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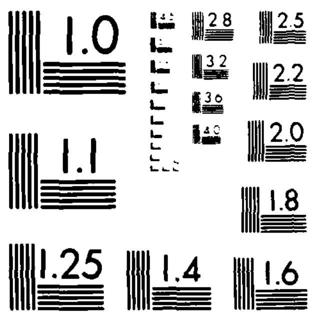

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A COMPUTER-BASED SIMULATION OF A SIMPLE AIRCRAFT-TYPE FUEL SYSTEM: PART I NORMAL TRANSFER

by

M. A. Beeny

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A COMPUTER-BASED SIMULATION OF A SIMPLE AIRCRAFT-TYPE FUEL SYSTEM: PART 1 NORMAL TRANSFER

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M. A. Beeny, M.Inst.P.

SUMMARY

A computer based model of a simple aircraft-type fuel system has been developed in Engineering Physics and latterly Flight Systems Department, Farnborough, RAE as a background activity over several years. This work was undertaken to furnish an emulation which could be useful for aircraft systems integration studies, to explore fuel management techniques and to furnish programming and documentation experience in an area which had previously relied upon conventional dc and ac signalling techniques.

This Memorandum contains definitions, logic flow diagrams, program listings and the results of 16 simulated engine runs. It is concluded that sophisticated fuel management should be accomplished while retaining a simple hardware architecture and that control of the fuel cg may be achieved without recourse to fixed, predetermined tank-use schedules. Control of the source of engine fuel supply, through reference to the current fuel cg position, would facilitate schemes for limiting fuel loss, subsequent to sustaining battle damage, by allowing redistribution from the affected fuel tank(s). It would also allow automatic detection and evaluation of hardware faults as they occur and permit contingency schemes to be evoked on an automatic or semi-automatic basis.

LIST OF CONTENTS

1 INTRODUCTION

The speedy evolution of electronic circuit design and miniaturisation has made it possible and desirable to replace traditional analogue control and instrumentation systems with digital systems based upon silicon micro-chips. In the aircraft development field, exploitation of this technology was stimulated through the need to eliminate dedicated cockpit displays, reduce wiring and to provide semi-intelligent systems which could reduce both pilot and ground-crew work loads. At the same time, the opportunity has been taken to improve fuel gauging accuracy by adopting more sophisticated data processing and to investigate the possibility of integrating all the aircraft's fuel functions into a unified fuel management system. Since work started on this concept, through a series of contracts placed upon Smiths Industries of Basingstoke in the mid-1970s the concept of utility system integration has been extended by BAe Warton under RAE EP/XR Contract[1]. It was thought that individual mechanical systems emulators would be required to aid further development as well as work arising from the engineering cockpit studies[2] which were also underway at Warton, supported by RAE FS/XR and elsewhere.

The computer based model fuel system program under development in Engineering Physics and latterly Flight Systems Department, Farnborough, as a low priority activity, was under-taken to furnish an emulation, gain an insight into fuel management systems operation, explore the control of fuel transfer by reference to the current fuel cg position rather than assume flow proportioning by mechanical means etc, provide programming and documenting experience and highlight possible problem areas before embarking upon more ambitious simulated and engineered models. This initial exercise did not start with a formal specification, as would normally be expected, since it was an exploratory exercise to aid specification of novel systems.

The completed model was intended for use by the author in the investigation of automated fault detection and effect amelioration principles and as an aid for assessing how far such concepts might be employed in a future military aircraft. A fuel management research project, utilizing the Jaguar fuel rig at BAe Warton, was under consideration as an EP/XR activity at this time[3] and the model was also expected to contribute to this activity.

This Memorandum contains, parameter definitions, logic flow diagrams, program listings and the results of some preliminary test runs of the model. It was originally intended to produce further notes to include such items as ground refuel, fuel jettison, failure modes etc and the emulation was to have been extended to include an additional collector tank, drop tanks and fuselage tanks. However, a recent reassessment of research activities within MOD(PE) now precludes this activity by the originating section.

2 COMPUTER AND LANGUAGE

The integrated system likely to be found in future military aircraft will be microprocessor based and programs will be written in a high level language such as Coral 66 or Ada. The use of assembly code is likely to be restricted to special control segments of programs that require the highest performance and shortest instruction cycle times. Consequently, it was considered adequate to employ a microprocessor based computer and a high language for in-house investigations. Man-power limitations also encouraged this approach.

The computer used was a Hewlett Packard Desktop Computer Type 9845a equiped with an integral VDU (visual display unit), thermal printer and twin mini-tapedrive units. The computer also had graphics capability. The machine was programed in BASIC and had a maximum of 64K bites of user definable memory. The program described occupies 33.678K bites of memory, in its fully documented form but it is capable of being significantly reduced in size, as the listings indicate (Tables 2 to 7). The machine has subsequently been updated to become a 9845b machine with two additional floppy disk units.

3 DESCRIPTION OF THE SIMPLE FUEL SYSTEM ASSUMED

The fuel transfer and feed configuration (Fig 1) was assumed to comprise, a collector tank F1, a forward fuselage tank F3 and a rear fuselage tank F2. In addition there were two wing tanks, W4 in the port wing which fed the rear fuselage tank F2 and W5 in the starboard wing which fed the forward tank F3.

A finite element method was employed to simulate the fuel flow. The process was to take small elements (slugs) of fuel from the collector tank at a rate governed by the current throttle setting. Each element removed from the collector tank was replaced by an element taken from the fuselage tanks F2 and F3 and these were topped up in their turn from their respective slave wing tanks. In the case of wing transfer the maximum flow rate was limited to that representative of the engine max-dry running condition plus 50% (max-dry + 50%) and not to the reheat demand flow.

Four possible engine fuel consumption rates were assumed as follows:

(i)	engine shut-down (selection number)	0
(ii)	engine idle	1
(iii)	cruise condition	2
(iv)	max-dry	3
(v)	max-dry with reheat	4

The engine fuel consumption was simulated through the 'Fuel Decrement loop' (Fuel Dec loop), to be found between line identifiers L20 and L30 of the program listings. The corresponding logic flow diagram is given in Fig 3.

The Fuel Dec loop simulates the fuel flow rate by taking a series of fuel elements (Dq) from the collector tank and adding them to a variable E which serves as the engine. The size of the element to be transferred from the collector tank to the engine is derived in sub-program 'Flooppara' (Fig 5) and is dependent upon the selected throttle setting, the assumed fuel gauging accuracy requirement and the pilots display update interval. The resultant elemental quantity is then divided by 5 to ensure that the fuel decrement element is sufficiently small not to influence the apparent performance but not so small as to carry a penalty in program operating time due to execution of an unnecessarily large number of fuel element transfers.

It is conventional to ensure that the cg of the fuel remains within prescribed limits by scheduling the tank use sequence. This system has proved to be quite adequate for aircraft applications to date, although it is somewhat inflexible and requires aircrew intervention in the event of an abnormal tank use sequence becoming necessary or modification action if a more permanent change is contemplated. With the trend in aircraft systems towards more automatic operation and the possibility of greater interaction between systems in the future, it was the authors contention that the control of fuel transfer by reference to the departure of the cg position from a preset datum position would lead to a more flexible and adaptable system. Consequently the program uses cg movement to control fuel transfers.

With the actual cg of the hypothetical aircraft within the limits placed upon its possible excursions from datum, the collector tank was replenished alternately from one or other of the fuselage tanks. On even numbered cycles of the Fuel Dec loop, the fuel required might be taken from the rear fuselage tank and on odd numbered entries it might be taken from front fuselage tank or vice versa. This routine was modified, whenever the cg excursion exceeded a preset value (Plmt) chosen by the operator. In this case, the supposed engine demand was drawn from the tank with the greater effective moment-arm until the disparity was reduced to half the preset limit value. A similar routine was followed to control any lateral imbalance but in this case the process was more complicated since there was no direct connection between the port and starboard wing tanks. In this case fuel transfer had to be either via one or other of the fuselage tanks or, in the case of the 'active' lateral correction (see next section), from one wing tank to the other, through all three of the fuselage tanks. The complication arose because one or other of the fuselage tanks, feeding the collector tank, could be isolated because it was either, too light or, transfer from the wing tank to its parent fuselage tank would increase the pitch imbalance by adding fuel to an already overweight tank.

When aircraft fuel tanks are not filled to capacity, and an imbalance occurs, it is possible to redistribute the fuel on-board to achieve a balanced condition through fuel transfer and cross-feed. This facility has been incorporated into the model and routine J14 (P-trans, Figs 8 to 13) is used to accomplish such transfers, whether they are initiated by the operator (pilot) or automatically through the control program. J14 assumes the existence of some form of motive power to allow outward transfers to occur and, in the case of cross-feed, this entails fuel transfer away from the collector tank, a potentially hazardous provision for a real aircraft which would require stringent safeguards.

The maximum pumping rates for fuel transfer were assumed to be the reheat flow requirement, in the case of fuselage transfers, and 80% × max-dry, for transfers from the wing tanks. In the event of a pump being selected 'OFF', transfer was still assumed to take place, but at a reduced rate (Gfr = 50% × max-dry) due to gravity or aircraft acceleration effects, see program listings, Table 3.

The fuel contents display update time (Ut) was made relatively long, 2 minutes, because the program required manual inputs of throttle setting and paused for these to be given after each display update action. A more frequent update would have made the program running time unnecessarily long and tedious for the operator to run during proving tests.

However, a 2 minute update interval would have led to an unrealistic simulation of the use of reheat power and, in this case, a cycle time of 30 seconds was adopted.

Whenever the level of fuel in the collector tank fell below 95% of the tank volume (*ie* to 190 gallons), a jump to routine J12 occurred, a warning was initiated and a check was made to ensure that all the other tanks were empty. If fuel remained in any of the other tanks, then the transfer cocks were reselected open and the transfer pumps re-energised. If fuel was not discovered, program execution passed back to the main program until a situation occurred in which the fuel remaining in F1 was insufficient to meet the transfer requirements of the next Fuel Dec loop cycle. The program was then terminated through a jump to J100.

This was not intended as a possible failure routine but was found necessary to simulate use of the greater part of the initial fuel load under the test conditions tried. It is intended that, failure routines to replace J12 will be the subject of a future work program.

4 PROGRAM ORGANISATION

The overall program organisation is given in Fig 2. The numbers preceded by a letter L , to the left of the action boxes, are program line identifiers and allow the boxes found in the figure to be tied to actual program segments and lines.

Referring to the listings, Table 1, L1 and L2 identify the program segment that contains the definitions of the variables used by the program. While the segment lying between L10 and L30 contains the setting-up procedures for the Fuel Dec loop (L10 to L20) and the Fuel Dec loop itself (L20 to L30). It comprises the throttle-change detection routine, fuel consumption and display update, as well as routines for checking and correcting cg movement. The Fuel Dec loop, together with its parameter initialisation, is amplified in Fig 3, while Fig 4 shows the program termination sequence.

The program logic flow generally assumes normal operation of the fuel transfer function, *ie* the aircraft is in level flight without acceleration, the cg is within limits and all pumps and cocks are ON or OPEN (0 for ON and 1 for OFF).

Abnormal functioning has been catered for by jump routines, *eg* J12, the collector tank fuel level-low routine and J14, the strategy adopted when fuel transfers, other than to feed the engine, are required. Repetitive tasks are serviced by subroutines such as 'Flopparra', 'Move' and Cgtfs'. Other jump routines may be identified in the listings. These are either, simple and do not require a flow chart (*ie* J99) or as in Table 7, they are concerned with graphical information output and are not strictly part of the simulation.

5 SUBPROGRAMS

The subprogram routines directly concerned with the simulation are 'Flooppara', 'Move' and 'Cgtfs'. Their logic flow diagrams are given in Figs 5 to 7 and they are described in more detail in Appendix A.

Subprogram 'Flooppara' (Fig 5) determines the parameters that are required to execute the Fuel Dec loop.

Subprogram 'Move' (Fig 6) transfers a fuel element from one tank to another. It checks that the transfer is consistent with the current fuel cg requirement and that the transfer pump is running. It then subtracts an element of fuel from the variable representing the donor tank and adds it to that representing the receiver. It checks that the supplying tank contents variable is not a negative quantity, and if it is, it adds this negative number to the receiver variable and sets the donor to zero. The receiving tank variable is also tested to ensure that it is not greater than the defined tank capacity and any necessary adjustments are made. The latent transfer capacity (the unused, or additional transfer potential) is also determined in case fuel redistribution is required. Two values are determined, corresponding to the two possible directions of transfer:

(i) an increased flow inwards, towards the collector tank F1,

(ii) an outward flow, away from F1 towards a wing tank.

These flow parameters have the form Tdq'XY' where X and Y are tank identification numbers and their order defines the flow direction. So that Tdq13 is the flow potential between the collector tank (F1) and the forward fuselage tank (F3).

The subprogram 'Cgtfs' (Fig 7) determines the effective position of the fuel cg relative to the datum position, chosen by the operator, of two fuel tanks or tank groups situated a given distance apart. In the case of the pitch axis this distance (Sft) is determined by the operator at the beginning of the run, while in the transverse or roll axis the distance (Swt) is set by the program (line 1270). Cgtfs checks that there is fuel in the two tanks to make a determination meaningful and determines the moment arm of the fuel in term of the full tank capacities of the tanks or groups concerned. The moment arm, or cg excursion, is compared with the limit value (Plmt or Rlmt) and if this is exceeded, transfer inhibit flags are set which are picked-up by subprogram 'Move' as described above.

6 PROGRAM JUMP ROUTINES

There are seven major jump routines and these are located within the program starting at line L40. Routines J12 and J14 are treated in more detail in Appendix B.

The flow diagrams for the inter tank transfer strategies (J14 P-trans) are given in Figs 8 to 13. Figs 12 and 13 of this routine require fuel to be transferred away from the collector tank and it has to be assumed that provision has been made to enable such a transfer to proceed. During the initial setting up of the run, the operator is given the choice of whether or not he requires this facility. The outward transfer pumps selections are identified by integer variables F12p, F13p, F24p and F34p. The two digit number comprises the identification digits of the tanks between which a transfer may occur while the order of the digits is indicative of the flow direction. Hence, F13p represents a pump which effects transfer away from the collector tank (F1) and into the forward fuselage tank (F3).

The flow diagram for the collector tank fuel level low routine J12, is given in Figs 14 and 15. This routine produces a warning that the collector tank fuel level is falling and it checks if there is fuel left in any of the other tanks. Any fuel located is transferred to the collector tank by triggering the inter-tank transfer routine J14 via the transfer-required flag Trf. If the fuel remaining is less than that required for the next cycle of the Fuel Dec loop, the program is terminated via a jump to the routine at address J100 (Fig 4).

7 FUEL SYSTEM SIMULATION PROGRAM TESTS

The test conditions chosen to illustrate the behaviour of the simulation of a simple fuel transfer system are summarised in Table 7 and the results of 16 tests are included, to demonstrate the effects of:

(i) the various throttle settings. Runs 1 and 2,

(ii) gross imbalance of fuel between the port and starboard wing tanks with cross-feed, (a) not allowed, (b) permitted. Runs 3 to 5,

(iii) both wing tank cocks closed (in the 12th minute). Run 6,

(iv) both fuselage tank cocks closed (in the 12th minute). Runs 7 and 8,

(v) partially filled tanks with cross-feed, (a) not allowed, (b) allowed. Runs 9 to 12,

(vi) extreme positions of the pitch cg datum position with cross-feed, (a) not allowed, (b) allowed. Runs 13 to 16.

The results of each run are given in the form of printed statements which are in three parts, viz:

(i) the initial conditions; tank contents, the distance between tank groups, pitch cg datum position and the pitch and roll cg deviations limits,

(ii) statements, with leading asterisks, which represent pilot warnings or flame-out conditions.

The print out is followed by a block of four graphs which summarise the test. At the top right of the block there is a graph showing fuel contents at various times during the simulated sortie while, to the right of this there is a graph showing the distribution of this fuel. At the bottom are figures giving the history of the deviations of the calculated cg position from the datum positions in both the pitch and roll axes.

The results of the first eight test runs are treated in detail so that the characteristics of the fuel system simulation program may be brought out and the graphs giving the results clarified. Test runs 9 to 12, which include cases where one or other of the fuselage tanks is initially part full and the effects of prohibiting or allowing fuel cross-feed to occur, are thought to be straight forward and not requiring of further explanation. Runs 13 to 16 include the extreme conditions where the hypothetical aircraft configuration might require the datum cg position to be close to one or other of the individual fuselage tank (F2 or F3) cg positions. Again the effects of not permitting and allowing fuel cross-feed to take place are covered. These tests were included to demonstrate the simple fuel system ability to cope with conditions that cause conflict between the pitch and roll axes control requirements.

Test 1, Fig 16. This figure presents the results from, what might be considered, a normal simulated flight, *eg* one in which the fuel tanks are initially full or near full and the hypothetical aircraft is in balance.

The graph, top right quadrant of figure, gives the contents history for each of the fuel tanks. It shows both wing tank contents falling steadily until about the 32nd minute of the simulated flight, whereupon, they become exhausted and the contents of the fuselage tanks start to fall. At the 55th minute, the forward tank becomes empty and the whole of the engine demand has to be met from the rear fuselage tank, which causes the rate of diminuation of the rear tank contents to increase. The run was terminated in the 60th minute when 150 gallons remained in the rear fuselage tank and 200 gallons remained in the collector tank.

The time histories of cg shifts from datum positions in the pitch and roll axes are given at the bottom of Fig 16. The pitch axis cg shift plot (bottom left) remains constant until the 32nd minute, when a steady rearward shift of the cg commences. This continues until the 53rd minute when the forward tank becomes empty and the cg shift reverses and moves steadily back towards the datum position.

Initially, the moments of the two fuselage tanks about the datum position are approximately equal and the hypothetical aircraft is close to being in balance. To maintain this state, while fuel is drawn from both tanks, would require that it is taken in proportions depending upon their moment arms and, in a practical case, a Fuel Proportioner would be used to achieve this.

However, in this simulation, proportioning of fuel flows has not been assumed and, consequently, the removal of equal masses of fuel from the two tanks has an enhanced effect upon the moments of the tank which initially held the smaller quantity of fuel. This effect is seen in the graph showing the pitch cg shift with time.

Test 2, Fig 17, demonstrates the effects of throttle settings 1, 3 and 4 which correspond to fuel consumption rates representing the engine conditions of idle, max-dry and re-heat respectively.

The run commences with the engine at idle (throttle setting 1) for three display update cycles, which is equivalent to 6 minutes of simulated sortie time. This is followed by a further three cycles in the simulated max-dry condition (throttle 3) which is maintained during the period 6th to the 12th minute. There then follows a further three update cycles of re-heat, (throttle 4) during the period 12th to the 13.5th minute. After which, the fuel consumption rate reverts to the max-dry condition which is maintained until the collector tank is empty and flame-out is assumed, at the 57.5th minute of the simulated sortie.

These events may be traced on the total fuel contents graph, top left-hand quadrant of Fig 17. This shows an increase in the rate at which fuel is used during the 6th to 12th minutes and a sharp increase during the 12th to 13.5th minute, after which there is a steady fall in the total fuel contents, due to the max-dry setting, until the end of the test. The graph of individual tank contents, top right-hand quadrant, also reflects the changes in the rates of fuel removal from the system. The magnitude of the gradients of the fuel contents curves for the two wing tanks increase during the second time interval, 6th to 12th minute, to meet the increased fuel requirement. At the 12th minute, three update cycles of re-heat were applied and the magnitudes of the gradients of the fuel extraction rates for the two wing tanks increase to their maximum value, Pfr = Mfr × 80%. However, this is insufficient to meet the total engine requirement and it has to be augmented by fuel supplied by the fuselage tanks the contents of which can be seen to fall during this period. After the 13.5th minute the fuel removal reverts to the max-dry rate. However, the wing tanks continue to supply fuel at their maximum rate until the 28th minute when they become empty. During this time, the fuselage tank contents increase and then subsequently fall as they are required to meet the engine demand. In the 46th minute, the forward fuselage tank is exptied and the whole demand is met from the rear tank. It too becomes exhausted in the 54th minute and, from then on, only collector tank fuel remains. When this tank's contents fall to 190 gallons, 54.57th minute into the simulated sortie, the program generates a series of collector tank low level warnings which continue to be confirmed until 57.5 minutes into the sorties, at which time only 14 gallons of fuel remain. The Fuel Dec loop of the main program removes 7.5 gallons from the system each time it is entered, with a throttle setting of 3, so the loop is traversed one more time. However, when routine J12 is entered this time, instead of generating yet another warning, the routine determines that there is insufficient fuel left for another entry into the Fuel Dec loop and transfers control to J99 which terminates the sortie and prints 'Flame Out'.

As in the previous example, the pitch cg shift plot reflects the effect of taking equal masses from a system comprising two unequal masses, which are initially balanced through their moment arms.

In the roll axis, the cg shift plot reflects the unequal fuel masses allocated to each of the wing tanks to separate their respective fuel contents plot symbols. The cg shift shows a small deviation from datum towards the port wing, which reduces to zero at about the 28th minute of the sortie when the starboard wing tank becomes empty.

Tests 3 to 5, Figs 18 to 20. These three tests demonstrate the programs ability to control fuel cross-feed between the two wing tanks and the effect that cross-feed has upon the control of lateral cg position. In each test, the fuselage tanks and one wing tank are initially full while the other wing tank remains empty. The fuel consumption rate is assumed equivalent to the engine idle condition in all three cases, throttle setting 1. Test 3 shows the response of the lateral cg control when cross-feed is not permitted. Tests 4 and 5 show the control responses when cross-feed is allowed to redistribute fuel between port and starboard tanks and *vice versa* respectively.

Test 3, Fig 18. The hypothetical aircraft is initially in balance about the pitch cg datum position and the supposed engine fuel requirement is met from both forward and rear fuselage tanks; cross-feed is not permitted. The port wing tank transfers fuel to the rear fuselage tank so that it remains full, while the contents of the forward fuselage tank falls. These fuel movements cause the pitch cg position to move slowly towards the tail and the lateral cg position to move slowly towards the balanced condition from outside the port-wing heavy display limit.

Test 4, Fig 19, is a repeat of the previous initial conditions but with cross-feed between the wing tanks permitted. Inter-wing fuel transfer commences immediately at the maximum flow rate determined by the respective transfer pump capacities, equivalent to max-dry × 80% in the case of the wing pumps and re-heat flow where the fuselage tank pumps are concerned. In consequence, the port wing contents fall, as does its parent rear fuselage tank contents. However, since the potential transfer flow rate of the fuselage tank pumps is greater than that of the wing tank pumps, port wing transfer cannot replace all the fuel that is transferred from the rear tank to the collector tank to meet engine feed requirements and transfer to the forward fuel tank. Both the port wing and the rear fuselage tanks lose fuel, while the forward fuselage tank remains full and the starboard wing tank fills. These actions continue until the 9th minute of the simulated sortie, when the cg shift falls below half of the roll limit (0.5 ft) necessary to cancel cg control action by the program. This happens to occur part way through a display update cycle and does not become effective until the 10th minute, when the contents of the port and starboard wing tanks are almost equal. During the 11th minute, the port wing tank makes up the fuel transfer deficit to the rear fuselage tank which results in the insignificant over correction seen in the lateral cg shift graph. Test 5, is similar to the previous test but, in this case, it is the starboard tank that initially contains fuel and the port tank that starts empty. As might be expected, the graphs display similar features with the tanks transposed.

Test 6, Fig 21. All the tanks start nominally full of fuel and cross-feed is not permitted. The wing tank cocks are selected 'OFF' at the 12th minute. Three fuel consumption rates are simulated, idle (throttle setting 1) was selected for the first 18 minutes, followed by the max-dry condition (throttle setting 3) during the 18th to 48th minute, at which time a throttle setting reduction requirement was signalled. The cruise setting (throttle 2) was maintained for the remainder of the sortie.

During the first 12 minutes, the contents of the port and starboard wing tanks fell. At the 12th minute, both wing stop-cocks were closed and the supposed engine fuel requirement was taken equally from the fuselage tanks. At the 18th minute the fuel consumption rate was increased to represent the max-dry engine condition and the magnitude of the gradients of both the total and fuselage tank contents graphs increase. The pitch cg moves towards the rear, while the roll cg is unaffected. This trend continues until the forward fuselage tank becomes empty in the 41st minute of the simulated sortie, whereupon, the flow from the rear fuselage tank doubles and the pitch cg shift starts to move towards datum. During the 47th minute the rear tank becomes empty and the collector tank fuel contents starts to fall. This triggers the collector tank fuel level low routine (J12, Fig 14), which initiates a warning 47.64 minutes into the sortie.

The sequence of events is as follows:

(i) Fuel Dec loop entry n. The collector tank contents start to fall, routine J12 is entered and a fuel level low warning is given. Fuel reserves are confirmed to be onboard and strategy J12-1 is followed. This cancels all master/slave flags and designates the collector tank as the 'master' tank. The transfer-required flag is set, the collector tank contents value is stored, fuel is confirmed to be in the wing tanks and they are assigned 'slave' status. Program execution then returns to the main program.

(ii) Fuel Dec loop entry n + 1. The first actions of the loop are the simulated fuel consumption transfers and any fuel redistribution that is scheduled occurs later. The fuselage tanks are empty and consequently, the collector tank contents are decreased further. The program reaches line L24b (Fig 3 and Table 3) and enters routine J14 (Fig 8). The collector tank (F1) is 'master' and therefore J14-0 (Fig 13) is entered and, since the starboard wing tank is a 'slave', an unsuccessful attempt is made to transfer fuel from the forward fuselage tank (F3) to the collector tank (F1). The contents of the collector tank are unaffected as the fuselage tank is empty at this instant. The program control reaches J14r13 (bottom of Fig 13), the wing tank cock is turned on temporarily and fuel is transferred from the starboard wing to the front fuselage tank (F3), the wing tank contents variable is tested and program execution returns to the main program, where the starboard wing tank cock is reset to the shut condition through reference to the cock select variable W5cs (Table 3, line 3570).

The collector tank contents are still low and routine J12 is triggered, the 'fuel level low' warning is repeated, fuel reserves are again confirmed to be on the aircraft, all existing master/slave flag setting are cancelled and tank F1 is redesignated as the master tank (J12-1). However, the contents of the collector tank are still falling and J12-2 is entered. The value corresponding to the current contents of the collector tank is stored and an 'inadequate fuel flow' warning and advice to reduce the throttle setting is printed. The port stop-cock (W4c) is then found to be closed, which causes program execution to pass to routine J12-3 (Fig 15). The 'port stop-cock was off' statement is printed, the cock is opened and the cock-select flag is cancelled.

(iii) Fuel Dec loop entry n + 2. As stated above, the fuel transfers required by engine demand are made first, fuel is transferred from the forward fuselage tank to replace that taken from the collector tank but there is a short fall of 2.18 gallons.

The forward tank (F3) is now empty as is the rear tank (F2). The fuel redistribution or transfer routine J14 is entered and, since tank F1 is the master tank, control passes to J14-0. The starboard wing tank is a slave so an attempt is made to transfer fuel from the empty forward tank to the collector tank with no success. However, fuel is transferred from the starboard wing tank to the forward fuselage tank. Control reverts to the main program which again ensures that the starboard wing transfer cock is shut. The collector tank contents are still low, routine J12 is entered again and another fuel level low warning is printed. Additional fuel is still available so that strategy J12-2 is followed, another inadequate flow warning is given and this time the starboard wing tank cock is found to be closed. A statement to this effect is printed out and the cock select variable (W5cs) is set to the open condition before returning to the main program. The end of this Fuel Dec cycle coincides with the next display up-date at the 48th minute, when the program allows new fuel system data to be fed in and the throttle setting is reduced to the cruise condition (throttle setting 2).

(iv) Fuel Dec loop cycles n + 3 and n + 4 . It takes execution of two further Fuel Dec cycles before the collector tank becomes full and low level warnings cease. After the 48.5 minute of the simulated sortie, the collector tank is full and the fuselage tanks start to fill up from their respective wing tanks.

Test 7 (Fig 22). At the start, the tanks are nominally full, the cg is very close to the datum position and fuel cross-feed is not permitted. Both of the fuselage tank cocks were closed at the 12th minute of the supposed sortie and at the 14th minute, the collector tank contents fall sufficiently to cause program control to enter the low fuel level routine J12. This causes a warning to be printed out and the routine confirms that there is additional fuel in the system. J12-1 is entered, the transfer-required flag is set and fuel is found to be in both the rear and forward fuselage tanks (F2 and F3) which are consequently designated as the slaves. The state of the stop-cocks are tested and they are found to be shut. No action is taken to open them since, at the present state of program development, there are no fuselage tank cock select variables to record the preferred selections and provide a means for reclosing the fuselage tank cocks once they have been opened by routine J12, so that it may perform its fuel redistribution function.

Test 8 (Fig 23) is a repeat of the previous situation but, this time, cross-feed of fuel between the wing tanks is allowed. As in the previous test, both fuselage tank cocks are closed at the 12th minute of the simulated sortie. At the 14th minute, the collector tank contents are deemed to have fallen to 188 gallons and routine J12 is entered. A collector tank fuel low-level warning is printed out and, since there is fuel in tanks other than the collector tank, control passes to J12-1 where the transfer-required flag is set, the two fuselage tank stop-cocks are tested and found to be shut. The results of these tests are printed out and, during the subsequent Fuel Dec cycles the deficit in the rear tank contents is made-up. From here on in, the simulated sortie progresses in a routine way.

Tests 9 to 13 (Figs 24 to 28) are presented without comment.

8 DISCUSSION

At the current stage of development, the simulation program only covers the fuel transfer system and further work is required to incorporate the other facilities necessary for a realistic simulation of a complete aircraft system. Ground and flight refuelling functions need to be included as do ground defuel and fuel jettison facilities, a process for introducing supposed component failures and malfunctions is also required together with strategies for dealing with them and minimising their effects. However, despite the limited nature of the simulation program, in its current form, it does tend to support the conjecture that computer type logic control of the fuel system should allow sophisticated management of the fuel on-board an aircraft while, hopefully, retaining a very simple system geometry and without the need for fuel proportioning. This possibility requires further consideration when the simulation program is complete and after an engineered model has been produced.

The current version of the simulation program demonstrates that control of fuel transfer by reference to the difference between the actual fuel cg and a predetermined datum position is feasible and could have application in cases where varying aircraft external loads might require a more adaptive control of the cg migrations due to fuel use than is possible with the preset tank scheduling procedures which are common in current aircraft. Control by reference to the current cg position makes for a more flexible and potentially more responsive system and should allow fuel conservation strategies to be implemented more readily. For instance, if leak detection were to be implemented and fuel redistribution were to be allowed to minimise loss, then the control system would have to ensure that cg limits were not exceeded. This is inherent in a system using cg position as a control parameter.

During analysis of the limited number of test runs made on the program, several inconsistencies or peculiarities were noted. These are attributed to the lengthy periods that occurred between development phases due to the low priority allocated to the development task. For example, in the collector-tank low routine J12 (Figs 14 and 15), in sections which start with line identifiers J12-5 and J12-6, there are tests to establish if the rear and forward fuselage tank cocks are closed or not. If one or other is closed then there is a print out to this effect but no action is taken to open the cock or cocks. Such action is not necessary since routine J12 only sets flags which trigger the required fuel transfers to be performed by routine J14 (P-trans) and this routine ensures that the necessary fuel cocks are open and pumps running. However, in another part of J12, in sections of the routine commencing at line identifiers J12-3 and J12-4, the states of the wing tank cocks are interrogated and if one or other of the cocks is closed there is, as in the previous case, a print-out to this effect but, this time, positive action is taken to open it and ensure that the pump is running. A fuel tank cock-select flag is also reset. This flag was introduced at a late stage of program development to enable simulated fuel transfers from the wing tanks to be inhibited when they tend to increase or maintain an existing pitch axis imbalance. In the event, that cg control caused an inadequate transfer of fuel to the collector tank, a means had to be provided, within routine J12, to cancel the cock-select flags. This prompted the superfluous actions to ensure cocks-open and pumps-on to be included.

Some other peculiarities of the program are:

(i) Master tank flags are used in two ways;

(a) to indicate tanks that require to have fuel transferred to them,

(b) as fuel transfer inhibit flags for cg control. The argument adopted was that fuel could not, in general, be transferred from a master to a slave tank.

(ii) Select flags are required to allow the normal program sequence to be overriden by external agencies such as manual selection of cocks and pump states.

(iii) In cases where the program run is terminated because of a supposed fuel exhaustion, fuel remains in the collector tank. The amount is less than the quantity transferred to the engine by the Fuel Dec loop as constituted at the time.

(iv) At low fuel consumption rates the quantities involved are so small that the fuel consumption that occurrs between consecutive update periods can be met by a limited number of cycles of the Fuel Dec loop. This leads to unrealistic fuel movements within the system which may be distinguished in some of the fuel contents plots as irregularities in what one would expect to be smooth curves.

These anomalies, which may not form a complete list, remain in the program which is considered to be adequate as the first stage of an iterative process to produce a model of a possible future fuel management system for a hypothetical aircraft.

9 CONCLUSIONS

(1) The fuel transfer simulation program could serve as the basis of a fuel management system emulator for investigations which are not related to a specific aircraft project.

(2) It would appear computer control could permit sophisticated fuel management routines to be implemented while retaining a simple hardware geometry.

(3) The control of fuel transfer, by reference to the current position of the fuel cg is possible and should be considered further since it could lead to (a) a responsive and flexible fuel management system for future aircraft, and (b) the elimination of flow proportioners.

Appendix A

DESCRIPTION OF SUBPROGRAMS DIRECTLY EMPLOYED BY THE SIMPLE AIRCRAFT FUEL SYSTEM SIMULATION PROGRAM

A.1 Subprogram 'Flooppara' (Fig 5)

This subprogram determines the initial parameters required by the Fuel Dec loop which may be found between lines L20 and L30 of the main program. The number of times this loop has to be entered is determined from the critical fuel element (defined at line L12), the chosen throttle setting and the display update time. The resultant fraction is rounded up and incremented by one to ensure that the Fuel Dec loop is entered at least once. The element of time represented by a single-loop cycle is calculated and a check figure of the total amount of fuel to be transferred through execution of the Fuel Dec loop is determined for a comparison made in the main program at line L26.

The first line of this subprogram is:

```
5720 SUBFlooppara(Ut,Elf,Fcr,Lpti,Dq,Dect,INTEGER I2)
```

where Ut = display update time
Elf = critical fuel element size
Fcr = throttle setting number (in the range 0 to 4)
Lpti = time interval equivalent to each Fuel Dec loop cycle
Dq = fuel element to be transferred during each Fuel Dec loop cycle
Dect = total quantity of fuel to be transferred,
I2 = number of times that Fuel Dec loop has to be entered.

A.2 Subprogram 'Move' (Fig 6)

'Move' transfers fuel from a slave tank to a master tank, or to the engine in the case of a normal transfer from the collector tank (line L21 of the main program). It checks that the slave tank cock is open, that the pump is running and that a transfer is to be allowed. If the pump select flag (Spf) is anything other than 0 (*ie* OFF), then a reduced flowrate is assumed on the argument that fuel will still continue to flow under gravity or 'g' effects, provided the line is not cocked OFF and transfer is allowed.

An elemental quantity of fuel Dq or Gfr is moved from the slave tank to the master. The variable that represents the slave tank contents is checked to ensure that it is not a negative quantity, if it should be then its value is added to that of the variable representing the contents of the master tank. The master tank contents variable is also tested to ensure that it is not in excess of the max-contents value assigned to that particular tank. Any excess is returned to the slave tank contents variable. This program also determines the potential capacity for any additional flow that may be required between the designated tanks. It is assumed that total flow is only limited by the pumping capability and the inter tank pipework. Two values are determined, Exci and Exco, which are the (additional) potential flows in both the normal, toward the collector tank, and abnormal case, away from the collector tank and towards one of the wing tanks.

The first line of the subprogram is:

5910 SUBMove(Mi.M.S.Dq,Gfr,Exci,Exco,INTEGER Tna.Scf.Spf)

where Mi = master tank volume

M = master tank contents

S = slave tank contents

Dq = fuel element to be transfered

Gfr = gravity fuel flow element

Exci = potential additional flow towards the collector tank

Exco = potential flow away from the collector tank

Tna = transfer inhibit flag (0 = allowed, 1 = not allowed)

Scf = stop-cock flag (0 = open, 1 = shut)

Spf = pump select flag (0 = on, 1 = off)

NOTE: any value other than 0 is treated as a 1.

A.3 Subprogram 'Cgtfs' (Fig 7)

This program determines the resultant moment arm of two fuel tanks or tank groups situated Ro + Fo feet apart about a datum position Fo from the 'forward' tank or tank group. It sets flags which are used by routine J14 (P-trans) and the subprogram 'Move'. The routine was written in terms of the pitch axis but it is also used to determine transverse cg positions. The cg determination is, in terms of the maximum fuel capacity, what the tanks are deemed to be capable of holding, so that the reduced effect that partially filled tanks would have upon the balance of the aircraft is taken into account.

The program checks whether a cg limit had been exceeded during the previous cycle by checking the flags Fm and Rm. If one or other of these flags is set (value other than zero), then the program requires that the cg shift should be reduced to 1/2 the preset limit value before allowing the normal transfer routine to be resumed. Alternatively, if during the previous cycle the cg position had been within the chosen limit (Fm and Rm = 0), then its current position is checked against the preset limit and transfer control flags are set accordingly.

The first line of the subprogram is:

6360 SUB Cgtfs(Fv,F,R,Fo,Ro,Lmt,S,INTEGER Fm,Fs,Rm,Rs,Trf)

where Fv = total fuel capacity of tanks F and R

F = front tank (or group) current fuel contents

R = rear tank (or group) current fuel contents

Fo = distance between the datum cg position and the front tank or tank group

Ro = distance between the datum cg position and the rear tank or group

Lmt = the limit placed upon the excursions of cg position from the datum position

S = current cg distance from the datum position

Fm = forward tank is 'Master-tank' flag (1 = master)

Fs = forward tank is 'Slave-tank' flag (1 = slave)

Rm = rear tank is 'Master-tank' flag (1 = master)

Rs = rear tank is 'Slave-tank' flag (1 = slave)

Trf = 'Transfer' is required flag.

Appendix B

JUMP ROUTINES WHICH FORM PART OF THE SIMPLE AIRCRAFT FUEL SYSTEM SIMULATION PROGRAM

B.1 Foreword

The routines to be introduced in Appendix B could have been implemented as sub-programs and this might have been a more elegant way of treating them. However, it was decided that in general all executive actions involving fuel system control and fuel transfer should be implemented within the main program and that sub-programs should only set flags which the main program would act upon.

The jump routines are considered in the order they occur in the program listings, consequently the routine J14 comes before routine J12.

B.2 Fuel transfer routine J14 (P-trans)

The flow diagram for this routine is reproduced as Figs 8 to 13 and it is implemented as a segment of the main program rather than as a subprogram because it has executive control of fuel transfer and because of the large number of parameters that it handles. It utilizes subprogram 'Move' but enters it using the "excess pump transfer capacity potential" (Tdq'XY') in place of the pump transfer figure (Dq) where the X and Y are the tank identification numbers of the tanks involved in the transfer, in an order which defines the direction of flow, *eg* Tdq35 represents the "excess pump transfer capacity potential" between the fuselage tank F3 and the wing tank W5 in the direction of the wing tank.

Fig 8 flow diagram identifies which fuel tank is the current master tank and transfers control to the appropriate segment represented by Figs 9 to 13. The transfer requirements for each master tank are considered in the order F2, F3, W4, W5 and finally F1, and some of the later strategies contain partial procedures which are common with parts of earlier strategies. When this occurs, the program jumps to the earlier sequence of program lines rather than repeats them, as the flow diagrams might suggest. This makes tracing program operation from the listings difficult and tedious.

The logic flow diagrams of Figs 8 to 13 are complete and a jump in the list of program statements is indicated by an arrow and an 'address' starting with J14 and followed by some unique combination of characters. In many cases dashed lines are used to indicate the logic flow paths when a jump is required, while a 'borrowed logic segment' is designated by enclosing it within a box formed of alternate long and short dashes. The address J14r1 is attached to a segment of Fig 8 which terminates fuel transfer when either, the master tank is full, or the slave tank is empty. It is encountered frequently and the address (J14r1) has been ringed for easy identification.

As intimated above, the collector tank (F1)-is-master strategy was the last to be considered, whereas, its importance in the fuel supply tank chain, would suggest that it should have been in the first strategy to be formulated. Normal fuel transfers, to replace fuel taken by the engine, are catered for directly within the Fuel Dec loop while collector tank fuel level low warnings are part of the jump routine J12 (which is to be considered in the next section). The F1-is-master strategy was originally part of the collector tank fuel-level-low routine and was incorporated as part of the J14 routines when this latter segment was added to the program, towards the end of the present development.

B.3 The collector-tank fuel-level-low routine J12 (Figs 14 and 15)

This routine has been kept as simple as possible, since it will be the subject of further study once the fuel system model has been completed and proved. It is entered when the collector tank fuel level is less than 10% of its maximum capacity. The routine then checks if there is any fuel remaining in any of the other tanks and if there is, it designates the collector tank as the master tank, identifies a slave tank and sets the 'Transfer is required' flat (Trs) which is picked-up by J14 (P-trans) during the next execution of the Fuel Dec loop. Normal program termination is triggered by this routine whenever it detects that the fuel quantity remaining in the collector tank is less than that required to complete a further cycle of the Fuel Dec loop.

Table 1

ROUTINES FOR DRAWING AXES AND PRINTING LABELS

```
10 L01:  PLOTTER IS 13,"GRAPHICS"
20   GRAPHICS
30   LINE TYPE 3
40   FRAME
50   LOCATE 14,63,52,98            !UPPER LEFT HAND PLOT.
60   LINE TYPE 1
70   SCALE 0,60,0,40
80   AXES 1,2,0,0,10,5
90   DEG
100  LORG 8
110  FOR N1=0 TO 40 STEP 4
120  MOVE -2,N1
130  LABEL USING "K";N1
140  NEXT N1
150  LDIR 90
160  MOVE -12,20
170  LORG 4
180  LABEL USING "K";"FUEL LEFT(GallsX100)"
190  CSIZE 2
200  LABEL USING "K";"TOTAL CONTENTS"
210  LDIR 0
220  LORG 5
230  CSIZE 3
240  FOR N=0 TO 60 STEP 10
250  MOVE N,-2
260  LABEL USING "K";N
270  NEXT N
280  MOVE 30,-4
290  LABEL USING "K";"FLIGHT TIMES(mins)"
300  LOCATE 70,120,52,98           !UPPER RIGHT HAND PLOT.
310  LINE TYPE 1
320  SCALE 0,60,0,12
330  AXES 1,1,0,0,10,10
340  DEG
350  LORG 8
360  FOR N1=0 TO 12
370  MOVE -2,N1
380  LABEL USING "K";N1
390  NEXT N1
400  LDIR 90
410  CSIZE 2
420  MOVE -8,6
430  LORG 5
440  LABEL USING "K";"INDIVIDUAL TANKS"
450  LDIR 0
460  LORG 5
470  CSIZE 3
480  FOR N=0 TO 60 STEP 10
490  MOVE N,-.6
500  LABEL USING "K";N
510  NEXT N
520  MOVE 30,-1.2
530  LABEL USING "K";"FLIGHT TIMES(mins)"
540  LOCATE 14,63,8,45                 !C OFG PLOT, PITCH
550  SCALE 0,60,-5,5
560  AXES 1,1,0,-5,10,5
570  SCALE 0,60,-5,5
580  FOR N3=-5 TO 5 STEP 5
590  MOVE -2,N3
600  LABEL USING "K";N3
610  NEXT N3
620  LDIR 90
630  LORG 4
640  MOVE -12,0
650  LABEL USING "K";"C of G SHIFT (ft)"
```

Table 1 (concluded)

```
660  CSIZE 2
670  MOVE -9.3,0
680  LABEL USING "K";"factored, act''orig'"
690  MOVE -6.6,-3.5
700  LABEL USING "K";"Tail heavy"
710  MOVE -6.6,3.5
720  LABEL USING "K";"Nose heavy"
730  LDIR 0
740  LORG 5
750  CSIZE 3
760  FOR N=0 TO 60 STEP 10
770  MOVE N,-5.5
780  LABEL USING "K";N
790  NEXT N
800  MOVE 30,-6.25
810  LABEL USING "K";"MINS"
820  LOCATE 70,120,8,45            !C OFG PLOT, ROLL
830  SCALE 0,60,-5,5
840  AXES 1,1,0,-5,10,5
850  SCALE 0,60,-5,5
860  FOR N3=-5 TO 5 STEP 5
870  MOVE -2,N3
880  LABEL USING "K";N3
890  NEXT N3
900  CSIZE 2
910  LDIR 90
920  LORG 4
930  MOVE -4,-3.5
940  LABEL USING "K";"Port heavy"
950  MOVE -4,3.5
960  LABEL USING "K";"Stbd heavy"
970  LDIR 0
980  LORG 5
990  CSIZE 3
1000 FOR N=0 TO 90 STEP 10
1010 MOVE N,-5.5
1020 LABEL USING "K";N
1030 NEXT N
1040 MOVE 30,-6.25
1050 LABEL USING "K";"MINS"
1060  EXIT GRAPHICS
1070 L02:! *****************************************************************
```

Table 2

PARAMETER DEFINITIONS (IN QUASI-ALPHABETICAL ORDER)

```
1070 L02:!
1080 ! THIS PROGRAM MODELS A SIMPLE AIRCRAFT TYPE FUEL SYSTEM.   IT IS STORED
     UNDER THE NAME  -  MODT1  -.
1090      COM INTEGER I2,N,Thr,REAL T,E,Q,Check,F,F1,F2,F3,W,W4,W5,F1v,F2v,F3v,W
4v,W5v,Swt,An$
1100    INTEGER F2c,F3c,W4c,W5c,Ec,Trf,Trfp,Trfr,Ctf,F1p,F2p,F3p,W4p,W5p,F12p,F1
3p,F24p,F35p,F1m,F2m,F3m,W4m,W5m,F2s,F3s,W4s,W5s,I,Nfw
1110 L1:! A list of parameters follows together with their values or default val
ues.
1120 !                  1     CONSTANTS
1130 !                  1(A),    LIMITING VALUES
1140 F1v=200                          !Galls.  Collector tank capacity
1150 F2v=1100                         !Galls.  Rear fuselage tank capacity
1160 F3v=700                          !Galls.  Forward fuselage tank capacity
1170 W4v=1000                         !Galls.  Port wing tank capacity
1180 W5v=1000                         !Galls.  Stbd wing tank capacity
1190 Rhtmx=.5                         !Mins.  Max allowable Reheat time
1200 Fv=F1v+F2v+F3v                   !Galls.  Total fuselage capacity
1210 Wv=W4v+W5v                       !Galls.  Total wing capacity
1220 Qv=Fv+Wv                         !Galls.  Total aircraft capacity.
1230 Sft=12                           !Feet.  Distance between fuselage tanks
1240 So3=7.5                          !Feet.  Distance between F3 and cofg
1250 So2=Sft-So3                      !Feet.  Distance between F2 and cofg
1260 So1=-2                           !Feet.  Dist and direction of F1 from cofg.
1270 Swt=20                           !Feet   Distance between wing tanks cofg's
1280 So5=Swt/2                        !Feet.  Distance between stbd tank and cofg
1290 So4=Swt/2                        !Feet.  Distance Between port tank and cofg
1300 !                  1(B),     INITIAL VALUES
1310 F1i=0                            !Galls,  Actual quantity put into collector
 tank
1320 F2i=0                            !Galls.  Actual into rear fuselage tank
1330 F3i=0                            !Galls.  Actual into forward fuselage tank
1340 W4i=0                            !Galls.  Actual into port wing tank
1350 W5i=0                            !Galls.  Actual into stbd wing tank
1360 Qi=F1i+F2i+F3i+W4i+W5i           !Galls.  Total fuel loaded into aircraft
1370 Plmt=1.5                         !Feet.  Permisable Pitch cofg movement +or-
1380 Rlmt=1                           !Feet.  Permisable roll cofg movement +or-
1390 Acf=1                            !%.     Required accuracy [display,1% of fu
ll]
1400 Acc=1                            !%.     Required accuracy [gauge,1% of cont
ents]
1410 Inac=.2                          !%.     Typical component inaccuracy
1420 !                  1(C),     (FUEL) FLOW RATES
1430 !  a).  fuel consumption rates of engine
1440 Lfr=6                            !Galls/min. Engine Idle     [1]
1450 Mfr=60                           !Galls/min. Engine Maxdry   [3]
1460 Cfr=Mfr*.75                      !Galls/min. Engine Cruise   [2]
1470 Hfr=600                          !Galls/min. Engine Reheat   [4]
1480 !  b).  pumping rates
1490 Pfr=Mfr*.8                       !Galls/min. normal transfer rate
1500 Gfr=Mfr*.5                       !Galls/min. "gravity" flow rate.
1510 !                  1(D),     FLAGS
1520 !           0=open(not energised)       1=shut(energised)
1530 F2c=0                            !Rear fuselage tank shutoff cock
1540 F3c=0                            !Forward fuselage tank cock
1550 W4c=0                            !Port wing tank cock
1560 W5c=0                            !Stbd wing tank cock
1570 Ec=0                             !Engine stopcock (inplace of F1c=0)
1580 Trf=0                            !Fuel transfer in progress or required.
1590 Trfp=0                           !Longitudinal fuel transfer required
1600 Trfr=0                           !Lateral fuel transfer required
1610 F1p=0                            !Collector tank pump. 0=ON, 1= OFF
1620 F2p=0                            !Rear tank pump ON
1630 F3p=0                            !Forward tank pump ON
1640 F12p=1                           !Pump to transfer fuel from collector
```

Table 2 (continued)

```
1650                              ! tank(F1) to rear tank, OFF *****
1660 F13p=1                       !Pump to transfer fuel from F1 to F3 OFF **
1670 F24p=1                       !Pump to transfer fuel from F2 to W4 OFF **
1680 F35p=1                       !Pump to transfer Fuel from F3 to W5 OFF **
1690 W4p=0                        !Port wing pump ON
1700 W5p=0                        !Stbd wing pump ON
1710 F1m=0                        !Collector tank is master during transfer
1720 F2m=0                        !Rear tank is master during transfer
1730 F3m=0                        !Forward tank is master
1740 W4m=0                        !Port wing tank is master
1750 W5m=0                        !Stbd wing tank is master
1760 F2s=0                        !Rear tank is slave during a transfer
1770 F3s=0                        !Forward tank is slave
1780 W4s=0                        !Port wing tank is slave
1790 W5s=0                        !Stbd tank is slave tank
1800 !              2  VARIABLES
1810 Dq=0                         !Galls/min. Actual element of fuel transfer
red to engine per cycle
1820 Dect=0                       !Galls. Amount of fuel to be transferred th
rough executing Loop.
1830 E=0                          !Galls/min. Fuel consumed by the engine
1840 Elf=0                        !Critical fuel element (from fuel gauge spe
c)
1850 Elt=0                        !Time interval (corresponds to Elf)
1860 F1=200                       !Galls. Actual fuel in collector tank
1870 F2=1100                      !Galls. Actual fuel in rear tank
1880 F3=700                       !Galls. Actual fuel in forward tank
1890 F=F1+F2+F3                   !Galls. Total fuel in fuselage
1900 Fcr=0                        !Galls/min. Current fuel consumption rate
1910 Lt=0                         !Mins. Actual time into mission
1920 Lpit=0                       !Mins. Time interval for each loop cycle
1930 Pcogs=0                      !Feet. Pitch cofg shift
1940 Pdq=0                        !Fuel transfer element/cycle for wing tanks
1950 Q=F+W          !(W=0!!)      !Galls. Total fuel remaining
1960 Rcogs=0                      !Feet. Roll cofg shift
1970 Rhpfr=0                      !Fuel transfer element for fuselage tank pu
mps
1980 Sum=0                        !Galls. Total fuel at any time(within loop)
1990 T=0                          !Mins. Time into mission(val. outside loop)
2000 Tdq12=0                      !Potential flow Through pipe connecting-
2010                              ! tanks F1 and F2, in direction of F2
2020 Tdq13=0                      !Potential flow, F1 to F3
2030 Tdq21=0                      !Transfer rate between F2 and F1-
2040                              ! normal direction.
2050 Tdq31=0                      !Transfer rate between F3 and F1.
2060 Tdq24=0                      !Potential flow through pipe connecting-
2070                              ! Tank F2 to W4
2080 Tdq35=0                      !Potential flow, F3 to W5
2090 Tdq42=0                      !Transfer rate between W4 and F2
2100 Tdq53=0                      !Transfer rate, W5 to F3
2110 Thr=1                        !Throttle setting [0,1,2,3or4]
2120 Ut=2                         !Mins. Fuel gaugeing system update interval
2130 W4=1000                      !Gals. Quantity of fuel in port wing tank
2140 W5=1000                      !Gals. Quantity of fuel in stbd wing tank
2150 W=W4+W5                      !Gals. Total fuel in wings
2160 !              3.    COUNTER REGISTERS
2170 N=1                          !Fuel display update cycle number
2180 Nfw=0                        !Failure warning display limiting counter
2190 I=0                          !Fuel decrement counter index
2200 I2=0                         !Number of fuel decrement cycles required
2210 !              4.    LINE IDENTIFIERS
2220 ! 4a).  Loops
2230 ! L01                        !First line of graphdrawing routine.
2240 ! L02                        !End of graphdrawing program.
2250 ! L1                         !Begining of parameter definitions.
```

Table 2 (concluded)

```
2260 ! L2                              !End ofparameter specification.
2270 ! L3                              !Begining of program proper.
2280 ! L10                             !Start of active part of program.
2290 ! L20                             !Fuel decrementing loop start.
2300 ! L21                             !Instruction which moves fuel to engine.
2310 ! L22                             !Identifier used to alternate feed to F1
2320 ! L23                             !     "       "       "       "       "
2330 ! L24                             !     "       "       "       "       "
2340 ! L24b                            !     "       "       "       "       "
2350 ! L25                             !Return from intertank transfer routine,J14
2360 ! L26                             !Return from Collector low routine, J12
2370 ! L30                             !Fuel decrementing loop ends.
2380 ! L40                             !Start of program jump routines.
2390 ! L100                            !Start of program SUB routines.
2400 ! Sflooppara                      !Sub program Flooppara
2410 ! Smove                           !Sub program Move
2420 ! Scgtfs                          !Sub program Cgtfs
2430 ! L200                            !End of SUB routines and program.
2440 !          4b).   JUMPS.
2450 ! J 9                              Fuel transfers carried over from former
                                                                  loop cycles.
2460 ! J10                             !Engine shutdown routine.
2470 ! J11                             !Throttle set out of range routine.
2480 ! J12                             !Collector tank low routine.
2490 ! J14                             !P_trans. Inter tank transfer routines.
2500 ! J16                             !Error trap print routine.
2510 ! J100                             Termination procedures
2520 L2: ! **********END OF SYSTEM PARAMETER SPECIFICATION%********************
2530  !          Parameters required for graph plotting routine.
2540  Lctp1=14                         !Location on graph of pitch cofg plot.
2550  Lctp2=63                         !    "     "     "    "  roll    "    "
2560  Lctr1=70                         !
2570  Lctr2=120                        !
2580  Tprint$="O"                      !Plot identification characters.
2590  F1print$="C"                     !Collector tank.
2600  F2print$="R"                     !Rear fuselage tank or group
2610  F3print$="F"                     !Front fuselage tank or group
2620  W4print$="P"                     !Port wing tank.
2630  W5print$="S"                     !Starboard wing tank.
2640                       ! END OF PARAMETER LIST.
2650 L3:  ! ***************************************************************
```

Table 3

INITIAL CONDITIONS AND MAJOR PROGRAM SEGMENT

```
2650 L3:  ! ****************************************************************
2660 PRINT "This is a simulation of a simple aircraft type fuel system comprisin
g five tanks. A collector tank (F1) and 2 fuselage tanks F2&F3"
2670 PRINT "F2 is the rear tank and F3 the forward one.  There are two wing tank
s, W4(port) and W5(stbd)."
2680 PRINT " The program is intended to form the basis for a more complex simula
tion.        It uses standard parameters which may be accessed by listing lines";
2690 PRINT "L1 to L2(LIST L1,L2).  The primary control of fuel transfer is the l
imit placed upon the cofg movement (Plmt,Rlmt) which you may chose."
2700 PRINT " Fuel flows from collector tank to engine and F1 fuel is topped up f
rom the      fuselage tanks F2 and F3 unless one of these transfers is ";
2710 PRINT "inhibited by pitch    cofg requirements.  In this case Fuel would be
 taken from the other.   Fuel     transfers from the wings are port wing to ";
2720 PRINT "rear fuselage and Stbd wing to forwardfuselage tank, subject to roll
 cofg requirements.   The collector tank is       presumed tobe at the a/c ";
2730 PRINT "c of g at all times"
2740 PRINT ""
2750 PRINT " The beep indicates that the program is halted for you to inspect th
e display."
2760  BEEP
2770  PRINT "                 (press CONT when you are ready to continue)"
2780  PAUSE
2790  PRINT PAGE
2800 PRINT " MAX TANK CAPACITIES ARE:-  F1v=";F1v;"Galls. F2v=";F2v;"Galls. F3v=
";F3v;"Galls.     W4v=";W4v;"Galls. W5v=";W5v;"Galls."
2810 PRINT "The default values for fuel contents are :- F1";F1;", F2";F2;", F3";
F3;", W4";W4;"                                          and W5";W5;"Gallons."
2820 PRINT "You can change the values by inserting new ones now."
2830 INPUT "enter any new values in the order F1,F2,F3,W4,W5",F1,F2,F3,W4,W5
2840 IF F1>F1v THEN F1=F1v
2850 IF F2>F2v THEN F2=F2v
2860 IF F3>F3v THEN F3=F3v
2870 IF W4>W4v THEN W4=W4v
2880 IF W5>W5v THEN W5=W5v
2890  PRINT ""
2900 PRINT "The distance between F2&F3 has been set as ";Sft;"feet and the curre
nt position of the cofg is ";So3;"feet from the forward tank F3."
2910 L5: INPUT "You have the opportunity to change the cofg distance relative to
 F3.",So3
2920  PRINT ""
2930 PRINT "The pitch and roll limits on cofg are:- ";Plmt;"feet and ";Rlmt;"fee
t."
2940 L6: INPUT "New limit values may now be set: Plmt,Rlmt.",Plmt,Rlmt
2950 LINPUT "Is cross-feed to be allowed? Yes or No",An$
2960  IF An$="Yes" THEN F12p=F13p=F24p=F35p=0
2970  IF An$<>"Yes" THEN F12p=F13p=F24p=F35p=1
2980          So2=Sft-So3                  !Dist of rear tank from c of g position
2990           CALL Cgtfs(Wv,W5,W4,Swt/2,Swt/2,Rlmt,Rcogs,W5m,W5s,W4m,W4s,Trf)
           !Find initial lateral c of g shift!
3000           CALL Cgtfs(Fv,F3,F2,So3,So2,Plmt,Pcogs,F3m,F3s,F2m,F2s,Trf)
           !Initial pitch c of g position
3010           IF F3m=1 THEN W4c=1
3020           IF F2m=1 THEN W5c=1
3030           F1i=F1                   !Store amended tank contents values.
3040           F2i=F2                   !              Ditto
3050           F3i=F3                   !              Ditto
3060           W4i=W4                   !              Ditto
3070           W5i=W5                   !              Ditto
3080           Qi=Q=F1+F2+F3+W4+W5      !Store initial value of Qi and set Q
3090           CALL Printintl(Sft,So3,Plmt,Rlmt)
3100           CALL Plotcofg(Pcogs,.30,Lctp1,Lctp2) !Plot the pitch inst. cofg sh
ift
3110           CALL Plotcofg(Rcogs,.25,Lctr1,Lctr2) !Plot the roll inst. cofg shi
ft
3120   ! ******************************************************************
```

Table 3 (continued)

```
3130 L10:     ! The fuel system simulation program proper follows.
3140 L12:     Elf=(Qv*Acf+Q*Acc)/100 !Crit element of fuel derived from gauging
requirements. Smallest change in fuel content that can be measured.
3150          Elf=Elf/5                !Crit element made small compared to gaugi
ng requirement accuracies.
3160          CALL Ploty((Q),Lt,Lctp1,Lctp2,(Tprint$),40)   !Plot current fuel q
uantities
3170          CALL Ploty((F1),Lt,Lctr1,Lctr2,(F1print$),12)
3180          CALL Ploty((F2),Lt,Lctr1,Lctr2,(F2print$),12)
3190          CALL Ploty((F3),Lt,Lctr1,Lctr2,(F3print$),12)
3200          CALL Ploty((W4),Lt,Lctr1,Lctr2,(W4print$),12)
3210          CALL Ploty((W5),Lt,Lctr1,Lctr2,(W5print$),12)
3220          BEEP
3230          PAUSE
3240          EXIT GRAPHICS
3250          PRINT "The current throttle setting is:-";Thr
3260          INPUT "If you want a new throttle setting, enter it now",Thr
3270          IF Thr<=0 THEN GOTO J10!Engine is OFF, pick up print out routine**
3280          IF Thr=1 THEN Fcr=Lfr  !Engine set at idle.                      **
3290          IF Thr=2 THEN Fcr=Cfr  !Engine set to cruise condition.          **
3300          IF Thr=3 THEN Fcr=Mfr  !Engine set to Max Dry condition          **
3310          IF Thr=4 THEN GOTO J9  !Engine set to Max Dry+Reheat             **
3320          IF Thr>4 THEN GOTO J11 !Selected throttle setting out of range   **
3330          CALL Flooppara(Ut,Elf,Fcr,Lpit,Dq,Dect,I2)
3340 L20:     Pdq=Pfr*Lpit             !Element of pump-transfer per cycle equival
ent to Dq
3350          Rhpfr=Hfr*Lpit
3360          W4cs=W4c                 !Remember if cock has been selected OFF
3370          W5cs=W5c                 !  "        "     "     "     "     "
3380          FOR I=1 TO I2 STEP 1     !******** fuel dec loop starts **********.-
        Start of loop.
3390          Lt=I*Lpit+T              ! Lpit is loop initial time
3400 L21:     CALL Move(Qv,E,F1,(Dq),Gfr,D1,D2,0,Ec,F1p) !F1 fuel used by Engine
3410          IF PROUND(E-Erem,-3)<>PROUND(Dq,-3) THEN GOTO J99     !Fuel suppli
ed to engine not that required by throttle setting!
3420 L22:     Erem=E
3430          IF FRACT((N+I)/2)=0 THEN GOTO L24
3440 L23:     CALL Move(F1v,F1,F2,(Rhpfr),Gfr,Tdq21,Tdq12,F2m,F2c,F2p) !F2 fuel
to F1. Note See L25 referring to the use F2m(tank master flag)
3450    ! F2c(tank cock flag).
3460          CALL Move(F2v,F2,W4,(Pdq),Gfr,Tdq42,Tdq24,W4m,W4c,W4p) !W4 fuel to
 F2
3470          IF FRACT((N+I)/2)=0 THEN GOTO L24b
3480 L24:     CALL Move(F1v,F1,F3,(Rhpfr),Gfr,Tdq31,Tdq13,F3m,F3c,F3p) !F3 fuel
to F1
3490          CALL Move(F3v,F3,W5,(Pdq),Gfr,Tdq53,Tdq35,W5m,W5c,W5p) !W5 fuel to
 F3
3500          IF FRACT((N+I)/2)=0 THEN GOTO L23
3510 L24b:    IF Trf=1 THEN GOTO J14  !Continue fuel redistribution transfers **
3520 L25:     CALL Cgtfs(Wv,W5,W4,Swt/2,Swt/2,Rlmt,Rcogs,W5m,W5s,W4m,W4s,Trfr)
3530  ! Note. W5m is used in place of W5c.  The cock(W5c) Is a manual selection.
 Program has to use a alternative control logic symbol.
3540     !   Swt is distance between wing tanks
3550          CALL Cgtfs(Fv,F3,F2,So3,So2,Plmt,Pcogs,F3m,F3s,F2m,F2s,Trfp)
3560          W4c=W4cs                 !Reset wing tank cock to selected position
3570          W5c=W5cs                 !   "     "    "    "    "     "     "
3580          IF F3m=1 THEN W4c=1      !If rear tank trans inhibited then inhibit
partners wing tank too
3590          IF F2m=1 THEN W5c=1      !  //          //           //          //
3600          CALL Plotcofg(Pcogs,Lt,Lctp1,Lctp2)!Plot the pitch inst. cofg shif
t
3610          CALL Plotcofg(Rcogs,Lt,Lctr1,Lctr2) !Plot the roll inst. cofg shif
t
3620          Trf=Trfr OR Trfp OR Trf!Prevents Trf(transfer required flag), set
in L25 b-ing cancelled by subsequent entry into Cgtfs.
```

Table 3 (concluded)

```
3630          Sum=Sum+Dq                !Accumulative total of fuel transfered.
3640          IF F1*1.05<F1v THEN GOTO J12!   Only  collector tank fuel left! **
3650 L26:     IF Dect*1.01<Sum THEN GOTO J16     !Test for comp error        **
3660 L27:     IF E<>Sum THEN PRINT "E not= Sum ";E;"not=";Sum
3670 L30:     NEXT I                    !******* fuel dec loop ends *************-
          End of loop.
3680          T=Lt                      !Update time into mission
3690          F=F1+F2+F3
3700          W=W4+W5
3710          Q=F+W
3720          N=N+1
3730          GOTO L10
3740          END
```

Table 4

```
3750 L40:! *********************************************************************
3760 ! PROGRAM JUMP ROUTINES FOLLOW
3770 J9:       CALL Flooppara(Rhtmx,Elf,Hfr,Lpit,Dq,Dect,I2)  !Rhtmx limits Rheat
 to30 secs
3780           IF W4c OR W5c THEN PRINT "WING-TANK STOP-COCKS OPENED."
3790           W4c=W5c=W4cs=W5cs=0   !Ensure max transfer for Reheat.
3800           GOTO L20
3810                                 ! ***
3820 J10:      PRINTER IS 0          ! Response to throttle setting 0
3830           PRINT "****  Engine has been shut down.  ****"
3840           N=N-1
3850           GOTO J101             !Print out and finish
3860                                 ! ***
3870 J11:      DISP "AN IMPERMISSIBLE VALUE FOR THE THROTTLE HAS BEEN SET. TRY AG
AIN"
3880           WAIT 4000
3890           GOTO L10
3900 !                                ***
3910 !         *************** COLLECTOR TANK FUEL LEVEL LOW ROUTINE *************
3920 J12:      EXIT GRAPHICS         ! prog exicution get here when collector tan
k fuel level is less than max
3930           F=F1+F2+F3            ! Sums fuselage fuel for printout routine
3940           W=W4+W5               ! Sums wing fuel for printout routine
3950           Q=F+W                 ! Sums wing and fuselage fuel
3960           IF F1<Dq THEN GOTO J100 !Out of fuel! Print results and finish  **
3970           PRINTER IS 0
3980           FIXED 2
3990           PRINT "****COLLECTOR TANK LOW!****** GALLS REMAINING=";F1;"******
TIME=";Lt;"*****"
4000           PRINTER IS 16
4010           GRAPHICS
4020           CALL Ploty((Q),Lt,Lctp1,Lctp2,(Tprint$),40)
4030           CALL Ploty((F1),Lt,Lctr1,Lctr2,(F1print$),12)
4040           IF F1<Q THEN GOTO J12_1  !Test if there is fuel in any tank
4050           GOTO L26                 ! Return to main segment
4060 J12_1:    F2m=F3m=W4m=W5m=F2s=F3s=W4s=W5s=0 !Master and slave flags cancelle
d
4070           F1m=1                    ! Prepare to transfer fuel to F1
4080           Trf=1                    !Set inter tank transfer-required flag
4090           PRINTER IS 0
4100           IF F1rem>F1 THEN J12_2  !Collector contents still falling!!
4110           F1rem=F1                 !Save Collector contents for test
4120           IF F2>0 THEN J12_5      !F2is slave                              **
4130 J12r5:    IF F3>0 THEN J12_6      !F3 is slave                             **
4140           IF W4>0 THEN W4s=1      !W4 is slave                             **
4150           W5s=1                    !Set slave flag for W5 tank
4160           PRINTER IS 16
4170           GOTO L26                 !Return to main segment
4180 J12_2:    !
4190           F1rem=F1                 !Save collector contents for test
4200           PRINT "** FLOW TO COLLECTOR TANK INADEQUATE!  REDUCE THROTTLE SETT
ING **"
4210           IF W4c<>0 THEN GOTO J12_3   !Test if port wing tank cock is OFF
4220           IF W5c<>0 THEN GOTO J12_4   !Test if stbd wing tank cock is OFF
4230           PRINTER IS 16
4240           GOTO L26
4250 J12_3:    PRINT "PORT STOP-COCK WAS  OFF "
4260           W4c=W4cs=W4p=0              !Turn pump and cock ON and cancel sele
ction
4270           PRINTER IS 16
4280           GOTO L26
4290 J12_4:    PRINT "STBD STOP-COCK WAS `OFF "
4300           W5c=W5cs=W5p=0              !Turn pump and cock ON and cancel sele
ction
4310           PRINTER IS 16
4320           GOTO L26
```

Table 4 (continued)

```
4330 J12_5:   F2s=1                        !Designate rear tank as a slave
4340          IF F2c=1 THEN PRINT "REAR TANK COCK WAS CLOSED"!J14 (P_trans) will
automatically open cock, since master and slave have been identified.
4350          GOTO J12r5
4360 J12_6:   F3s=1                        !Forward tank is slave
4370          IF F3c=1 THEN PRINT "FORWARD TANK COCK WAS CLOSED"
4380          PRINTER IS 16
4390          GOTO L26
4400 !                                     ***
4410 ! *********************************************************************
*
4420 J14:        ! P_trns
4430 ! The subroutine contains the various inter tank transfer posibilites for
4440 ! a simple four, plus collector tank fuel system. It is assumed that there
4450 ! can only be one slave tank. However more than one master tank may be
4460 ! designated.  The program selects the tank with the lowest number in its
address(variable name).
4470  ! The routine sets the necessarty flags (cocks & pumps) to facilitate tran
sfers required.
4480 !        ************* FUEL TRANSFER ROUTINE **************
4490          PRINT "Prog in J14  P_trans";
4500          IF F2s+F3s+W4s+W5s<1 THEN GOTO J14r1   ! Test, there is a slave!
4510          IF F1m=1 THEN GOTO J14_0!   F1 is master tank,  a late entry!
4520          IF F2m=1 THEN GOTO J14_1!   Is F2 a master tank?
4530          IF F3m=1 THEN GOTO J14_2!   Is F3 a master tank?
4540          IF W4m=1 THEN GOTO J14_3!   Is W4 a master tank?
4550          IF W5m=1 THEN GOTO J14_4!   Is W5 a master tank?
4560 J14r1:   Trf=0                        !Master or slave tank was not identified!
4570          F2s=0                        !Reset all transfer flags
4580          F3s=0
4590          W4s=0
4600          W5s=0
4610          F1m=0
4620          F2m=0
4630          F3m=0
4640          W4m=0
4650          W5m=0
4660          PRINT "J14r1"
4670          GOTO L25                     !Return to main segment
4680 !        ********* End of master tank identification ***********
4690 J14_1:     PRINT "J14_1"
4700          IF F2>=F2v THEN GOTO J14r1 !Test if master, F2, is now full     **
4710          IF W4s=0 THEN GOTO J14r5!                                       **
4720          W4c=W4p=0
4730          CALL Move(F2v,F2,W4,(Tdq42),Gfr,D1,D2,0,W4c,W4p)  ! W4 fuel to F2
4740          IF W4<=0 THEN GOTO J14r1 ! Is slave tank W4, empty?             **
4750          GOTO L25                     ! Return
4760 J14r5:     PRINT "J14r5";
4770          F2c=0
4780          Dfr=Gfr
4790          IF F12p=1 THEN Dfr=0
4800          CALL Move(F2v,F2,F1,(Tdq12),Dfr,D1,D2,0,F2c,F12p)  ! F1 fuel to F2
4810 J14r10:  PRINT "J14r10";
4820          F3c=F3p=0
4830          CALL Move(F1v,F1,F3,(Tdq31),Gfr,D1,D2,0,F3c,F3p)  ! F3 fuel to F1
4840          IF F3s=1 THEN GOTO J14_6!  Test,    Slave tank F3 empty         **
4850 J14r13:    PRINT "J14r13"
4860          W5c=W5p=0
4870          CALL Move(F3v,F3,W5,(Tdq53),Gfr,D1,D2,0,W5c,W5p)  ! W5 fuel to F3
4880          IF W5<=0 THEN GOTO J14r1 ! Test if slave is now empty.          **
4890          GOTO L25                     !  Return to main segment
4900 J14_6:   PRINT "J14_6"
4910          IF F3<=0 THEN GOTO J14r1!
4920          GOTO L25                     !  Return to main segment
4930          !    ******** End of F2 master/slave routine*********
```

Table 4 (continued)

```
4940 J14_2:    PRINT "J14_2"
4950           IF F3>=F3v THEN GOTO J14r1 ! Test if master F3 is now full.      **
4960           IF W5s=0 THEN GOTO J14r7   !                                      **
4970           GOTO J14r13              !W5 fuel to F3 etc.
4980 J14r7:      PRINT "J14r7";
4990           F3c=0
5000           Dfr=Gfr
5010           IF F13p=1 THEN Dfr=0
5020           CALL Move(F3v,F3,F1,(Tdq13),Dfr,D1,D2,0,F3c,F13p)!  F1 fuel to F3
5030 J14r12:     PRINT "J14r12";
5040           F2c=F2p=0
5050           CALL Move(F1v,F1,F2,(Tdq21),Gfr,D1,D2,0,F2c,F2p)!  F2 fuel to F1
5060           IF F2s=1 THEN GOTO J14r8 !                                        **
5070           W4c=W4p=0
5080           CALL Move(F2v,F2,W4,(Tdq42),Gfr,D1,D2,0,W4c,W4p)!  W4 fuel to F2
5090           IF W4<=0 THEN GOTO J14r1 !                                        **
5100           GOTO L25                 !Return to main program
5110 J14r8:       PRINT "J14r8"
5120           IF F2<=0 THEN GOTO J14r1 !                                        **
5130           GOTO L25                 !  Return to main program
5140           !          *****End of F3 master/slave routine ******
5150 J14_3:    PRINT "J14_3"
5160           IF W4>=W4v THEN GOTO J14r1!                                       **
5170           W4c=0
5180           Dfr=Gfr
5190           IF F24p=1 THEN Dfr=0
5200           CALL Move(W4v,W4,F2,(Tdq24),Dfr,D1,D2,0,W4c,F24p)!  F2 fuel to W4
5210           IF F2s=0 THEN GOTO J14r5!                                         **
5220           IF F2<=0 THEN GOTO J14r1!                                         **
5230           GOTO L25                 !  Return to main program
5240           ! *************End of W4 master/slave routine ****************
5250 J14_4:    PRINT "J14_4"
5260           IF W5>=W5v THEN GOTO J14r1 !                                      **
5270           W5c=0
5280           Dfr=Gfr
5290           IF F35p=1 THEN Dfr=0
5300           CALL Move(W5v,W5,F3,(Tdq35),Dfr,D1,D2,0,W5c,F35p)!  F3 fuel to W5
5310           IF F3s=0 THEN GOTO J14r7 !                                        **
5320           IF F3<=0 THEN GOTO J14r1 !                                        **
5330           GOTO L25                 !  Return to main program
5340           ! ************ End of W5 master/slave routine ***********
5350 J14_0:    PRINT "J14_0"            !This segment is entered subsequent to J12
5360           IF F1>=F1v THEN GOTO J14r1
5370           IF F3s=1 THEN GOTO J14r10 !                                       **
5380           IF W5s=0 THEN GOTO J14r12 !                                       **
5390           F3c=F3p=0
5400           CALL Move(F1v,F1,F3,(Tdq31),Gfr,D1,D2,0,F3c,F3p) ! F3 fuel to F1
5410           GOTO J14r13
5420           ! *********** End of F1 master routine **********
5430           ! ********** END OF FUEL TRANSFER ROUTINE ***********
5440 J16:      PRINTER IS 0
5450           PRINT "Dect*1.01<Sum.  Dect&Sum are:- ";Dect;Sum
5460           PRINT "I= ";I,"I2= ";I2
5470           PRINTER IS 16
5480           GOTO L27
5490           !                        ***
5500 J99:      PRINTER IS 0
5510           PRINT LIN(1)
5520           PRINT "Engine is being starved! Throttle setting requires";Dq;"Eng
ine getting";E-Erem
5530           IF E-Erem>Dq*1.01 THEN GOTO J101
5540           IF E-Erem<Dq*.99 THEN GOTO J101
5550           PRINTER IS 16
5560           GOTO L22
5570 J100:     PRINTER IS 0
5580           PRINT ""
```

Table 4 (concluded)

```
5590          PRINT " ********************COLLECTOR TANK EMPTY!*****************
+*********************** FLAME OUT ********* FLAME OUT ************************"
5600 J101:    PRINT ""
5610          PRINT ""
5620          DUMP GRAPHICS
5630          PRINT ""
5640          PRINT ""
5650          PRINTER IS 16
5660          END
5670 L100:! *****************************************************************
```

Table 5

SUBPROGRAMS BELONGING TO THE SIMULATION

```
5680 !  SUB programs follow:-
5690 ! Flooppara, This routine determins the values of parameters derived
5700 ! from the selected flowrate, derived from the throttle setting Thr in
5710 ! the main program.
5720 SUB Flooppara(Ut,Elf,Fcr,Lpti,Dq,Dect,INTEGER I2)
5730        Elt=Elf/Fcr                  !Element of time equivalent to fuel eleme
nt Elf.
5740        I2=PROUND(Ut/Elt,0)+1        !Number of times the loop is entered.
5750        Lpti=Ut/I2                   !Individual cycle time.
5760        Dq=Fcr*Lpti                  !Element of fuel transfered each cycle.
5770        Dect=Dect+Fcr*Ut             !Fuel that will have been removed when lo
ops is completed.
5780        SUBEND
5790 ! ****************************************************************
5800 ! Sub-program Move transfers fuel from a slave tank to a master tank,or to
5810 ! an engine, for which Mi=Qi.  It checks that the slave tank cock is open
5820 ! and that the pump is on.  A reduced flowrate is assumed if the pump is
5830 ! off.  Transfer is also conditional upon Tna not being set.
5840 ! Mi=Master tank volume, M= master-t contentents, S=Slave-t contents
5850 ! Dq=Quantity to be transfered (at equivalent pump rate), Gfr= flow that
5860 ! would take place due to gravity etc, Exci= excess transfer potential
5870 ! towards centre,Exco= excess flow potential towards wing tanks.
5880 !   The program returnes updated figures for slave tank and master tank
5890 ! contents.
5900  ! When used to transfer fuel to the engine, a check should be made that al
l of it gets there!
5910 SUB Move(Mi,M,S,Dq,Gfr,Exci,Exco,INTEGER Tna,Scf,Spf)
5920            Rems=S                       !Store slave tank contents
5930            IF Tna<>0 THEN GOTO Mj1      !Transfer not allowed (=1)
5940            IF Scf<>0 THEN GOTO Mj2      !Shut-off valve closed (=1)
5950            IF Spf<>0 THEN Dq=Gfr        !Pump not running (=1)
5960            IF Dq=Gfr THEN PRINT "Pump not running"   !Default value of flow
5970            S=S-Dq                       !Fuel removed from slave tank
5980            M=M+Dq                       !Fuel added to master tank
5990            IF S<=0 THEN GOTO Mj3        !Test if slave contents is 0 or -ve
6000 Mjr3:      IF M>Mi THEN GOTO Mj4        !Test if master is over full
6010 Mjr4:      Exci=Rems-S                  !Actual transfer per cycle
6020            Exci=Dq-Exci                 !Spare transfer potential per cycle
6030            Exco=2*Dq-Exci              !Spare outward transfer potential/cycle
6040            SUBEND
6050 Mj1:                 PRINT "Cofg flag set to 1"
6060            Exci=Exco=Dq                 !Flow potential is max!
6070            SUBEXIT
6080 Mj2:                 PRINT "Fuel cock shut "
6090            Exci=Exco=Dq                 !Flow potential is max!
6100            SUBEXIT
6110 Mj3:                 PRINT "Slave  tank is empty or flow to/from it is ina
dequate!"
6120            M=M+S                        !Correct master tank contents (S is -)
6130            S=0                          !Correct slave tank contents
6140            GOTO Mjr3                    !Return to test if master is overfull
6150            SUBEXIT
6160 Mj4:                PRINT "Master tank is overfull. Correct!"
6170            S=S+(M-Mi)                   !Correct slave tank contents (M-Mi -ve
6180            M=Mi                         !Correct master contents
6190            GOTO Mjr4
6200            SUBEXIT
6210            SUBEND
6220 ! ****************************************************************
```

Table 5 (concluded)

```
6230 !      ********    SUB PROGRAM Cgtfs FOLLOWS    ********
6240 ! Cgtfs calculates the movement of the cofg and outputs this as parameter
6250 ! (S) weighted by the proportion of fuel remaining.  The movement is
6260 ! compared with a limiting value (Lmt) and if this limit is exceded the
6270 ! appropriate master (Fm,Sm) flags are set.  The slave and transfer flags
6280 ! are not required in this application and have been deleted from the
6290 ! active pass parameter list.
6300 ! Fv is total fuselage fuel capacity, F&R are actual fuel remaining in thes
e
6310 ! tanks, Fo&Ro are distances from cofg datum, Fm&Rm are respective master
6320 ! flags, Fs&Rs are respective slave flags, Trf is the transfer-required fla
g
6330  ! NOTE  When using this program, Fuel should not, in general, be taken
6340  ! from a MASTER Tank.  It is intended to receive fuel only!
6350                            ! ********
6360 SUB Cgtfs(Fv,F,R,Fo,Ro,Lmt,S,INTEGER Fm,Fs,Rm,Rs,Trf)
6370       IF F+R=0 THEN GOTO Scj5      !Default value of S set
6380       Xo=(F*Fo-R*Ro)/(F+R)          !moment-arm about cofg origin
6390       S=Xo*(F+R)/Fv                 !moment weighted to account for fuel red
uction
6400       IF Fm=1 THEN GOTO Scj1        !was nose previously too heavy?
6410       IF Rm=1 THEN GOTO Scj2        !was tail previously too heavy?
6420       IF S-Lmt>0 THEN GOTO Scj3     !shift is excessive and toward nose
6430       IF S+Lmt<0 THEN GOTO Scj4     !shift is excessive and toward tail
6440 Scjr5:Fm=0                          !shift not excessive, ensure flags are 0
6450       Rm=0
6460       Fs=0
6470       Rs=0
6480       Trf=0
6490       SUBEND
6500 Scj1: IF S+Lmt/2>0 THEN GOTO Scjr5 !cg tailward shift reduced to 1/2*limit
6510 Scj4: Fm=1
6520       Rm=0
6530       Fs=0
6540       Rs=1
6550       Trf=1
6560       SUBEXIT
6570 Scj2: IF S-Lmt/2<0 THEN GOTO Scjr5 !cg noseward shift reduced to 1/2* limit
6580 Scj3: Fm=0
6590       Rm=1
6600       Fs=1
6610       Rs=0
6620       Trf=1
6630       SUBEXIT
6640 Scj5:             S=0
6650       GOTO Scjr5
6660       SUBEND
6670         !                  ***
```

Table 6

SUBPROGRAMS WHICH SUPPORT DATA OUTPUT

```
6680 Sploty: ! ******************************************************************
6690   SUB Ploty(Y,Tim,Abs1,Abs2,C$,Fmax)
6700       COM INTEGER I2,N,Thr,REAL T,E,Q,Check,F,F1,F2,F3,W,W4,W5,F1v,F2v,F3v,W
4v,W5v
6710   Nn=N+2
6720   R=FRACT(Nn/3)                    !The numerator in the fraction sets the
Symbol repeat interval.
6730   LORG 5
6740          GRAPHICS
6750          LOCATE Abs1,Abs2,52,98
6760          SCALE 0,60,0,Fmax
6770          Y=Y/100
6780          PLOT Tim,Y,1
6790          CSIZE 2
6800          IF R=0 THEN LABEL USING "K";C$
6810          PENUP
6820          SUBEND
6830          !                      ***
6840 ! ***********************************************************************
6850 Splotcofg:      SUB Plotcofg(Xo,T,Ab1,Ab2)
6860          GRAPHICS
6870          LOCATE Ab1,Ab2,8,45
6880          SCALE 0,60,-5,5
6890          PLOT T,Xo,1
6900          PENUP
6910          SUBEND
6920          !                      ***
6930  ! **********************************************************************
6940 Sprintintl:     SUB Printintl(Sft,So3,Plmt,Rlmt)
6950          COM INTEGER I2,N,Thr,REAL T,E,Q,Check,F,F1,F2,F3,W,W4,W5,F1v,F2v,F
3v,W4v,W5v,Swt,An$
6960          PRINTER IS 0
6970          FIXED 2
6980 PRINT "Tank contents are:-F1=";F1;"Galls F2=";F2;"Galls F3=";F3;"Galls F4="
;F4;"Galls                           W4=";W4;"Galls W5=";W5;"Galls."
6990 PRINT "Distance between fuselage tank groups=";Sft;"feet.
        Distance of c of g from forward group=";So3;"feet."
7000 PRINT "Distance between wing tank groups    =";Swt;"feet."
7010 PRINT "C of g movement limits are, +/-";Plmt,"feet in pitch and +/-";Rlmt;"
feet in roll"
7020          IF An$<>"Yes" THEN GOTO J1
7030 PRINT "                        Fuel cross-feed is allowed"
7040          GOTO End
7050 J1: PRINT "                        Fuel cross-feed is NOT allowed"
7060 End: PRINT LIN(3)
7070          PRINTER IS 16
7080          SUBEND
7090 ! ***********************************************************************
7100  STOP
```

Table 7

TEST CONDITIONS CHOSEN TO DEMONSTRATE THE SIMPLE AIRCRAFT FUEL SYSTEM SIMULATION

Test No.	Results in figure	Initial fuel state *Note 1	Distance of cg datum *Note 2 (ft)	Cg excursion limits Pitch (ft)	Roll (ft)	Active fuel transfer	Throttle settings 1, idle; 2, cruise; 3, max-dry; 4, reheat	Comments
1		Full*	7.5	1.5	1	No	3, throughout	
2		Full	7.5	1.5	1	No	1, 0-6 min; 3, 6-12 min; 4, 12-13.5 min; 3, 13.5-end	
3		Star-board tank empty	7.5	1.5	1	No	1, 0-30 min	
4		Star-board tank empty	7.5	1.5	1	Yes	1, 0-30 min	
5		Port tank empty	7.5	1.5	1	Yes	1, 0-30 min	
6		Full	7.5	1.5	1	No	1, 1-18 min; 3, 18-48 min; 2, 48-end	Both wing cocks closed at 12th minute
7		Full	7.5	1.5	1	No	1, 1-18 min 3, 18-end	Both fuselage tank cocks closed at 12th minute
8		Full	7.5	1.5	1	Yes	1, 1-18 min; 3, 18-end	Both fuselage tank cocks closed at 12 minute
9		Rear tank 650 galls	7.5	1.5	1	No	1, 1-18 min; 3, 18-end	
10		Rear tank 650 galls	7.5	1.5	1	Yes	1, 1-18 min; 3, 18-end	
11		Front tank 350 galls	7.5	1.5	1	No	1, 1-18 min; 3, 18-end	
12		Front tank 350 galls	7.5	1.5	1	Yes	1, 1-18 min; 3, 18-end	
13		Full	2	1.5	1	No	1, 1-18 min; 3, 18-end	
14		Full	2	1.5	1	Yes	1, 1-18 min; 3, 18-end	
15		Full	10	1.5	1	No	1, 1-18 min; 3, 18-end	
16		Full	10	1.5	1	Yes	1, 1-18 min; 3, 18-end	

* NOTES: (1) The full condition has fuel distributed as follows: collector tank (F1) = 200 galls; rear fuselage tank (F2) = 1100 galls; forward fuselage (F3) = 700 galls; port wing tank (W4) = 1000 galls, starboard wing (W5) = 950 galls.

(2) The distance between the forward and rear fuselage tanks is 12 ft.

REFERENCES

No.	Author	Title, etc
1	M.A. Beeny	A review of recent UK developments in aircraft fuel management systems. RAE Technical Report 81110 (1982)
2	BAe (Warton) Report	A study of the engineer design of an advanced combat aircraft cockpit. TNAS 34
3	BAe (Warton) Report	Proposal for rig work using the Jaguar fuel rig at BAe Warton. TNAM 3396, December 1980

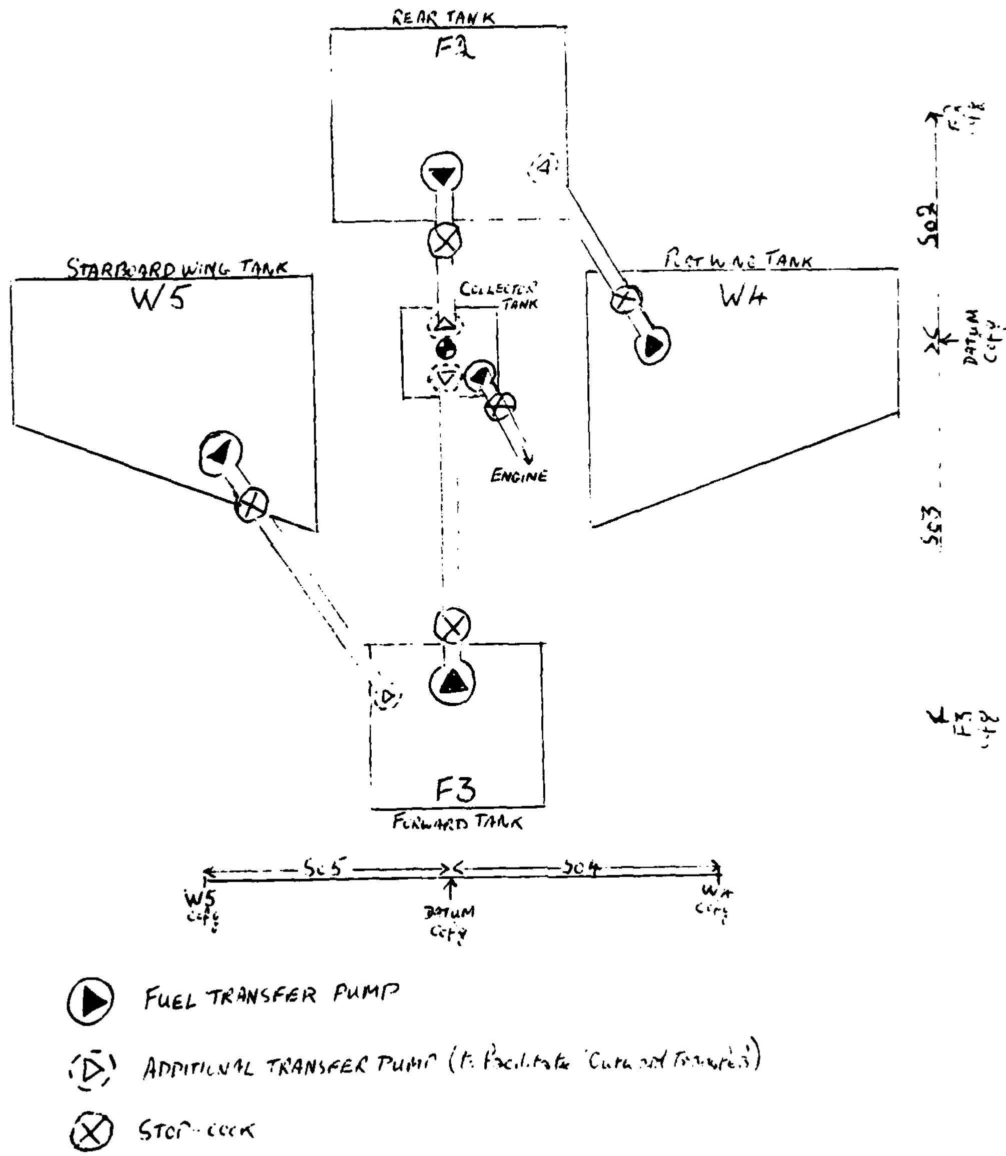


Fig 1 Assumed tank configuration for the simple aircraft type fuel system

Fig 2

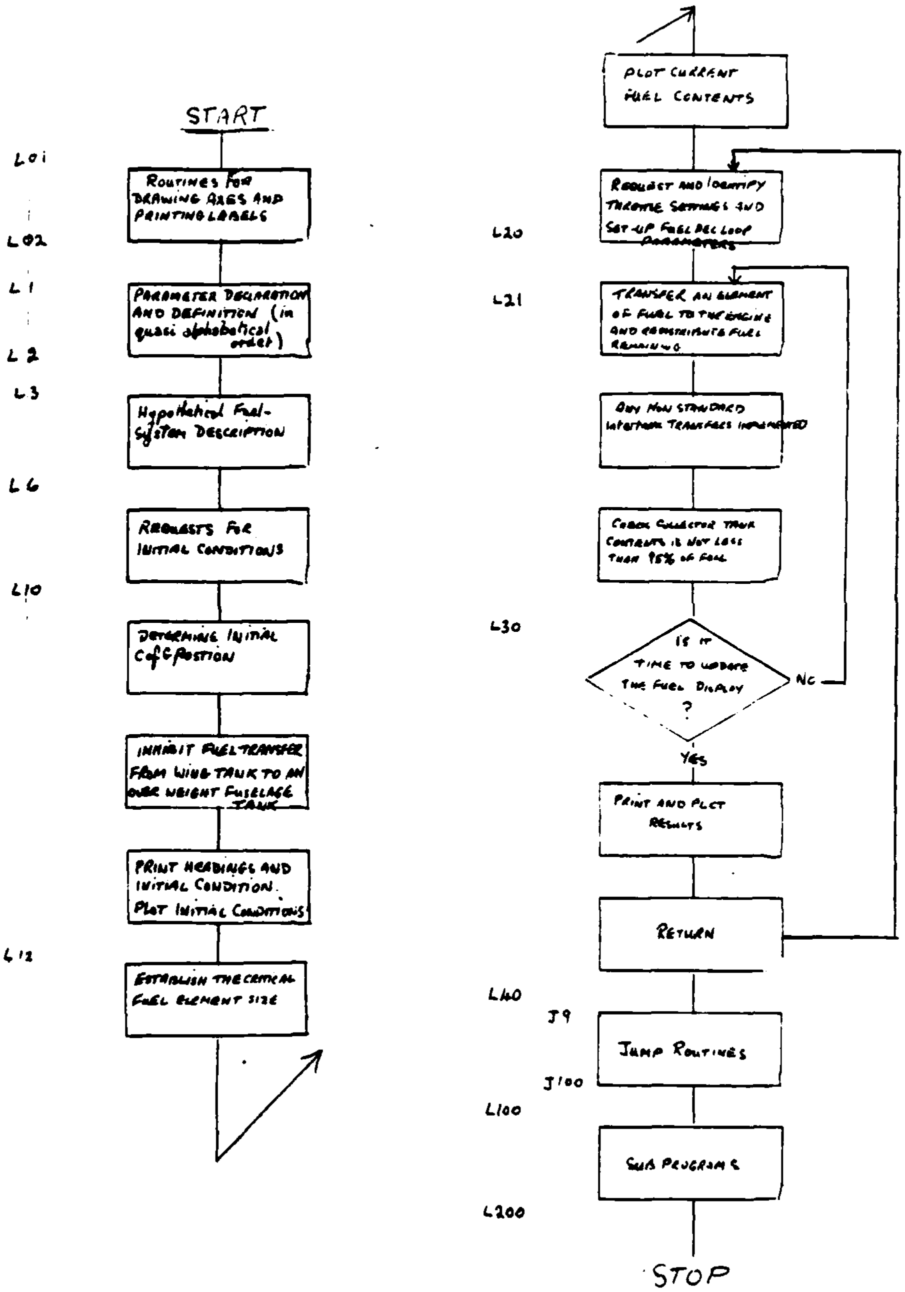


Fig 2 Organisation of program 'MODT1'

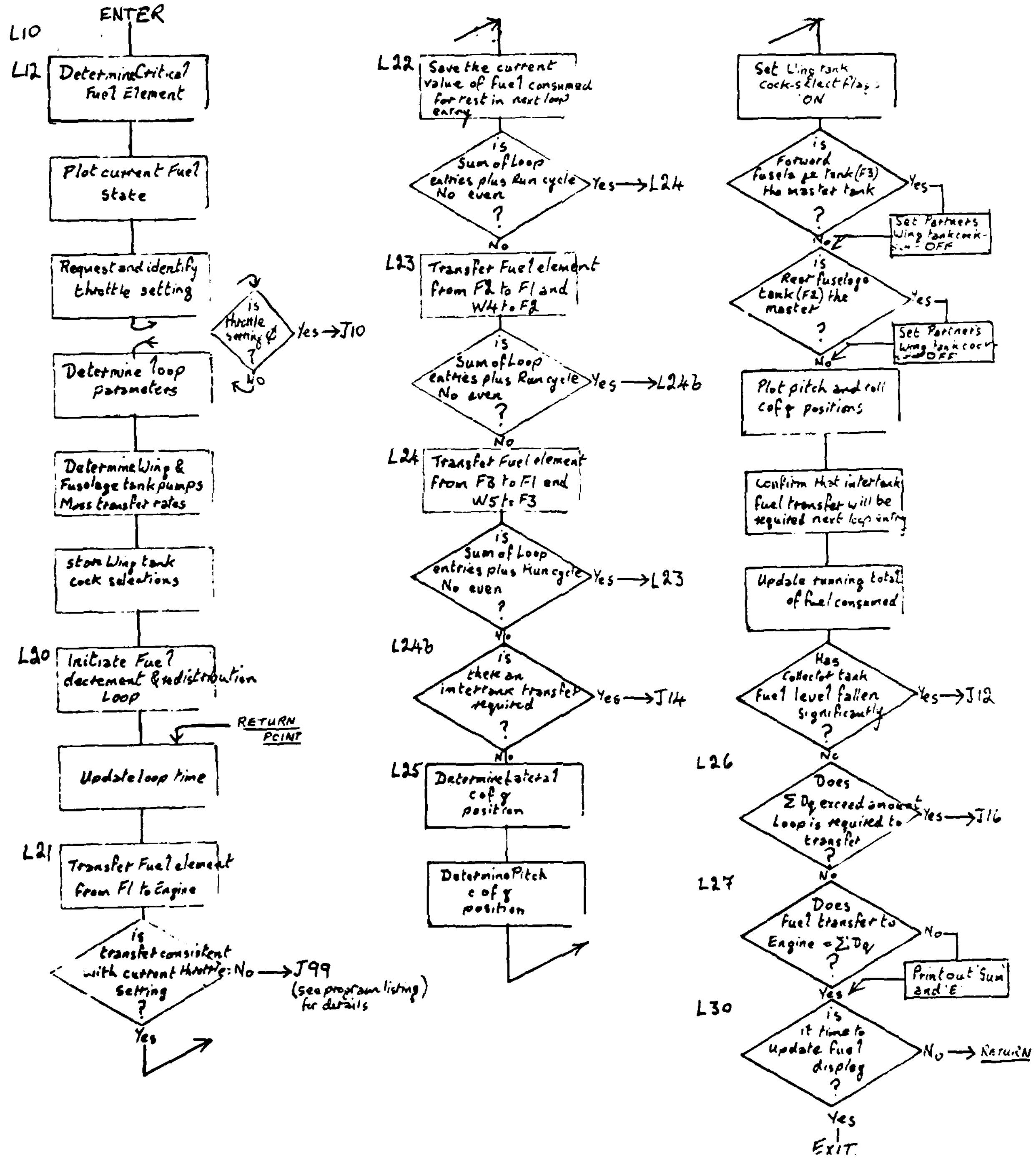
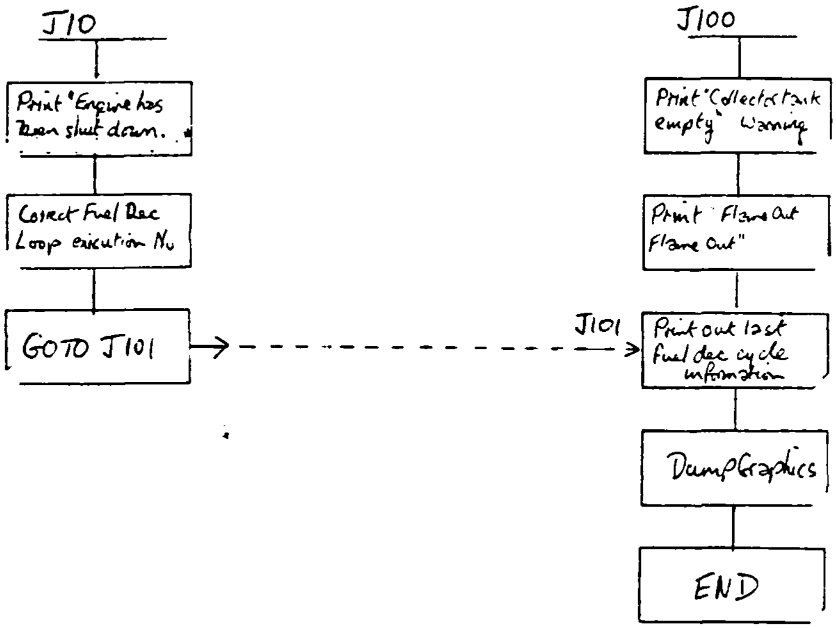


Fig 3 Fuel decrement and redistribution loop and initiation procedures

Fig 4



J10 is entered whenever the chosen throttle setting is ∅

J100 is entered via J12, the Collector tank fuel level-low routine (Fig 14)

Fig 4 Program termination

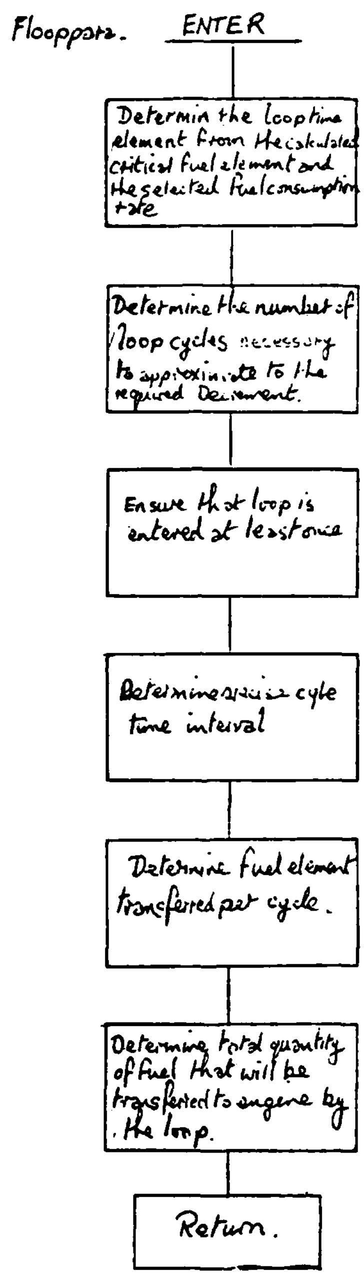


Fig 5 Subprogram 'Flooppara'

Fig 6

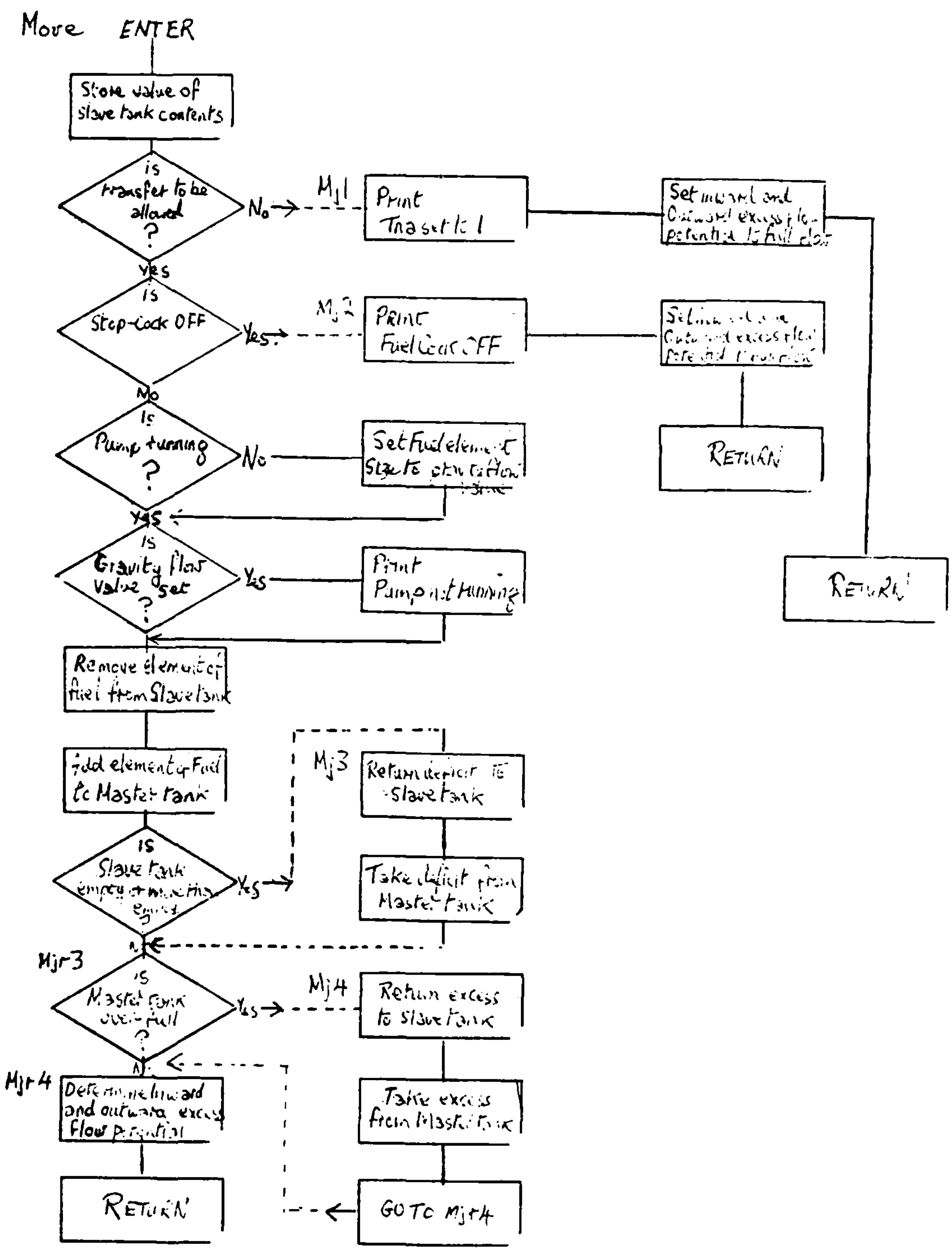


Fig 6 Subprogram 'Move'

TM FS(F) 466

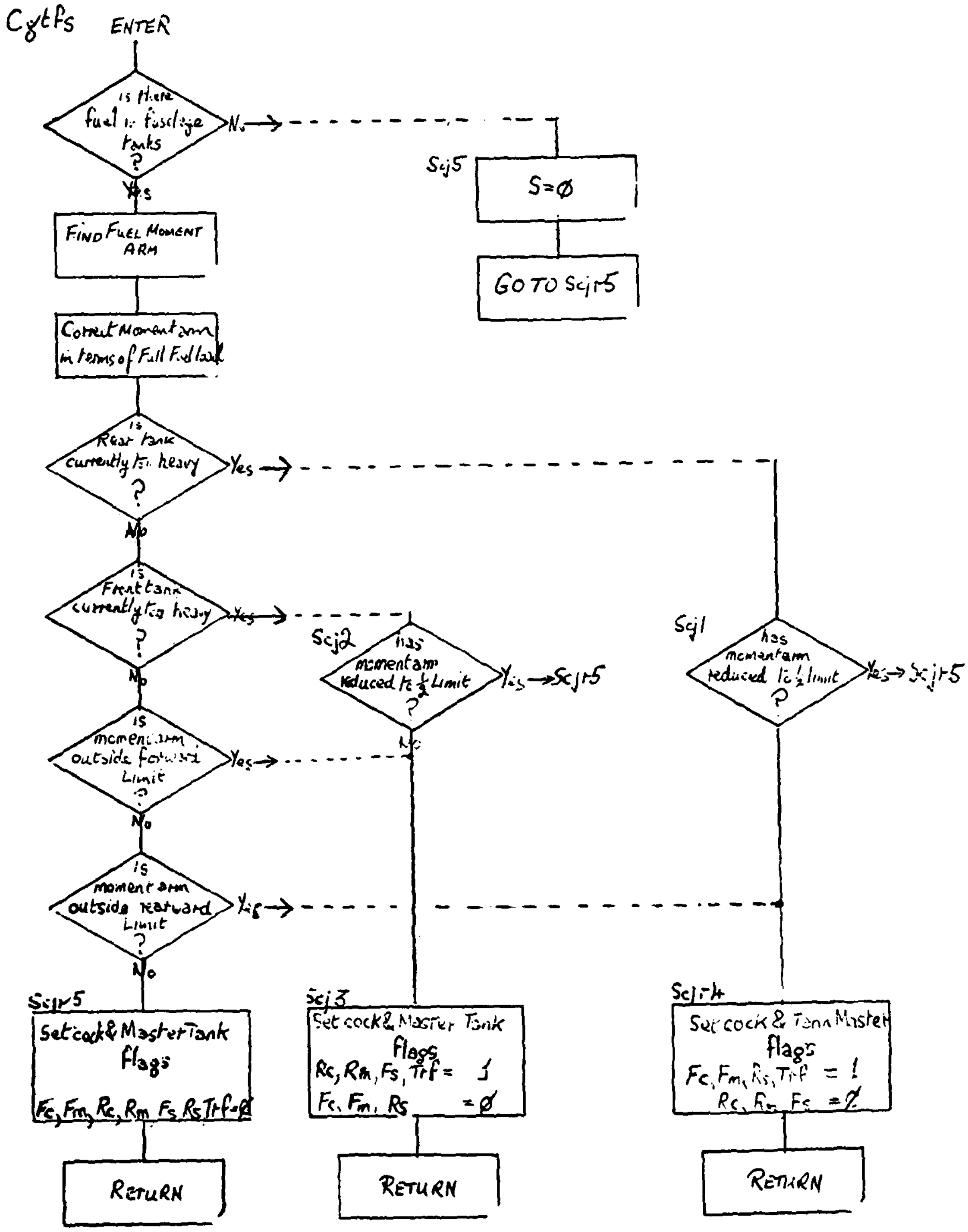


Fig 7 Subprogram 'Cgtfs'

Fig 8

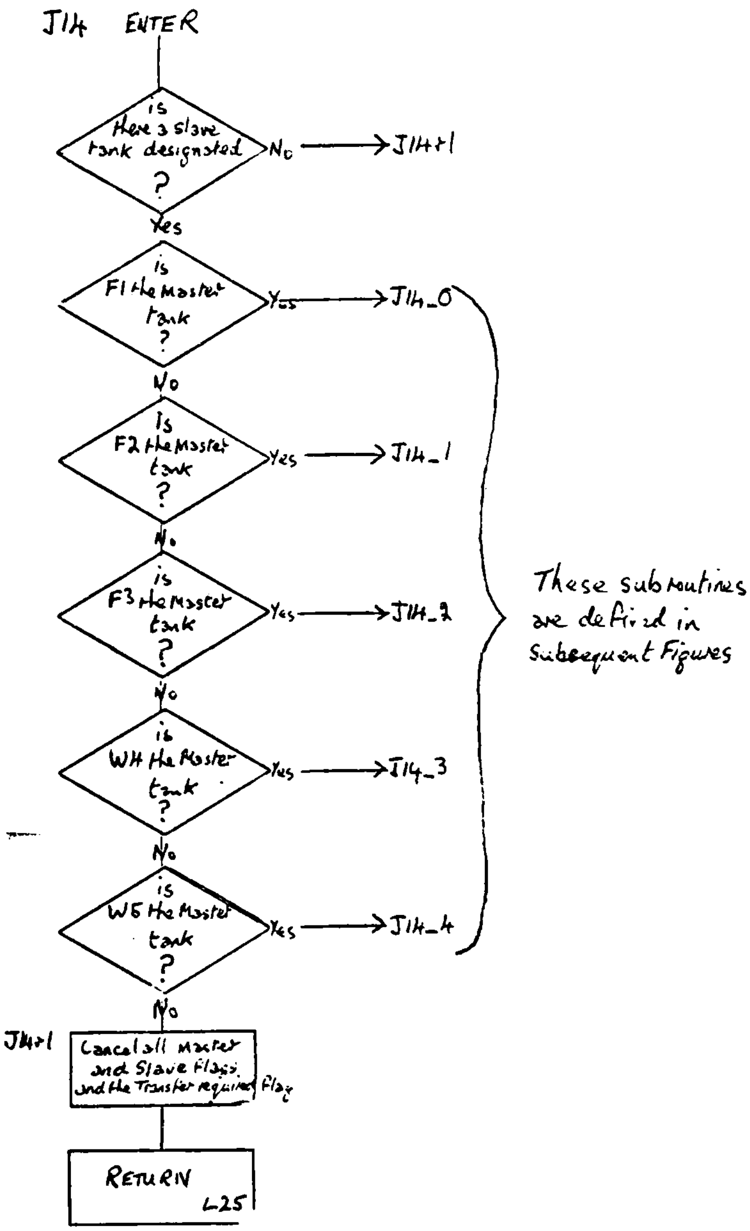


Fig 8 Intertank fuel transfer routines (J14:P-trans)
'identify master tank'

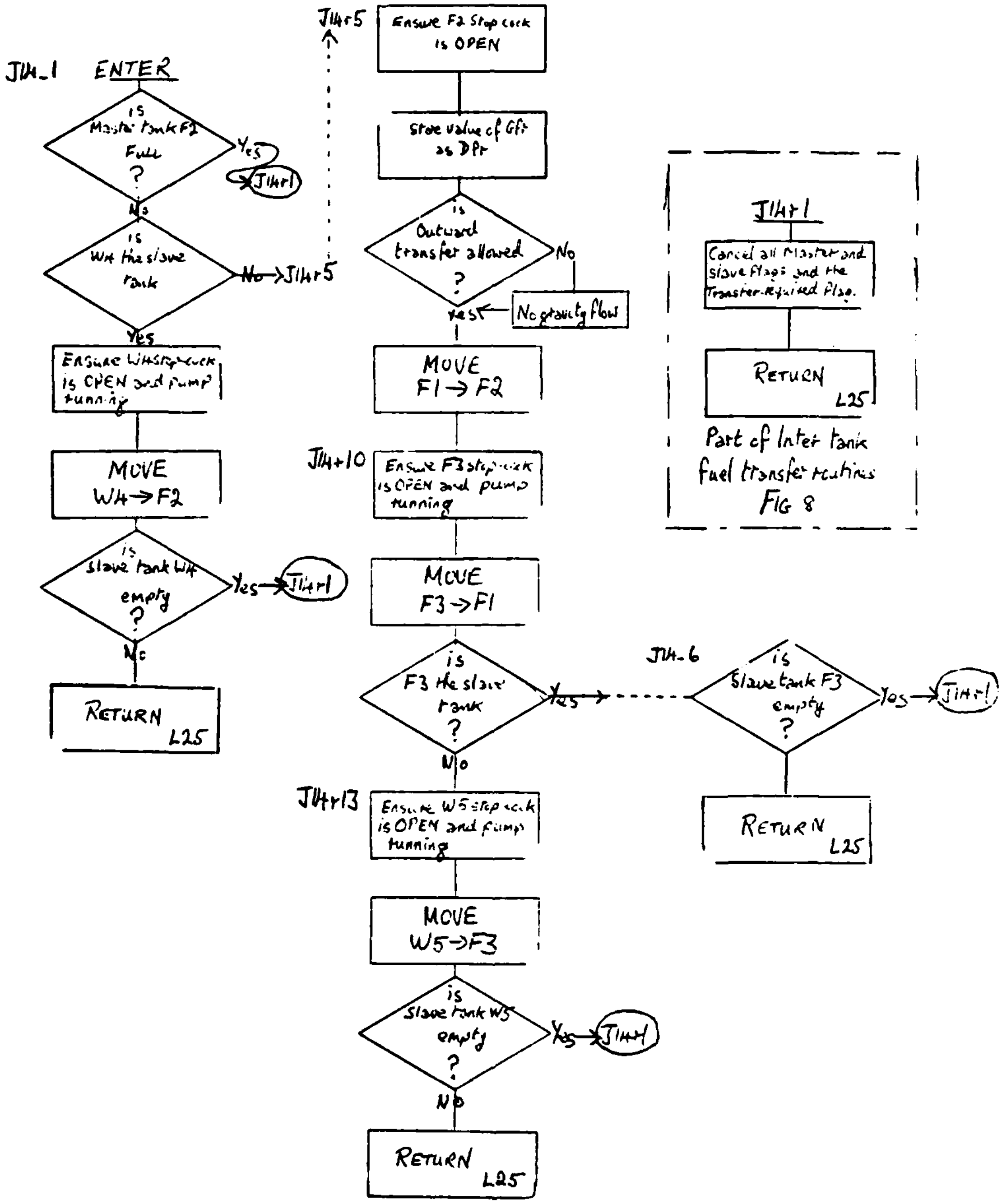


Fig 9 (J14 continued) Rear fuselage tank (F2) is master

Fig 10

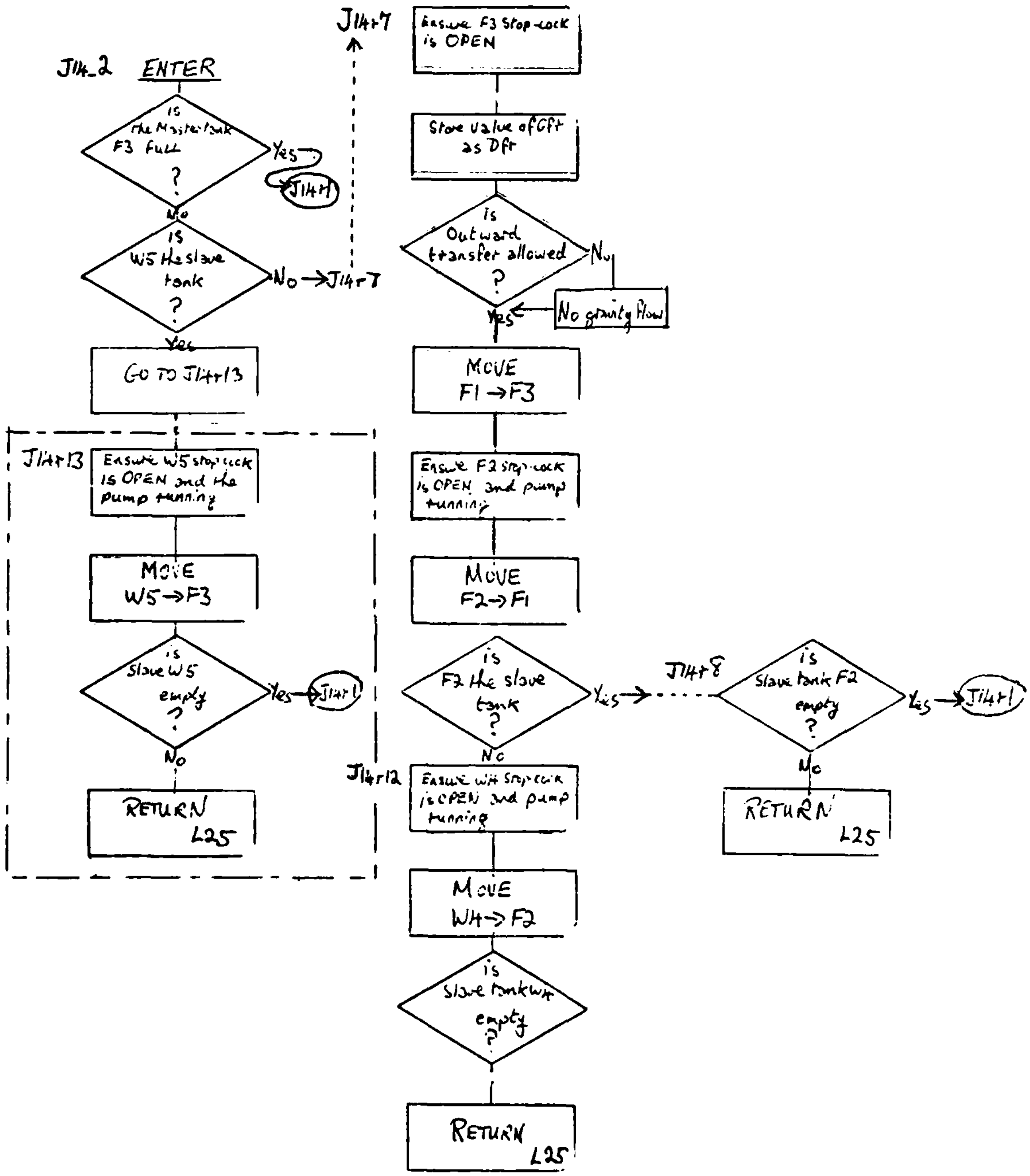


Fig 10 (J14 continued) Forward fuselage tank (F3) is master

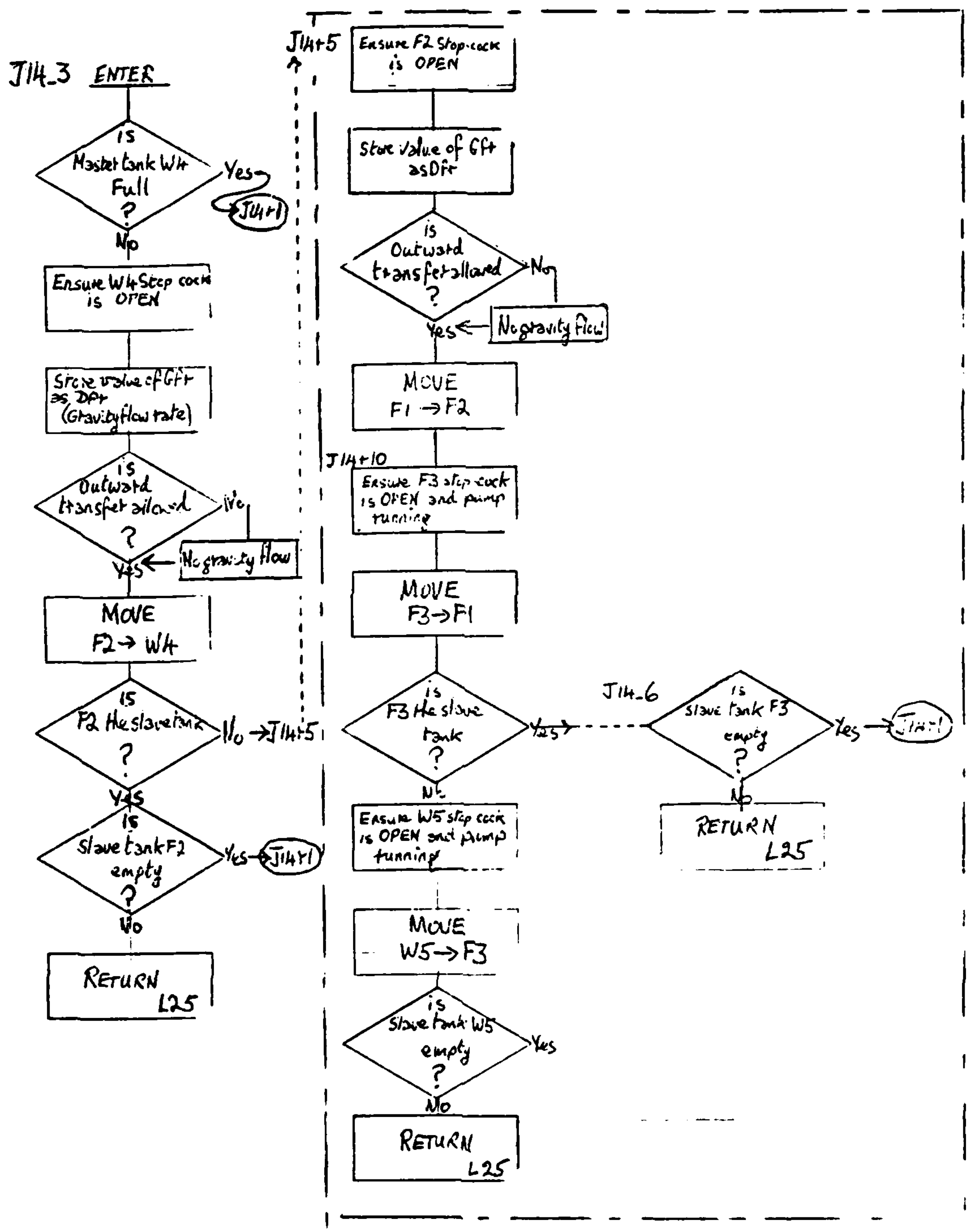


Fig 11 (J14 continued) Port wing tank (W4) is master

Fig 12

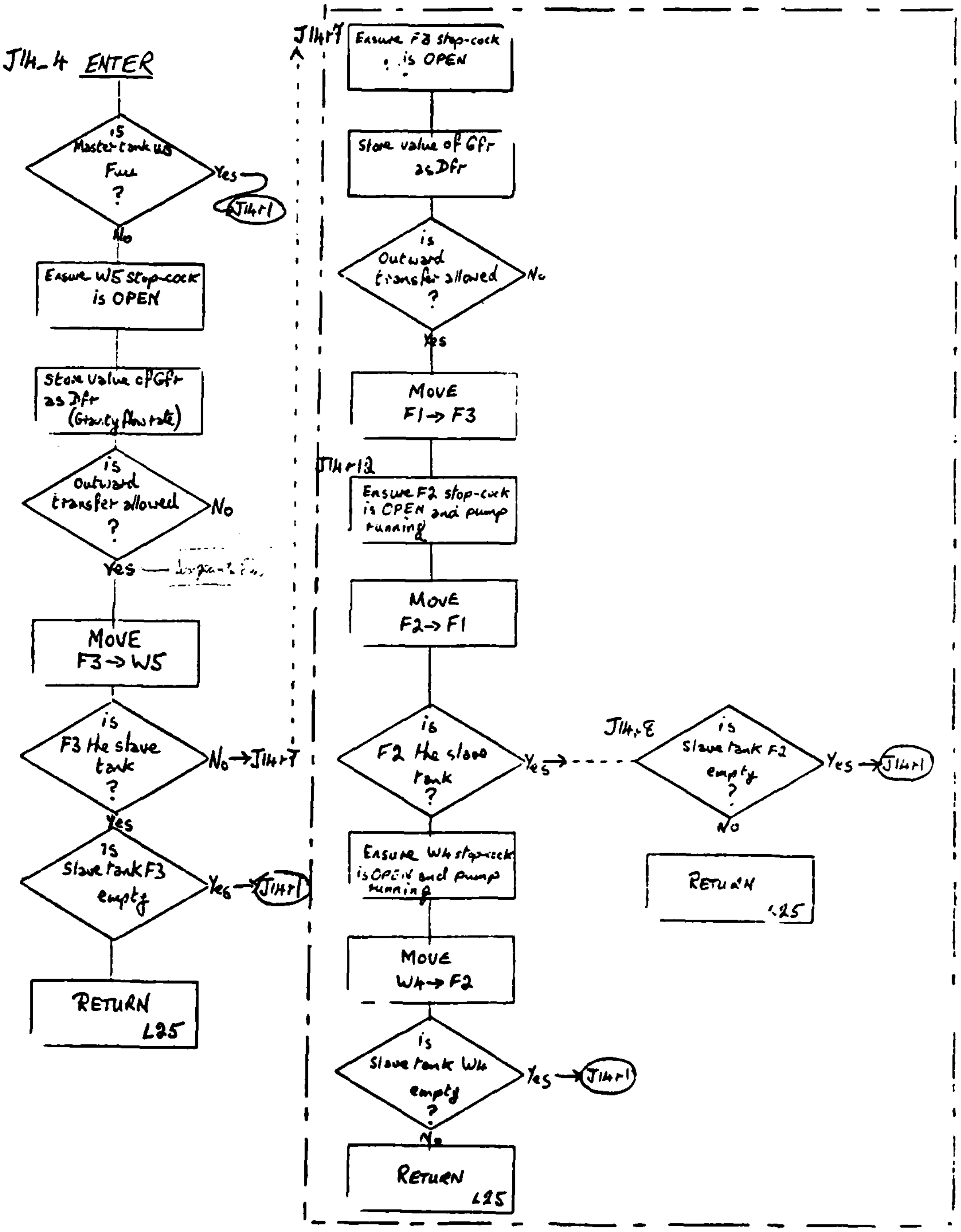


Fig 12 (J14 continued) Starboard wing tank (W5) is master

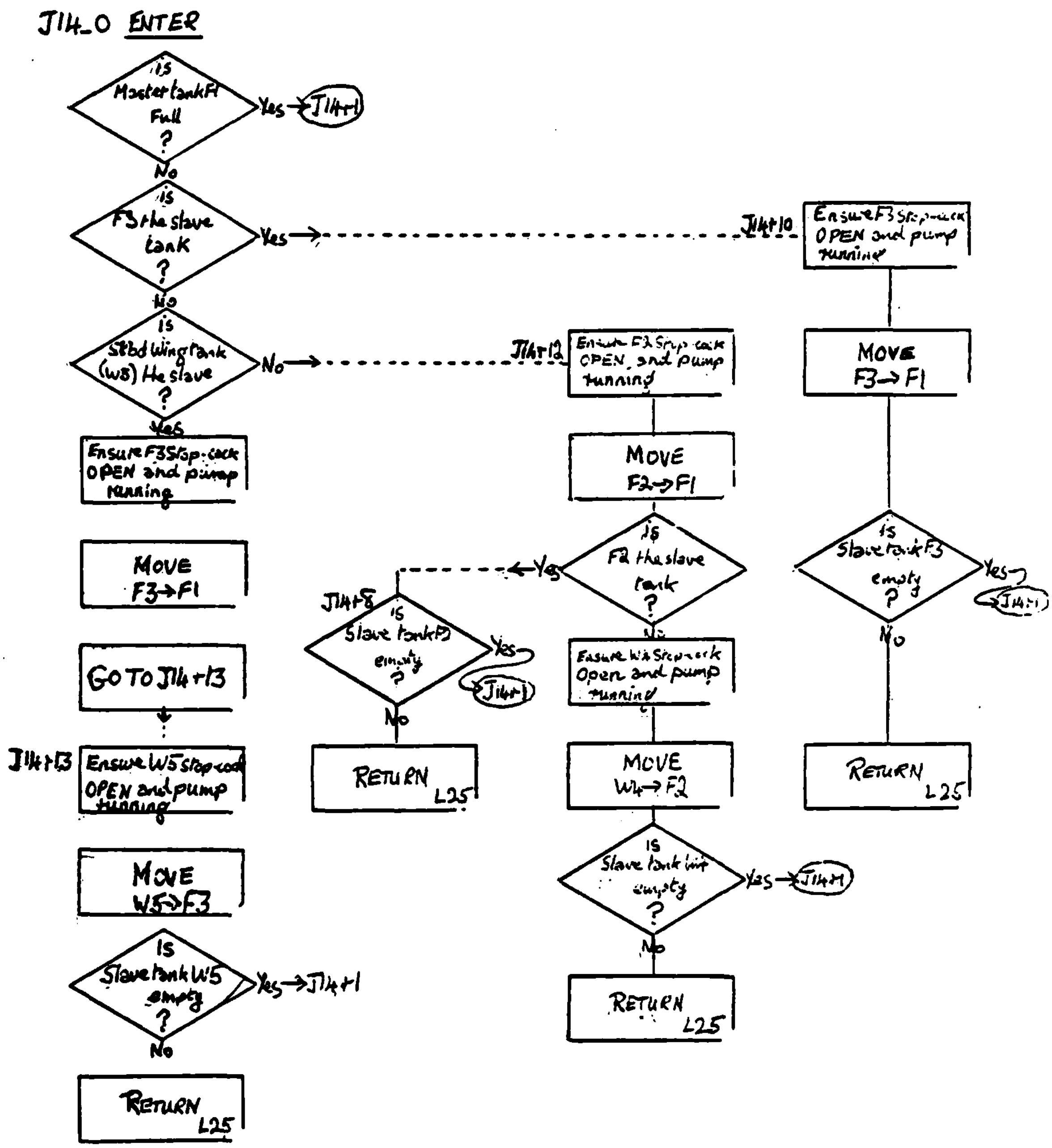


Fig 13 (J14 concluded) Collector tank is master

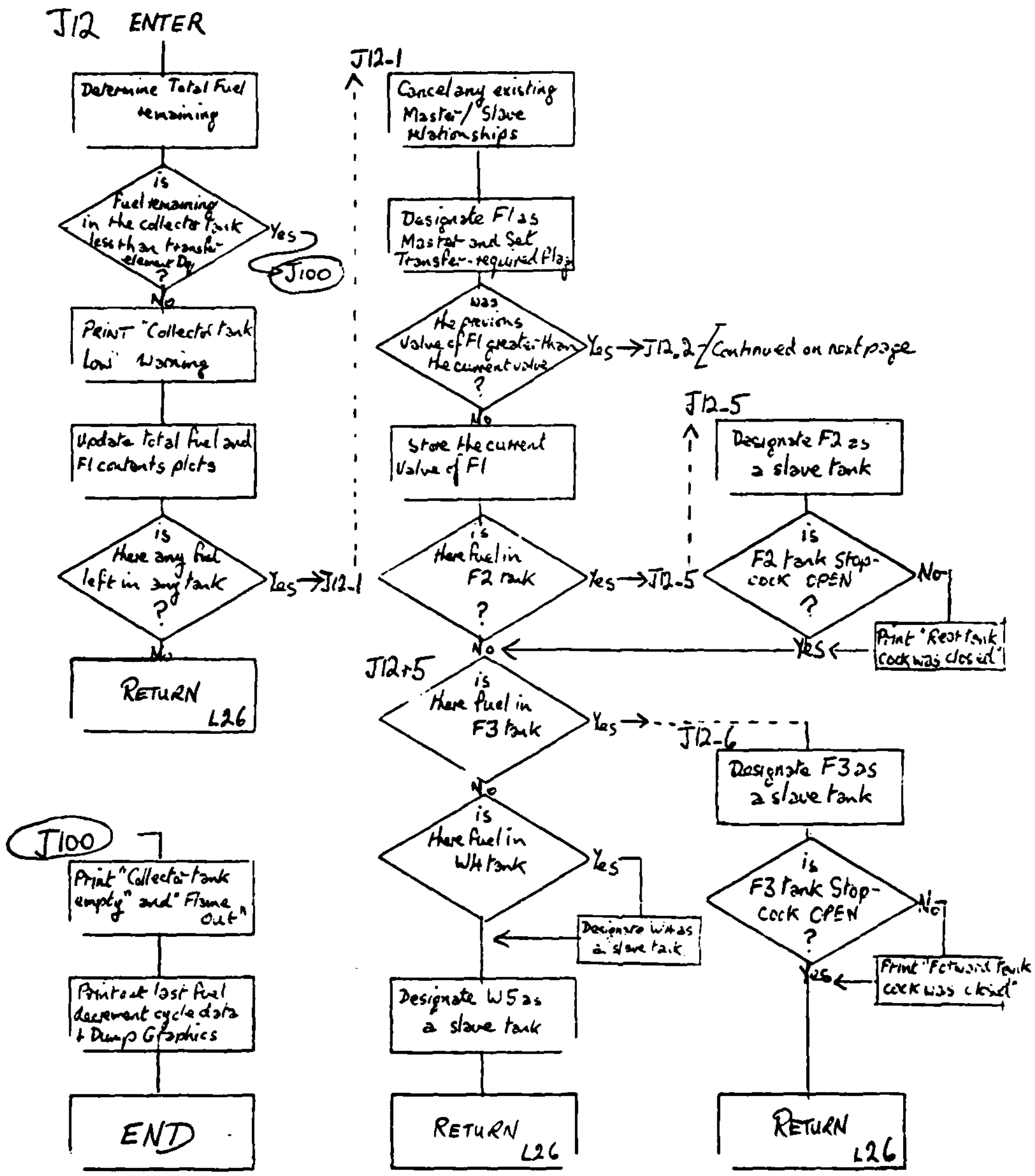


Fig 14 Collector tank fuel-level-low routine (J12)

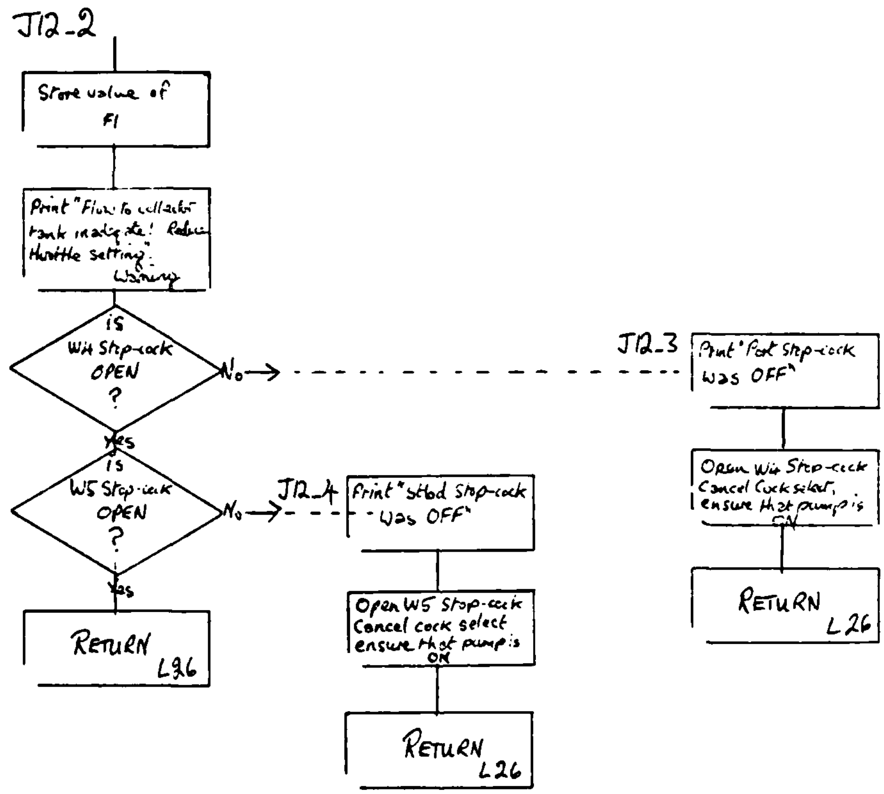


Fig 15 (J12 concluded) Collector tank fuel-level-low routine

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

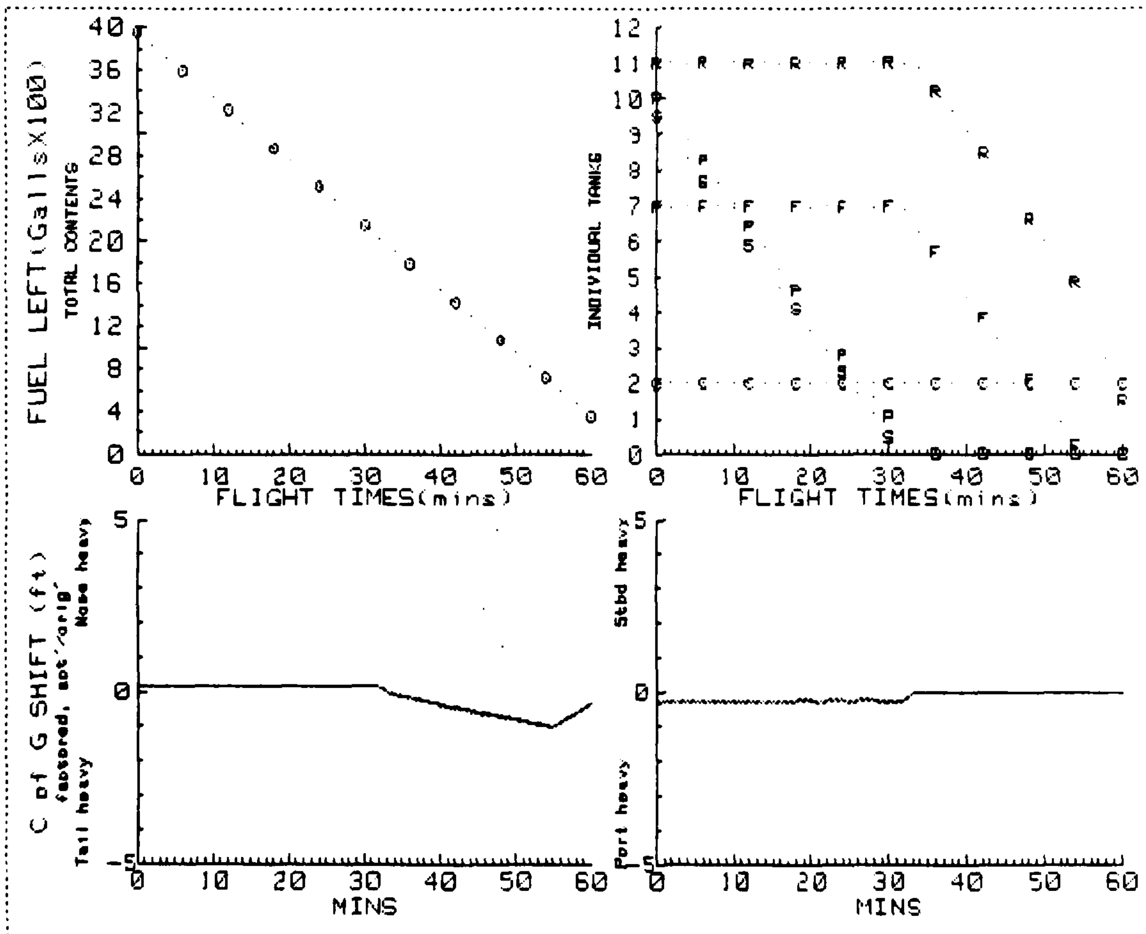


Fig 16 Test 1

```
Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00
Galls                                   W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups    = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
                   Fuel cross-feed is NOT allowed



****COLLECTOR TANK LOW!****** GALLS REMAINING= 190.00 ****** TIME= 54.57 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 182.00 ****** TIME= 54.70 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 174.00 ****** TIME= 54.83 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 166.00 ****** TIME= 54.97 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 158.00 ****** TIME= 55.10 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 150.00 ****** TIME= 55.23 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 142.00 ****** TIME= 55.37 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 134.00 ****** TIME= 55.50 *****

****COLLECTOR TANK LOW!****** GALLS REMAINING= 126.50 ****** TIME= 55.63 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 119.00 ****** TIME= 55.75 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 111.50 ****** TIME= 55.88 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 104.00 ****** TIME= 56.00 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 96.50 ****** TIME= 56.13 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 89.00 ****** TIME= 56.25 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 81.50 ****** TIME= 56.38 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 74.00 ****** TIME= 56.50 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 66.50 ****** TIME= 56.63 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 59.00 ****** TIME= 56.75 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 51.50 ****** TIME= 56.88 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 44.00 ****** TIME= 57.00 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 36.50 ****** TIME= 57.13 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 29.00 ****** TIME= 57.25 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 21.50 ****** TIME= 57.38 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 14.00 ****** TIME= 57.50 *****
```

Fig 17a Leading data to Fig 17

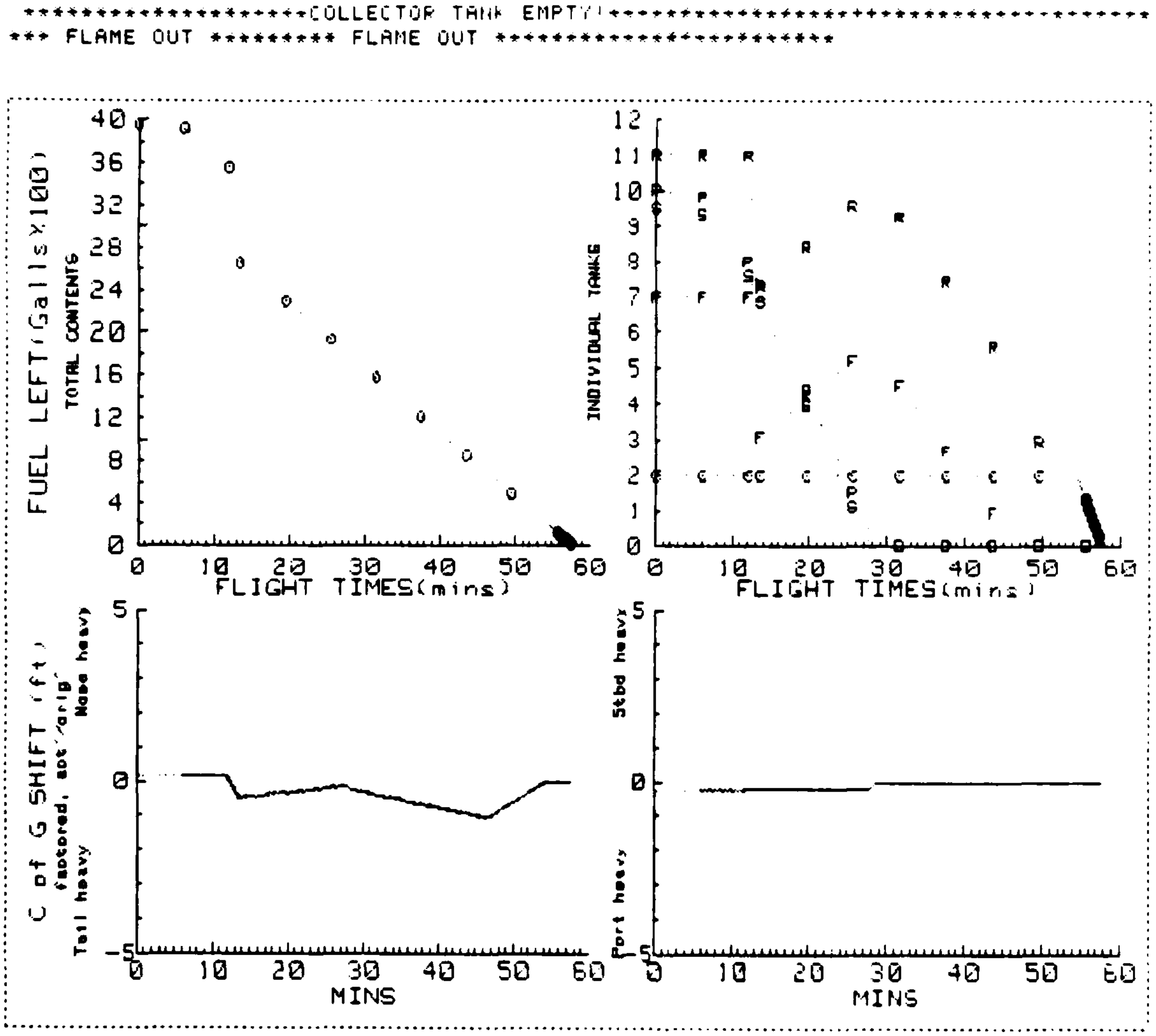

********************COLLECTOR TANK EMPTY!**
*** FLAME OUT ********* FLAME OUT ***********************
FUEL LEFT (Galls X100)
TOTAL CONTENTS
INDIVIDUAL TANKS
FLIGHT TIMES(mins)
FLIGHT TIMES(mins)
C of G SHIFT (ft)
(factored, aot 'orig')
Nose heavy
Tail heavy
Stbd heavy
Port heavy
MINS
MINS

Fig 17 Test 2

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 0.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

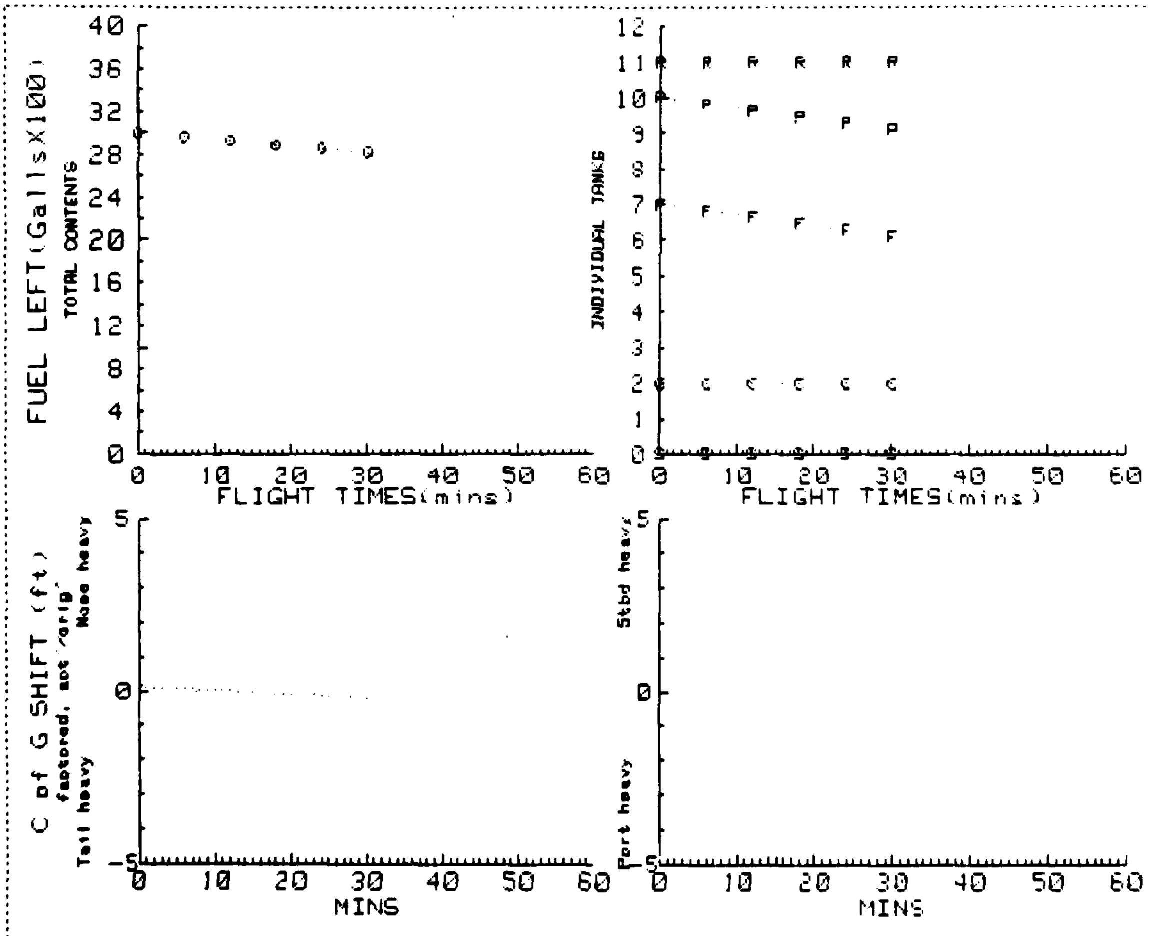


Fig 18 Test 3

Fig 19

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 0.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is allowed

**** Engine has been shut down. ****

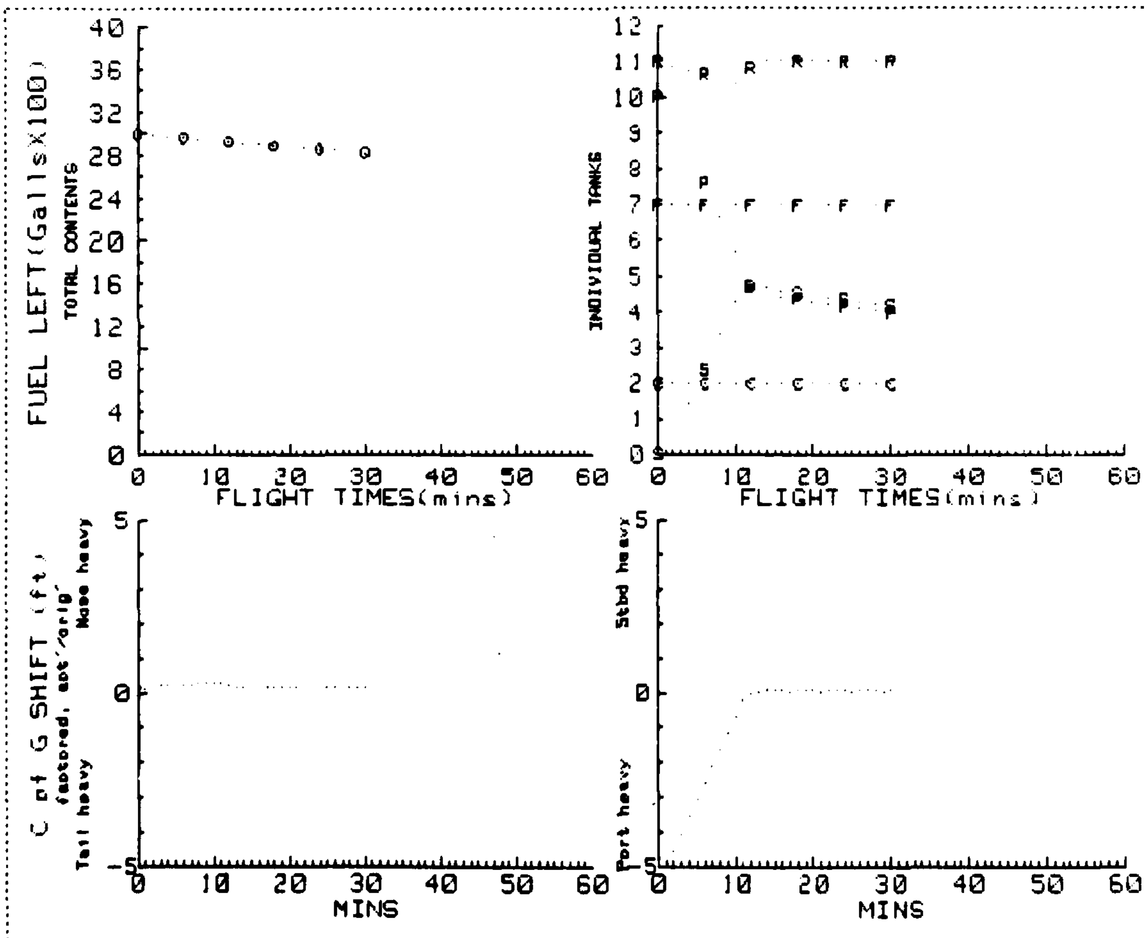


Fig 19 Test 4

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 0.00 Galls W5= 1000.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is allowed

**** Engine has been shut down. ****

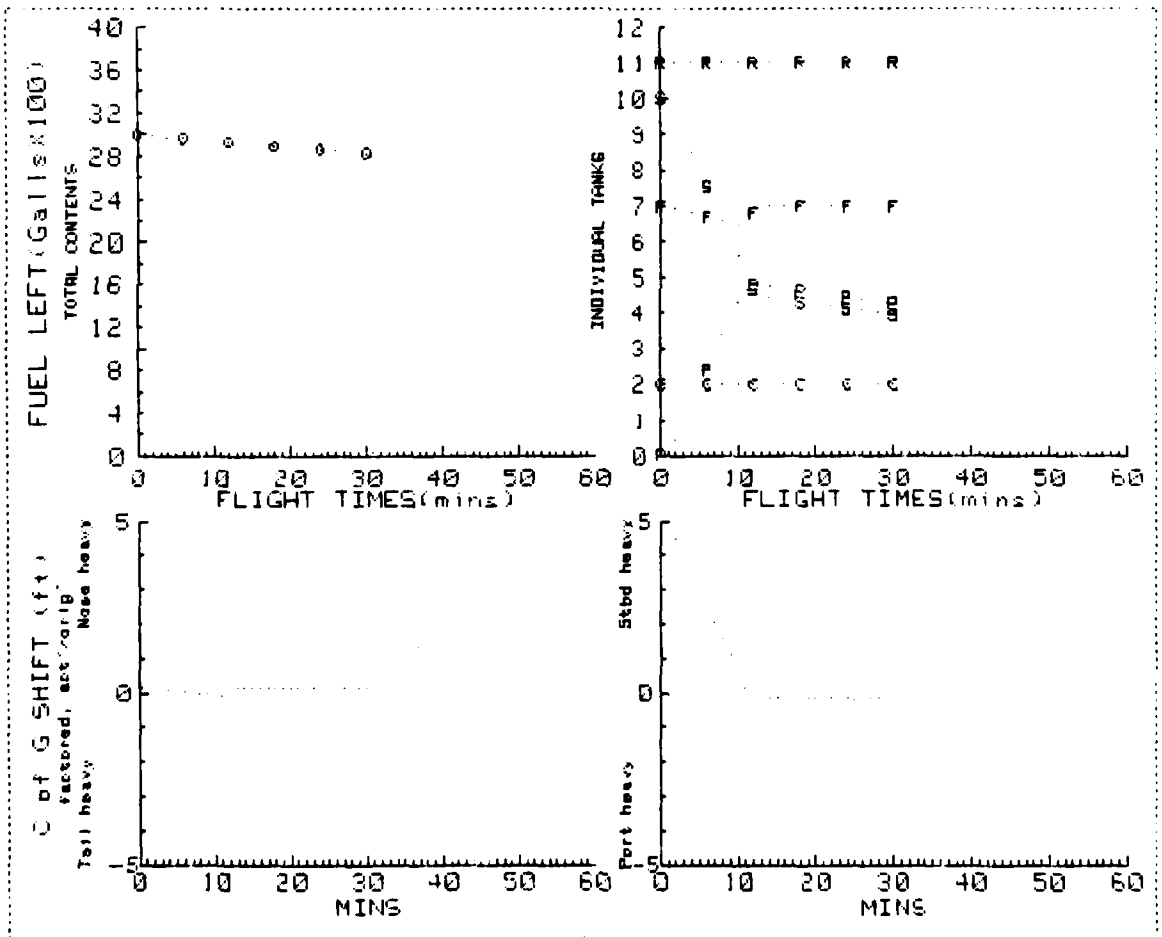


Fig 20 Test 5

Fig 21

```
Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00
Galls                              W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups    = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
                      Fuel cross-feed is NOT allowed


****COLLECTOR TANK LOW!****** GALLS REMAINING= 185.82 ****** TIME= 47.64 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 174.91 ****** TIME= 47.82 *****
** FLOW TO COLLECTOR TANK INADEQUATE!  REDUCE THROTTLE SETTING **
PORT STOP-COCK WAS 'OFF'
****COLLECTOR TANK LOW!****** GALLS REMAINING= 172.73 ****** TIME= 48.00 *****
** FLOW TO COLLECTOR TANK INADEQUATE!  REDUCE THROTTLE SETTING **
STBD STOP-COCK WAS 'OFF'

****COLLECTOR TANK LOW!****** GALLS REMAINING= 170.20 ****** TIME= 48.25 *****
** FLOW TO COLLECTOR TANK INADEQUATE!  REDUCE THROTTLE SETTING **
****COLLECTOR TANK LOW!****** GALLS REMAINING= 182.95 ****** TIME= 48.50 *****
****  Engine has been shut down.  ****
```

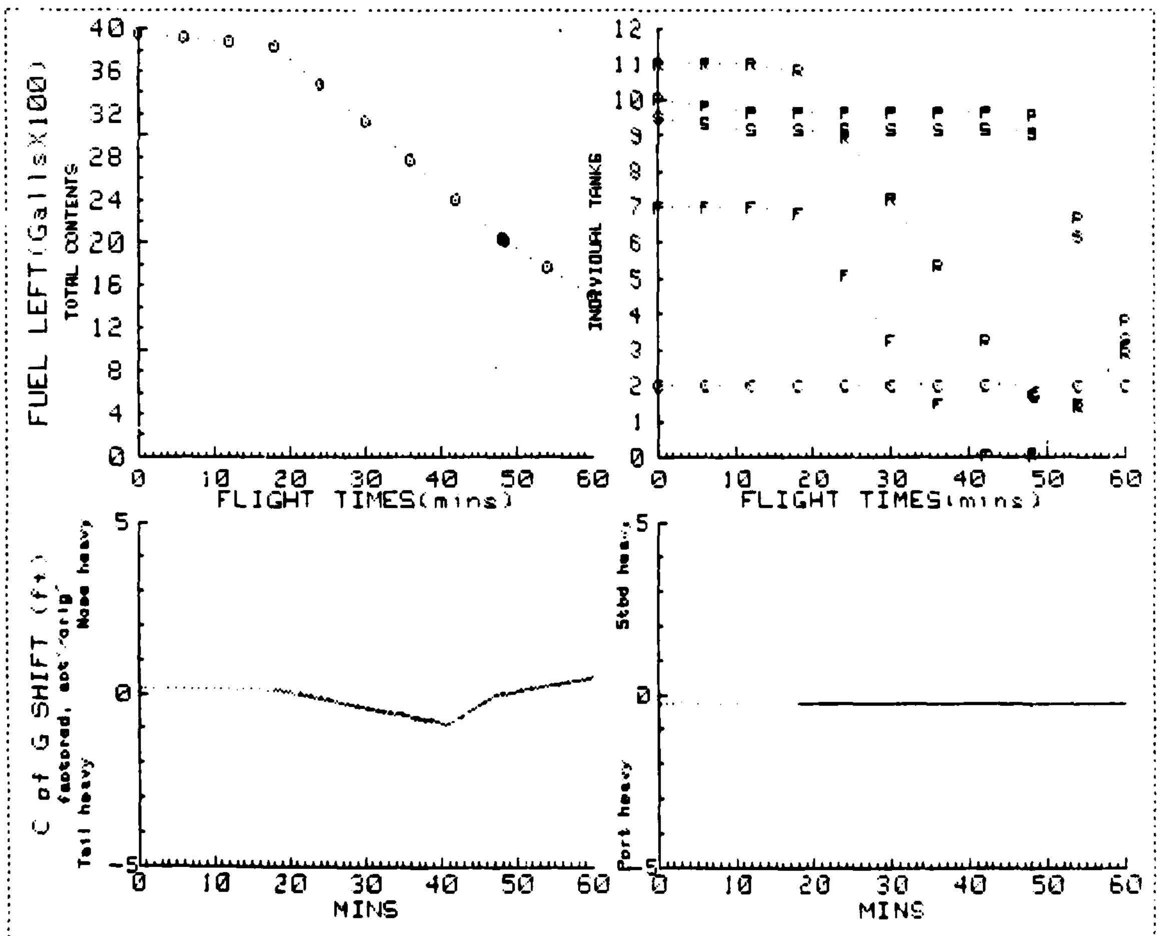


Fig 21 Test 6

TM FS(F)

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

****COLLECTOR TANK LOW!****** GALLS REMAINING= 188.00 ****** TIME= 14.00 *****
REAR TANK COCK WAS CLOSED
FORWARD TANK COCK WAS CLOSED

**** Engine has been shut down. ****

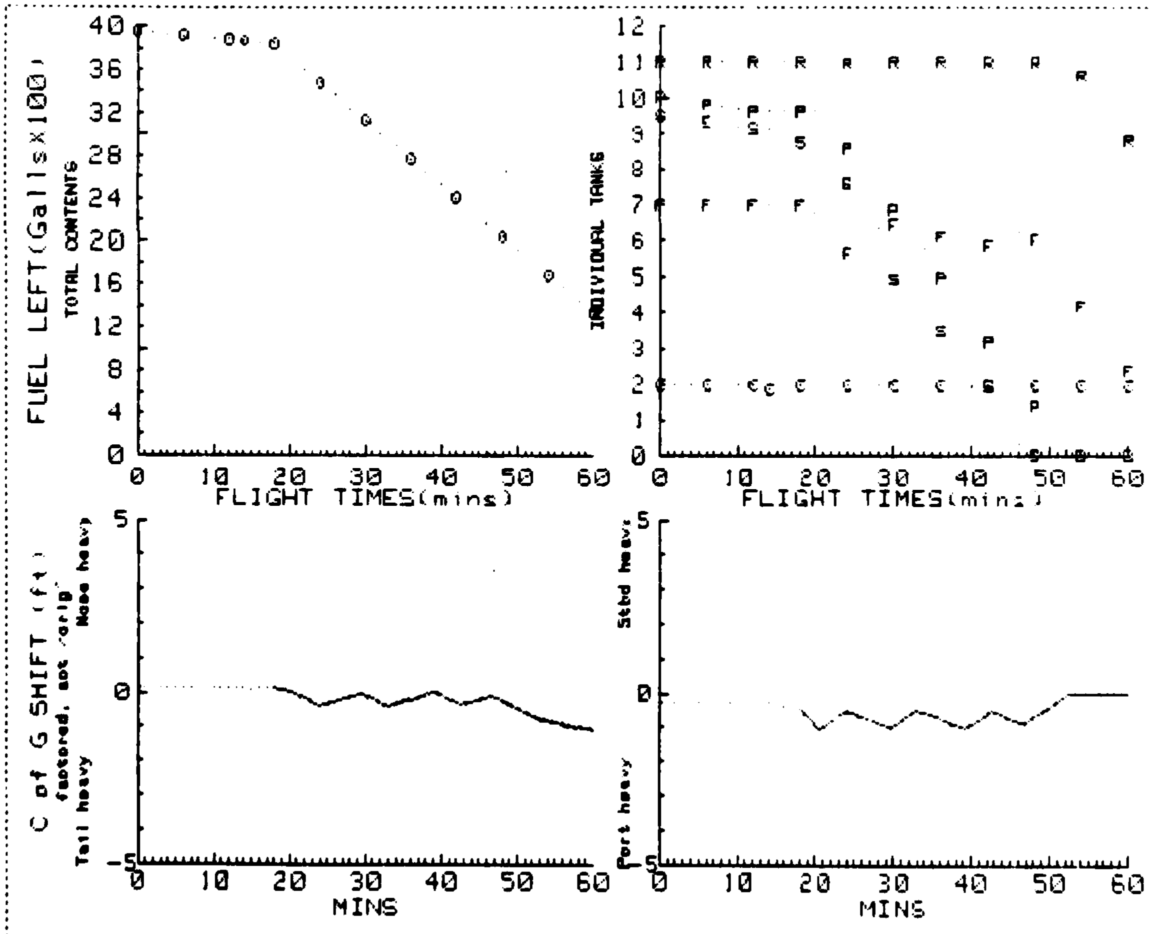


Fig 22 Test 7

Fig 23

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is allowed

****COLLECTOR TANK LOW!****** GALLS REMAINING= 188.00 ****** TIME= 14.00 *****
REAR TANK COCK WAS CLOSED
FORWARD TANK COCK WAS CLOSED

**** Engine has been shut down. ****

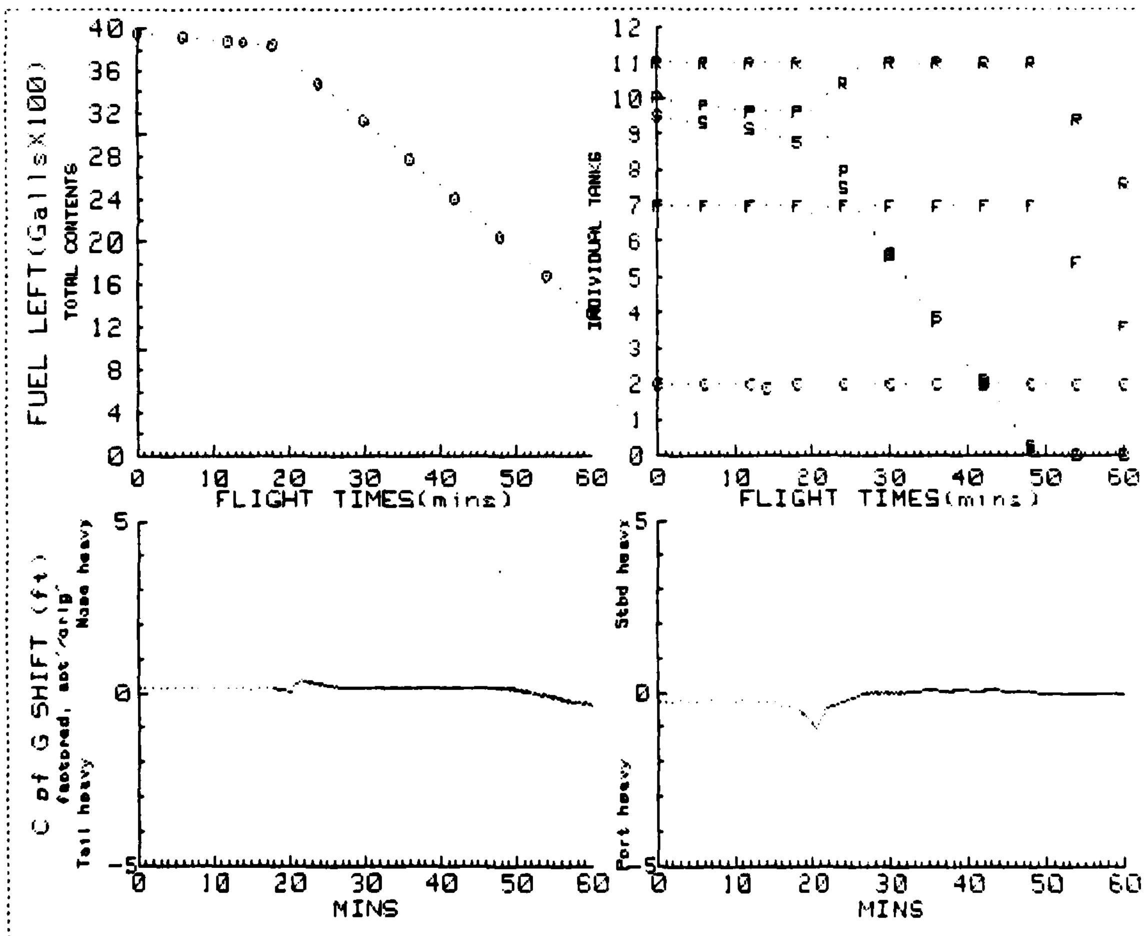


Fig 23 Test 8

Tank contents are:-F1= 200.00 Galls F2= 650.00 Galls F3= 700.00 Galls F4= 0.00 G
alls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

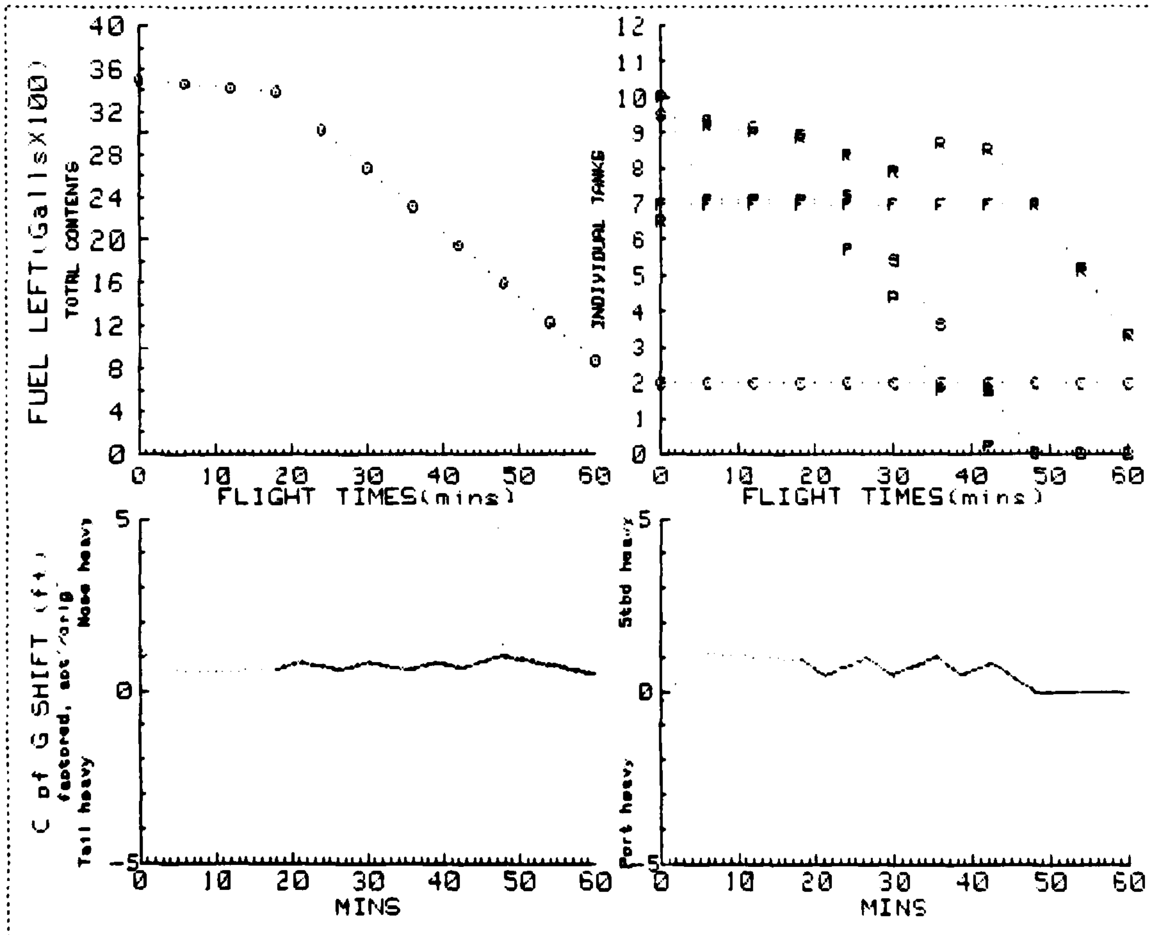


Fig 24 Test 9

Fig 25

Tank contents are:-F1= 200.00 Galls F2= 650.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is allowed

**** Engine has been shut down. ****

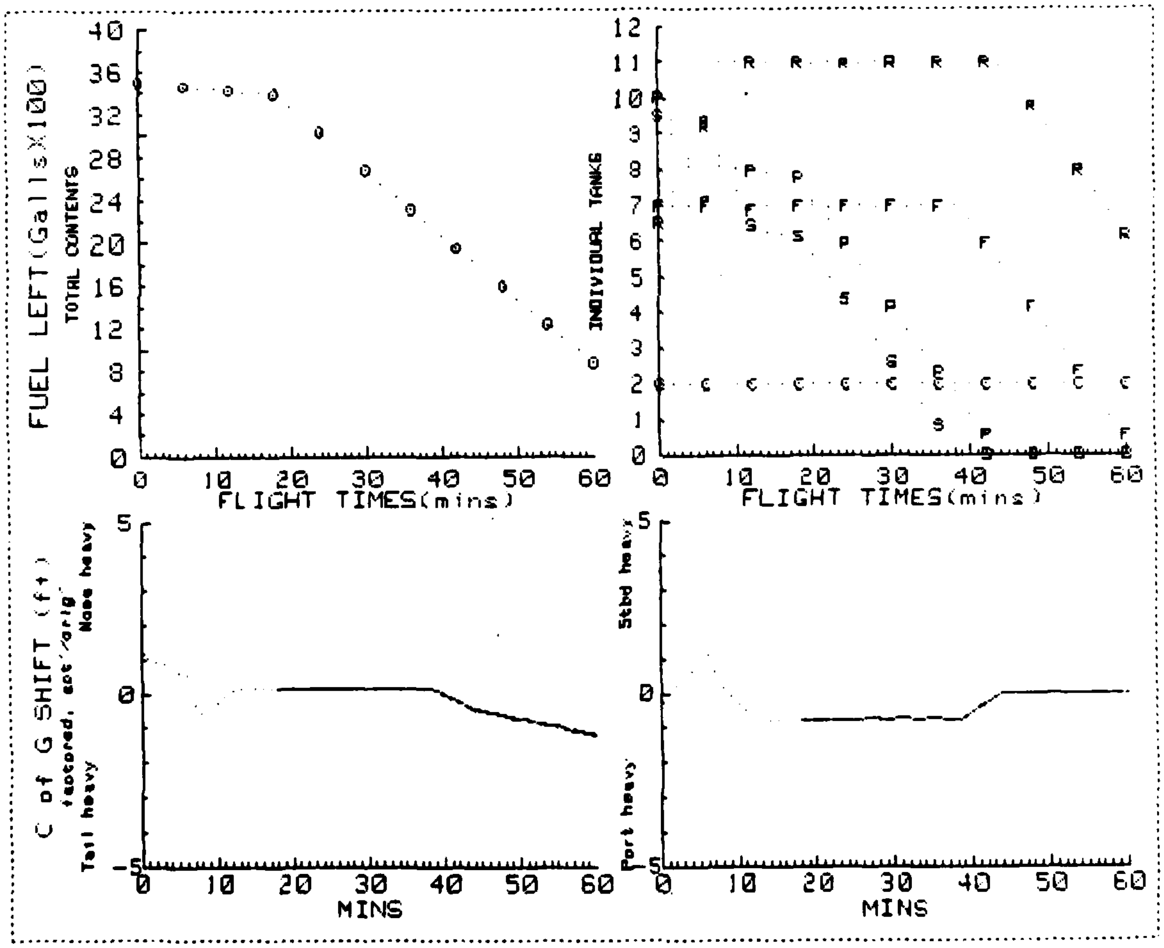


Fig 25 Test 10

.M FS(F) 466

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 350.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

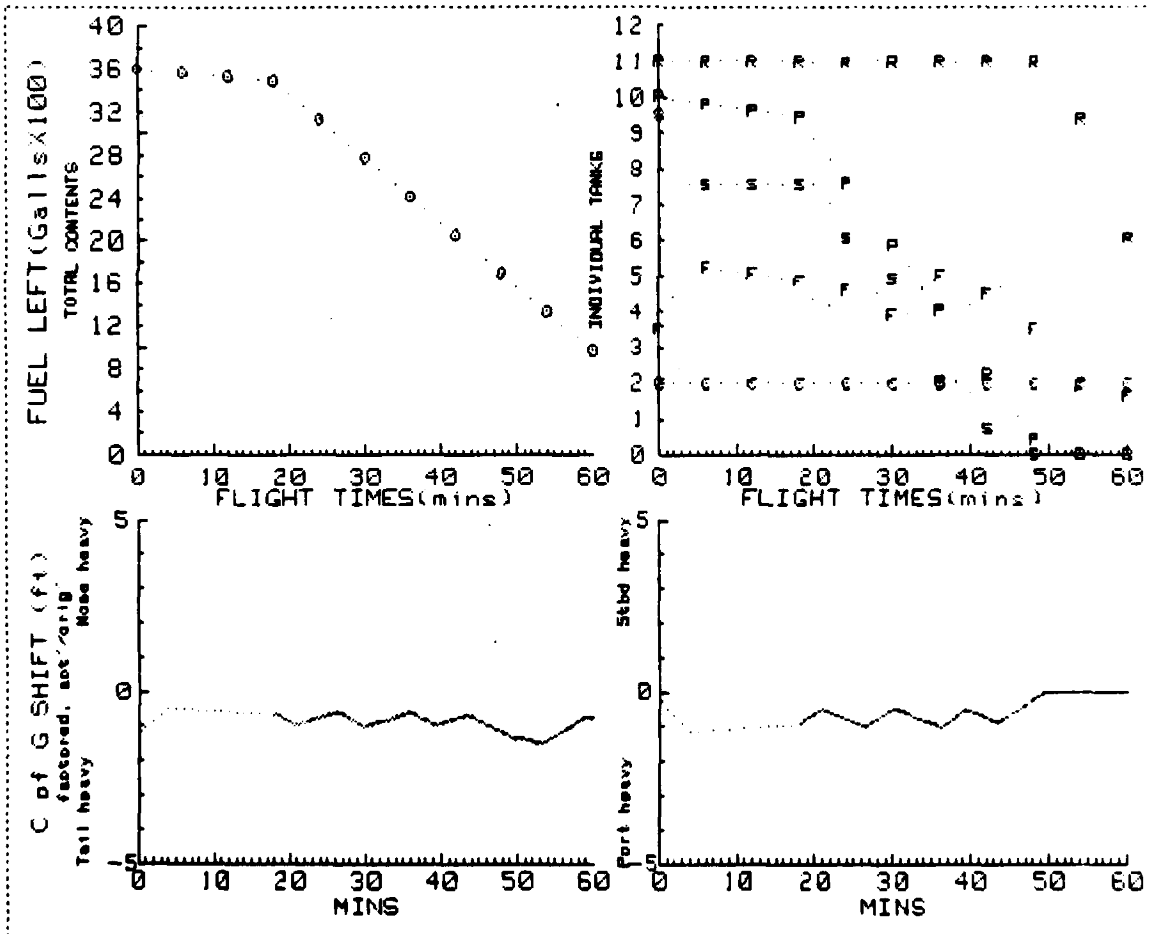


Fig 26 Test 11

Fig 27

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 350.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 7.50 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is allowed

**** Engine has been shut down. ****

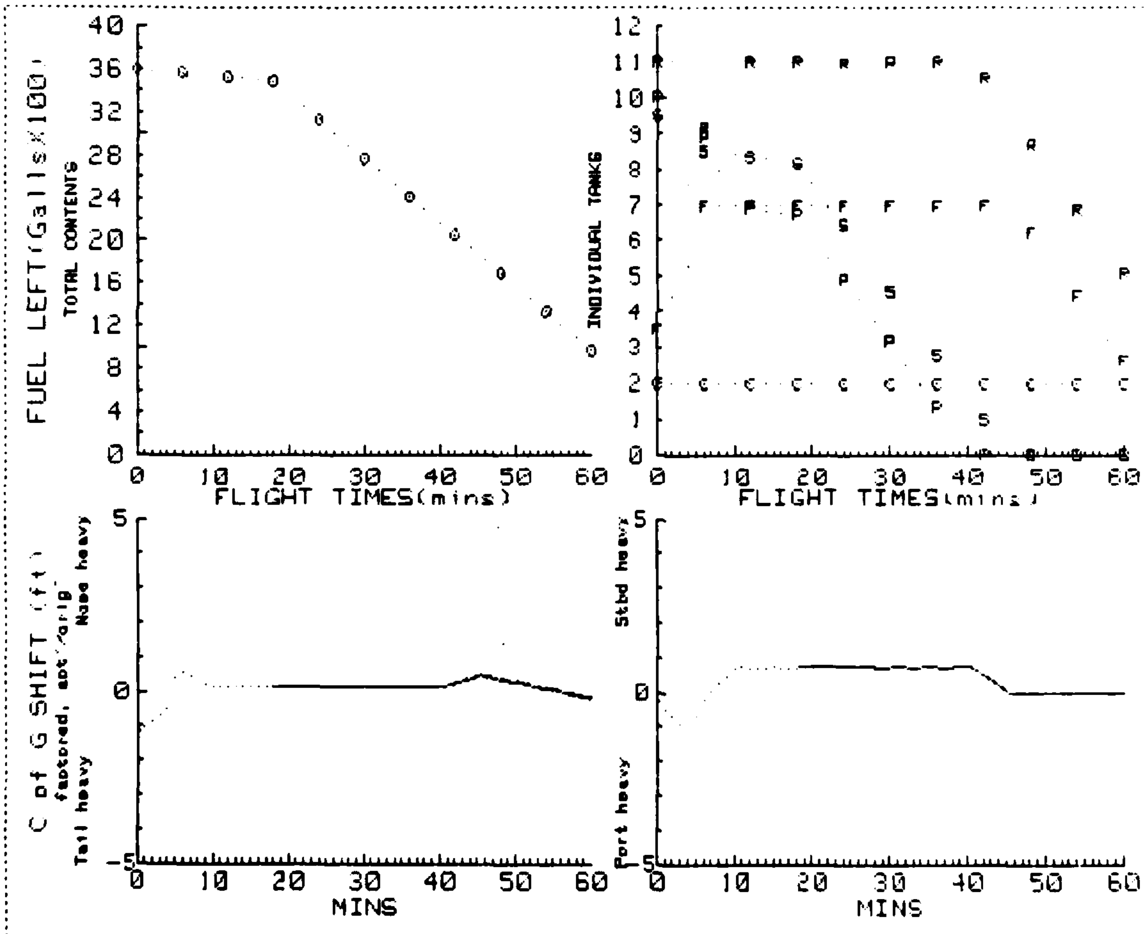


Fig 27 Test 12

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 2.00 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

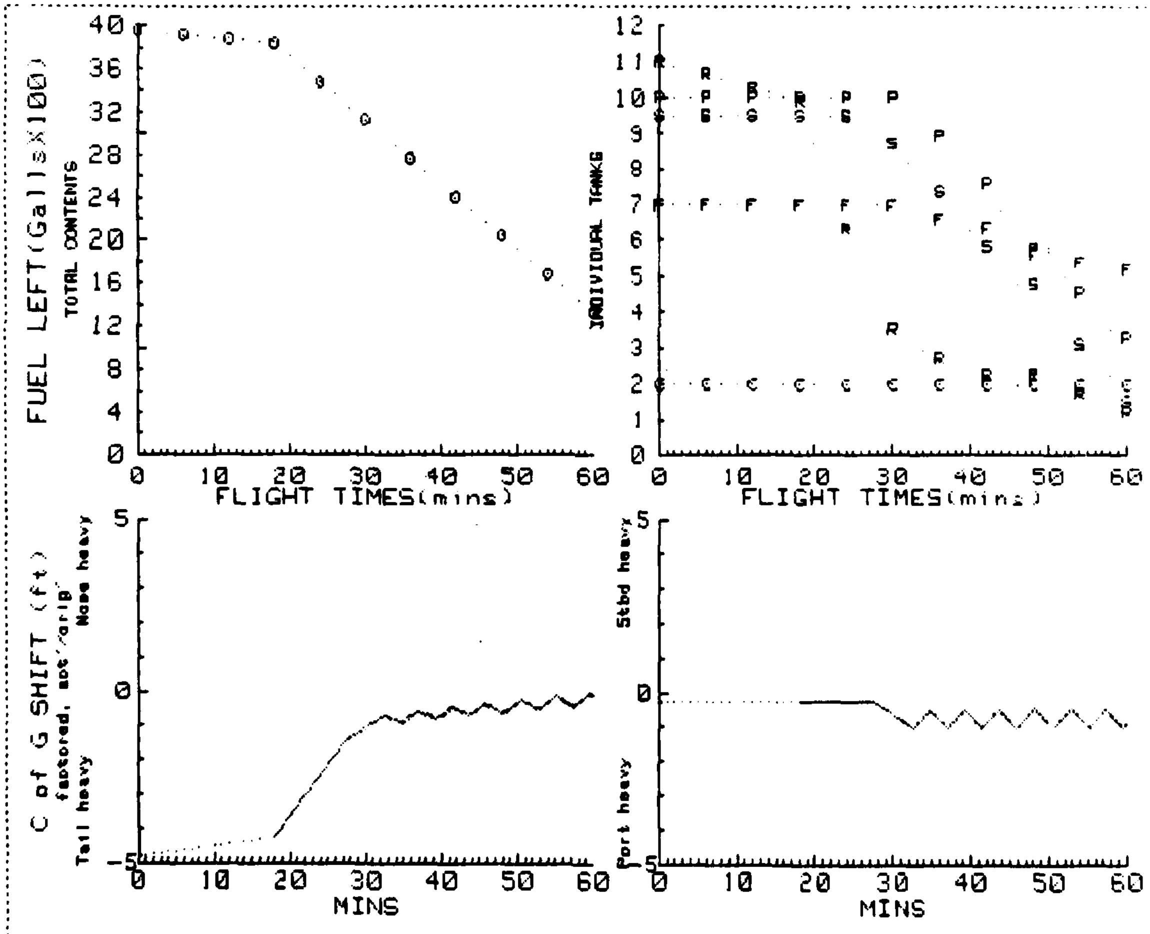


Fig 28 Test 13

Fig 29

Tank contents are: F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls [illegible] .00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 2.00 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, + - 1.50 feet in pitch and +- 1.00 feet in roll
Fuel cross-feed is allowed

****COLLECTOR TANK LOW****** GALLS REMAINING= 154.13 ****** TIME= 41.60 *****

****COLLECTOR TANK LOW****** GALLS REMAINING= 137.33 ****** TIME= 42.20 *****
** FLOW TO COLLECTOR TANK INADEQUATE! REDUCE THROTTLE SETTING **
PORT STOP-COCK WAS 'OFF'
**** Engine has been shut down. ****

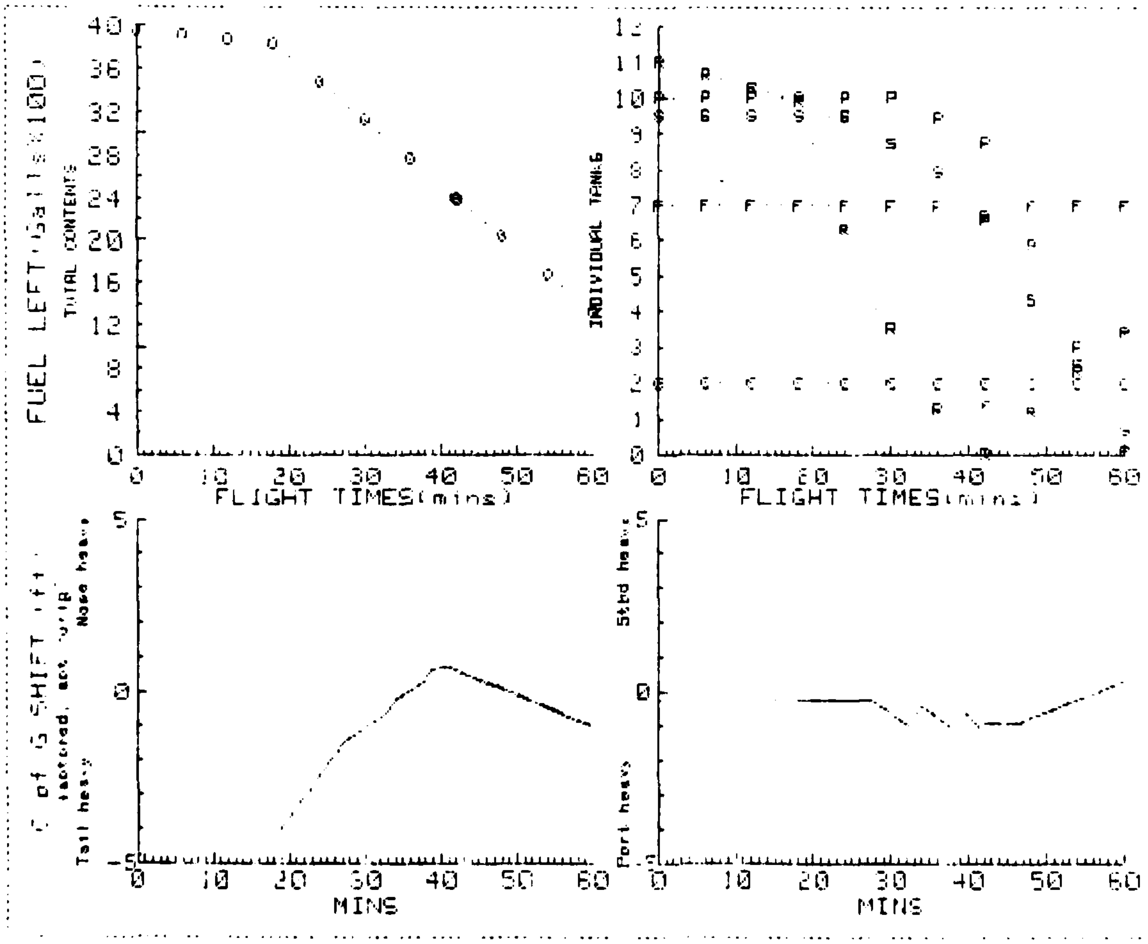


Fig 29 Test 14

Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00 Galls W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 10.00 feet.
Distance between wing tank groups = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
Fuel cross-feed is NOT allowed

**** Engine has been shut down. ****

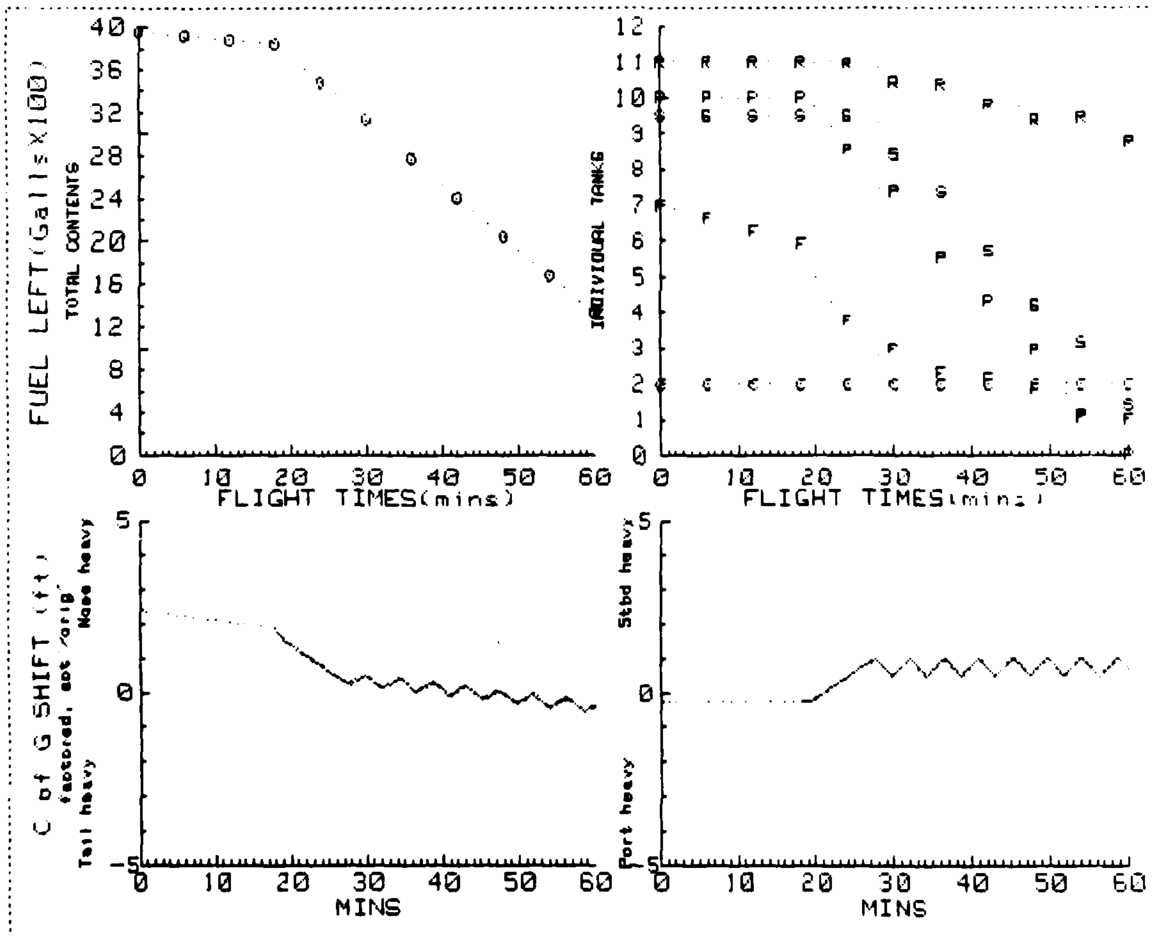


Fig 30 Test 15

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Tank contents are:-F1= 200.00 Galls F2= 1100.00 Galls F3= 700.00 Galls F4= 0.00
Galls                                W4= 1000.00 Galls W5= 950.00 Galls.
Distance between fuselage tank groups= 12.00 feet.
Distance of c of g from forward group= 10.00 feet.
Distance between wing tank groups    = 20.00 feet.
C of g movement limits are, +/- 1.50 feet in pitch and +/- 1.00 feet in roll
                     Fuel cross-feed is allowed


****COLLECTOR TANK LOW!****** GALLS REMAINING= 158.13 ****** TIME= 36.40 *****
****COLLECTOR TANK LOW!****** GALLS REMAINING= 141.33 ****** TIME= 37.00 *****
** FLOW TO COLLECTOR TANK INADEQUATE!  REDUCE THROTTLE SETTING **
STBD STOP-COCK WAS 'OFF'
****  Engine has been shut down.  ****
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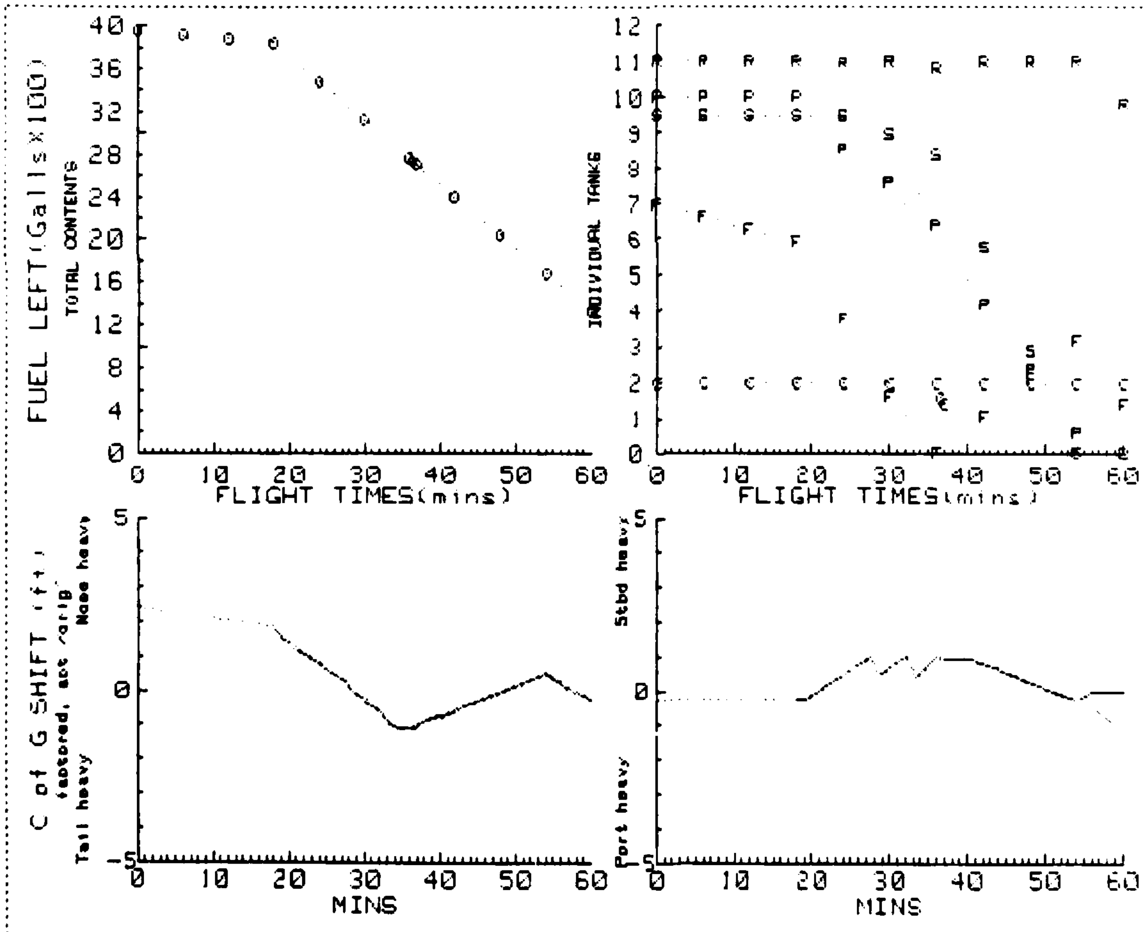

Fig 31 Test 16

REPORT DOCUMENTATION PAGE

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17. Abstract

A computer based model of a simple aircraft-type fuel system has been developed in Engineering Physics and latterly Flight Systems Department, Farnborough, RAE as a background activity over several years. This work was undertaken to furnish an emulation which could be useful for aircraft systems integration studies, to explore fuel management techniques and to furnish programming and documenation experience in an area which had previously relied upon conventional dc and ac signalling techniques.

This Memorandum contains definitions, logic flow diagrams, program listings and the results of 16 simulated engine runs. It is concluded that sophisticated fuel management should be accomplished while retaining a simple hardware architecture and that control of the fuel cg may be achieved without recourse to fixed, predetermined tank-use schedules. Control of the source of engine fuel supply, through reference to the current fuel cg position, would facilitate schemes for limiting fuel loss, subsequent to sustaining battle damage, by allowing redistribution from the affected fuel tank. It would also allow automatic detection and evaluation of hardware faults as they occur and simplify contingency schemes to be evoked on an automatic or semi-automatic basis.

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