10.3)
      if(ibug.eq.1) write(7,400) air
 400  format('air = ',1pe10.3)
      if(ibug.eq.1) write(7,305) rhoamb
 305  format('rhoamb = ',1pe10.3)
      if(ibug.eq.1) write(7,306) q
 306  format('q = ',1pe10.3)
      if(ibug.eq.1) write(7,307) dust
 307  format('dust = ',1pe10.3)
      if(ibug.eq.1) write(7,308) accdust
 308  format('accdust = ',1pe10.3)
c
c     calculate core speed
c
      xn2rate=FXN2RATE(ibug,ib(ienc),accdust,c(ienc))
      xn2del=xn2rate*delt(ienc)
      xn2=xn2nom-xn2del-xn2sum
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,309) xn2rate
 309  format('xn2rate = ',1pe10.3)
      if(ibug.eq.1) write(7,310) xn2del
 310  format('xn2del = ',1pe10.3)
      if(ibug.eq.1) write(7,312) xn2sum
 312  format('xn2sum = ',1pe10.3)
      if(ibug.eq.1) write(7,311) xn2nom
 311  format('xn2nom = ',1pe10.3)
      if(ibug.eq.1) write(7,313) xn2
 313  format('xn2(final) = ',1pe10.3)
```

```
c
c     calculate cdp
c
      cdpnom=FCDPNOM(xn2)
      if(ib(ienc).eq.1) cdprate=cdprate1
      if(ib(ienc).eq.2) cdprate=cdprate2
      cdpdel=cdprate*c(ienc)*delt(ienc)
      cdp=cdpnom+cdpdel+cdpsum
c
c     check for surge probability
c
      if(((cdpdel+cdpsum).gt.cdplim).and.(icdpflag.eq.0)) then
       icdpflag=1
       cdpdelc=cdplim-cdpsum
       tau=cdpdelc/(cdprate*c(ienc))
       write(7,700) tau,ienc
 700   format('*** engine surge at ',f7.1,' minutes into the ',i2
     &,'-th encounter')
      endif
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,314) xn2
 314  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,315) cdpnom
 315  format('cdpnom = ',1pe10.3)
      if(ibug.eq.1) write(7,316) cdprate
 316  format('cdprate = ',1pe10.3)
      if(ibug.eq.1) write(7,317) cdpdel
 317  format('cdpdel = ',1pe10.3)
      if(ibug.eq.1) write(7,318) cdpsum
 318  format('cdpsum = ',1pe10.3)
      if(ibug.eq.1) write(7,319) cdp
 319  format('cdp = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     calculate fuel
c
      fuelnom=FFUELNOM(xn2)
      if(ib(ienc).eq.1) fuelrate=fuelrate1
      if(ib(ienc).eq.2) fuelrate=fuelrate2
      fueldel=fuelrate*c(ienc)*delt(ienc)
      fuel=fuelnom+fueldel+fuelsum
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,320) xn2
 320  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,321) fuelnom
 321  format('fuelnom = ',1pe10.3)
      if(ibug.eq.1) write(7,322) fuelrate
 322  format('fuelrate = ',1pe10.3)
      if(ibug.eq.1) write(7,323) fueldel
 323  format('fueldel = ',1pe10.3)
      if(ibug.eq.1) write(7,324) fuelsum
 324  format('fuelsum = ',1pe10.3)
      if(ibug.eq.1) write(7,325) fuel
 325  format('fuel = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
```

```
      if(ibug.eq.1) write(7,*)
c
c     calculate thrust
c
      thrustnom=FTHRUSTNOM(xn2)
      if(ib(ienc).eq.1) thrustrate=thrustrate1
      if(ib(ienc).eq.2) thrustrate=thrustrate2
      thrustdel=thrustrate*c(ienc)*delt(ienc)
      thrust=thrustnom+thrustdel+thrustsum
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,330) xn2
 330  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,331) thrustnom
 331  format('thrustnom = ',1pe10.3)
      if(ibug.eq.1) write(7,332) thrustrate
 332  format('thrustrate = ',1pe10.3)
      if(ibug.eq.1) write(7,333) thrustdel
 333  format('thrustdel = ',1pe10.3)
      if(ibug.eq.1) write(7,334) thrustsum
 334  format('thrustsum = ',1pe10.3)
      if(ibug.eq.1) write(7,335) thrust
 335  format('thrust = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     update the sum terms of each engine parameter
c
      xn2sum=xn2sum+xn2del
      cdpsum=cdpsum+cdpdel
      fuelsum=fuelsum+fueldel
      thrustsum=thrustsum+thrustdel
      write(7,550) ienc,ib(ienc),c(ienc),delt(ienc)
     &,air,accdust,xn2,cdp,fuel,thrust
 550  format((1x,i2),(2x,i1,2x),2((1x,f7.1,2x))
     &,((f7.1,2x)),((1pe9.3)),((2x,0pf7.1)),3((1x,0pf7.1,1x)))
 2    continue
      stop
      end
```

```
c
c     this function calculates the airflow
c
      function FAIR(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a0,a1,a2,a3,a4,a5
     &/440922.79744,-174.0731208,0.027346652504
     &,-2.1376216416e-06,8.3178976743e-11,-1.2891058570e-15/
c
      if(x.lt.10348.) fair=0.
      if(x.gt.15000.) fair=0.
      if((x.ge.10348.).and.(x.le.15000.)) then
       fair=a0+a1*x+a2*x**2+a3*x**3+a4*x**4+a5*x**5
      endif
      return
      end
```

```
c
c     this function calculates the nominal cdp
c
      function FCDPNOM(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a0,a1,a2,a3,a4,a5
     &/52767.656799,-20.435530217,0.0031594211659,-2.4414893530e-07
     &,9.4426267256e-12,-1.4592076519e-16/
c
      if(x.lt.10348.) fcdpnom=0.
      if(x.gt.15000.) fcdpnom=0.
      if((x.ge.10348.).and.(x.le.15000.)) then
       fcdpnom=a0+a1*x+a2*x**2+a3*x**3+a4*x**4+a5*x**5
      endif
      return
      end
```

```
c
c     this function calculates the nominal fuel
c
      function FFUELNOM(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a0,a1,a2,a3,a4,a5
     &/-49816.415015,15.16955213,-0.00090483247417,-1.0788972042e-07
     &,1.3439057313e-11,-3.6898802700e-16/
c
      if(x.lt.10348.) ffuelnom=0.
      if(x.gt.15000.) ffuelnom=0.
      if((x.ge.10348.).and.(x.le.15000.)) then
       ffuelnom=a0+a1*x+a2*x**2+a3*x**3+a4*x**4+a5*x**5
      endif
      return
      end
```

```
c
c     this function calculates the nominal thrust
c
      function FTHRUSTNOM(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11,a12,a13,a14,a15
     &/-90190833.084,38206.13731,-6.4537917919,0.00054340227729
     &,-2.2807645464e-08,3.8182035691e-13/
      data a20,a21,a22,a23,a24,a25
     &/-26525834.184,5596.7412494,-0.24258263565,-2.2544154617e-05
     &,2.2276804666e-09,-5.2033103514e-14/
c
      if(x.lt.10543.) fthrustnom=0.
      if(x.gt.15000.) fthrustnom=0.
      if((x.ge.10543.).and.(x.lt.13246.)) then
       fthrustnom=a10+a11*x+a12*x**2+a13*x**3+a14*x**4+a15*x**5
      endif
      if((x.ge.13246.).and.(x.le.15000.)) then
       fthrustnom=a20+a21*x+a22*x**2+a23*x**3+a24*x**4+a25*x**5
      endif
      return
      end
```

```
c
c     this function calculates the core speed drop rate due to dust
c
      function FXN2RATE(ibug,i,acc,c)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a110,a111
     &/0.,0.031091666884/
      data a120
     &/2.2386/
      data a130,a131
     &/0.41616348802,0.062687011283/
      data a210,a211,a212,a213
     &/-0.023120229598,0.19569725331,-0.001954960762
     &,6.9569031307e-06/
c
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,100)
 100  format('--- inside fxn2rate ---')
      if(ibug.eq.1) write(7,300) i
 300  format('i = ',i2)
      if(ibug.eq.1) write(7,301) acc
 301  format('accdust = ',1pe10.3)
      if(ibug.eq.1) write(7,302) c
 302  format('c = ',1pe10.3)
      if(acc.le.0.) fxn2rate=0.
      if(i.eq.1) then
       if(ibug.eq.1) write(7,303)
 303   format(' mpb blend correlation')
       if(acc.lt.72.) then
        if(ibug.eq.1) write(7,305)
 305    format(' acc < 72 kg')
        if((c.ge.0.).and.(c.lt.72.)) then
         if(ibug.eq.1) write(7,306)
 306     format(' 0 < c < 72 mg/m^3')
         fxn2rate=a110+a111*c
         if(ibug.eq.1) write(7,311) fxn2rate
 311     format('fxn2rate = ',1pe10.3)
        endif
        if((c.ge.72.).and.(c.le.293.)) then
         if(ibug.eq.1) write(7,307)
 307     format(' 72 < c < 293 mg/m^3')
         fxn2rate=a120
         if(ibug.eq.1) write(7,311) fxn2rate
        endif
        if(c.gt.293.) then
         if(ibug.eq.1) write(7,312)
 312     format('c > 293 mg/m^3')
         fxn2rate=1.0d+10
         if(ibug.eq.1) write(7,311) fxn2rate
        endif
       endif
       if(acc.ge.72.) then
        if(ibug.eq.1) write(7,308)
 308    format(' acc > 72 kg')
        if((c.ge.0.).and.(c.le.282.)) then
```

```
         if(ibug.eq.1) write(7,309)
 309     format(' 0 < c < 282 mg/m^3')
         fxn2rate=a130+a131*c
         if(ibug.eq.1) write(7,311) fxn2rate
        endif
        if(c.gt.282.) then
         if(ibug.eq.1) write(7,313)
 313     format('c > 282 mg/m^3')
         fxn2rate=1.0d+10
         if(ibug.eq.1) write(7,311) fxn2rate
        endif
       endif
      endif
      if(i.eq.2) then
      if(ibug.eq.1) write(7,304)
 304  format(' blend #2 correlation')
       if((c.ge.0.).and.(c.le.295.)) then
        if(ibug.eq.1) write(7,310)
 310    format(' 0 < c < 295 mg/m^3')
        fxn2rate=a210+a211*c+a212*c**2+a213*c**3
        if(ibug.eq.1) write(7,311) fxn2rate
       endif
       if(c.gt.295.) then
        if(ibug.eq.1) write(7,314)
 314    format('c > 295 mg/m^3')
        fxn2rate=1.0d+10
        if(ibug.eq.1) write(7,311) fxn2rate
       endif
      endif
      return
      end
```

```
c
c     this function calculates the nominal value of core speed
c
      function FXN2NOM(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11
     &/10353.360465,0.18067978533/
      data a20,a21,a22,a23,a24,a25
     &/10306.641571,220.99533596,-21.326092808,0.69563112177
     &,-0.0087987179757,3.8820512919e-05/
c
      if(x.lt.16.5) fxn2nom=0.
      if(x.gt.80.) fxn2nom=0.
      if((x.ge.16.5).and.(x.lt.30.)) then
       fxn2nom=a10+a11*x
      endif
      if((x.ge.30.).and.(x.le.80.)) then
       fxn2nom=a20+a21*x+a22*x**2+a23*x**3+a24*x**4+a25*x**5
      endif
      return
      end
```

APPENDIX B

TF33 ENGINE RESPONSE MODEL

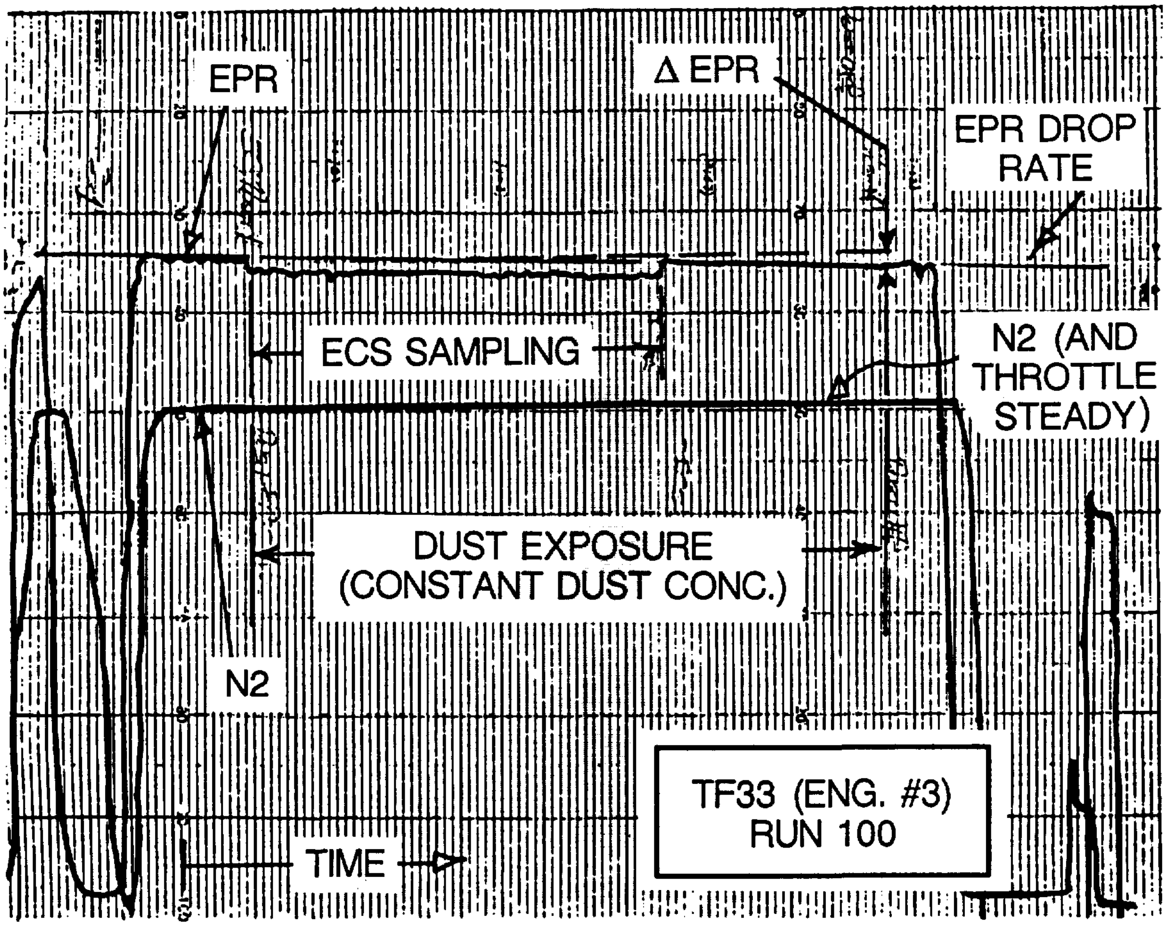
This appendix contains the detailed information required for the TF33 engine response model. It consists of:

- Observations made during the TF33 experiments
- An example of EPR decrease at constant throttle setting as experienced in the TF33 experiments
- The correlation of EPR decrease with accumulated dust mass
- The pre-dust (nominal) engine behavior curve fits to the TF33 controlling parameter, EPR.
- The general representation of a sample environment
- The general form of the TF33 engine response (dust effects) model
- The TF33 engine response algorithm
- The engine surge model for the TF33

OBSERVATIONS

- NO MATERIAL DEPOSITION IN THE ENGINE
- DUST EFFECTS MAINLY A RESULT OF COMPRESSOR WEAR
- ENGINE OPERATES AT CONSTANT ENGINE PRESSURE RATIO (EPR) FOR A GIVEN THROTTLE SETTING (CRUISE,MILITARY POWER,etc.)
- AT CONSTANT THROTTLE (PLA), THE ENGINE EXPERIENCES A LOSS IN EPR (AND CDP) DUE TO EROSION OF THE COMPRESSOR BECAUSE OF THE PRESENCE OF DUST IN THE ENVIRONMENT
- IN ORDER TO OPERATE AT CONSTANT EPR, THE THROTTLE NEEDS TO BE INCREASED TO COMPENSATE FOR THE LOSS IN EPR
- AN INCREASE IN THROTTLE (PLA) SETTING RESULTS IN INCREASED FUEL FLOW, EGT, AND N2
- DECREASED RANGE IS ONE OF TWO PRIMARY EFFECTS OF DUST EXPOSURE FOR THE TF33 ENGINE
- THE SECOND IS ENGINE SURGES EXPERIENCED AFTER SUBSTANTIAL COMPRESSOR EROSION WHICH MAKES THROTTLE EXCURSIONS DIFFICULT AND CAN RENDER THE ENGINE UNCONTROLLABLE

DATA:



MODEL:

$\Delta EPR_n(t)$ = linear function of accumulated dust mass with dependence on target EPR.

Extent of erosion is mainly a function of the amount of dust passed through the engine. EPR will decrease further with continued exposure to the dust environment. Use of accumulated dust mass as a dependent variable is a reasonable approximation and allows for implicit accounting of the history of dust exposure.

Figure B-1. EPR decrease correlation (at constant PLA).

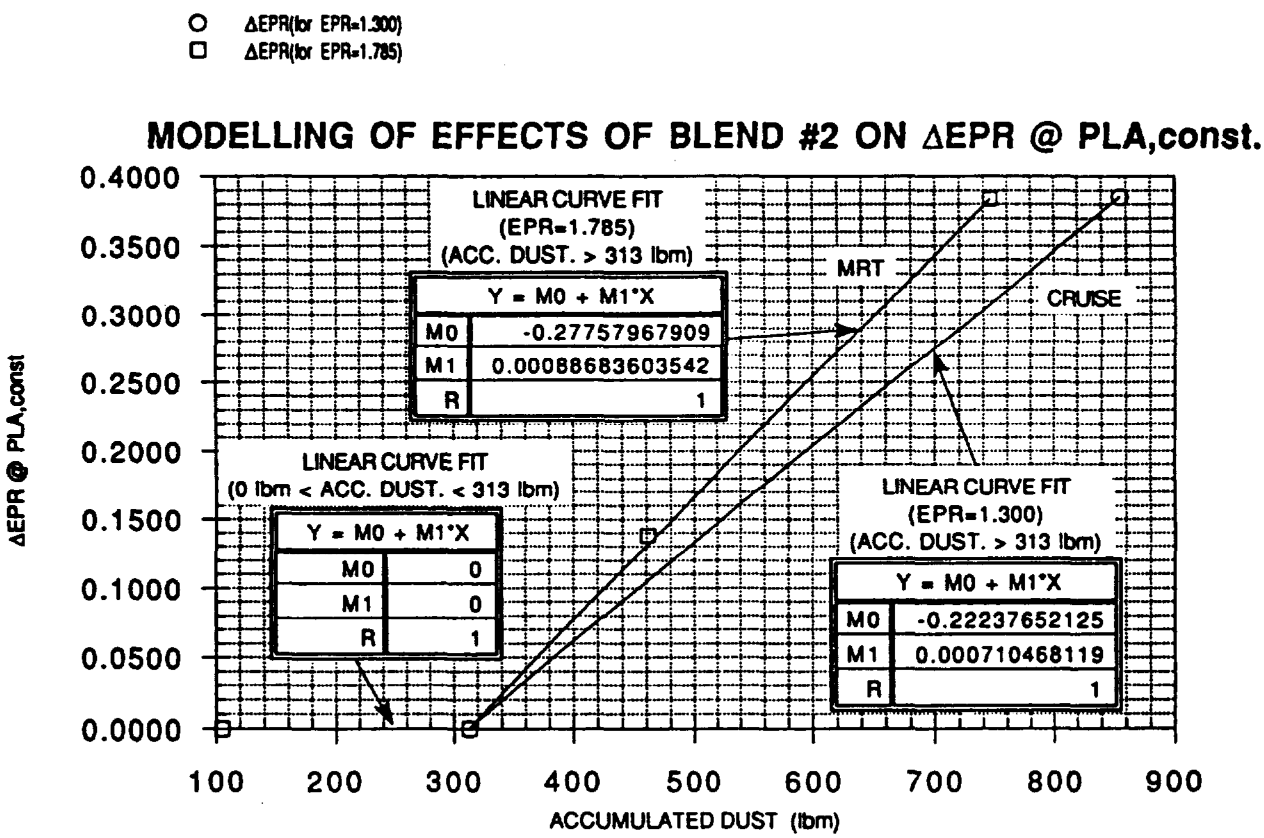


Figure B-2. Correlation of EPR decrease with accumulated dust mass.

CURVE FIT OF PRE-DUST DATA

PARAMETERS FIT TO ENGINE PRESSURE RATIO (EPR)
(MEASURED EPR)

- THRUST
- AIRFLOW
- EXHAUST GAS TEMPERATURE (EGT)
- FUEL FLOW
- CORE SPEED (N2)

Table B-1. Pre-dust curve fits - nominal behavior.

P = a0 + a1*EPR + a2*EPR^2 + a3*EPR^3 + a4*EPR^4 + a5*EPR^5 + a6*EPR^6 + a7*EPR^7 + a8*EPR^8
a9*EPR^9

where: P = parameter
EPR = engine pressure ratio

parameter	units	EPR lower bound (-)	EPR upper bound (-)	a0 / a6	a1 / a7	a2 / a8	a3 / a9	a4	a5
				---------polynomial	coefficients	(3 significant	figures)----------		
THRUST	lbf	1.015	1.300	-3.02E+05	+6.98E+05	-5.30E+05	+1.36E+05		
		1.300	1.566	-3.75E+03	+9.32E+03				
		1.566	1.866	+9.85E+02	+6.25E+03				
AIRFLOW	lbm/sec	1.015	1.550	-6.61E+04	+2.31E+05	-3.23E+05	+2.26E+05	-7.85E+04	+1.09E+04
		1.550	1.866	+1.78E+02	+1.31E+02				
EGT	deg F	1.015	1.866	-9.00E+01	+5.80E+02				
FUEL FLOW	gal/min	1.015	1.866	-2.11E+01	+2.41E+01				
N2	%	1.015	1.330	-9.53E+04	+3.74E+05	-5.86E+05	+4.58E+05	-1.79E+05	+2.78E+04
		1.330	1.866	+6.57E+01	+2.19E+01				

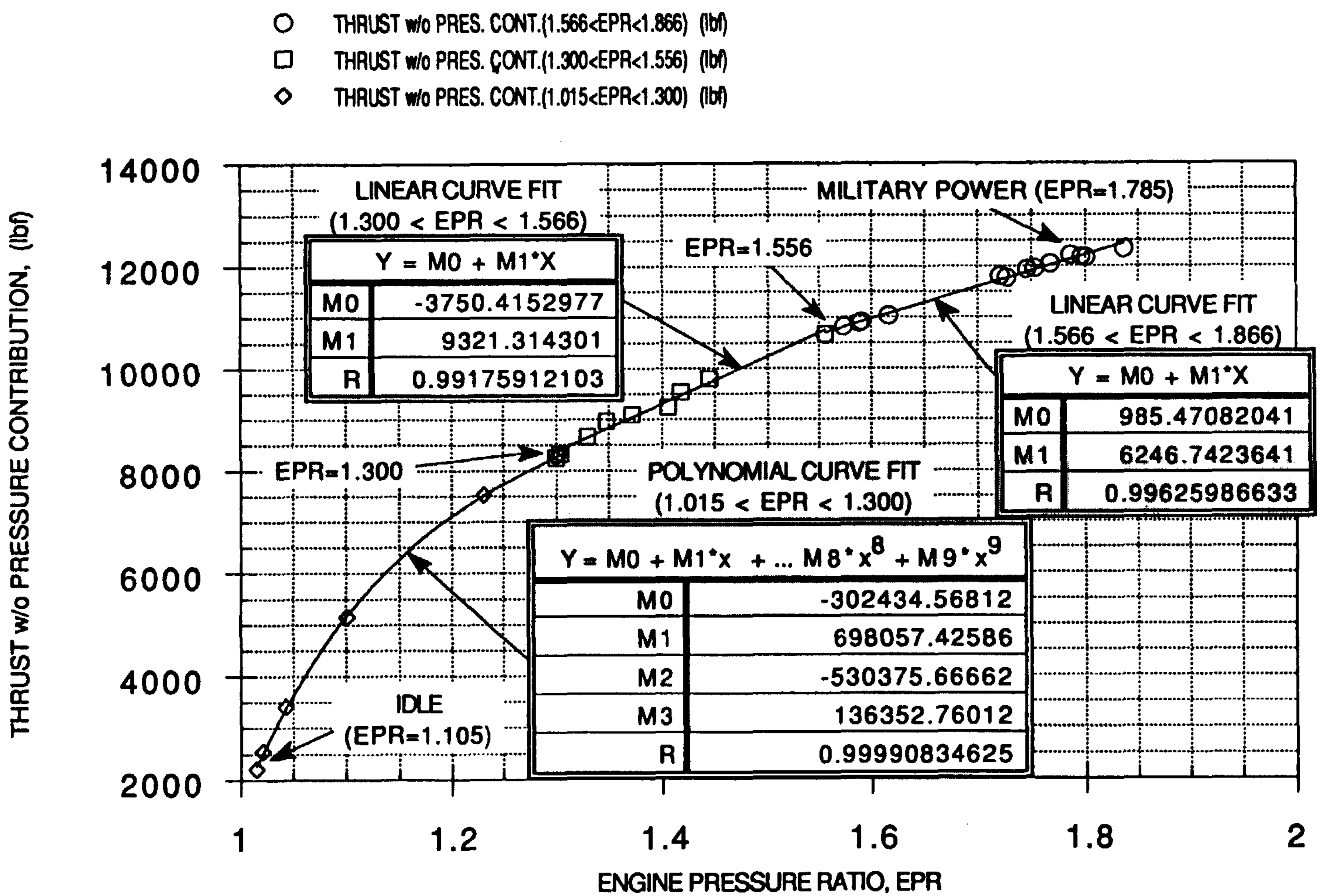


Figure B-3. Thrust w/o pressure contribution pre-dust behavior.

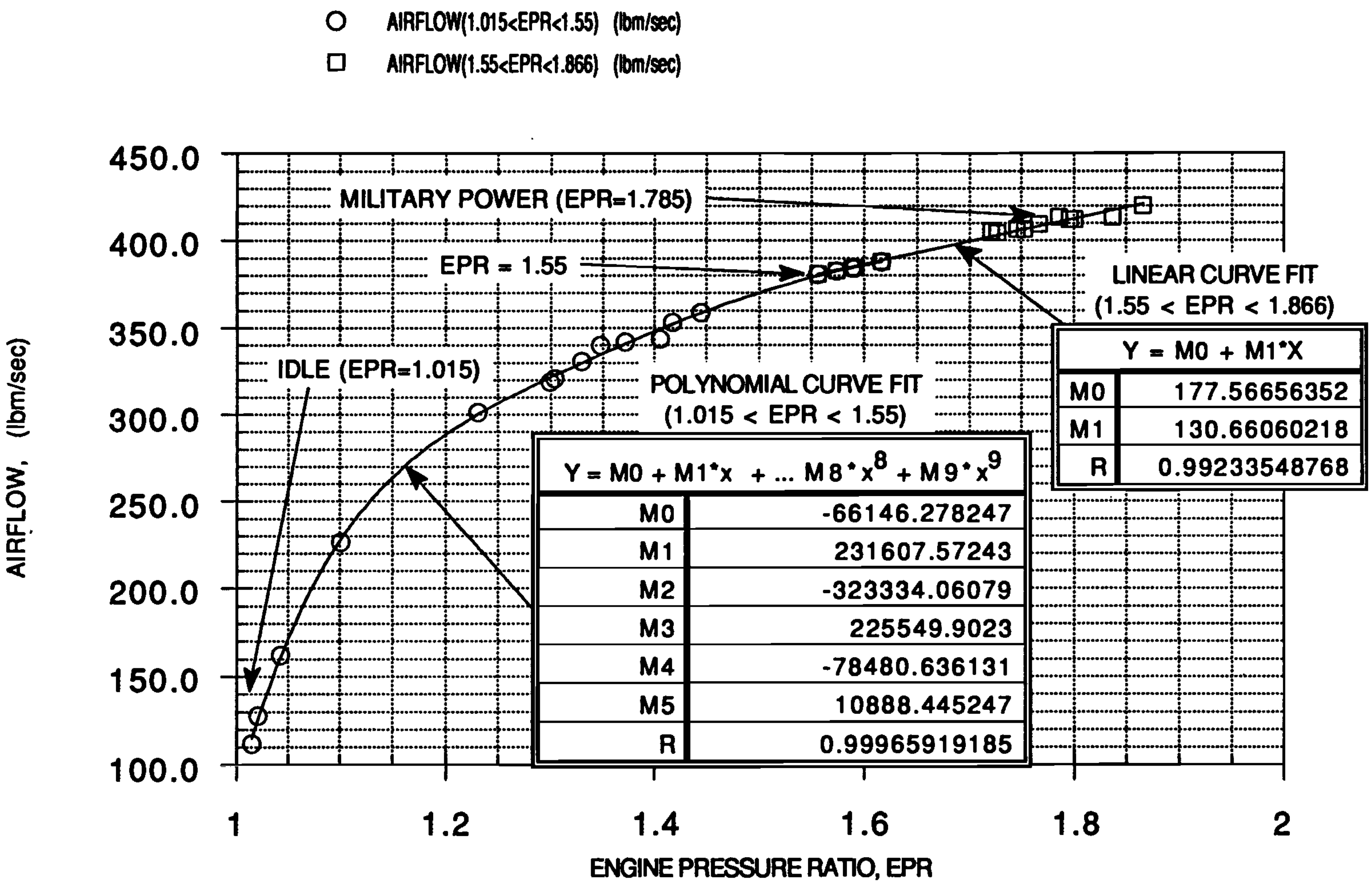


Figure B-4. Airflow pre-dust behavior.

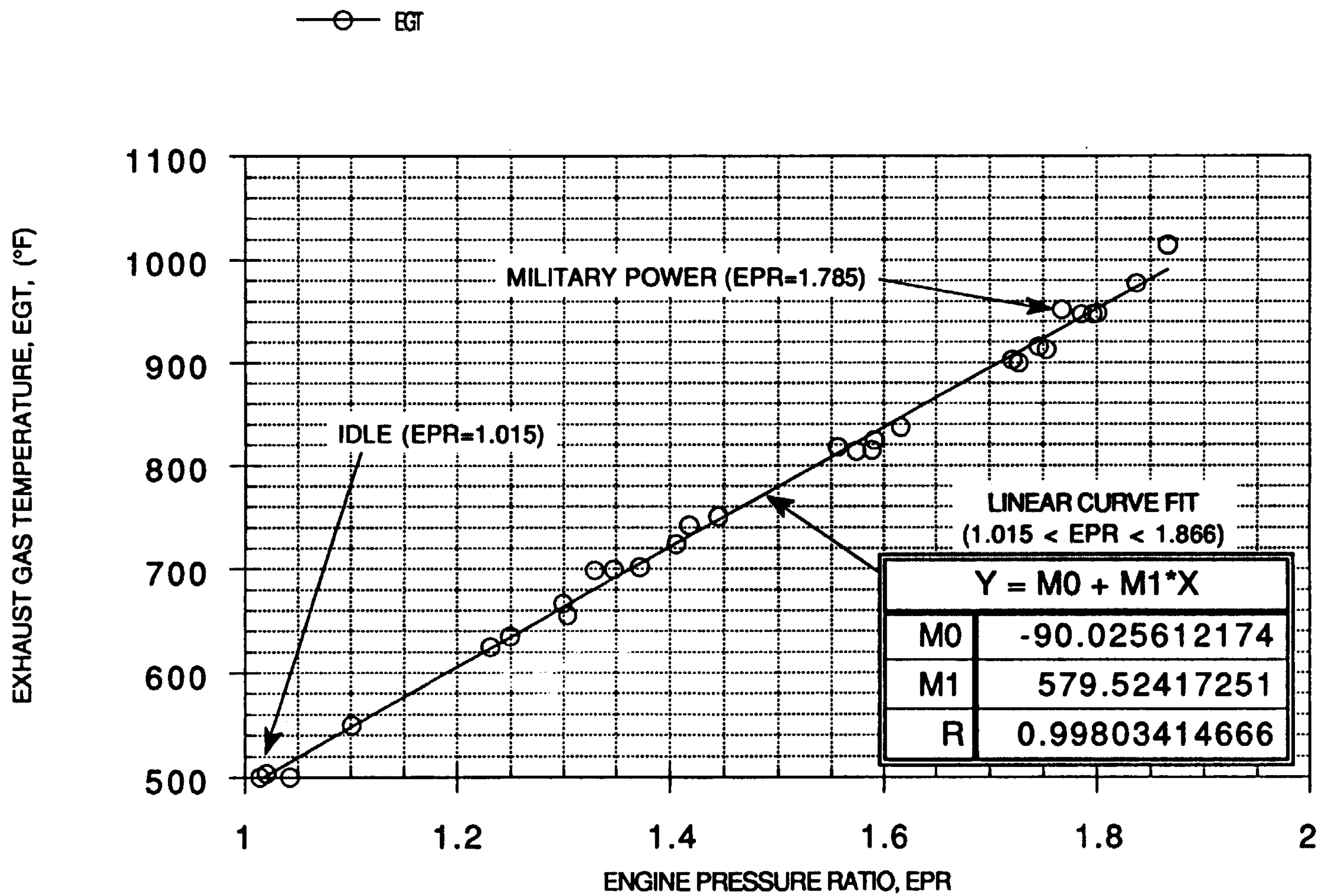


Figure B-5. EGT pre-dust behavior.

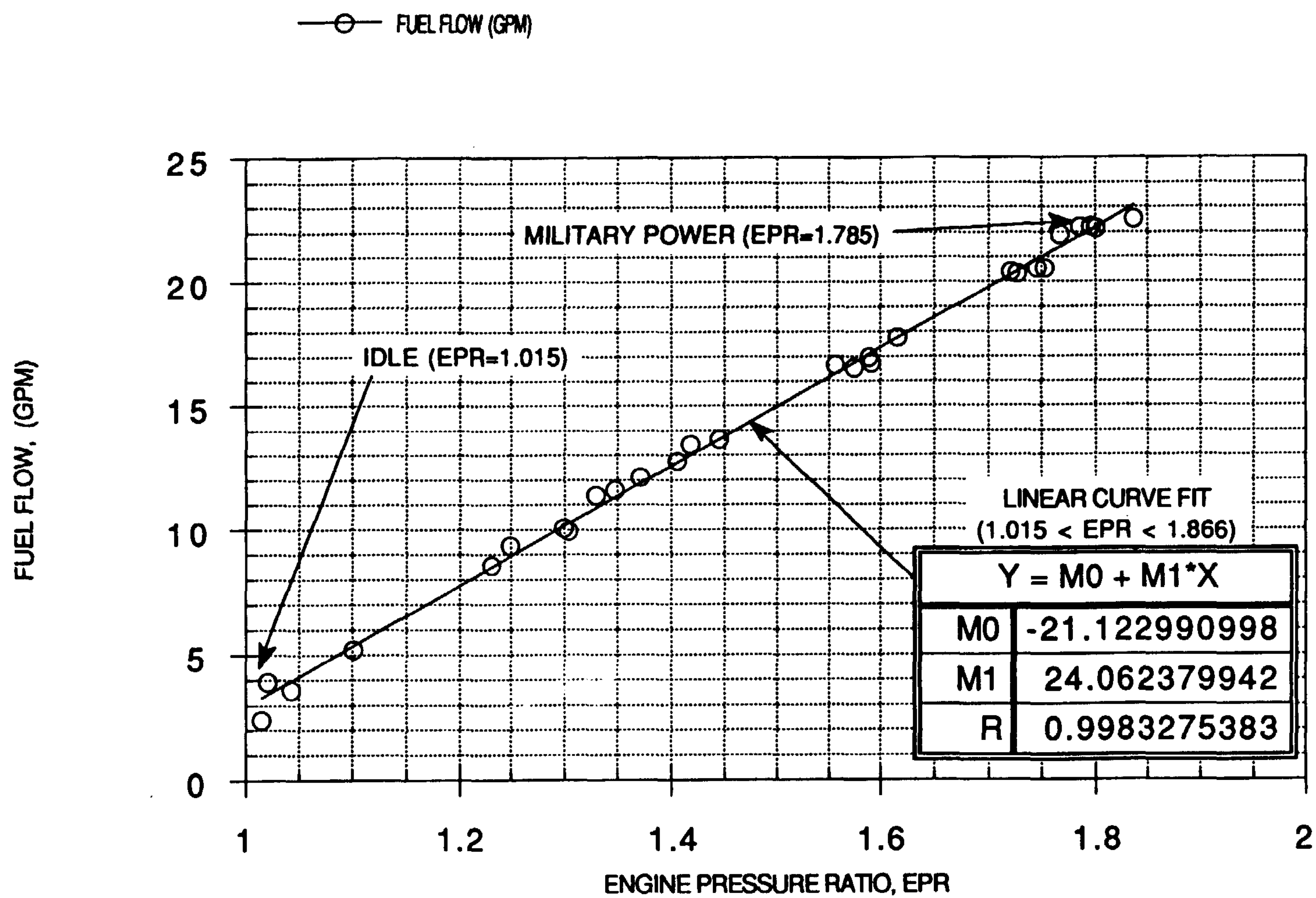


Figure B-6. Fuel flow pre-dust behavior.

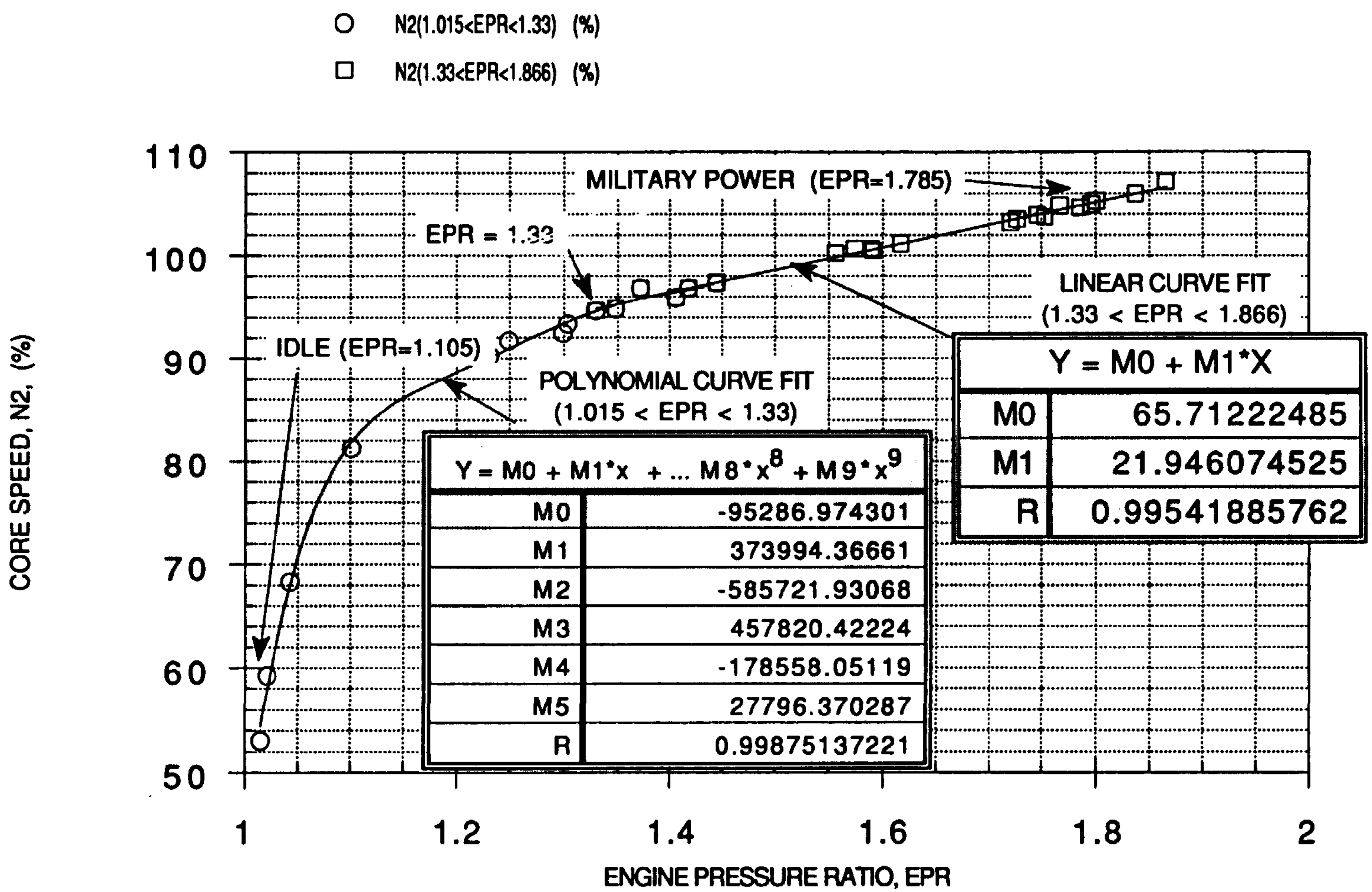
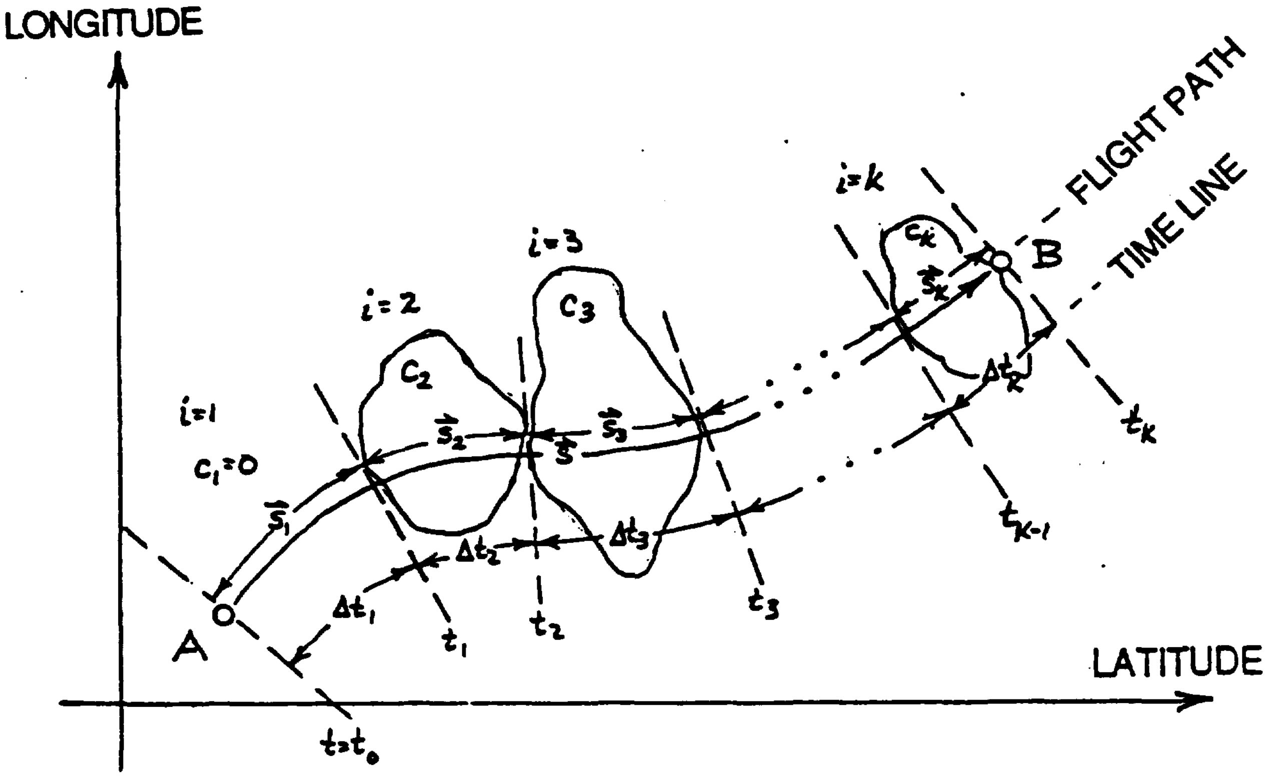


Figure B-7. Core speed pre-dust behavior.

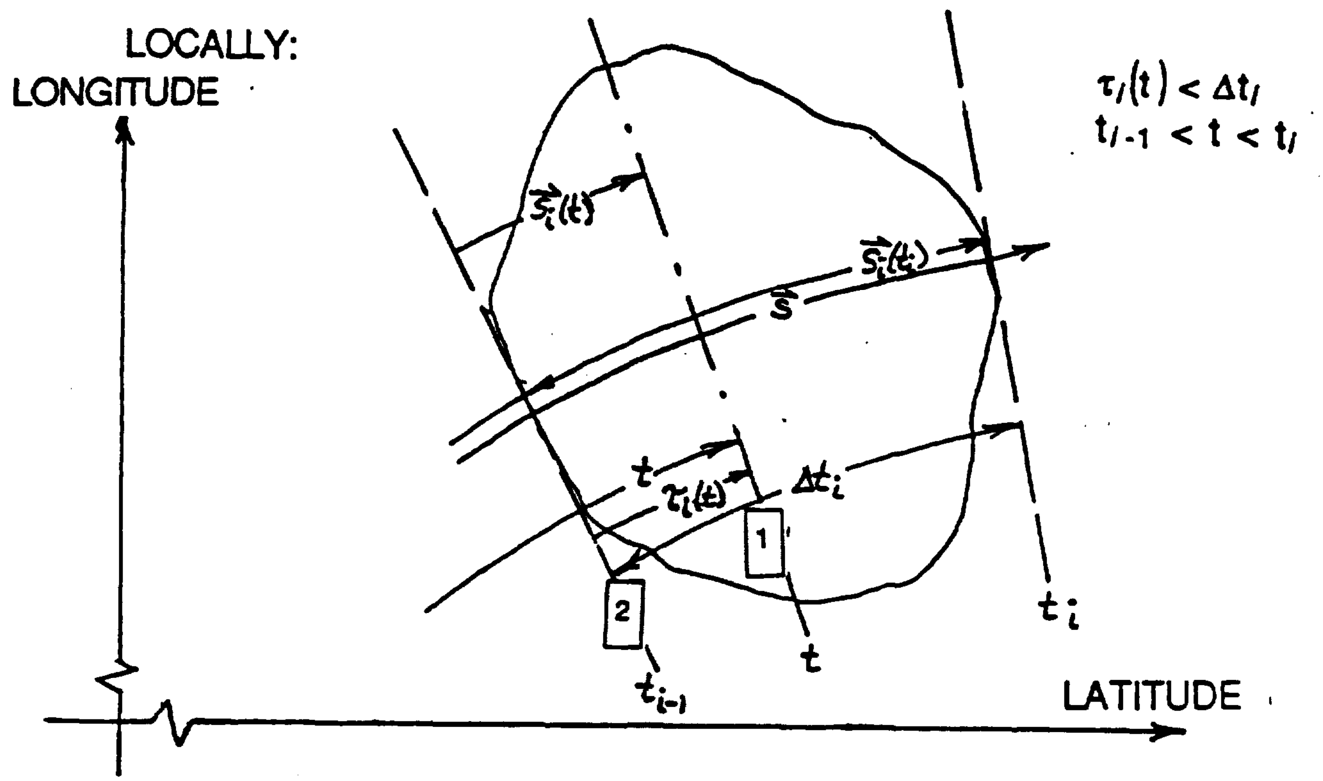
- CONSIDER A PIECEWISE REPRESENTATION OF AN INTENDED FLIGHT PATH, $\vec{s}$, BASED ON DISCRETE REGIONS, i, OF LOCALLY CONSTANT DUST CONCENTRATION, c_i.



where,

$\vec{s}$	=	flight path from A to B
t	=	time from origin
k	=	total # of discrete environments along $\vec{s}$
i	=	index for current environment encounter
n	=	dummy index for prior environment encounters
t_i	=	time at conclusion of encounter i
Δt_i	=	time duration of encounter i
$\tau_i(t)$	=	elapsed time within encounter i
c_i	=	dust concentration (constant throughout i)
$\vec{s}_i$	=	path traversed through encounter i

Figure B-8. Sample environment.



GENERAL FORM:

$$P_i(t) = [P_{nominal}(EPR_d(t)) + \Delta P_i(\Delta EPR_i(t))]$$

[1] (under $P_i(t)$) [2] (under $P_{nominal}(EPR_d(t))$) [3] (under $\Delta P_i(\Delta EPR_i(t))$)

where,

[1] PARAMETER WITH EROSION EFFECTS DURING ENCOUNTER *i*

[2] PARAMETER VARIATION DUE TO CHANGES IN ENGINE THROTTLE SETTING (TARGET EPR)

[3] EROSION EFFECTS CAUSED BY CURRENT ENCOUNTER

Figure B-9. General form of parameter response.

DUST EFFECTS MODEL

PARAMETER VALUE MUST:

- REFLECT PRE-DUST PERFORMANCE
- REFLECT EFFECTS OF CHANGING TARGET EPR
- REFLECT CURRENT DUST ENVIRONMENT AND THE AMOUNT THAT EPR NEEDS TO BE COMPENSATED FOR.
- REFLECT CUMULATIVE EROSION EFFECTS

$$P_i(t) = [P_{nominal}(EPR_d(t)) + \Delta P_i(\Delta EPR_i(t))]$$

- ΔP_i: EROSION EFFECTS DURING *i* INCLUDING CUMULATIVE EROSION EFFECTS TO DATE
- EPR_d: TARGET EPR (THROTTLE SETTING OF CRUISE, MILITARY POWER, etc.)
- $P_{nominal}$: PARAMETER VALUE (PRE-DUST PERFORMANCE)
- $P_i(t)$: PARAMETER VALUE WITH EROSION EFFECTS AND HISTORY OF EROSION EFFECTS

WHERE,

$$\Delta P_i(\Delta EPR_i(t)) = [P_{nominal}(EPR_d(t)) - P_{nominal}(EPR_d(t) - \Delta EPR_i(t))]$$

- $P_{nominal}(EPR_d(t))$: PARAMETER VALUE AT TARGET EPR
- $P_{nominal}(EPR_d(t) - \Delta EPR_i(t))$: PARAMETER VALUE AT REDUCED EPR

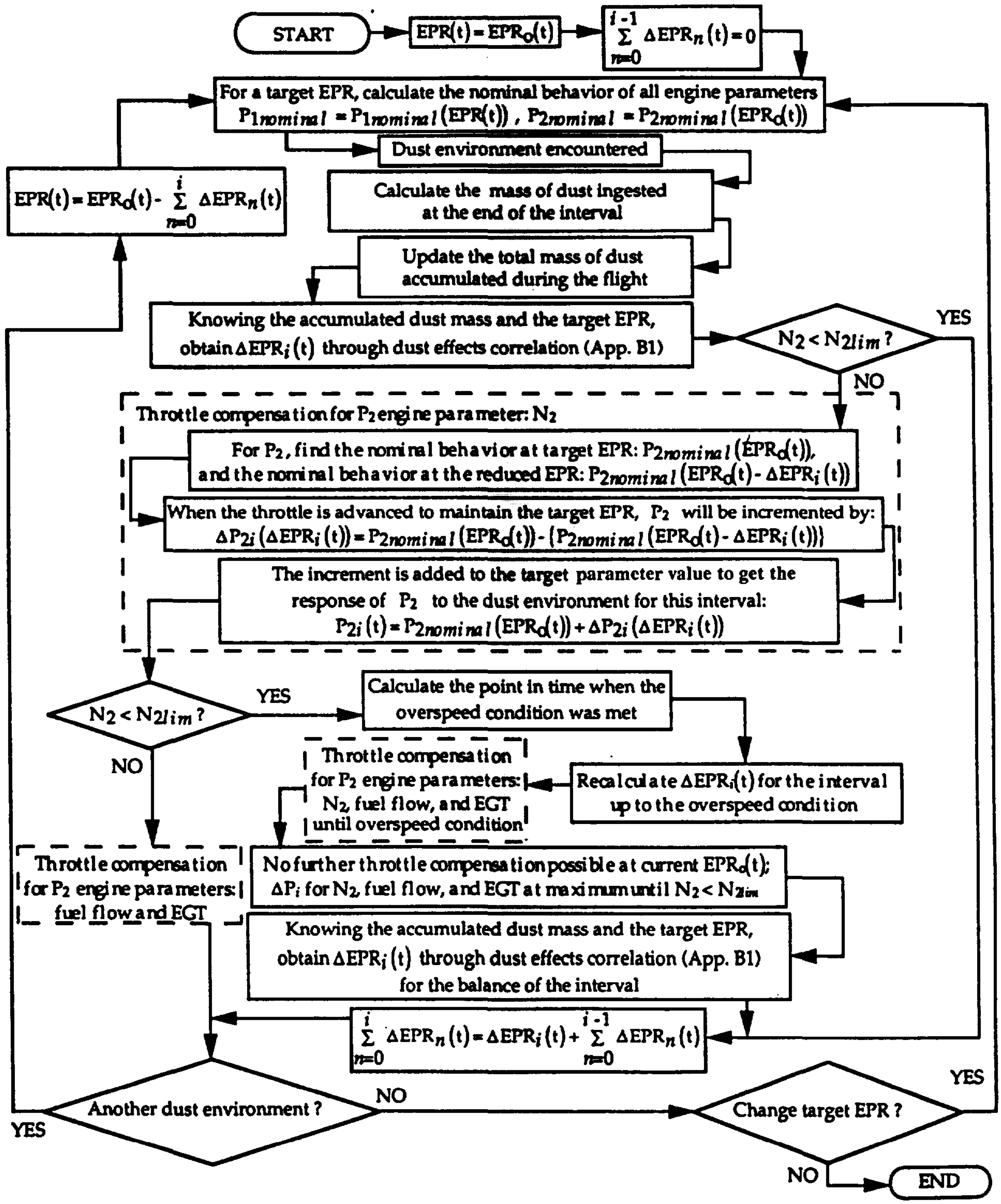


Figure B-10. TF33 engine response algorithm.

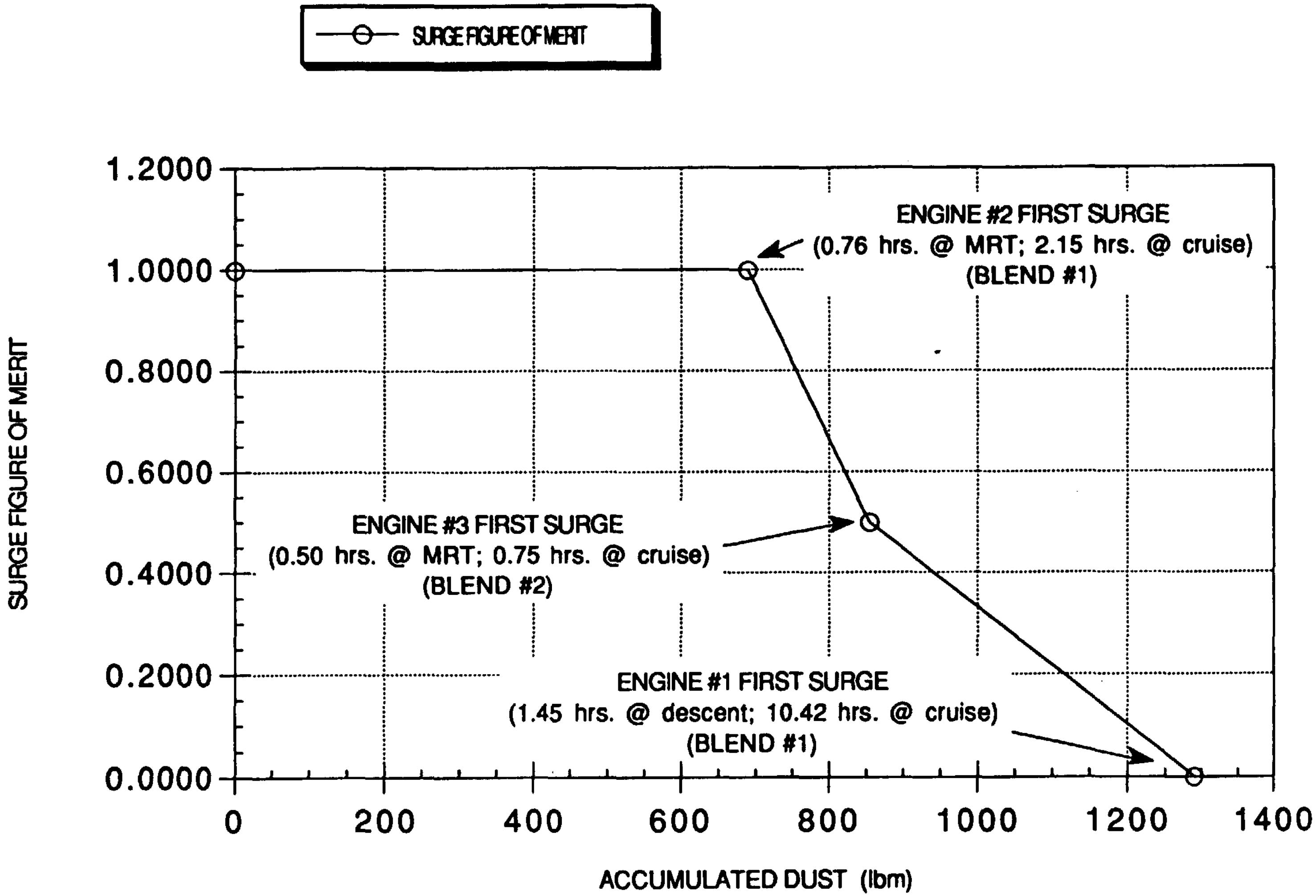


Figure B-11. Effects of dust on onset of surge.

Solutions for the TF33 Sample Problems

This appendix contains the Calspan solutions for the set of sample problems for the TF33 engine response model. The solutions were generated by the Calspan version of the TF33 engine response model, named TF33.f, whose source listing is presented in later in this appendix. The solutions are labelled as:

tf33.out(a)(b)

where: (a) = the problem #
(b) = the part # (for problems 1-3)

PEARL - TF33 response model

inputs :

target EPR (1.015-1.866) => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 5.000E+02 6.000E+00
ienc= 2 => 1 5.000E+02 6.000E+00
ienc= 3 => 1 5.000E+02 6.000E+00
ienc= 4 => 1 5.000E+02 6.000E+00
ienc= 5 => 1 5.000E+02 6.000E+00
ienc= 6 => 1 5.000E+02 6.000E+00
ienc= 7 => 1 5.000E+02 6.000E+00
ienc= 8 => 1 5.000E+02 6.000E+00
ienc= 9 => 1 5.000E+02 6.000E+00
ienc= 10 => 1 5.000E+02 6.000E+00

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	500.0	6.0	1.70	399.7	2.662E+01	895.2	8184.5	103.0	11604.9	1.00
2	1	500.0	6.0	1.70	399.7	5.325E+01	895.2	8184.5	103.0	11604.9	1.00
3	1	500.0	6.0	1.70	399.7	7.987E+01	895.2	8184.5	103.0	11604.9	1.00
4	1	500.0	6.0	1.70	399.7	1.065E+02	895.2	8184.5	103.0	11604.9	1.00
5	1	500.0	6.0	1.70	399.7	1.331E+02	895.2	8184.5	103.0	11604.9	1.00
6	1	500.0	6.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00
*** engine at overspeed limit of 104.0 at 1.4 minutes into the 7-th encounter											
7	1	500.0	6.0	1.57	383.0	1.864E+02	921.0	8628.8	104.0	10808.6	1.00
8	1	500.0	6.0	1.45	359.7	2.119E+02	921.0	8628.8	104.0	9761.8	1.00
9	1	500.0	6.0	1.29	319.7	2.358E+02	921.0	8628.8	104.0	8203.0	1.00
10	1	500.0	6.0	1.11	238.9	2.571E+02	921.0	8628.8	104.0	5506.6	1.00

```
PEARL - TF33 response model


inputs :

target EPR  (1.015-1.866) => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 5
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  5.000E+02  1.200E+01
ienc=  2 =>  1  5.000E+02  1.200E+01
ienc=  3 =>  1  5.000E+02  1.200E+01
ienc=  4 =>  1  5.000E+02  1.200E+01
ienc=  5 =>  1  5.000E+02  1.200E+01

debug mode (0=off,1=on) => 0


calculation begun


 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2    THRUST  SURGE
        (mg/m^3)    (min)       (lbm/sec) (kg)     (F)   (lbm/hr) (%)    (lbf)  (FOM)
+--+----+---------+--------+---+--------+--------+------+--------+-----+--------+----
  0  0       0.0       0.0 1.70  399.7 0.000E+00  895.2  8184.5  103.0 11604.9  1.00
  1  1     500.0      12.0 1.70  399.7 5.325E+01  895.2  8184.5  103.0 11604.9  1.00
  2  1     500.0      12.0 1.70  399.7 1.065E+02  895.2  8184.5  103.0 11604.9  1.00
  3  1     500.0      12.0 1.70  399.7 1.597E+02  914.3  8513.2  103.7 11604.9  1.00
*** engine at overspeed limit of   104.0 at     1.4 minutes into the  4-th encounter
  4  1     500.0      12.0 1.52  374.4 2.130E+02  921.0  8628.8  104.0 10443.0  1.00
  5  1     500.0      12.0 1.31  325.7 2.629E+02  921.0  8628.8  104.0  8504.5  1.00
```

```
PEARL - TF33 response model

inputs :

target EPR  (1.015-1.866) => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 3
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  5.000E+02  2.000E+01
ienc=  2 =>  1  5.000E+02  2.000E+01
ienc=  3 =>  1  5.000E+02  2.000E+01

debug mode (0=off,1=on) => 0

calculation begun

 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2   THRUST  SURGE
         (mg/m^3)    (min)       (lbm/sec)  (kg)     (F)   (lbm/hr)  (%)    (lbf)  (FOM)
+--+----+---------+--------+---+--------+--------+------+--------+-----+--------+----
  0  0       0.0       0.0  1.70  399.7 0.000E+00  895.2  8184.5  103.0 11604.9  1.00
  1  1     500.0      20.0  1.70  399.7 8.874E+01  895.2  8184.5  103.0 11604.9  1.00
*** engine at overspeed limit of   104.0 at   17.4 minutes into the  2-nd encounter
  2  1     500.0      20.0  1.59  385.2 1.775E+02  921.0  8628.8  104.0 10912.4  1.00
  3  1     500.0      20.0  1.37  341.5 2.630E+02  921.0  8628.8  104.0  9061.5  1.00
```

```
PEARL - TF33 response model

inputs :

target EPR  {1.015-1.866} => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  5.000E+02  6.000E+01

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2    THRUST  SURGE
         (mg/m^3)     (min)       (lbm/sec) (kg)    (F)    (lbm/hr) (%)     (lbf)  {FOM}
+--+----+---------+--------+---+--------+--------+------+--------+------+--------+----
  0  0       0.0          0.0  1.70  399.7 0.000E+00  895.2  8184.5  103.0 11604.9  1.00
*** engine at overspeed limit of   104.0 at   37.4 minutes into the  1-st encounter
  1  1     500.0         60.0  1.42  353.5 2.662E+02  921.0  8628.8  104.0  9514.0  1.00
```

PEARL - TF33 response model

```
inputs :

target EPR  {1.015-1.866} => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 => 1  9.000E+02  6.000E+00
ienc=  2 => 1  9.000E+02  6.000E+00
ienc=  3 => 1  9.000E+02  6.000E+00
ienc=  4 => 1  9.000E+02  6.000E+00
ienc=  5 => 1  9.000E+02  6.000E+00
ienc=  6 => 1  9.000E+02  6.000E+00
ienc=  7 => 1  9.000E+02  6.000E+00
ienc=  8 => 1  9.000E+02  6.000E+00
ienc=  9 => 1  9.000E+02  6.000E+00
ienc= 10 => 1  9.000E+02  6.000E+00

debug mode {0=off,1=on} => 0


calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	900.0	6.0	1.70	399.7	4.792E+01	895.2	8184.5	103.0	11604.9	1.00
2	1	900.0	6.0	1.70	399.7	9.584E+01	895.2	8184.5	103.0	11604.9	1.00
3	1	900.0	6.0	1.70	399.7	1.438E+02	897.0	8215.5	103.1	11604.9	1.00
*** engine at overspeed limit of 104.0 at 2.8 minutes into the 4-th encounter											
4	1	900.0	6.0	1.56	381.7	1.917E+02	921.0	8628.8	104.0	10814.7	1.00
5	1	900.0	6.0	1.40	346.8	2.375E+02	921.0	8628.8	104.0	9256.0	1.00
6	1	900.0	6.0	1.17	275.9	2.790E+02	921.0	8628.8	104.0	6685.1	1.00
7	1	900.0	6.0	0.92	0.0	3.121E+02	921.0	8628.8	104.0	0.0	1.00
8	1	900.0	6.0	****	0.0	3.121E+02	921.0	8628.8	104.0	0.0	1.00
9	1	900.0	6.0	****	0.0	3.121E+02	921.0	8628.8	104.0	0.0	1.00
10	1	900.0	6.0	****	0.0	3.121E+02	921.0	8628.8	104.0	0.0	1.00

```
PEARL - TF33 response model

inputs :

target EPR  (1.015-1.866) =>  1.700E+00
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) (1-10) =>  5
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

iencー 1 =>  1  9.000E+02  1.200E+01
iencー 2 =>  1  9.000E+02  1.200E+01
iencー 3 =>  1  9.000E+02  1.200E+01
iencー 4 =>  1  9.000E+02  1.200E+01
iencー 5 =>  1  9.000E+02  1.200E+01

debug mode (0=off,1=on) => 0


calculation begun


 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2   THRUST  SURGE
        (mg/m^3)     (min)       (lbm/sec) (kg)     (F)   (lbm/hr) (%)    (lbf)  (FOM)
+--+----+---------+--------+---+--------+--------+------+---------+-----+--------+----
  0  0       0.0        0.0  1.70   399.7 0.000E+00  895.2  8184.5  103.0 11604.9  1.00
  1  1     900.0       12.0  1.70   399.7 9.584E+01  895.2  8184.5  103.0 11604.9  1.00
*** engine at overspeed limit of   104.0 at    8.8 minutes into the  2-nd encounter
  2  1     900.0       12.0  1.56   381.7 1.917E+02  921.0  8628.8  104.0 10814.7  1.00
  3  1     900.0       12.0  1.32   325.8 2.832E+02  921.0  8628.8  104.0  8507.8  1.00
*** surge FOM below 1.0 at     4.6 minutes into the  4-th encounter
  4  1     900.0       12.0  0.97     0.0 3.613E+02  921.0  8628.8  104.0     0.0  0.68
  5  1     900.0       12.0  ****     0.0 3.613E+02  921.0  8628.8  104.0     0.0  0.68
```

PEARL - TF33 response model

inputs :

target EPR {1.015-1.866} => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 9.000E+02 2.000E+01
ienc= 2 => 1 9.000E+02 2.000E+01
ienc= 3 => 1 9.000E+02 2.000E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	900.0	20.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00
*** surge FOM below 1.0 at 19.2 minutes into the 2-nd encounter											
*** engine at overspeed limit of 104.0 at 0.8 minutes into the 2-nd encounter											
2	1	900.0	20.0	1.32	328.1	3.195E+02	921.0	8628.8	104.0	8584.9	0.96
3	1	900.0	20.0	0.84	0.0	4.506E+02	921.0	8628.8	104.0	0.0	0.34

```
PEARL - TF33 response model

inputs :

target EPR  {1.015-1.866} =>  1.700E+00
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) {1-10} =>  1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  9.000E+02  6.000E+01

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2   THRUST  SURGE
         (mg/m^3)    (min)      (lbm/sec) (kg)     (F)   (lbm/hr) (%)    (lbf)  {FOM}
+--+----+---------+--------+---+--------+--------+------+--------+-----+--------+----
  0  0       0.0        0.0  1.70  399.7 0.000E+00  895.2  8184.5  103.0 11604.9  1.00
*** surge FOM below 1.0 at    39.2 minutes into the  1-st encounter
*** engine at overspeed limit of   104.0 at   20.8 minutes into the  1-st encounter
  1  1     900.0       60.0  1.02  131.4 4.792E+02  921.0  8628.8  104.0  2658.0  0.27
```

```
PEARL - TF33 response model

inputs :

target EPR  (1.015-1.866) =>  1.700E+00
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  3.000E+02  6.000E+00
ienc=  2 =>  1  3.000E+02  6.000E+00
ienc=  3 =>  1  3.000E+02  6.000E+00
ienc=  4 =>  1  3.000E+02  6.000E+00
ienc=  5 =>  1  3.000E+02  6.000E+00
ienc=  6 =>  1  3.000E+02  6.000E+00
ienc=  7 =>  1  3.000E+02  6.000E+00
ienc=  8 =>  1  3.000E+02  6.000E+00
ienc=  9 =>  1  3.000E+02  6.000E+00
ienc= 10 =>  1  3.000E+02  6.000E+00

debug mode (0=off,1=on) => 0

calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	300.0	6.0	1.70	399.7	1.597E+01	895.2	8184.5	103.0	11604.9	1.00
2	1	300.0	6.0	1.70	399.7	3.195E+01	895.2	8184.5	103.0	11604.9	1.00
3	1	300.0	6.0	1.70	399.7	4.792E+01	895.2	8184.5	103.0	11604.9	1.00
4	1	300.0	6.0	1.70	399.7	6.389E+01	895.2	8184.5	103.0	11604.9	1.00
5	1	300.0	6.0	1.70	399.7	7.987E+01	895.2	8184.5	103.0	11604.9	1.00
6	1	300.0	6.0	1.70	399.7	9.584E+01	895.2	8184.5	103.0	11604.9	1.00
7	1	300.0	6.0	1.70	399.7	1.118E+02	895.2	8184.5	103.0	11604.9	1.00
8	1	300.0	6.0	1.70	399.7	1.278E+02	895.2	8184.5	103.0	11604.9	1.00
9	1	300.0	6.0	1.70	399.7	1.438E+02	897.0	8215.5	103.1	11604.9	1.00
10	1	300.0	6.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00

PEARL - TF33 response model

inputs :

target EPR {1.015-1.866} => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 5
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 3.000E+02 1.200E+01
ienc= 2 => 1 3.000E+02 1.200E+01
ienc= 3 => 1 3.000E+02 1.200E+01
ienc= 4 => 1 3.000E+02 1.200E+01
ienc= 5 => 1 3.000E+02 1.200E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	300.0	12.0	1.70	399.7	3.195E+01	895.2	8184.5	103.0	11604.9	1.00
2	1	300.0	12.0	1.70	399.7	6.389E+01	895.2	8184.5	103.0	11604.9	1.00
3	1	300.0	12.0	1.70	399.7	9.584E+01	895.2	8184.5	103.0	11604.9	1.00
4	1	300.0	12.0	1.70	399.7	1.278E+02	895.2	8184.5	103.0	11604.9	1.00
5	1	300.0	12.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00

PEARL - TF33 response model

inputs :

target EPR {1.015-1.866} => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 3.000E+02 2.000E+01
ienc= 2 => 1 3.000E+02 2.000E+01
ienc= 3 => 1 3.000E+02 2.000E+01

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	300.0	20.0	1.70	399.7	5.325E+01	895.2	8184.5	103.0	11604.9	1.00
2	1	300.0	20.0	1.70	399.7	1.065E+02	895.2	8184.5	103.0	11604.9	1.00
3	1	300.0	20.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00

PEARL - TF33 response model

inputs :

target EPR (1.015-1.866) => 1.700E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 1
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 3.000E+02 6.000E+01

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.70	399.7	0.000E+00	895.2	8184.5	103.0	11604.9	1.00
1	1	300.0	60.0	1.70	399.7	1.597E+02	914.3	8513.2	103.7	11604.9	1.00

PEARL - TF33 response model

inputs :

target EPR (1.015-1.866) => 1.300E+00
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 1 9.000E+02 6.000E+00
ienc= 2 => 1 9.000E+02 6.000E+00
ienc= 3 => 1 9.000E+02 6.000E+00
ienc= 4 => 1 9.000E+02 6.000E+00
ienc= 5 => 1 9.000E+02 6.000E+00
ienc= 6 => 1 9.000E+02 6.000E+00
ienc= 7 => 1 9.000E+02 6.000E+00
ienc= 8 => 1 9.000E+02 6.000E+00
ienc= 9 => 1 9.000E+02 6.000E+00
ienc= 10 => 1 9.000E+02 6.000E+00

debug mode (0=off,1=on) => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	EPR	AIR FLOW (lbm/sec)	ACC DUST (kg)	EGT (F)	FUEL FLOW (lbm/hr)	N2 (%)	THRUST (lbf)	SURGE (FOM)
0	0	0.0	0.0	1.30	321.6	0.000E+00	663.4	4202.6	93.4	8367.3	1.00
1	1	900.0	6.0	1.30	321.6	3.856E+01	663.4	4202.6	93.4	8367.3	1.00
2	1	900.0	6.0	1.30	321.6	7.712E+01	663.4	4202.6	93.4	8367.3	1.00
3	1	900.0	6.0	1.30	321.6	1.157E+02	663.4	4202.6	93.4	8367.3	1.00
4	1	900.0	6.0	1.30	321.6	1.542E+02	674.4	4391.8	94.3	8367.3	1.00
5	1	900.0	6.0	1.30	321.6	1.928E+02	709.3	4992.5	97.3	8367.3	1.00
6	1	900.0	6.0	1.30	321.6	2.314E+02	744.3	5593.2	100.1	8367.3	1.00
*** engine at overspeed limit of 104.0 at 34.0 minutes into the 7-th encounter											
7	1	900.0	6.0	0.62	0.0	2.699E+02	921.0	8628.8	104.0	0.0	1.00
8	1	900.0	6.0	****	0.0	2.699E+02	921.0	8628.8	104.0	0.0	1.00
9	1	900.0	6.0	****	0.0	2.699E+02	921.0	8628.8	104.0	0.0	1.00
10	1	900.0	6.0	****	0.0	2.699E+02	921.0	8628.8	104.0	0.0	1.00

```
PEARL - TF33 response model

inputs :

target EPR  (1.015-1.866) => 1.700E+00
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) (1-10) => 10
blend (1=mpb,2=blend2) , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  5.000E+01  6.000E+01
ienc=  2 =>  0  0.000E+00  5.000E+00
ienc=  3 =>  2  1.000E+02  1.000E+01
ienc=  4 =>  2  3.000E+02  1.000E+01
ienc=  5 =>  2  9.000E+02  3.000E+01
ienc=  6 =>  2  3.000E+02  1.000E+01
ienc=  7 =>  1  1.000E+02  1.000E+01
ienc=  8 =>  0  0.000E+00  5.000E+00
ienc=  9 =>  1  5.000E+02  6.000E+01
ienc= 10 =>  1  5.000E+01  2.400E+02

debug mode (0=off,1=on) => 0


calculation begun

 i blend dust conc time int EPR AIR FLOW ACC DUST  EGT  FUEL FLOW  N2   THRUST  SURGE
        (mg/m^3)     (min)       (lbm/sec) (kg)     (F)  (lbm/hr) (%)    (lbf)  (FOM)
+--+----+---------+--------+----+--------+--------+------+--------+-----+--------+----
  0  0        0.0       0.0 1.70   399.7 0.000E+00  895.2   8184.5  103.0 11604.9  1.00
  1  1       50.0      60.0 1.70   399.7 2.662E+01  895.2   8184.5  103.0 11604.9  1.00
  2  0        0.0       5.0 1.70   399.7 2.662E+01  895.2   8184.5  103.0 11604.9  1.00
  3  2      100.0      10.0 1.70   399.7 3.550E+01  895.2   8184.5  103.0 11604.9  1.00
  4  2      300.0      10.0 1.70   399.7 6.212E+01  895.2   8184.5  103.0 11604.9  1.00
*** engine at overspeed limit of  104.0 at    13.0 minutes into the  5-th encounter
  5  2      900.0      30.0 1.36   336.9 3.017E+02  921.0   8628.8  104.0  8894.6  1.00
*** surge FOM below 1.0 at     5.1 minutes into the  6-th encounter
  6  2      300.0      10.0 1.06   190.4 3.242E+02  921.0   8628.8  104.0  4135.0  0.93
  7  1      100.0      10.0 0.80     0.0 3.284E+02  921.0   8628.8  104.0     0.0  0.90
  8  0        0.0       5.0 ****     0.0 3.284E+02  921.0   8628.8  104.0     0.0  0.90
  9  1      500.0      60.0 ****     0.0 3.284E+02  921.0   8628.8  104.0     0.0  0.90
 10  1       50.0     240.0 ****     0.0 3.284E+02  921.0   8628.8  104.0     0.0  0.90
```

Source Code Listings for the Calspan Version of the TF33 Engine Response Model

This appendix contains the sorce code listings for the Calspan version of the TF33 engine response model.

The main program :

- tf33.f

Associated subprograms:

- fair.f
- fegt.f
- feprdrop.f
- ffuel.f
- fthrust.f
- fxn2.f

```
c
c     tf33.f is a code which evaluates the aircraft responses model
c      developed for DNA through SAIC and KAMAN under W/A # L0380500
c      during the period 06/01/92 thru 10/31/92.
c
c     engine parameters:
c
c        eprt     - target engine pressure ratio
c        epre     - engine pressure ratio (at constant throttle) at
c                    the conclusion of the encounter
c
c      (epr correlation)
c
c        air      - airflow (lbm/sec)
c        thrust   - thrust (lbf)
c        egt      - exhaust gas temperature (F)
c        fuel     - fuel flow (gal/min), output as (lbm/hr)
c                 - conversion factor = 413.71458 (lbm/hr)/(gal/min)
c                 - fuel density = 51.58 (lbm/ft^3)
c        xn2      - core speed (%)
c
c       (subscripts)
c
c        ()       - value after throttle adjustment maintaining constant EPR
c        ()s      - value at the start of the encounter
c        ()e      - value at the conclusion of the encounter
c                    (at constant throttle)
c        ()c      - critical value
c                    (at overspeed or overtemp condition)
c        ()del    - (in/de)crement over current interval
c        ()sum    - sum of (in/de)crements over previous intervals
c
c       (prescripts)
c        f()      - function which generates the value of the variable
c
      implicit integer*4(i-n),real*8(a-h,o-z)
      dimension ib(10),c(10),delt(10)
c
      data const/1.699e-06/
      data xk0,xn0,xn1
     &/313.0,2.1578198e+03,-5.771516206e+02/
      data b0,b1
     &/-90.025612174,579.52417251/
      data b20,b21
     &/65.71222485,21.946074525/
c
      open(7,file='tf33.out',status='unknown')
c
      write(*,*)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'PEARL - TF33 response model'
      write(*,*)
      write(*,*)
      write(*,'(a)') 'inputs :'
      write(*,*)
```

```
      write(*,100)
 100  format('target EPR  {1.015-1.866} => ',$)
      read(*,*) eprt
      write(7,*)
      write(7,*)
      write(7,*)
      write(7,'(a)') 'PEARL - TF33 response model'
      write(7,*)
      write(7,*)
      write(7,'(a)') 'inputs :'
      write(7,*)
      write(7,200) eprt
 200  format('target EPR  {1.015-1.866} => ',1pe10.3)
      write(*,101)
 101  format('ambient pressure (psia) => ',$)
      read(*,*) pamb
      write(7,201) pamb
 201  format('ambient pressure (psia) => ',1pe10.3)
      write(*,102)
 102  format('ambient temperature (F) => ',$)
      read(*,*) tamb
      write(7,202) tamb
 202  format('ambient temperature (F) => ',1pe10.3)
      write(*,*)
      write(7,*)
      write(*,103)
 103  format('# of encounters (-) {1-10} => ',$)
      read(*,*) nenc
      write(7,203) nenc
 203  format('# of encounters (-) {1-10} => ',i2)
      write(*,104)
 104  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(*,*)
      write(7,204)
 204  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(7,*)
      do 1 ienc=1,nenc
       write(*,105) ienc
 105   format('ienc= ',i2,' => ',$)
       read(*,*) ib(ienc),c(ienc),delt(ienc)
       write(7,205) ienc,ib(ienc),c(ienc),delt(ienc)
 205   format('ienc= ',i2,' => ',i2,1x,1pe10.3,1x,1pe10.3)
 1    continue
      write(*,*)
      write(*,150)
 150  format('debug mode {0=off,1=on} => ',$)
      read(*,*) ibug
      write(7,*)
      write(7,250) ibug
 250  format('debug mode {0=off,1=on} => ',i1)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'calculation begun'
      write(*,*)
```

```
      write(*,*)
      write(7,*)
      write(7,*)
      write(7,'(a)') 'calculation begun'
      write(7,*)
      write(7,*)
c
c     initialize all engine parameters to zero
c
      ienc=0
      none=0
      dust=0.
      i1flag=0
      i3flag=0
      s1lim=313.26
      s2lim=388.17
      s3lim=586.11
      xn2lim=104.
      egtlim=1040.
      ixn2flag=0
      iegtflag=0
      fom1=1.
      fom2=.5
      fom3=0.
      a10=3.0909099057
      a11=-0.0066746786711
      a20=1.4805043916
      a21=-0.0025259665476
      accdust=0.
      airdel=0.
      airsum=0.
      thrustdel=0.
      thrustsum=0.
      egtdel=0.
      egtsum=0.
      fueldel=0.
      fuelsum=0.
      xn2del=0.
      xn2sum=0.
c
c     calculate the ambient density (lbm/sec)
c
      rhoamb=144.*pamb/(53.3*(tamb+460.))
c
c     calculate the engine parameters
c
c     nominal clear air engine parameter values
c
      air=FAIR(eprt)
      xn2=FXN2(eprt)
      egt=FEGT(eprt)
      fuel=FFUEL(eprt)
      thrust=FTHRUST(eprt)
c
c     write the header
c
```

```
      write(7,500)
 500  format(' i ','blend',' dust conc',' time int',' EPR'
     &,' AIR FLOW',' ACC DUST','   EGT  ','FUEL FLOW'
     &,'   N2   ',' THRUST  ','SURGE')
      write(7,501)
 501  format('   ','      ',' (mg/m^3) ','    (min) ','     '
     &,' (lbm/sec)',' (kg)    ','   (F)   ',' (lbm/hr)'
     &,' (%)   ','  (lbf)   ','(FOM)')
      write(7,502)
 502  format('+--','+----','+---------','+---------','+---'
     &,'+--------','+---------','+------','+---------'
     &,'+-----','+--------','+----')
      write(7,550) ienc,none,none,none,eprt
     &,air,accdust,egt,(413.71458)*fuel,xn2,thrust,fom1
c
c     loop over all encounters
c
      do 2 ienc=1,nenc
      if(ibug.eq.1) write(7,300) ienc
 300  format('ienc = ',i2)
      if(ibug.eq.1) write(7,301) ienc,ib(ienc)
 301  format('ib(',i2,') = ',i2)
      if(ibug.eq.1) write(7,302) ienc,c(ienc)
 302  format('c(',i2,') = ',1pe10.3)
      if(ibug.eq.1) write(7,303) ienc,delt(ienc)
 303  format('delt(',i2,') = ',1pe10.3)
c
c     calculate the airflow, injested dust over this interval, and the
c      total accumulated dust (based on conditions at the start of the
c      encounter)
c
      airs=FAIR(eprt)
      q=airs/rhoamb
      dust=const*q*c(ienc)*delt(ienc)
      accdust=dust+accdust
c
c     check for where the surge fom deviated from 1.0 and
c      also where the surge fom went to zero.
c
      if((accdust.gt.s1lim).and.(i1flag.eq.0)) then
       i1flag=1
       dust1c=s1lim-(accdust-dust)
       tau1=dust1c/(const*q*c(ienc))
       write(7,700) fom1,tau1,ienc
 700   format('*** surge FOM below ',f3.1,' at ',f7.1,' minutes',
     &,' into the ',i2,'-th encounter')
      endif
      if((accdust.gt.s3lim).and.(i3flag.eq.0)) then
       i3flag=1
       dust3c=s3lim-(accdust-dust)
       tau3=dust3c/(const*q*c(ienc))
       write(7,701) fom3,tau3,ienc
 701   format('*** surge FOM went to ',f3.1,' at ',f7.1,' minutes',
     &,' into the ',i2,'-th encounter')
      endif
      if(ibug.eq.1) write(7,*)
```

```
      if(ibug.eq.1) write(7,304) eprt
 304  format('eprt = ',1pe10.3)
      if(ibug.eq.1) write(7,400) airs
 400  format('airs = ',1pe10.3)
      if(ibug.eq.1) write(7,305) rhoamb
 305  format('rhoamb = ',1pe10.3)
      if(ibug.eq.1) write(7,306) q
 306  format('q = ',1pe10.3)
      if(ibug.eq.1) write(7,307) dust
 307  format('dust = ',1pe10.3)
      if(ibug.eq.1) write(7,308) accdust
 308  format('accdust = ',1pe10.3)
c
c     check for surge probability
c
       if((accdust.ge.0.).and.(accdust.lt.s1lim)) fom=fom1
       if((accdust.ge.s1lim).and.(accdust.lt.s21im)) then
        fom=a10+a11*accdust
       endif
       if((accdust.ge.s21im).and.(accdust.lt.s31im)) then
        fom=a20+a21*accdust
       endif
       if((accdust.ge.s31im)) fom=fom3
c
c     calculate epr drop
c
      eprdrop=FEPRDROP(accdust,eprt)
      eprdel=eprdrop
      epre=eprt-eprdel
      if(ixn2flag.eq.1) eprt=eprt-eprdel
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,313) accdust
 313  format('accdust = ',1pe10.3)
      if(ibug.eq.1) write(7,311) eprt
 311  format('eprt = ',1pe10.3)
      if(ibug.eq.1) write(7,309) eprdrop
 309  format('eprdrop = ',1pe10.3)
      if(ibug.eq.1) write(7,310) eprdel
 310  format('eprdel = ',1pe10.3)
      if(ibug.eq.1) write(7,312) epre
 312  format('epre = ',1pe10.3)
c
c     calculate xn2
c
      xn2s=FXN2(eprt)
      xn2e=FXN2(epre)
      if(ixn2flag.eq.0) xn2del=xn2e-xn2s
      if(ixn2flag.eq.0) xn2=xn2s-xn2del
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,360) xn2s
 360  format('xn2s = ',1pe10.3)
      if(ibug.eq.1) write(7,361) xn2e
 361  format('xn2e = ',1pe10.3)
      if(ibug.eq.1) write(7,362) xn2del
 362  format('xn2del = ',1pe10.3)
c      if(ibug.eq.1) write(7,364) xn2sum
```

```
c 364  format('xn2sum = ',1pe10.3)
      if(ibug.eq.1) write(7,363) xn2
 363  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     check for overspeed conditions
c
      if((xn2.gt.xn2lim).and.(ixn2flag.eq.0)) then
       ixn2flag=1
       xn2delc=xn2s-xn2lim
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,401) xn2s
 401  format('xn2s = ',1pe10.3)
      if(ibug.eq.1) write(7,402) xn2lim
 402  format('xn2lim = ',1pe10.3)
      if(ibug.eq.1) write(7,403) xn2delc
 403  format('xn2delc = ',1pe10.3)
       eprdelc=xn2delc/b21
      if(ibug.eq.1) write(7,404) b21
 404  format('b21 = ',1pe10.3)
      if(ibug.eq.1) write(7,405) eprdelc
 405  format('eprdelc = ',1pe10.3)
       dustcl=(.454)*xk0-(accdust-dust)
      if(ibug.eq.1) write(7,406) xk0
 406  format('xk0 = ',1pe10.3)
      if(ibug.eq.1) write(7,407) (.454)*xk0
 407  format('(.454)*xk0 = ',1pe10.3)
      if(ibug.eq.1) write(7,408) accdust
 408  format('accdust = ',1pe10.3)
      if(ibug.eq.1) write(7,409) dust
 409  format('dust = ',1pe10.3)
      if(ibug.eq.1) write(7,410) dustcl
 410  format('dustcl = ',1pe10.3)
       taucl=dustcl/(const*q*c(ienc))
      if(ibug.eq.1) write(7,411) const
 411  format('const = ',1pe10.3)
      if(ibug.eq.1) write(7,412) q
 412  format('q = ',1pe10.3)
      if(ibug.eq.1) write(7,413) c(ienc)
 413  format('c(ienc) = ',1pe10.3)
      if(ibug.eq.1) write(7,414) taucl
 414  format('taucl = ',1pe10.3)
       accdustc=xk0+(xn1*eprt+xn0)*(-eprdelc)
      if(ibug.eq.1) write(7,415) xn1
 415  format('xn1 = ',1pe10.3)
      if(ibug.eq.1) write(7,416) eprt
 416  format('eprt = ',1pe10.3)
      if(ibug.eq.1) write(7,417) xn0
 417  format('xn0 = ',1pe10.3)
      if(ibug.eq.1) write(7,418) accdustc
 418  format('accdustc = ',1pe10.3)
       accdustc=(0.454)*accdustc
      if(ibug.eq.1) write(7,419) accdustc
 419  format('(0.454)*accdustc = ',1pe10.3)
       dustc2=accdustc-(.454)*xk0
```

```
      if(ibug.eq.1) write(7,420) dustc2
 420  format('dustc2 = ',1pe10.3)
       tauc2=dustc2/(const*q*c(ienc))
      if(ibug.eq.1) write(7,421) tauc2
 421  format('tauc2 = ',1pe10.3)
       tauc=tauc1+tauc2
      if(ibug.eq.1) write(7,422) tauc
 422  format('tauc = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
       write(7,703) xn2lim,tauc,ienc
 703   format('*** engine at overspeed limit of ',f7.1,' at',
     &,f7.1,' minutes into the ',i2,'-th encounter')
c
c     calcuate engine parameters at time of overspeed
c
      eprc=(xn2lim-b20)/b21
      xn2s=FXN2(eprc)
      xn2=xn2s
      airs=FAIR(eprt)
      air=airs
      thrusts=FTHRUST(eprt)
      thrust=thrusts
      egts=FEGT(eprc)
      egt=egts
      fuels=FFUEL(eprc)
      fuel=fuels
c
c     calculate the eprdrop in the time between overspeed and the
c      next time interval
c
      eprdel=eprdel-eprdelc
      eprt=eprt-eprdel
      endif
c
c     calculate air
c
      airs=FAIR(eprt)
      air=airs
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,320) airs
 320  format('airs = ',1pe10.3)
      if(ibug.eq.1) write(7,323) air
 323  format('air = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     calculate thrust
c
      thrusts=FTHRUST(eprt)
      thrust=thrusts
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,330) thrusts
 330  format('thrusts = ',1pe10.3)
      if(ibug.eq.1) write(7,333) thrust
 333  format('thrust = ',1pe10.3)
```

```
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     calculate egt
c
      egts=FEGT(eprt)
      egte=FEGT(epre)
      if(ixn2flag.eq.0) egtdel=egte-egts
      if(ixn2flag.eq.0) egt=egts-egtdel
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,340) egts
 340  format('egts = ',1pe10.3)
      if(ibug.eq.1) write(7,341) egte
 341  format('egte = ',1pe10.3)
      if(ibug.eq.1) write(7,342) egtdel
 342  format('egtdel = ',1pe10.3)
c      if(ibug.eq.1) write(7,344) egtsum
c 344  format('egtsum = ',1pe10.3)
      if(ibug.eq.1) write(7,343) egt
 343  format('egt = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     calculate fuel
c
      fuels=FFUEL(eprt)
      fuele=FFUEL(epre)
      if(ixn2flag.eq.0) fueldel=fuele-fuels
      if(ixn2flag.eq.0) fuel=fuels-fueldel
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,350) fuels
 350  format('fuels = ',1pe10.3)
      if(ibug.eq.1) write(7,351) fuele
 351  format('fuele = ',1pe10.3)
      if(ibug.eq.1) write(7,352) fueldel
 352  format('fueldel = ',1pe10.3)
c      if(ibug.eq.1) write(7,354) fuelsum
c 354  format('fuelsum = ',1pe10.3)
      if(ibug.eq.1) write(7,353) fuel
 353  format('fuel = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     check for overtemp conditions
c
      if((egt.gt.egtlim).and.(iegtflag.eq.0)) then
       iegtflag=1
       egtdelc=egts-egtlim
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,431) egts
 431  format('egts = ',1pe10.3)
      if(ibug.eq.1) write(7,432) egtlim
 432  format('egtlim = ',1pe10.3)
      if(ibug.eq.1) write(7,433) egtdelc
 433  format('egtdelc = ',1pe10.3)
       eprdelc=egtdelc/b1
```

```
      if(ibug.eq.1) write(7,434) b1
 434  format('b1 = ',1pe10.3)
      if(ibug.eq.1) write(7,435) eprdelc
 435  format('eprdelc = ',1pe10.3)
       dustc1=(.454)*xk0-(accdust-dust)
      if(ibug.eq.1) write(7,436) xk0
 436  format('xk0 = ',1pe10.3)
      if(ibug.eq.1) write(7,437) (.454)*xk0
 437  format('(.454)*xk0 = ',1pe10.3)
      if(ibug.eq.1) write(7,438) accdust
 438  format('accdust = ',1pe10.3)
      if(ibug.eq.1) write(7,439) dust
 439  format('dust = ',1pe10.3)
      if(ibug.eq.1) write(7,440) dustc1
 440  format('dustc1 = ',1pe10.3)
       tauc1=dustc1/(const*q*c(ienc))
      if(ibug.eq.1) write(7,441) const
 441  format('const = ',1pe10.3)
      if(ibug.eq.1) write(7,442) q
 442  format('q = ',1pe10.3)
      if(ibug.eq.1) write(7,443) c(ienc)
 443  format('c(ienc) = ',1pe10.3)
      if(ibug.eq.1) write(7,444) tauc1
 444  format('tauc1 = ',1pe10.3)
       accdustc=xk0+(xn1*eprt+xn0)*(-eprdelc)
      if(ibug.eq.1) write(7,445) xn1
 445  format('xn1 = ',1pe10.3)
      if(ibug.eq.1) write(7,446) eprt
 446  format('eprt = ',1pe10.3)
      if(ibug.eq.1) write(7,447) xn0
 447  format('xn0 = ',1pe10.3)
      if(ibug.eq.1) write(7,448) accdustc
 448  format('accdustc = ',1pe10.3)
       accdustc=(0.454)*accdustc
      if(ibug.eq.1) write(7,449) accdustc
 449  format('(0.454)*accdustc = ',1pe10.3)
       dustc2=accdustc-(.454)*xk0
      if(ibug.eq.1) write(7,450) dustc2
 450  format('dustc2 = ',1pe10.3)
       tauc2=dustc2/(const*q*c(ienc))
      if(ibug.eq.1) write(7,451) tauc2
 451  format('tauc2 = ',1pe10.3)
       tauc=tauc1+tauc2
      if(ibug.eq.1) write(7,452) tauc
 452  format('tauc = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
       write(7,704) egtlim,tauc,ienc
 704   format('*** engine at overtemp limit of ',f7.1,' at'
     &,f7.1,' minutes into the ',i2,'-th encounter')
      endif
c
      write(7,550) ienc,ib(ienc),c(ienc),delt(ienc),eprt
     &,air,accdust,egt,(413.71458)*fuel,xn2,thrust,fom
 550  format((1x,i2),(2x,i1,2x),(1x,f7.1,2x),(1x,f7.1,1x),(1x,f4.2),
     &((f7.1,1x)),((1pe9.3)),(0pf7.1),(1x,0pf7.1,1x),
```

```
     &(0pf6.1),(1x,0pf7.1,1x),(f5.2))
 2    continue
      stop
      end
```

```
c
c     this function calculates the airflow
c
      function FAIR(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11,a12,a13,a14,a15
     &/-66146.278247,231607.57243,-323334.06079,225549.9023
     &,-78480.636131,10888.445247/
      data a20,a21
     &/177.56656352,130.66060218/
c
      if(x.lt.1.015) fair=0.
      if(x.gt.1.866) fair=0.
      if((x.ge.1.015).and.(x.lt.1.55)) then
       fair=a10+a11*x+a12*x**2+a13*x**3+a14*x**4+a15*x**5
      endif
      if((x.ge.1.55).and.(x.le.1.866)) then
       fair=a20+a21*x
      endif
      return
      end
```

```
c
c     this function calculates the egt
c
      function FEGT(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a0,a1
     &/-90.025612174,579.52417251/
c
      if(x.lt.1.015) fegt=0.
      if(x.gt.1.866) fegt=0.
      fegt=a0+a1*x
      return
      end
```

```
c
c     this function calculates the EPR drop
c
      function FEPRDROP(a,x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data xk0,xn0,xn1
     &/313.0,2.1578198e+03,-5.771516206e+02/
c
c      Correlation is in terms of accumulated dust in lbm.
c     Value of 'a' coming into the subroutine is in kg.
c
c     convert 'a' from kg to lbm
c
      a=a/(0.454)
c
      if(a.le.313.) feprdrop=0.
      if(a.gt.313.) then
       if(x.lt.1.015) feprdrop=-1000.
       if(x.gt.1.866) feprdrop=-1000.
       if((x.ge.1.015).and.(x.lt.1.866)) then
        feprdrop=(a-xk0)/(xn1*x+xn0)
       endif
      endif
c
c     convert 'a' from lbm to kg
c
      a=a*(0.454)
      return
      end
```

```
c
c     this function calculates the fuel
c
      function FFUEL(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a0,a1
     &/-21.122990998,24.062379942/
c
      if(x.lt.1.015) ffuel=0.
      if(x.gt.1.866) ffuel=0.
      ffuel=a0+a1*x
      return
      end
```

```
c
c      this function calculates the thrust
c
       function FTHRUST(x)
       implicit integer*4(i-n),real*8(a-h,o-z)
c
       data a10,a11,a12,a13
      &/-302434.56812,698057.42586,-530375.66662,136352.76012/
       data a20,a21
      &/-3750.4152977,9321.314301/
       data a30,a31
      &/985.47082041,6246.7423641/
c
       if(x.lt.1.015) fthrust=0.
       if(x.gt.1.866) fthrust=0.
       if((x.ge.1.015).and.(x.lt.1.30)) then
        fthrust=a10+a11*x+a12*x**2+a13*x**3
       endif
       if((x.ge.1.30).and.(x.lt.1.566)) then
        fthrust=a20+a21*x
       endif
       if((x.ge.1.566).and.(x.le.1.866)) then
        fthrust=a30+a31*x
       endif
       return
       end
```

```
c
c     this function calculates the core speed
c
      function FXN2(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11,a12,a13,a14,a15
     &/-95286.974301,373994.36661,-585721.93068,457820.42224
     &,-178558.05119,27796.370287/
      data a20,a21
     &/65.71222485,21.946074525/
c
      if(x.lt.1.015) fxn2=0.
      if(x.gt.1.866) fxn2=0.
      if((x.ge.1.015).and.(x.lt.1.33)) then
       fxn2=a10+a11*x+a12*x**2+a13*x**3+a14*x**4+a15*x**5
      endif
      if((x.ge.1.33).and.(x.le.1.866)) then
       fxn2=a20+a21*x
      endif
      return
      end
```

APPENDIX C
F107 ENGINE RESPONSE MODEL

This appendix contains the detailed information required for the F107 engine response model. It consists of:

- Observations made during the F107 experiments
- An example of oil pressure decrease at constant core speed as experienced during the F107 experiments
- The correlation of oil pressure decrease with accumulated dust mass and dust concentration
- Nominal behavior of thrust, airflow, and oil pressure
- The general representation of a sample environment
- The general form of the F107 engine response (dust effects) model
- The F107 engine response algorithm

OBSERVATIONS

- MATERIAL DEPOSITION OCCURS IN THE ENGINE BUT INDICATIONS OF THIS MODE OF ENGINE FAILURE OCCUR WELL AFTER A FAILURE MODE INVOLVING A SIGNIFICANT LOSS OF OIL PRESSURE

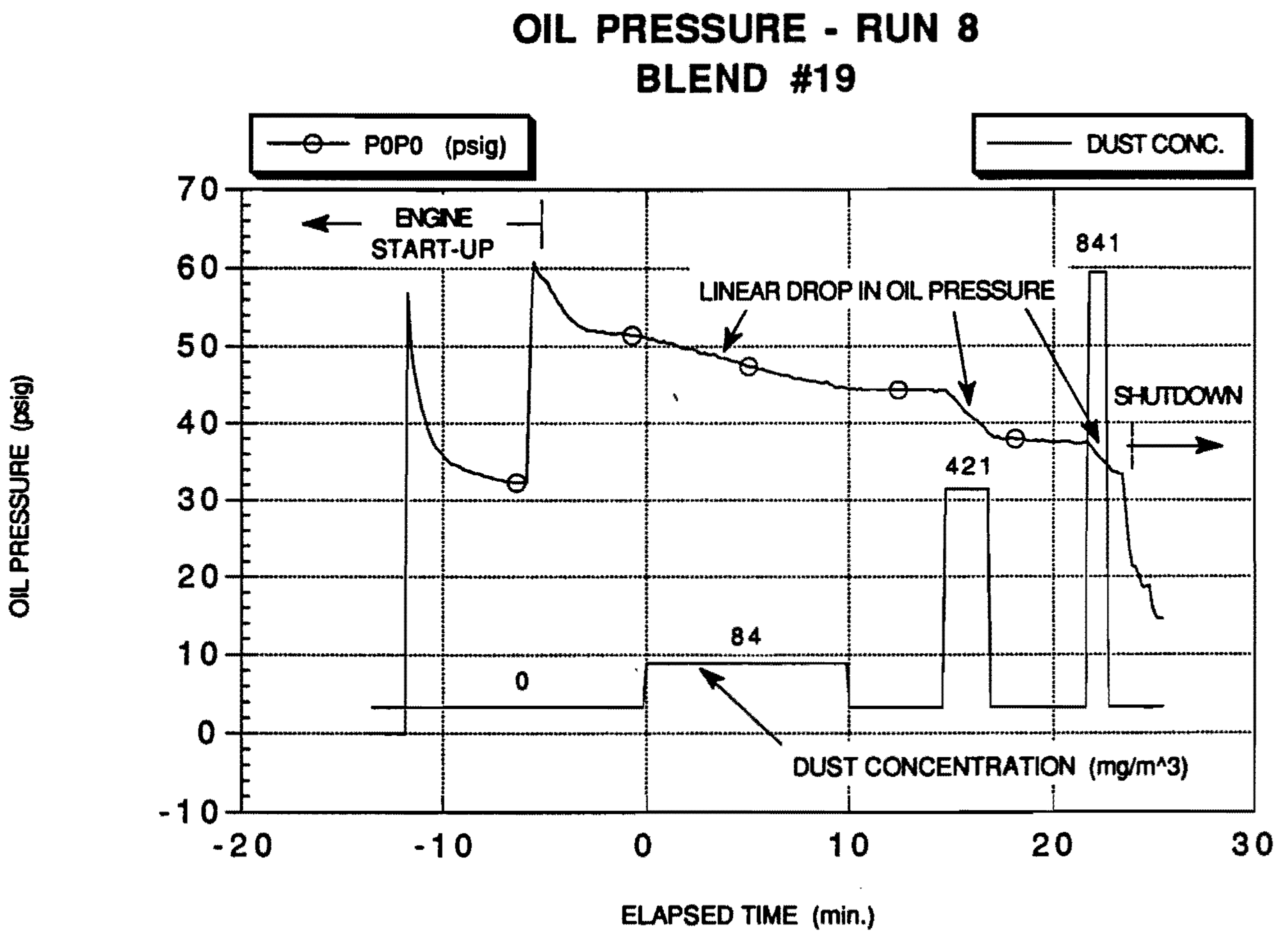
- DUST EFFECTS SOLELY A RESULT OF CONTAMINATION OF THE LUBRICATION SYSTEM OIL FILTER AND A SUBSEQUENT LOSS OF OIL PRESSURE

- ALL OTHER PARAMETERS REMAIN UNCHANGED (INCLUDING THRUST AND AIRFLOW)

- ENGINE OPERATES AT CONSTANT CORE SPEED (N2) FOR A GIVEN POWER SETTING (CRUISE,MILITARY POWER,etc.)

- A SUDDEN SEIZURE OF THE ENGINE RESULTING FROM UNACCEPTABLY LOW OIL PRESSURE (25 psig) IS THE PRIMARY EFFECT OF DUST EXPOSURE

DATA:



MODEL:

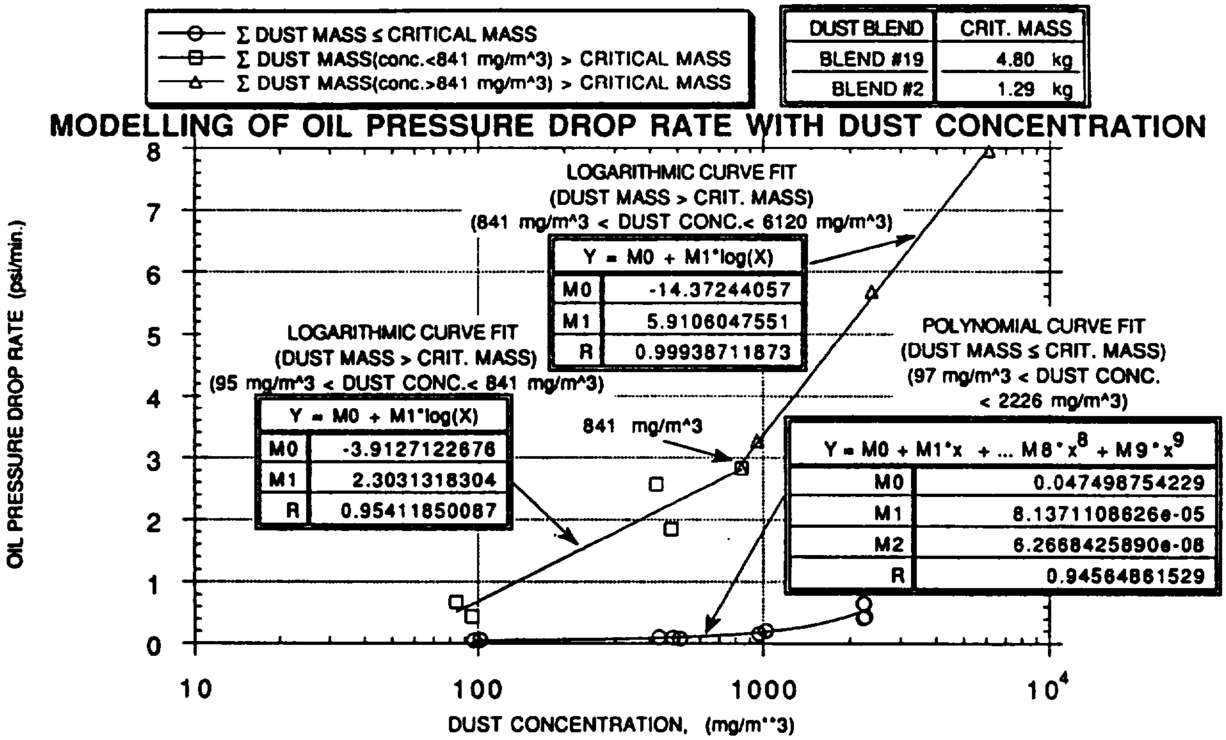
$$\Delta P_{2n}(t) = \frac{d(P_2)}{dt} * \tau_n(t)$$

where,

$$0 < \tau_n(t) < \Delta t_n$$

$$t_{n-1} < t < t_n$$

Figure C–1. Oil pressure decrease.



ACCOUNTING FOR CRITICAL MASS PARAMETER WHEN ENCOUNTERING MULTIPLE DUST BLEND ENVIRONMENTS:

x_{19} = fraction of total dust mass consisting of blend #19
x_2 = fraction of total dust mass consisting of blend #2

$crit_{19}$ = critical mass for blend #19
$crit_2$ = critical mass for blend #2
crit = representative critical mass for multiple blend environments

$$crit = x_{19} * crit_{19} + x_2 * crit_2$$

Figure C-2. Correlation of oil pressure decrease rate with accumulated dust mass and dust concentration.

Table C-1. Pre-dust curve fits - nominal behavior.

P = a0 + a1*N2 + a2*N2^2 + a3*N2^3 + a4*N2^4 + a5*N2^5 + a6*N2^6 + a7*N2^7 + a8*N2^8 + a9*N2^

where: P = parameter
N2 = engine core speed

parameter	units	N2 lower bound (rpm)	N2 upper bound (rpm)	---------polynomial coefficients (3 significant figures)---------- a0 / a6	a1 / a7	a2 / a8	a3 / a9	a4	a5
THRUST	lbf	49295	57171	+2.52E+03	-1.07E-01	+1.23E-06			
		57171	62016	-1.68E+03	+3.65E-02				
AIRFLOW	lbm/sec	49295	53027	+3.93E+02	-2.19E+02	+4.05E-07	-2.45E-12		
		53027	62016	-1.83E+01	+5.10E-04				
POPO	psig	49295	62016	-9.65E+00	+1.40E-03				

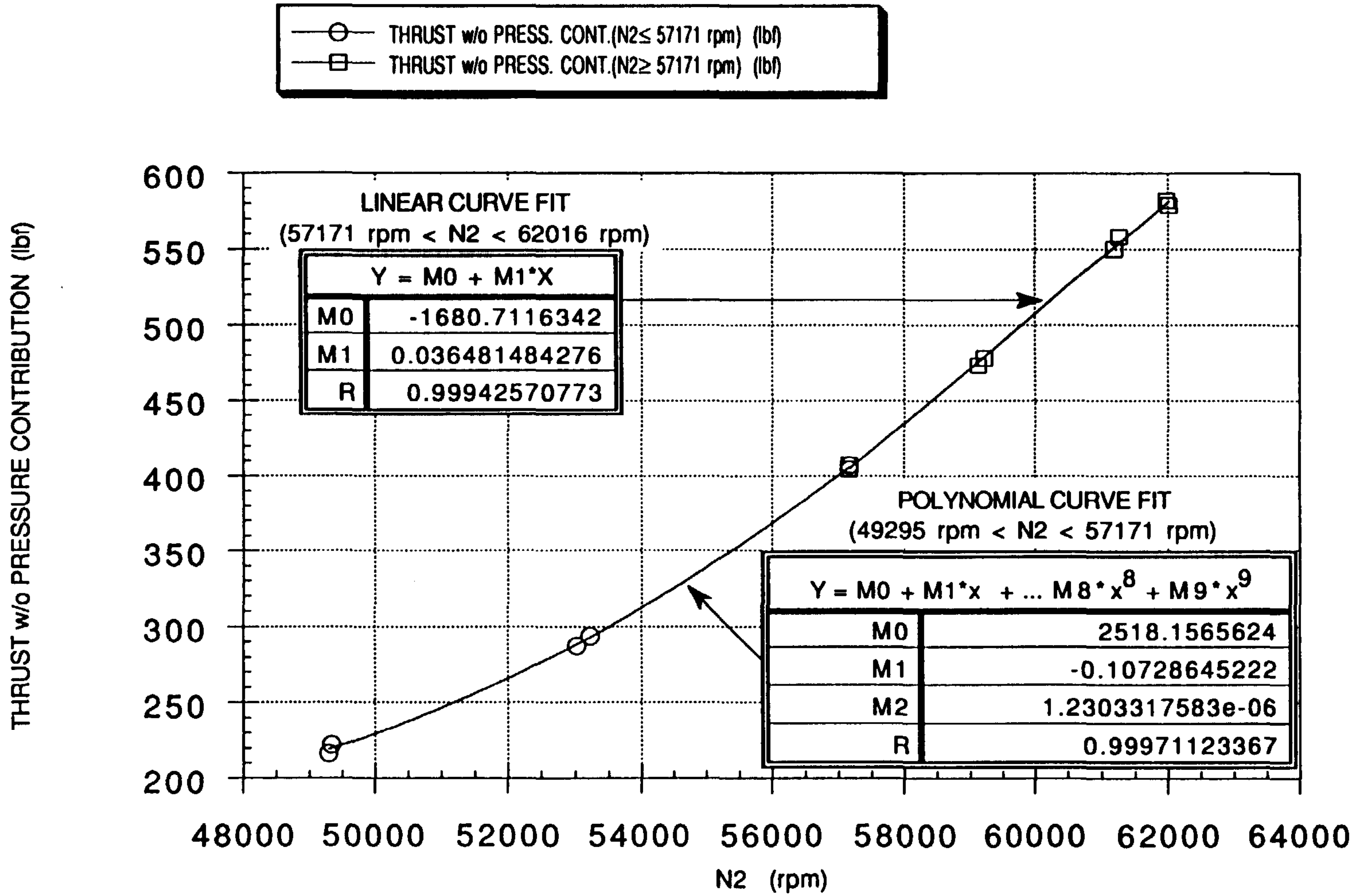


Figure C-3. Thrust calculation nominal behavior.

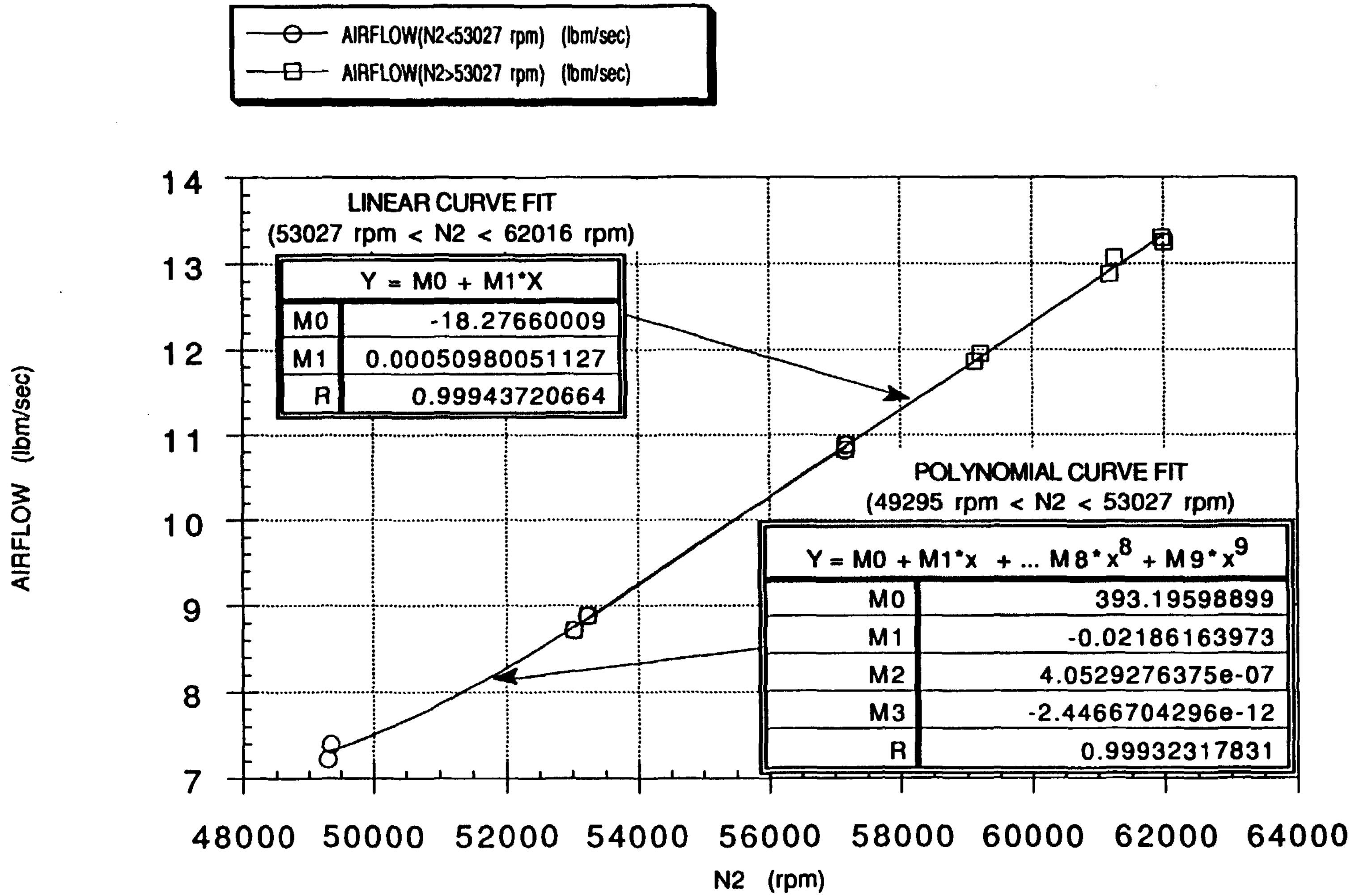


Figure C-4. Airflow nominal behavior.

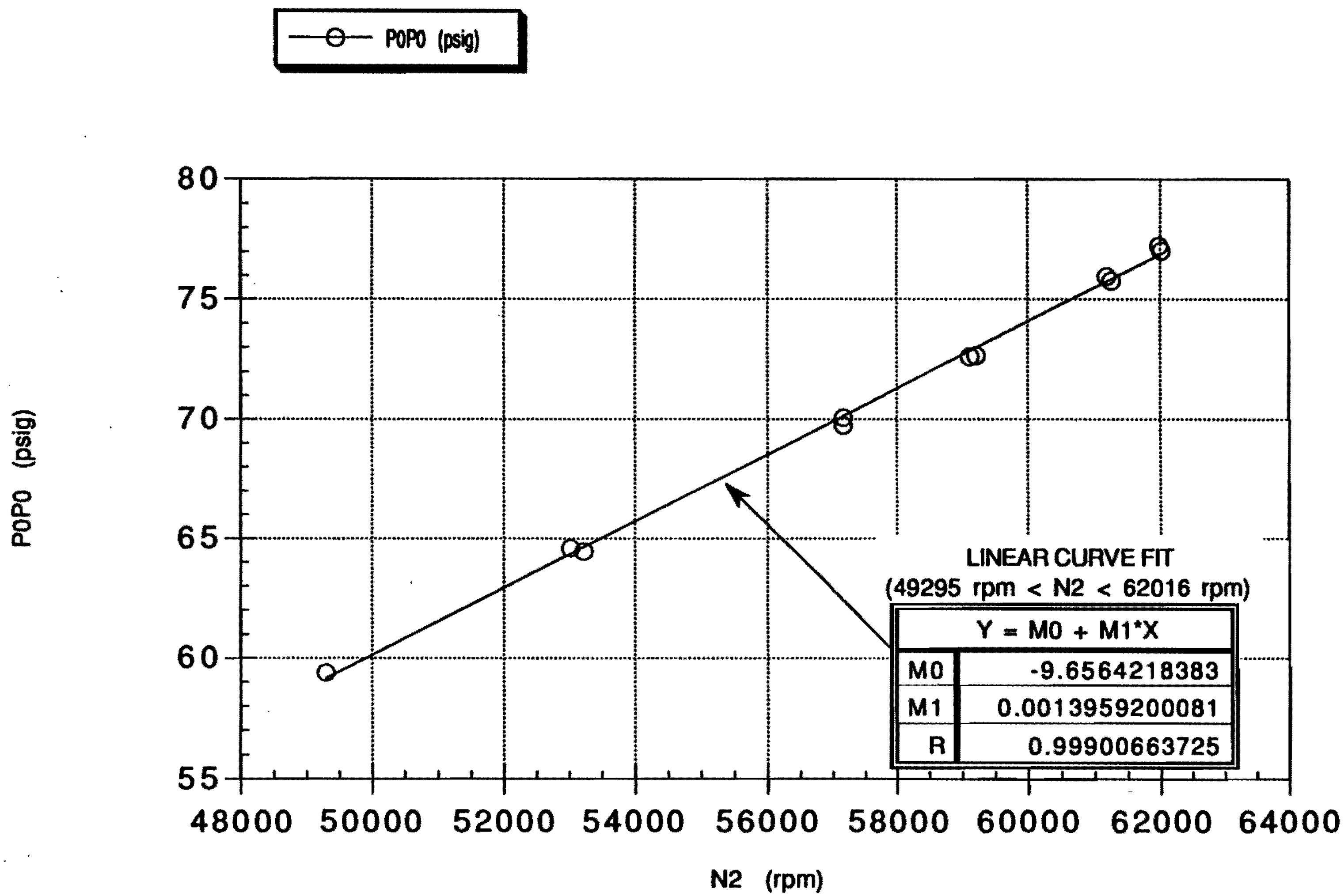
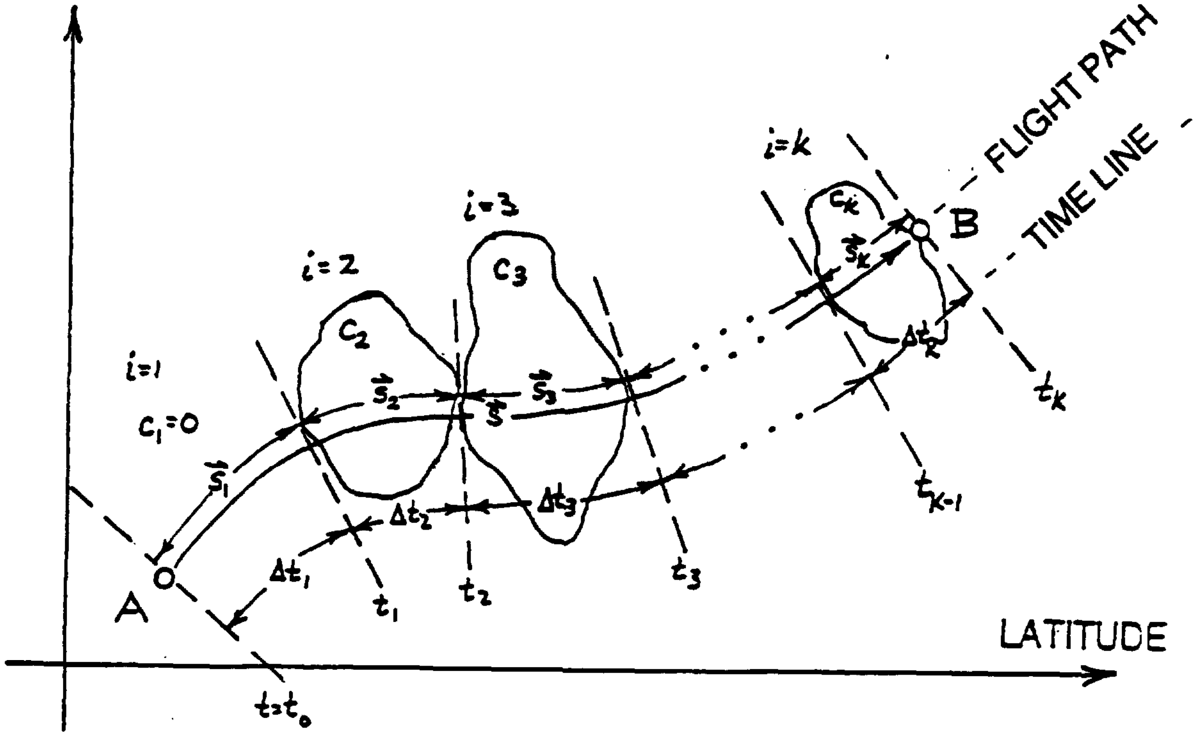


Figure C-5. Oil pressure nominal behavior.

- CONSIDER A PIECEWISE REPRESENTATION OF AN INTENDED FLIGHT PATH, $\vec{s}$, BASED ON DISCRETE REGIONS, i, OF LOCALLY CONSTANT DUST CONCENTRATION, c_i.

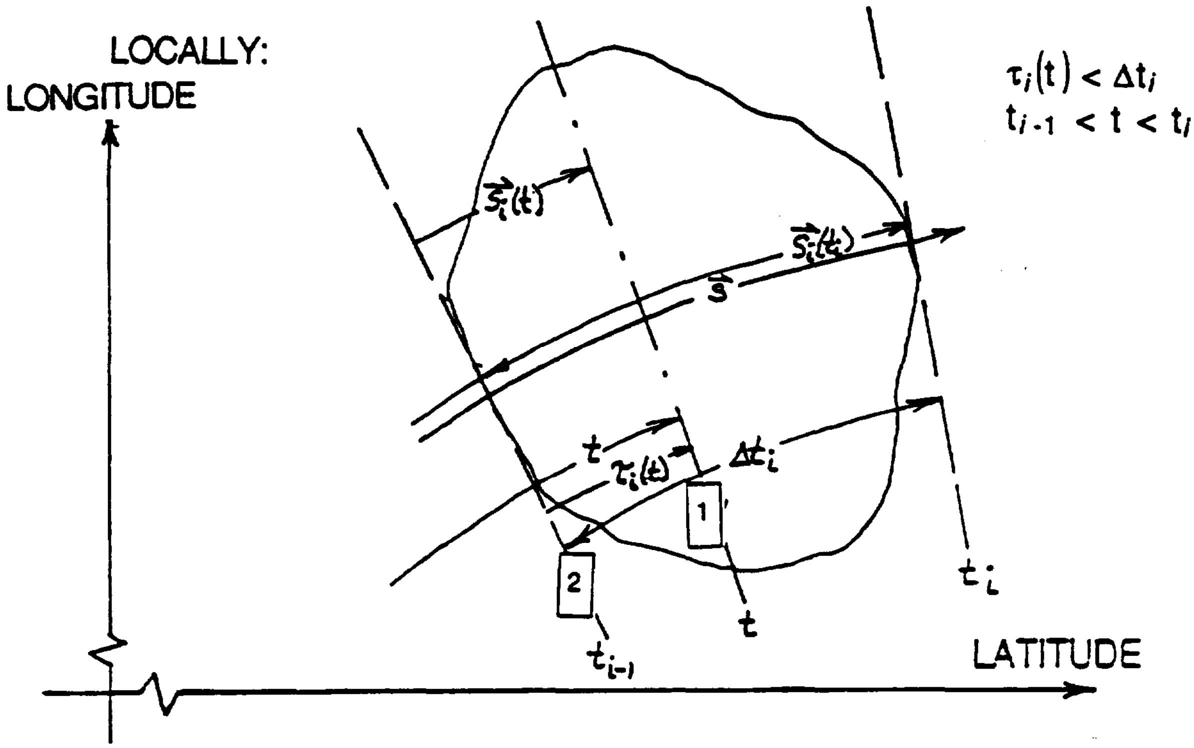


where,

$\vec{s}$	=	flight path from A to B
t	=	time from origin
k	=	total # of discrete environments along $\vec{s}$
i	=	index for current environment encounter
n	=	dummy index for prior environment encounters

t_i	=	time at conclusion of encounter i
Δt_i	=	time duration of encounter i
$\tau_i(t)$	=	elapsed time within encounter i
c_i	=	dust concentration (constant throughout i)
$\vec{s}_i$	=	path traversed through encounter i

Figure C-6. Sample environment.



GENERAL FORM:

$$P_{2i}(t) = -\sum_{n=1}^{(i-1)} \Delta P_{2n}(t_n) + \left[P_{2nominal}(N_2(t)) - \Delta P_{2i}(t)\right]$$

1 2 4 3 5

where,

1 OIL PRESSURE WITH DUST EFFECTS DURING ENCOUNTER *i*

2 ACCUMULATED DUST EFFECTS TO DATE (not a function of time)

3 INCREMENT IN DUST EFFECTS ON P DURING *i* (a function of time)

4 NOMINAL BEHAVIOR OF OIL PRESSURE SET BY POWER SETTING (N2)

5 DUST EFFECTS IN CURRENT ENCOUNTER

Figure C-7. General form of parameter response.

DUST EFFECTS MODEL

OIL PRESSURE MUST:

- REFLECT PRE-DUST PERFORMANCE
- REFLECT EFFECTS OF CHANGING POWER SETTING (N2)
- REFLECT CURRENT DUST CONCENTRATION
- REFLECT CUMULATIVE EROSION EFFECTS

$$P_{2i}(t) = -\sum_{n=1}^{(i-1)} \Delta P_{2n}(t_n) + \left[P_{2nominal}\left(N_2(t)\right) - \Delta P_{2i}(t)\right]$$

DUST EFFECTS DURING *i*

N2 (POWER SETTING OF
CRUISE, MILITARY POWER, etc.)

OIL PRESSURE VALUE (PRE-DUST PERFORMANCE)

CUMULATIVE DUST EFFECTS TO DATE

OIL PRESSURE VALUE WITH DUST EFFECTS AND HISTORY OF DUST EFFECTS

WHERE,

$$\Delta P_{2n}(t) = \frac{d(P_2)}{dt} * \tau_n(t)$$

DURATION THROUGH ENCOUNTER

OIL PRESSURE DROP RATE

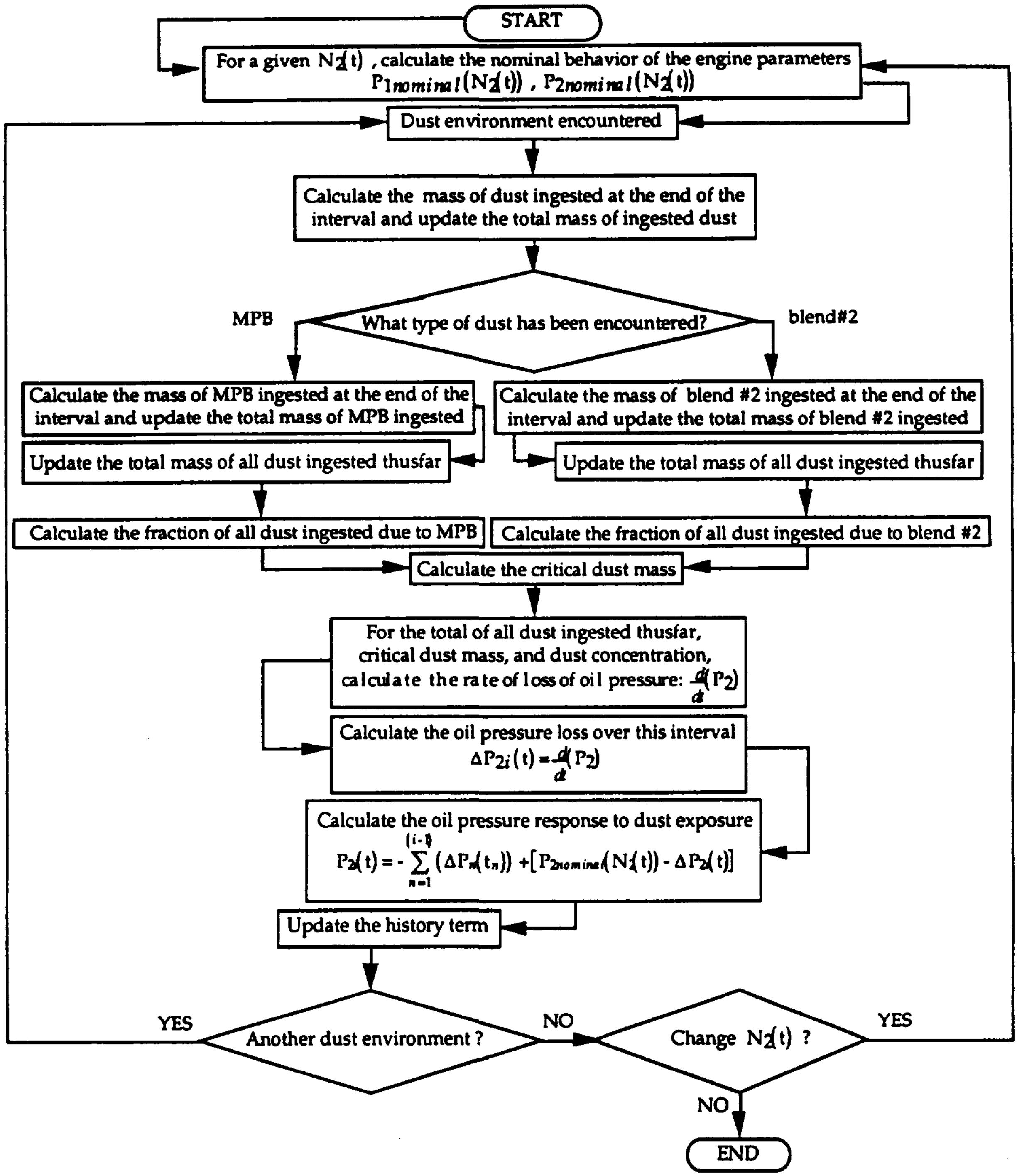


Figure C-8. F107 engine response algorithm.

Solutions for the F107 Sample Problems

This appendix contains the Calspan solutions for the set of sample problems for the F107 engine response model. The solutions were generated by the Calspan version of the F107 engine response model, named F107.f, whose source listing is presented in later in this appendix. The solutions are labelled as:

f107.out(a)(b)

where: (a) = the problem #
(b) = the part # (for problems 1-3)

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  5.000E+02  1.200E+00
ienc=  2 =>  2  5.000E+02  1.200E+00
ienc=  3 =>  2  5.000E+02  1.200E+00
ienc=  4 =>  2  5.000E+02  1.200E+00
ienc=  5 =>  2  5.000E+02  1.200E+00
ienc=  6 =>  2  5.000E+02  1.200E+00
ienc=  7 =>  2  5.000E+02  1.200E+00
ienc=  8 =>  2  5.000E+02  1.200E+00
ienc=  9 =>  2  5.000E+02  1.200E+00
ienc= 10 =>  2  5.000E+02  1.200E+00

debug mode {0=off,1=on} => 0

calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	13.3	0.000E+00	76.9	581.1
1	2	500.0	1.2	13.3	1.776E-01	76.8	581.1
2	2	500.0	1.2	13.3	3.552E-01	76.7	581.1
3	2	500.0	1.2	13.3	5.328E-01	76.6	581.1
4	2	500.0	1.2	13.3	7.104E-01	76.5	581.1
5	2	500.0	1.2	13.3	8.880E-01	76.4	581.1
6	2	500.0	1.2	13.3	1.066E+00	76.3	581.1
7	2	500.0	1.2	13.3	1.243E+00	76.1	581.1
8	2	500.0	1.2	13.3	1.421E+00	73.4	581.1
9	2	500.0	1.2	13.3	1.598E+00	70.6	581.1
10	2	500.0	1.2	13.3	1.776E+00	67.9	581.1

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 5
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2  5.000E+02  2.400E+00
ienc= 2 => 2  5.000E+02  2.400E+00
ienc= 3 => 2  5.000E+02  2.400E+00
ienc= 4 => 2  5.000E+02  2.400E+00
ienc= 5 => 2  5.000E+02  2.400E+00

debug mode {0=off,1=on} => 0

calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	13.3	0.000E+00	76.9	581.1
1	2	500.0	2.4	13.3	3.552E-01	76.7	581.1
2	2	500.0	2.4	13.3	7.104E-01	76.5	581.1
3	2	500.0	2.4	13.3	1.066E+00	76.3	581.1
4	2	500.0	2.4	13.3	1.421E+00	70.7	581.1
5	2	500.0	2.4	13.3	1.776E+00	65.2	581.1

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2  5.000E+02  4.000E+00
ienc= 2 => 2  5.000E+02  4.000E+00
ienc= 3 => 2  5.000E+02  4.000E+00

debug mode {0=off,1=on} => 0

calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	13.3	0.000E+00	76.9	581.1
1	2	500.0	4.0	13.3	5.920E-01	76.5	581.1
2	2	500.0	4.0	13.3	1.184E+00	76.2	581.1
3	2	500.0	4.0	13.3	1.776E+00	67.0	581.1

```
PEARL - F107 response model


inputs :

core speed (rpm)  {16.5-80} =>  6.200E+04
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) {1-10} =>  1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  5.000E+02  1.200E+01

debug mode {0=off,1=on} => 0


calculation begun
```

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	13.3	0.000E+00	76.9	581.1
1	2	500.0	12.0	13.3	1.776E+00	49.3	581.1

PEARL - F107 response model

inputs :

```
core speed (rpm)  {16.5-80} =>  6.200E+04
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  6.000E+03  1.200E+00
ienc=  2 =>  2  6.000E+03  1.200E+00
ienc=  3 =>  2  6.000E+03  1.200E+00
ienc=  4 =>  2  6.000E+03  1.200E+00
ienc=  5 =>  2  6.000E+03  1.200E+00
ienc=  6 =>  2  6.000E+03  1.200E+00
ienc=  7 =>  2  6.000E+03  1.200E+00
ienc=  8 =>  2  6.000E+03  1.200E+00
ienc=  9 =>  2  6.000E+03  1.200E+00
ienc= 10 =>  2  6.000E+03  1.200E+00

debug mode {0=off,1=on} => 0
```

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	13.3	0.000E+00	76.9	581.1
1	2	6000.0	1.2	13.3	2.131E+00	67.3	581.1
2	2	6000.0	1.2	13.3	4.262E+00	57.8	581.1
3	2	6000.0	1.2	13.3	6.394E+00	48.2	581.1
4	2	6000.0	1.2	13.3	8.525E+00	38.7	581.1
5	2	6000.0	1.2	13.3	1.066E+01	29.1	581.1
*** oil press. below 25.0 psig limit at 0.5 minutes into the 6-th encounter							
6	2	6000.0	1.2	13.3	1.279E+01	19.6	581.1
7	2	6000.0	1.2	13.3	1.492E+01	10.0	581.1
8	2	6000.0	1.2	13.3	1.705E+01	0.5	581.1
9	2	6000.0	1.2	13.3	1.918E+01	-9.1	581.1
10	2	6000.0	1.2	13.3	2.131E+01	-18.6	581.1

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 5
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  6.000E+03  2.400E+00
ienc=  2 =>  2  6.000E+03  2.400E+00
ienc=  3 =>  2  6.000E+03  2.400E+00
ienc=  4 =>  2  6.000E+03  2.400E+00
ienc=  5 =>  2  6.000E+03  2.400E+00

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)    (min)  (lbm/sec)   (kg)     (psig)    (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0       0.0       0.0      13.3  0.000E+00    76.9     581.1
  1  2    6000.0       2.4      13.3  4.262E+00    57.8     581.1
  2  2    6000.0       2.4      13.3  8.525E+00    38.7     581.1
*** oil press. below 25.0 psig limit at     1.7 minutes into the  3-rd encounter
  3  2    6000.0       2.4      13.3  1.279E+01    19.6     581.1
  4  2    6000.0       2.4      13.3  1.705E+01     0.5     581.1
  5  2    6000.0       2.4      13.3  2.131E+01   -18.6     581.1
```

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 6.000E+03 4.000E+00
ienc= 2 => 2 6.000E+03 4.000E+00
ienc= 3 => 2 6.000E+03 4.000E+00

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)     (min)  (lbm/sec)    (kg)     (psig)    (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0       0.0       0.0      13.3  0.000E+00    76.9     581.1
  1  2    6000.0       4.0      13.3  7.104E+00    45.1     581.1
*** oil press. below 25.0 psig limit at     2.5 minutes into the  2-nd encounter
  2  2    6000.0       4.0      13.3  1.421E+01    13.2     581.1
  3  2    6000.0       4.0      13.3  2.131E+01   -18.6     581.1
```

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 6.000E+03 1.200E+01

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)    (min)  (lbm/sec)   (kg)    (psig)    (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0       0.0        0.0      13.3  0.000E+00    76.9     581.1
*** oil press. below 25.0 psig limit at      6.5 minutes into the  1-st encounter
  1  2    6000.0       12.0      13.3  2.131E+01   -18.6     581.1
```

```
PEARL - F107 response model


inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 => 2  2.000E+03  1.200E+00
ienc=  2 => 2  2.000E+03  1.200E+00
ienc=  3 => 2  2.000E+03  1.200E+00
ienc=  4 => 2  2.000E+03  1.200E+00
ienc=  5 => 2  2.000E+03  1.200E+00
ienc=  6 => 2  2.000E+03  1.200E+00
ienc=  7 => 2  2.000E+03  1.200E+00
ienc=  8 => 2  2.000E+03  1.200E+00
ienc=  9 => 2  2.000E+03  1.200E+00
ienc= 10 => 2  2.000E+03  1.200E+00

debug mode {0=off,1=on} => 0


calculation begun


 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
           (mg/m^3)    (min)  (lbm/sec)   (kg)    (psig)   (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0        0.0       0.0      13.3  0.000E+00    76.9    581.1
  1  2     2000.0       1.2      13.3  7.104E-01    76.6    581.1
  2  2     2000.0       1.2      13.3  1.421E+00    70.5    581.1
  3  2     2000.0       1.2      13.3  2.131E+00    64.3    581.1
  4  2     2000.0       1.2      13.3  2.842E+00    58.1    581.1
  5  2     2000.0       1.2      13.3  3.552E+00    52.0    581.1
  6  2     2000.0       1.2      13.3  4.262E+00    45.8    581.1
  7  2     2000.0       1.2      13.3  4.973E+00    39.6    581.1
  8  2     2000.0       1.2      13.3  5.683E+00    33.5    581.1
  9  2     2000.0       1.2      13.3  6.394E+00    27.3    581.1
*** oil press. below 25.0 psig limit at     0.4 minutes into the 10-th encounter
 10  2     2000.0       1.2      13.3  7.104E+00    21.1    581.1
```

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 5
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.000E+03 2.400E+00
ienc= 2 => 2 2.000E+03 2.400E+00
ienc= 3 => 2 2.000E+03 2.400E+00
ienc= 4 => 2 2.000E+03 2.400E+00
ienc= 5 => 2 2.000E+03 2.400E+00

debug mode {0=off,1=on} => 0

calculation begun

 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)     (min)  (lbm/sec)    (kg)    (psig)   (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0       0.0       0.0      13.3  0.000E+00    76.9    581.1
  1  2    2000.0       2.4      13.3  1.421E+00    64.6    581.1
  2  2    2000.0       2.4      13.3  2.842E+00    52.2    581.1
  3  2    2000.0       2.4      13.3  4.262E+00    39.9    581.1
  4  2    2000.0       2.4      13.3  5.683E+00    27.6    581.1
*** oil press. below 25.0 psig limit at      0.5 minutes into the  5-th encounter
  5  2    2000.0       2.4      13.3  7.104E+00    15.2    581.1
```

PEARL - F107 response model

inputs :

core speed (rpm) {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 3
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc= 1 => 2 2.000E+03 4.000E+00
ienc= 2 => 2 2.000E+03 4.000E+00
ienc= 3 => 2 2.000E+03 4.000E+00

debug mode {0=off,1=on} => 0

calculation begun

```
 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
        (mg/m^3)     (min)  (lbm/sec)    (kg)     (psig)    (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0        0.0        0.0      13.3  0.000E+00     76.9     581.1
  1  2    2000.0        4.0      13.3  2.368E+00     56.3     581.1
  2  2    2000.0        4.0      13.3  4.736E+00     35.8     581.1
*** oil press. below 25.0 psig limit at      2.1 minutes into the  3-rd encounter
  3  2    2000.0        4.0      13.3  7.104E+00     15.2     581.1
```

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) =>  1.470E+01
ambient temperature (F) =>  5.900E+01

# of encounters (-) {1-10} =>  1
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  2.000E+03  1.200E+01

debug mode {0=off,1=on} => 0


calculation begun


 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)     (min)  (lbm/sec)    (kg)     (psig)    (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0       0.0        0.0      13.3  0.000E+00    76.9     581.1
*** oil press. below 25.0 psig limit at    10.1 minutes into the  1-st encounter
  1  2    2000.0       12.0      13.3  7.104E+00    15.2     581.1
```

```
PEARL - F107 response model


inputs :

core speed (rpm)  {16.5-80} => 5.800E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  2  6.000E+03  1.200E+00
ienc=  2 =>  2  6.000E+03  1.200E+00
ienc=  3 =>  2  6.000E+03  1.200E+00
ienc=  4 =>  2  6.000E+03  1.200E+00
ienc=  5 =>  2  6.000E+03  1.200E+00
ienc=  6 =>  2  6.000E+03  1.200E+00
ienc=  7 =>  2  6.000E+03  1.200E+00
ienc=  8 =>  2  6.000E+03  1.200E+00
ienc=  9 =>  2  6.000E+03  1.200E+00
ienc= 10 =>  2  6.000E+03  1.200E+00

debug mode {0=off,1=on} => 0


calculation begun


 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)    (min)  (lbm/sec)   (kg)    (psig)   (lbf)
+--+----+---------+---------+--------+---------+--------+--------
  0  0       0.0       0.0      11.3  0.000E+00    71.3    435.2
  1  2    6000.0       1.2      11.3  1.805E+00    61.8    435.2
  2  2    6000.0       1.2      11.3  3.610E+00    52.2    435.2
  3  2    6000.0       1.2      11.3  5.416E+00    42.7    435.2
  4  2    6000.0       1.2      11.3  7.221E+00    33.1    435.2
*** oil press. below 25.0 psig limit at     1.0 minutes into the  5-th encounter
  5  2    6000.0       1.2      11.3  9.026E+00    23.6    435.2
  6  2    6000.0       1.2      11.3  1.083E+01    14.0    435.2
  7  2    6000.0       1.2      11.3  1.264E+01     4.5    435.2
  8  2    6000.0       1.2      11.3  1.444E+01    -5.1    435.2
  9  2    6000.0       1.2      11.3  1.625E+01   -14.6    435.2
 10  2    6000.0       1.2      11.3  1.805E+01   -24.2    435.2
```

```
PEARL - F107 response model

inputs :

core speed (rpm)  {16.5-80} => 6.200E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

ienc=  1 =>  1  1.000E+02  1.000E+01
ienc=  2 =>  0  0.000E+00  2.000E+00
ienc=  3 =>  2  2.000E+02  1.000E+01
ienc=  4 =>  2  5.000E+02  5.000E+00
ienc=  5 =>  2  2.000E+02  1.000E+01
ienc=  6 =>  0  0.000E+00  2.000E+00
ienc=  7 =>  1  1.000E+03  5.000E+00
ienc=  8 =>  1  2.000E+03  2.000E+00
ienc=  9 =>  1  1.000E+03  5.000E+00
ienc= 10 =>  2  1.000E+02  2.000E+01

debug mode {0=off,1=on} => 0


calculation begun


 i blend dust conc time int AIR FLOW ACC DUST OIL PRESS  THRUST
         (mg/m^3)     (min)  (lbm/sec)    (kg)     (psig)   (lbf)
+--+----+---------+---------+--------+--------+--------+--------
  0  0        0.0       0.0      13.3  0.000E+00     76.9     581.1
  1  1      100.0      10.0      13.3  2.960E-01     76.3     581.1
  2  0        0.0       2.0      13.3  2.960E-01     76.3     581.1
  3  2      200.0      10.0      13.3  8.880E-01     75.7     581.1
  4  2      500.0       5.0      13.3  1.628E+00     75.3     581.1
  5  2      200.0      10.0      13.3  2.220E+00     61.4     581.1
  6  0        0.0       2.0      13.3  2.220E+00     61.4     581.1
  7  1     1000.0       5.0      13.3  3.700E+00     44.6     581.1
  8  1     2000.0       2.0      13.3  4.884E+00     34.3     581.1
*** oil press. below 25.0 psig limit at      2.8 minutes into the  9-th encounter
  9  1     1000.0       5.0      13.3  6.364E+00     17.5     581.1
 10  2      100.0      20.0      13.3  6.956E+00      3.6     581.1
```

PEARL - F107 response model

inputs :

core speed (rpm) {16.5-80} => 5.800E+04
ambient pressure (psia) => 1.470E+01
ambient temperature (F) => 5.900E+01

# of encounters (-) {1-10} => 10
blend {1=mpb,2=blend2} , dust conc. (mg/m^3) , duration (min)

```
ienc=  1 => 1  6.000E+03  1.200E+00
ienc=  2 => 1  6.000E+03  1.200E+00
ienc=  3 => 1  6.000E+03  1.200E+00
ienc=  4 => 1  6.000E+03  1.200E+00
ienc=  5 => 1  6.000E+03  1.200E+00
ienc=  6 => 1  6.000E+03  1.200E+00
ienc=  7 => 1  6.000E+03  1.200E+00
ienc=  8 => 1  6.000E+03  1.200E+00
ienc=  9 => 1  6.000E+03  1.200E+00
ienc= 10 => 1  6.000E+03  1.200E+00
```

debug mode {0=off,1=on} => 0

calculation begun

i	blend	dust conc (mg/m^3)	time int (min)	AIR FLOW (lbm/sec)	ACC DUST (kg)	OIL PRESS (psig)	THRUST (lbf)
0	0	0.0	0.0	11.3	0.000E+00	71.3	435.2
1	1	6000.0	1.2	11.3	1.805E+00	70.7	435.2
2	1	6000.0	1.2	11.3	3.610E+00	70.0	435.2
3	1	6000.0	1.2	11.3	5.416E+00	60.5	435.2
4	1	6000.0	1.2	11.3	7.221E+00	50.9	435.2
5	1	6000.0	1.2	11.3	9.026E+00	41.4	435.2
6	1	6000.0	1.2	11.3	1.083E+01	31.8	435.2
*** oil press. below 25.0 psig limit at 0.9 minutes into the 7-th encounter							
7	1	6000.0	1.2	11.3	1.264E+01	22.3	435.2
8	1	6000.0	1.2	11.3	1.444E+01	12.7	435.2
9	1	6000.0	1.2	11.3	1.625E+01	3.2	435.2
10	1	6000.0	1.2	11.3	1.805E+01	-6.4	435.2

Source Code Listings for the Calspan Version of the F107 Engine Response Model

This appendix contains the sorce code listings for the Calspan version of the F107 engine response model.

The main program :

- f107.f

Associated subprograms:

- fair.f
- foil.f
- foilrate.f
- fthrust.f

```
c
c     f107.f is a code which evaluates the aircraft responses model
c      developed for DNA through SAIC and KAMAN under W/A # L0380500
c      during the period 06/01/92 thru 10/31/92.
c
c     engine parameters:
c
c        xn2      - core speed (rpm)
c
c      (core speed correlation)
c
c        thrust   - thrust (lbf)
c        air      - airflow (lbm/sec)
c        xoil     - oil pressure (psig)
c
c       (subscripts)
c
c        ()nom    - nominal value
c        ()del    - (in/de)crement over current interval
c        ()sum    - sum of (in/de)crements over previous intervals
c        ()1      - most probable blend
c        ()2      - blend #2
c
c       (prescripts)
c        f()      - function which generates the value of the variable
c
      implicit integer*4(i-n),real*8(a-h,o-z)
      dimension ib(10),c(10),delt(10)
c
      data const/1.699e-06/
c
      open(7,file='f107.out',status='unknown')
c
      write(*,*)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'PEARL - F107 response model'
      write(*,*)
      write(*,*)
      write(*,'(a)') 'inputs :'
      write(*,*)
      write(*,100)
 100  format('core speed (rpm)  {49295-62016} => ',$)
      read(*,*) xn2
      write(7,*)
      write(7,*)
      write(7,*)
      write(7,'(a)') 'PEARL - F107 response model'
      write(7,*)
      write(7,*)
      write(7,'(a)') 'inputs :'
      write(7,*)
      write(7,200) xn2
 200  format('core speed (rpm)  {16.5-80} => ',1pe10.3)
      write(*,101)
 101  format('ambient pressure (psia) => ',$)
```

```
      read(*,*) pamb
      write(7,201) pamb
 201  format('ambient pressure (psia) => ',1pe10.3)
      write(*,102)
 102  format('ambient temperature (F) => ',$)
      read(*,*) tamb
      write(7,202) tamb
 202  format('ambient temperature (F) => ',1pe10.3)
      write(*,*)
      write(7,*)
      write(*,103)
 103  format('# of encounters (-) {1-10} => ',$)
      read(*,*) nenc
      write(7,203) nenc
 203  format('# of encounters (-) {1-10} => ',i2)
      write(*,104)
 104  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(*,*)
      write(7,204)
 204  format('blend {1=mpb,2=blend2} , dust conc. (mg/m^3) ,'
     &,' duration (min)')
      write(7,*)
      do 1 ienc=1,nenc
       write(*,105) ienc
 105   format('ienc= ',i2,' => ',$)
       read(*,*) ib(ienc),c(ienc),delt(ienc)
       write(7,205) ienc,ib(ienc),c(ienc),delt(ienc)
 205   format('ienc= ',i2,' => ',i2,1x,1pe10.3,1x,1pe10.3)
 1    continue
      write(*,*)
      write(*,150)
 150  format('debug mode {0=off,1=on} => ',$)
      read(*,*) ibug
      write(7,*)
      write(7,250) ibug
 250  format('debug mode {0=off,1=on} => ',i1)
      write(*,*)
      write(*,*)
      write(*,'(a)') 'calculation begun'
      write(*,*)
      write(*,*)
      write(7,*)
      write(7,*)
      write(7,'(a)') 'calculation begun'
      write(7,*)
      write(7,*)
c
c     initialize all engine parameters to zero
c
      ienc=0
      none=0
      dust=0.
      oillim=25.
      noilflag=0
      accdust=0.
```

```
      accdust1=0.
      accdust2=0.
      xn2nom=0.
      xn2del=0.
      xn2sum=0.
      cdpnom=0.
      cdpdel=0.
      cdpsum=0.
      fuelnom=0.
      fueldel=0.
      fuelsum=0.
      thrustnom=0.
      thrustdel=0.
      thrustsum=0.
c
c     calculate the ambient density (lbm/sec)
c
      rhoamb=144.*pamb/(53.3*(tamb+460.))
c
c     calculate the engine parameters
c
c     nominal clear air engine parameter values
c
      airnom=FAIR(xn2)
      air=airnom
      oilnom=FOIL(xn2)
      oil=oilnom
      thrustnom=FTHRUST(xn2)
      thrust=thrustnom
c
c     write the header
c
      write(7,500)
 500  format(' i ','blend',' dust conc',' time int '
     &,'AIR FLOW ','ACC DUST ','OIL PRESS','  THRUST ')
      write(7,501)
 501  format('   ','     ',' (mg/m^3) ','   (min)  '
     &,'(lbm/sec)','   (kg)  ','  (psig) ','  (lbf)  ')
      write(7,502)
 502  format('+--','+----','+---------','+---------'
     &,'+--------','+--------','+--------','+--------')
      write(7,550) ienc,none,none,none
     &,air,accdust,oil,thrust
c
c     loop over all encounters
c
      do 2 ienc=1,nenc
      if(ibug.eq.1) write(7,300) ienc
 300  format('ienc = ',i2)
      if(ibug.eq.1) write(7,301) ienc,ib(ienc)
 301  format('ib(',i2,') = ',i2)
      if(ibug.eq.1) write(7,302) ienc,c(ienc)
 302  format('c(',i2,') = ',1pe10.3)
      if(ibug.eq.1) write(7,303) ienc,delt(ienc)
 303  format('delt(',i2,') = ',1pe10.3)
c
```

```
c     calculate the airflow, injested dust over this interval, and the
c      total accumulated dust (based on conditions at the start of the
c      encounter)
c
      air=FAIR(xn2)
      q=air/rhoamb
      dust=const*q*c(ienc)*delt(ienc)
      accdust=dust+accdust
      if(ib(ienc).eq.1) accdust1=dust+accdust1
      if(ib(ienc).eq.2) accdust2=dust+accdust2
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,304) xn2
 304  format('xn2(initial) = ',1pe10.3)
      if(ibug.eq.1) write(7,400) air
 400  format('air = ',1pe10.3)
      if(ibug.eq.1) write(7,305) rhoamb
 305  format('rhoamb = ',1pe10.3)
      if(ibug.eq.1) write(7,306) q
 306  format('q = ',1pe10.3)
      if(ibug.eq.1) write(7,307) dust
 307  format('dust = ',1pe10.3)
      if(ibug.eq.1) write(7,308) accdust1
 308  format('accdust1 = ',1pe10.3)
      if(ibug.eq.1) write(7,309) accdust2
 309  format('accdust2 = ',1pe10.3)
      if(ibug.eq.1) write(7,310) accdust
 310  format('accdust = ',1pe10.3)
c
c     calculate oil
c
      oilrate=FOILRATE(ibug,ib(ienc),accdust1,accdust2
     &,accdust,c(ienc))
      oilnom=FOIL(xn2)
      oildel=oilrate*delt(ienc)
      oil=oilnom-oildel-oilsum
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,314) xn2
 314  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,315) oilnom
 315  format('oilnom = ',1pe10.3)
      if(ibug.eq.1) write(7,316) oilrate
 316  format('oilrate = ',1pe10.3)
      if(ibug.eq.1) write(7,317) oildel
 317  format('oildel = ',1pe10.3)
      if(ibug.eq.1) write(7,318) oilsum
 318  format('oilsum = ',1pe10.3)
      if(ibug.eq.1) write(7,319) oil
 319  format('oil = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     check for oil pressure exceeding operational limits
c
      if(oil.le.oillim) then
       if(noilflag.eq.0) then
        noilflag=1
```

```
        oildelc=oillim-(oilnom-oilsum)
        tau=-oildelc/oilrate
        write(7,600) oillim,tau,ienc
 600    format('*** oil press. below ',f4.1,' psig limit'
     &,' at ',f7.1,' minutes into the ',i2,'-th encounter')
       endif
      endif
c
c     calculate thrust
c
      thrustnom=FTHRUST(xn2)
      thrust=thrustnom
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,330) xn2
 330  format('xn2 = ',1pe10.3)
      if(ibug.eq.1) write(7,331) thrustnom
 331  format('thrustnom = ',1pe10.3)
      if(ibug.eq.1) write(7,335) thrust
 335  format('thrust = ',1pe10.3)
      if(ibug.eq.1) write(7,*)
      if(ibug.eq.1) write(7,*)
c
c     update the sum terms of each engine parameter
c
      oilsum=oilsum+oildel
      write(7,550) ienc,ib(ienc),c(ienc),delt(ienc)
     &,air,accdust,oil,thrust
 550  format((1x,i2),(2x,i1,2x),2((1x,f7.1,2x)),
     &((f7.1,2x)),((1pe9.3)),2((1x,0pf7.1,1x)))
 2    continue
      stop
      end
```

```
c
c     this function calculates the airflow
c
      function FAIR(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11,a12,a13
     &/393.19598899,-0.02186163973,4.052976375e-07,-2.4466704296e-12/
      data a20,a21
     &/-18.2760009,0.00050980051127/
c
      if(x.lt.49295.) fair=0.
      if(x.gt.62016.) fair=0.
      if((x.ge.49295.).and.(x.lt.53027.)) then
       fair=a10+a11*x+a12*x**2+a13*x**3
      endif
      if((x.ge.53027.).and.(x.le.62016.)) then
       fair=a20+a21*x
      endif
      return
      end
```

```
c
c     this function calculates the nominal value of oil pressure
c
      function FOIL(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11
     &/-9.6564218383,0.0013959200081/
c
      if(x.lt.49295.) foil=0.
      if(x.gt.62016.) foil=0.
      if((x.ge.49295.).and.(x.lt.62016.)) then
       foil=a10+a11*x
      endif
      return
      end
```

```
c
c     this function calculates the oil pressure drop rate due to dust
c
      function FOILRATE(ibug,i,acc1,acc2,acc,c)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data crit1,crit2/4.80,1.29/
      data a10,a11,a12
     &/0.047498754229,8.1371108626e-05,6.2668425890e-08/
      data a20,a21
     &/-3.9127122676,2.3031318304/
      data a30,a31
     &/-14.37244057,5.9106047551/
c
      if(acc.eq.0.) then
       if(i.eq.1) crit=crit1
       if(i.eq.2) crit=crit2
      endif
      if(acc.gt.0.) then
       x1=acc1/acc
       x2=acc2/acc
       crit=x1*crit1+x2*crit2
      endif
      foilrate=0.
      if((acc.gt.0.).and.(acc.lt.crit).and.(c.gt.0.)) then
       if(ibug.eq.1) write(7,'(a)') 'correlation #1'
       if(ibug.eq.1) write(7,100) i,acc1,acc2,acc,crit,c
 100   format('i=',i1,1x,'acc1=',1pe10.3,1x,'acc2=',1pe10.3
     &,1x,'acc=',1pe10.3,1x,'crit=',1pe10.3,1x,'c=',1pe10.3)
       foilrate=a10+a11*c+a12**2
      endif
      if((acc.ge.crit).and.(c.gt.0.)) then
       if((c.ge.95.).and.(c.lt.841.)) then
        if(ibug.eq.1) write(7,'(a)') 'correlation #2'
        if(ibug.eq.1) write(7,100) i,acc1,acc2,acc,crit,c
        foilrate=a20+a21*log10(c)
       endif
       if((c.ge.841.).and.(c.le.6120.)) then
        if(ibug.eq.1) write(7,'(a)') 'correlation #3'
        if(ibug.eq.1) write(7,100) i,acc1,acc2,acc,crit,c
        foilrate=a30+a31*log10(c)
       endif
      endif
      return
      end
```

```
c
c     this function calculates the nominal thrust
c
      function FTHRUST(x)
      implicit integer*4(i-n),real*8(a-h,o-z)
c
      data a10,a11,a12
     &/2518.1565624,-0.10728645222,1.2303317583e-06/
      data a20,a21
     &/-1680.7116342,0.036481484276/
c
      if(x.lt.49295.) fthrust=0.
      if(x.gt.62016.) fthrust=0.
      if((x.ge.49295.).and.(x.lt.57171.)) then
       fthrust=a10+a11*x+a12*x**2
      endif
      if((x.ge.57171.).and.(x.le.62016.)) then
       fthrust=a20+a21*x
      endif
      return
      end
```

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