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Study of Advanced Fuel System Concepts for Commercial Aircraft and Engines

by

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16. Abstract

An analytical study was performed in order to assess relative performance and economic factors involved with alternative advanced fuel systems for future commercial aircraft operating with broadened property fuels. The DC-10-30 wide-body tri-jet aircraft and the CF6-80X engine were used as a baseline design for the study. Three advanced systems were considered and were specifically aimed at addressing freezing point, thermal stability and lubricity fuel properties. Actual DC-10-30 routes and flight profiles were simulated by computer modeling and resulted in prediction of aircraft and engine fuel system temperatures during a nominal flight and during statistical one-day-per-year cold and hot flights. Emergency conditions were also evaluated. Fuel consumption and weight and power extraction results were obtained. An economic analysis was performed for new aircraft and systems, based on present value and return on investment economic factors.

Advanced system means for fuel tank heating included fuel recirculation loops using engine lube heat and generator heat. Environmental control system bleed air heat was used for tank heating in a water recirculation loop. Advanced system components included centrifugal fuel pumps and low pressure fuel nozzles. The results showed that fundamentally all of the three advanced systems are feasible but vary in their degree of compatibility with broadened-property fuel. Use of engine compressor bleed air for tank heating along with centrifugal fuel pumps and low pressure nozzles yielded the best performance and economic results. Ultimately however, systems design decisions would depend on the degree of anticipated fuel property change and other objectives involving the design of the aircraft and engines.

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FOREWORD

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The General Electric Company Technical Program Manager for this program was George A. Coffinberry. Computer Modeling was performed by T. A. Hobbs. The Administrative Program Manager was Bruno A. Alexander.

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NOMENCLATURE AND ABBREVIATIONS

AERO	Aerodynamic
A/C	Aircraft
APU	Auxiliary Power Unit
AUX	Auxiliary
AVG	Average
BLD	Bleed
BTU	British Thermal Unit
° C	Degrees Celsius
CAMAL	Commercial Aircraft Mission Analysis
CAP	Capacity
CDP	Compressor Discharge Pressure
CFRSA	Commercial Forecasting Route Structure Analysis
COMP	Compartment
Cp	Specific Heat
cSt	Centistokes
DAC	Douglas Aircraft Company
dc	Direct Current
DOC	Direct Operating Costs
DSFC	Delta (Change in) Specific Fuel Consumption
E	Energy
ECS	Environmental Control System
ENG'G	Engineering
F	Filter
f( )	Function of ( )
° F	Degrees Fahrenheit
FAR	Federal Aviation Regulation
FP	Freezing Point
ft	Feet
'	Feet
ft^3	Cubic Feet
Gal	Gallon
G/B	Gearbox

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NOMENCLATURE AND ABBREVIATIONS (Continued)

GE	General Electric Company
GNP	Gross National Product
GPM	Gallons Per Minute
HP	High Pressure
hp	Horsepower
hr	Hour
HX	Heat Exchanger
IDG	Integrated Drive Generator
IFR	Federal Aviation Regulation International Fuel Reserves
ISA	International Standard Atmosphere
k	Thousand
K	Degrees Kelvin
kg	Kilogram
kJ	Kilojoule
kVA	Kilovolt Amperes
lbs	Pounds
LP	Low Pressure
M	Mass
M	Motor
Max	Maximum
MEC	Main Engine Control
MFF	Main Fuel Filter
MFP	Main Fuel Pump
MHX	Main Heat Exchanger
Min	Minimum
min	Minutes
Mp	Mach Number
NM	Nautical Miles
NMI	Nautical Miles
No.	Number
OB	Outboard
P	Pump

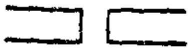
NOMENCLATURE AND ABBREVIATIONS (Continued)

ΔP	Differential Pressure
pph	Pounds Per Hour
ppm	Pounds Per Minute
pps	Pounds Per Second
press	Pressure
psi	Pounds Per Square Inch
Q	Heat
Q_L	Lube Heat Rejection
Q_P	Pump Heat Rejection
QTY	Quantity
REG	Regulator
ROR	Rate of Return
RPM	Revolutions Per Minute
sfc	Specific Fuel Consumption
S/O	Shutoff
SPEC	Specification
SST	Supersonic Transport
SYS	System
SYST	System
T	Temperature
ΔT	Differential Temperature
T_A	Air Temperature
$T_A{}^*$	Air Film Temperature
T_{AMB}	Ambient Temperature
TBC	The Boeing Company
TEMP	Temperature
T_R	Recovery Temperature
TRANS	Transfer
T_W	Wall Temperature
T_2	Air Total Temperature
U	Air Film Coefficient
UCR	Unscheduled Component Removal Rate

NOMENCLATURE AND ABBREVIATIONS (Concluded)

V	Velocity
VOL	Volume
W	Mass Flow
WFE	Engine Metered Fuel Flow (Weight)
WHRS	Waste Heat Recovery System
WT	Weight

SYMBOL FREQUENTLY USED:

 Throttling Process

1.0 SUMMARY

A computer model representation was made of the DC-10-30 aircraft fuel system and the fuel, lubrication, bleed air, and generator cooling systems for the CF6-80X engine. This model was derived from engine thermal models for CF6-80A/A1 engines used on the B-767 and A-310. The thermal model was used in conjunction with General Electric Commercial Engine mission analysis computer codes to project and simulate actual routes and flight profiles for the DC-10-30. The flights included nominal and statistical one-day-per-year cold and hot extremes.

With the DC-10-30 and CF6-80X serving as a baseline, three new advanced fuel systems were evaluated under the same simulated flight conditions in order to assess differences in performance. The primary objective of this work was to determine feasibility and relative degree of compatibility of these alternative systems with future broadened-property fuels. The fuel properties determined to be of primary interest were freezing point, thermal stability and lubricity. An emergency flight condition representing low fuel reserves was also evaluated.

In addition to system performance considerations, fuel consumption and economic tradeoffs were also addressed. Component weight, engine air bleed and shaft power extraction, and the effect of fuel heating were determined in order to arrive at relative differences in fuel consumption for the different systems. These results along with estimates of acquistion cost and maintenance cost were used in an economic analysis which yielded differences in economic incentive for each system.

The three advanced systems included means for aircraft tank heating by energy extraction from existing engine systems. These heat sources included engine lubricating oil, generator oil, and engine compressor bleed air for the aircraft environmental control system. Fuel recirculation to the tanks was used for the engine lube and generator oil approach. A water recirculation loop was used with the bleed air system. The advanced systems also included

alternative fuel pump designs for increased tolerance to low fuel lubricity. A centrifugal pump was used with the most advanced system. Fuel nozzle configurations to increase tolerance to low thermal stability fuel properties included air atomization and alternative nozzle divider valve designs.

The resuts of the study showed that all systems are generally feasible but vary in degree of compatibility with broadened-property fuels. The coldest bulk fuel temperature predicted for the main wing tanks was -45° C (-49° F) for the baseline design. This is 5° C (9° F) less than the maximum freezing point for Jet-A fuel indicating the probable use of Jet-B or Jet-A1 by the airline for this flight. These results during the same cold flight improved to -33.9° C (-29° F) using engine lube oil heat and -41.7° C (-43° F) using generator oil heat. Bleed air heat would have resulted in a -32.2° C (-26° F) tank temperature if the precooler setpoint was 121° C (250° F). Thus the bleed air system affords a 12.8° C (23° F) increase in fuel freezing point. The only significant problem revealed by the study was the use of engine lube oil heat for fuel freezing protection. Engine oil temperature might become too cold for proper distribution in the engine. Oversizing the oil-to-fuel heat exchanger (degrading performance) might be a solution but is not desirable from a weight standpoint.

Fuel lubricity problems caused by severe hydrotreating could be solved with the use of new pump gear materials or by changing to centrifugal pumps. It is highly uncertain, however, that low lubricity will be a fuel problem in any event.

Thermal stability for the study fuel was estimated to be 220° C (428° F) minimum (breakpoint) as compared to 245° C (473° F) minimum for Jet-A. This reduction would increase projected unscheduled component removal (UCR) rate from 50 per 10^6 hours to 140 per 10^6 hours using the study fuel. The worst of the advanced systems nozzle concepts yielded a UCR rate of 41 per 10^6 hours using the study (broadened-property) fuel. Hence from a fuel nozzle standpoint, it is believed that thermal stability reduction could be accommodated with a new design.

The emergency flight simulations with low fuel reserves and continuation of tank heating did not reveal major problems. With relatively simple provisions the fuel tanks would not be subject to overheating.

The economic results showed that only a small improvement is needed in fuel consumption to offset the initial cost of the most complex system. Using fuel as a heat sink for engine bleed air eliminated engine fan bleed cooling (precooling) and resulted in a 0.312 percent improvement in block fuel consumption for the nominal flight. After consideration of initial investment and maintenance cost differentials, the net 1982-dollar investment incentive for this system was $93,669 ($69,254 with study fuels) per engine system over the 15-year life of the aircraft.

An additional result gained from this program was the apparent benefit of system computer modeling. Advanced systems and flight simulations are far too complex to afford assessment in a simple manner. The relative differences are small. In future work, this type of approach may be of absolute necessity if the best designs and operational decisions are to be made.

2.0 INTRODUCTION

This final report presents the results of a study performed by the General Electric Company Aircraft Engine Business Group, under NASA Contract NAS3-23267 for the NASA-Lewis Research Center. The study involved computer modeling of the fuel system for a wide-body commercial aircraft using high bypass jet engines. Advanced fuel systems were compared with a baseline design on the basis of similar flight conditions in order to ascertain compatibility with fuel properties and economic impact to the aircraft user.

In the future it can be expected that there will be a general reduction in the availability of petroleum crude sources. This, coupled with a relative increase in aviation transportation and increased competition for kerosene-type fuel may lead to an incentive for the use of broadened-property aviation jet fuel. In the aircraft and engine fuel system, fuel property change may influence tank fuel freezing protection, combustor fuel nozzle deposits related to thermal stability, and engine fuel pump wear resulting from low lubricity fuel characteristics.

It is recognized that the design evolution of aircraft and engine fuel systems should anticipate such changes to enable the aviation industry to provide a reliable and cost-effective product. The objective of this program was therefore to define and analyze a variety of advanced fuel systems which address these fuel property issues. Performance of the advanced systems relative to fuel compatibility, aircraft safety and economic benefits was the key objective.

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3.0 BASELINE AIRCRAFT AND ENGINE

3.1 AIRCRAFT

The MacDonnell Douglas DC-10-30 wide-body tri-jet aircraft was chosen for the study because it represents a size and range which is of particular interest from the standpoint of low temperature fuel. Figure 1 shows the DC-10-30 aircraft. The DC-10 fuel system involves fuel transfer from several tanks to a particular engine during the course of a prolonged flight. Thus, the combination of prolonged fuel cooldown time and a modern tank-to-engine fuel management system provided an excellent baseline for this study of advanced systems involving tank heating.

Other particulars of the DC-10-30 are as follows:

11,112 km	6,000	nmi range
256,284 kg	565,000	lbs max gross take-off weight
45,360 kg	100,000	lbs max payload
	277	seat passenger load

The DC-10-30 fuel system includes eight fuel tank compartments. Triple or quadruple redundant tank boost pumps for all tanks and all-attitude suction-feed for wing engines is provided. Figure 2 shows the overall fuel management system.

For the study, only the No. 1 engine (left wing) was considered. Referring to the simplified fuel system in Figure 3, fuel is transferred by boost pumps from the auxiliary (center) tank and No. 2 (tail engine) tank to the main outboard tank, then to the main tank. This occurs at the beginning of the flight in order to burn off fuel in the center of the aircraft. This is desirable on large aircraft from the standpoint of wing structural load and for aerodynamic stability. As the flight progresses, fuel weight distribution shifts toward the outward fuel tanks. At the end of the flight, fuel is transferred from the main outboard tanks to the main tanks as shown in

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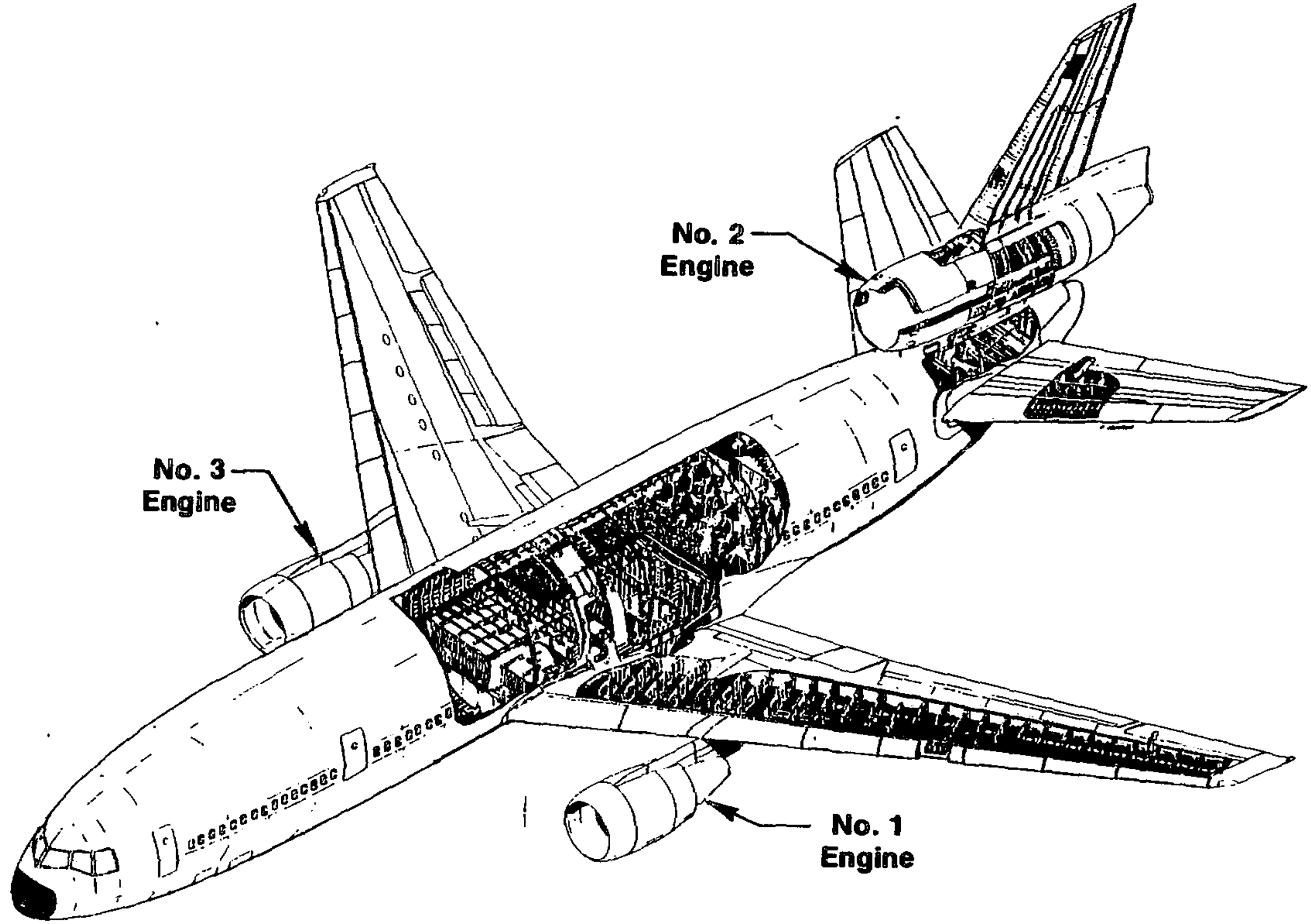

Figure 1. DC-10 Aircraft.

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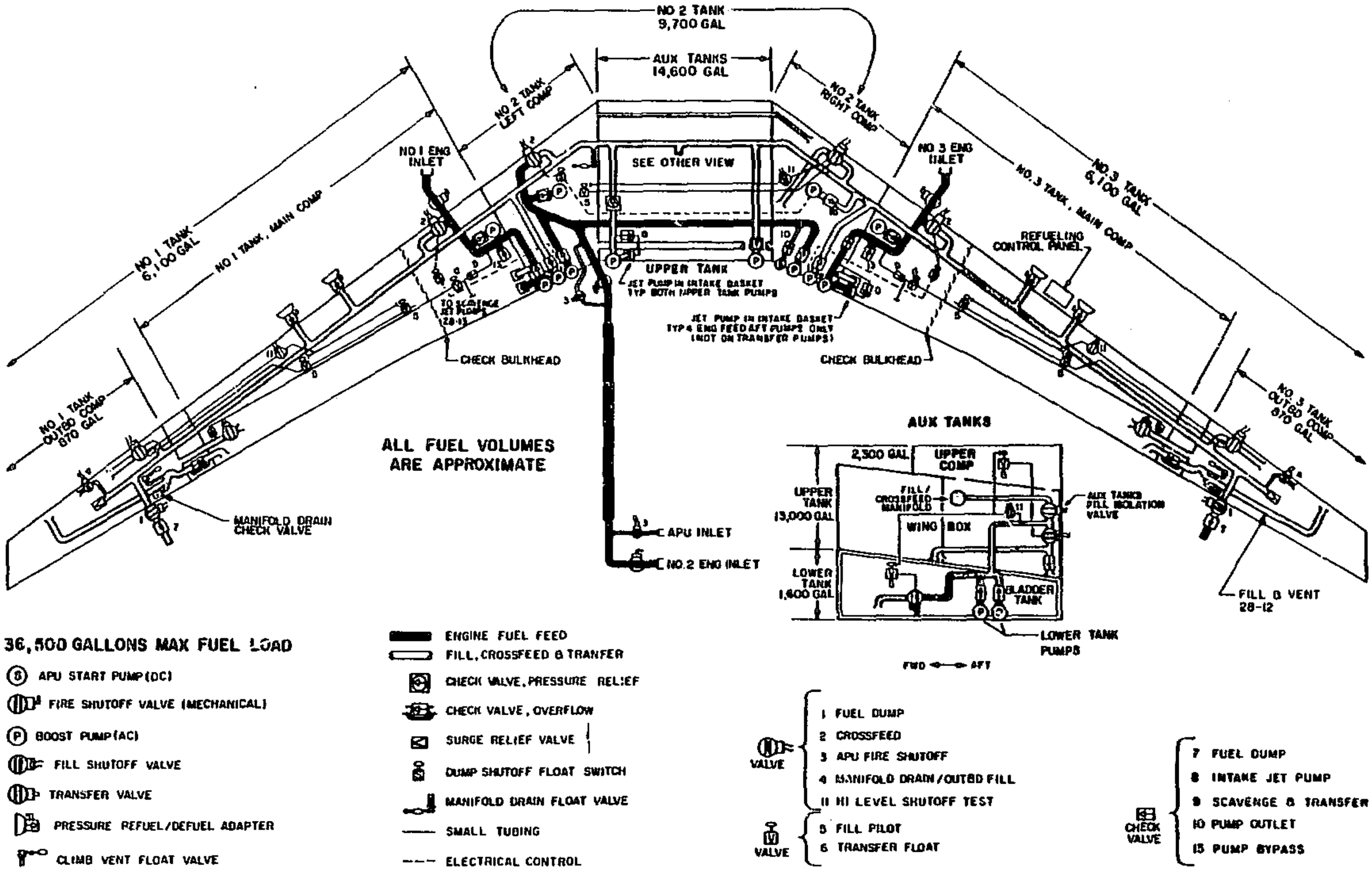
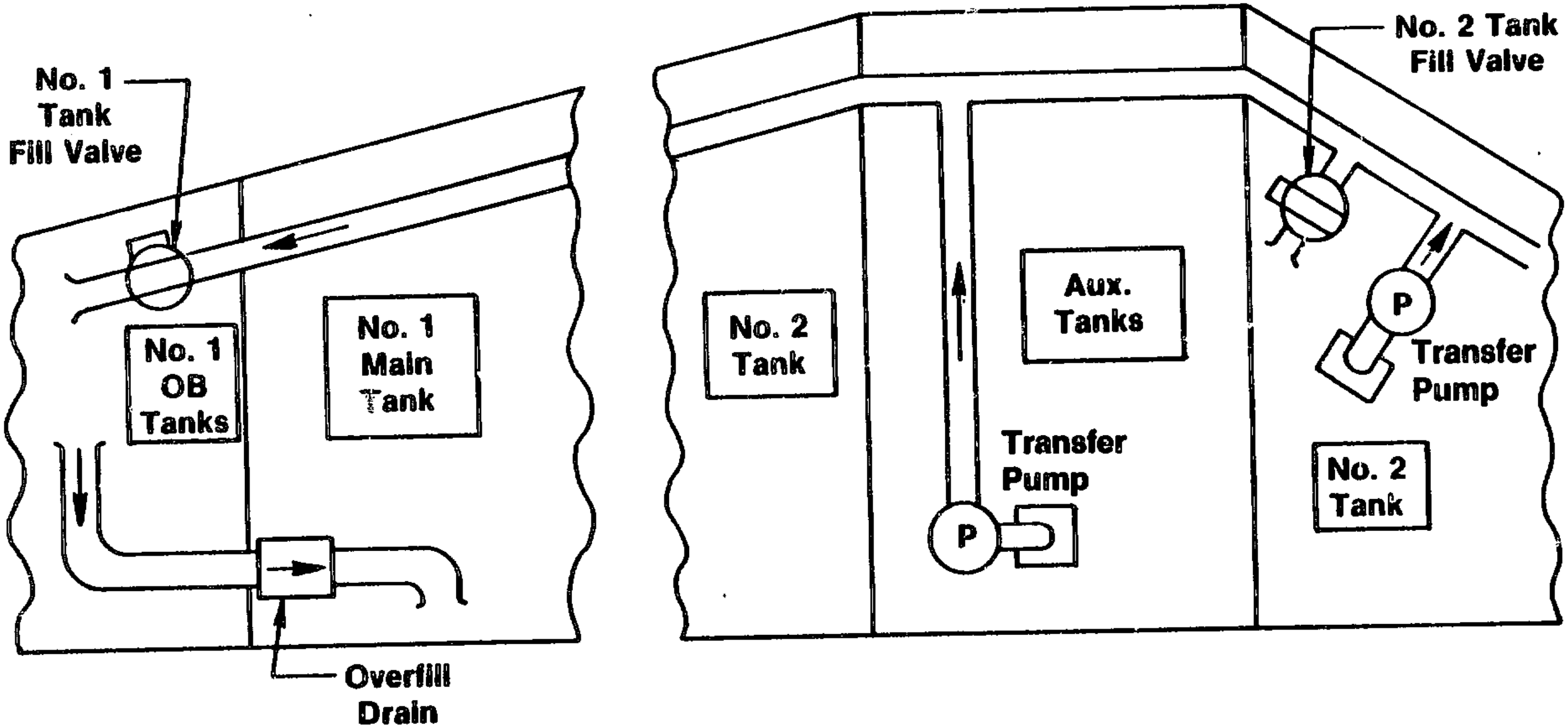


Figure 2. DC-10 Tank Fuel System.



- Fuel is Transferred When Transfer Pumps are Turned On and Fill Valves are Opened by Flight Engineer
- Relief Valves (Not Shown) Prevent Overpressurization

Figure 3. Auxiliary and No. 2 Tank Transfer to Main Tanks at Beginning of Flight.

Figure 4. This occurs automatically on the DC-10 if the main tank level is low enough that it becomes desirable to consolidate all remaining fuel reserves in the main tanks which are directly feeding the engines. Figure 5 shows sequentially how fuel is transferred and burned during a long-range flight extended to minimum fuel reserves. Figure 6 shows the flight engineer's panel and the fuel transfer/burn selections which can be made.

The computer model used for this study included the fuel transfer and fuel burn aspects discussed previously and shown in the figures. Figure 7 further describes the fuel transfer schedules used in the model.

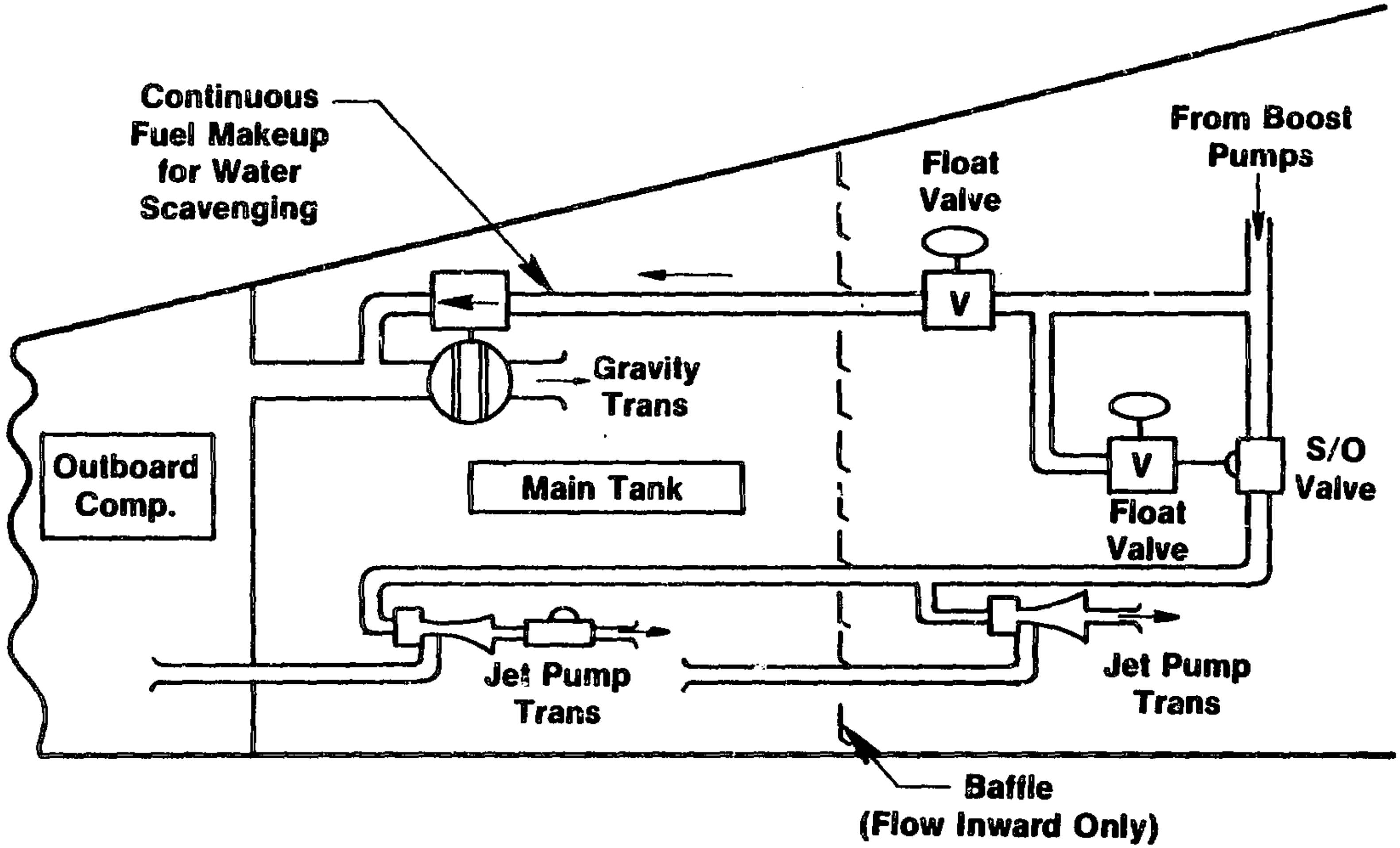
Advanced System C uses engine compressor bleed air as a heat source for tank heating. This bleed air is normally used on the DC-10 for wing anti-icing and for the cabin environmental control system (ECS). Figure 8 shows the baseline DC-10 pneumatic system associated with this bleed air. Note the location of the precooler setpoint which affects the amount of heat removed from the engine bleed air.

3.2 ENGINE

The General Electric engine currently used on the DC-10-30 is the CF6-50C. For the study, however, a newer engine, the CF6-80X, was modeled. The CF6-80X is a potential growth version of the CF6-80 used on the B-767 and A-310. The -80X engine would have about 6 percent better cruise sfc than the -50C. For the installed engine, standard day sea level static rating would be as follows:

249.1 kN	56,000	lb. thrust
	4.1:1	fan bypass
131.5 kg/s	290	pps core airflow
8890.4 kg/h	19,600	pph fuel flow

The CF6-80X engine is shown in Figure 9. The engine installation on the DC-10 is shown in Figure 10. The engine fuel system is shown schematically in



- **Low Fuel Level in Main Tank Causes Float Valves to Automatically Open Outboard Compartment Gravity Drain Valve and Activates Jet Transfer Pumps — Transferring Fuel to Inward Area of Main Tank Regardless of Aircraft Maneuver**

Figure 4. Outboard Tank Fuel Transfer To Main Tank at End of Flight.

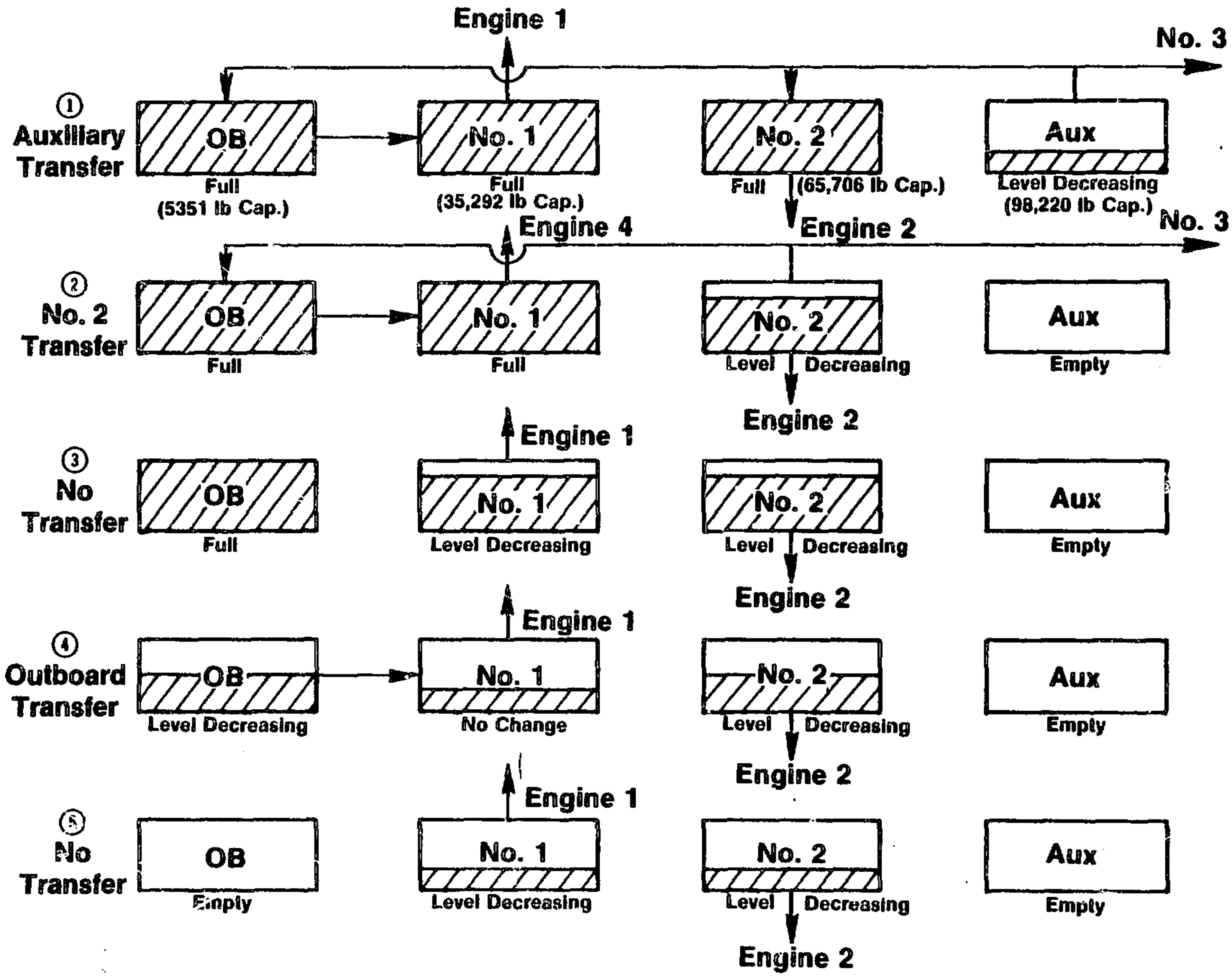


Figure 5. Fuel Usage.

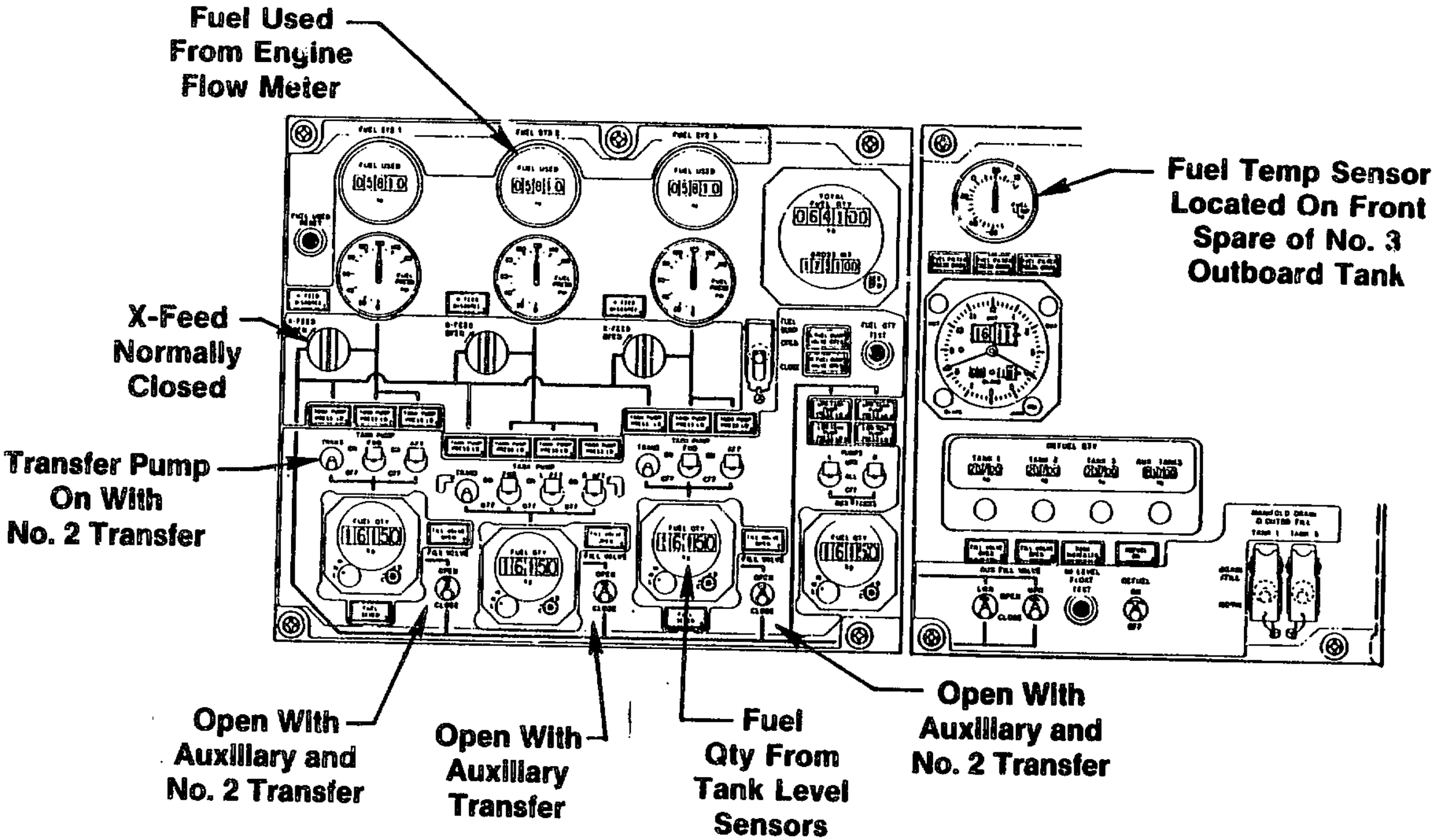


Figure 6. Flight Engineer Fuel Panel.

① Auxiliary Tank Transfer

- Used on Cold Flight Only (Long Range)
- Starts at Beginning of Flight
- Rate Equals Engine Burn Rate
- No Change in Other Tank Levels (Full)
- From Aux Equals 98,220 lbs (44,550 kg) (Full) to 400 lbs (181 kg) (Residual)

② No. 2 Tank Transfer

- Starts When No. 1 or No. 3 Mains Plus Outboards at 27,000 lbs (12,250 kg) to 33,770 lbs (15,320 kg)
- Rate of 25,200 pph (3.2 kg/s) to No. 1 and 25,200 pph (3.2 kg/s) to No. 3
- Main Tank Levels Increase — No Change in Outboard Levels (Full)
- Stops When No. 2 Tank 500 lbs (227 kg) More Than All Other Tanks Combined

③ Outboard Transfer

- Starts When Main Tank Level Goes Below 5000 lbs (2270 kg)
- Rate Equals Engine Burn Rate
- No Changes in Main Level (<5000 lbs) (<2270 kg)
- Stops When Outboard Goes Below 400 lbs (181 kg) (Residual)

Figure 7. Fuel Transfer Schedule.
(Model Representation)

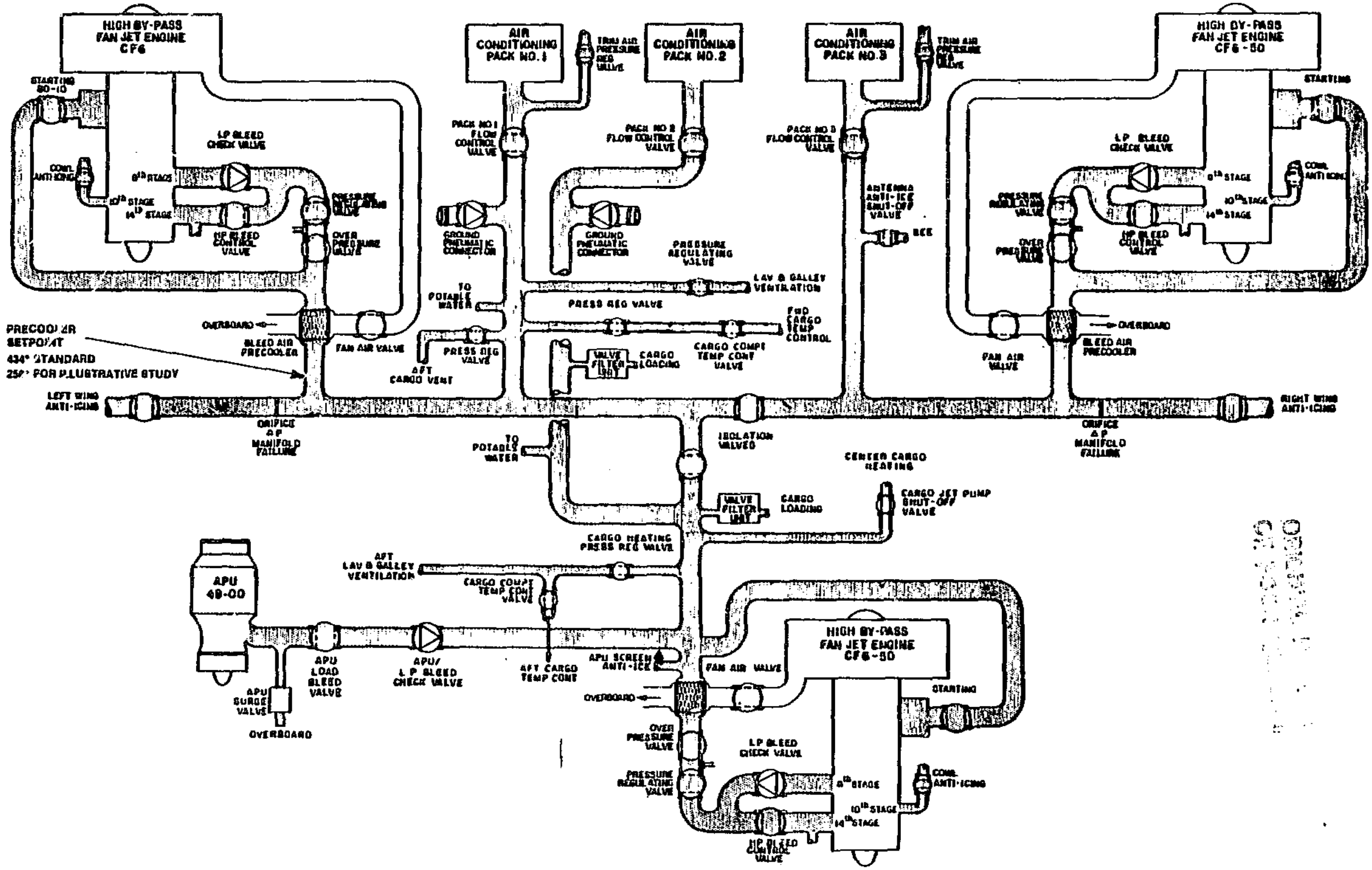


Figure 8. DC-10 Pneumatic System.

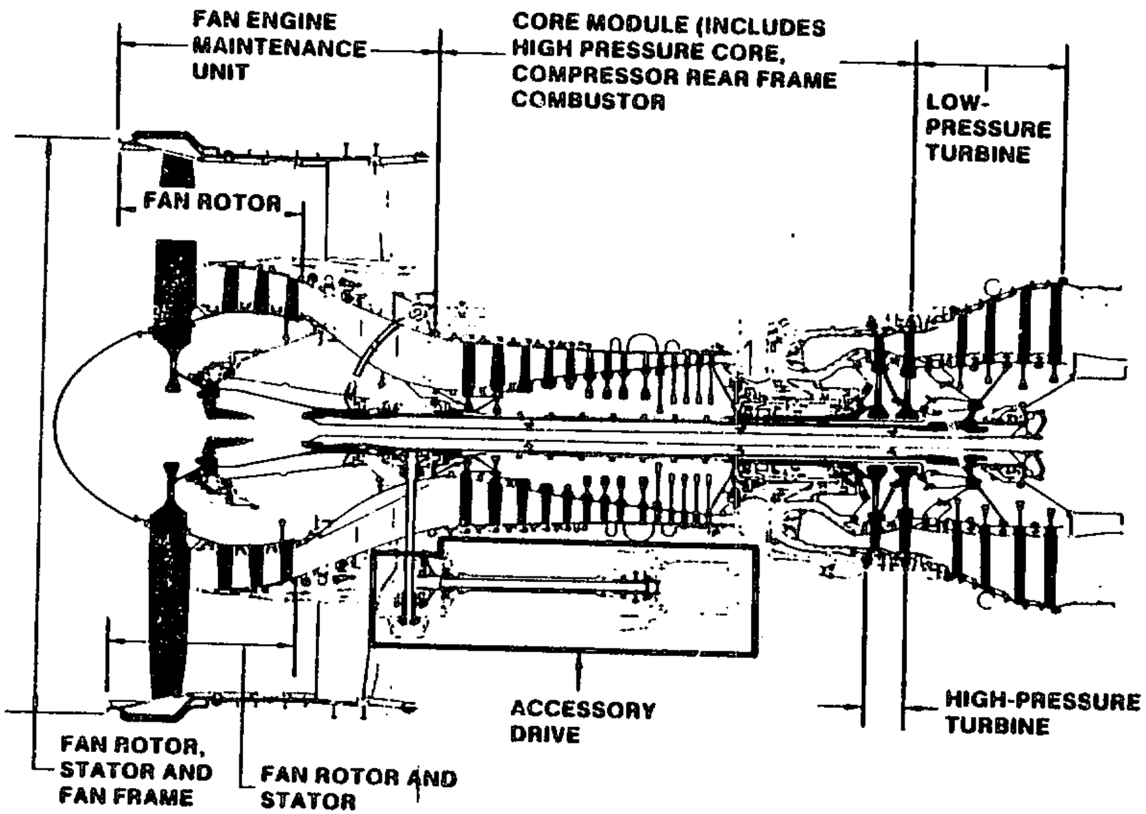


Figure 9. CF6-80 Engine.

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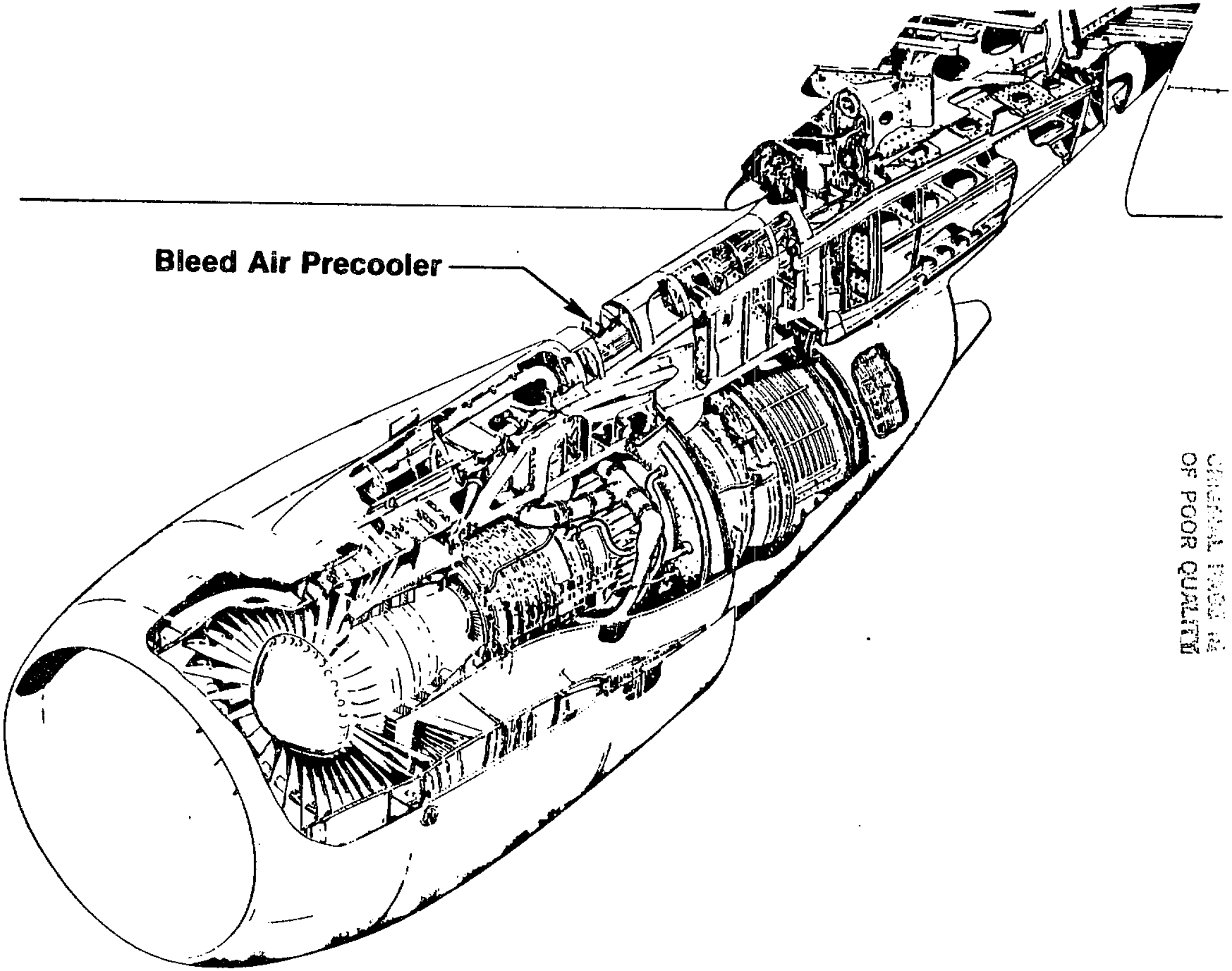

Figure 10. CF6-80 Engine on DC-10.

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Figures 11 and 12. The fuel system arrangement is typical of General Electric large commercial engines. The CF6-80 engines (B-767 and A-310) include fuel cooling of the integrated drive generator (IDG). Air cooling is provided as an alternative heat sink for fuel cooling of the IDG oil. The arrangement is shown in Figure 13.

For this study, the engine fuel system components of particular interest are the fuel pump and fuel nozzles. The gear-type pump is shown in Figure 14. Although, as mentioned, the CF6-80X was used for the study, it was decided to use CF6-50 fuel nozzles in the Baseline model. This was done because good knowledge of field service performance is presently available for the -50 nozzle thus permitting a more accurate assessment of fuel temperature effects. The baseline fuel nozzle (CF6-50) and manifold arrangement is shown in Figures 15 and 16.

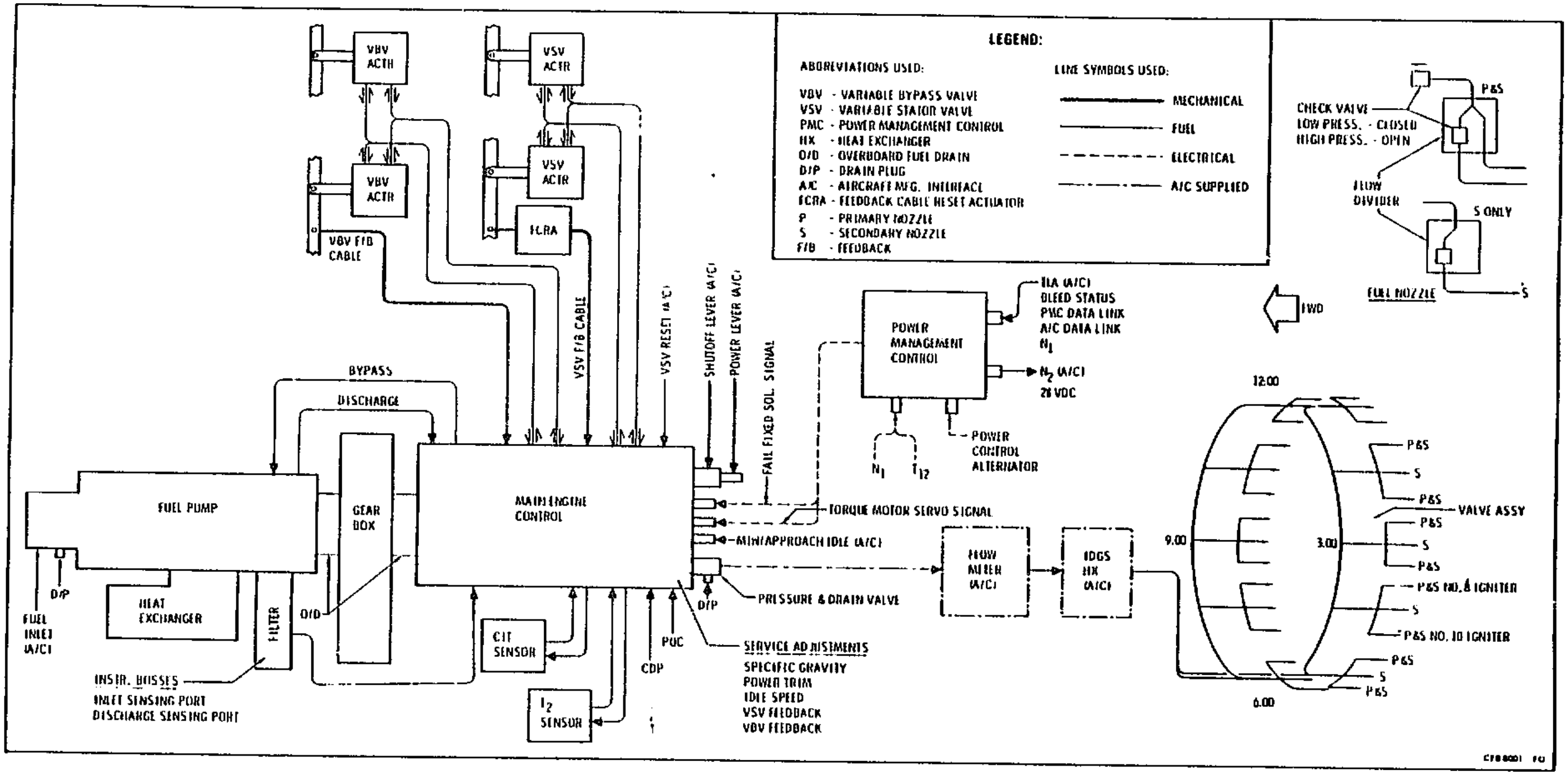


Figure 11. Fuel System Schematic.

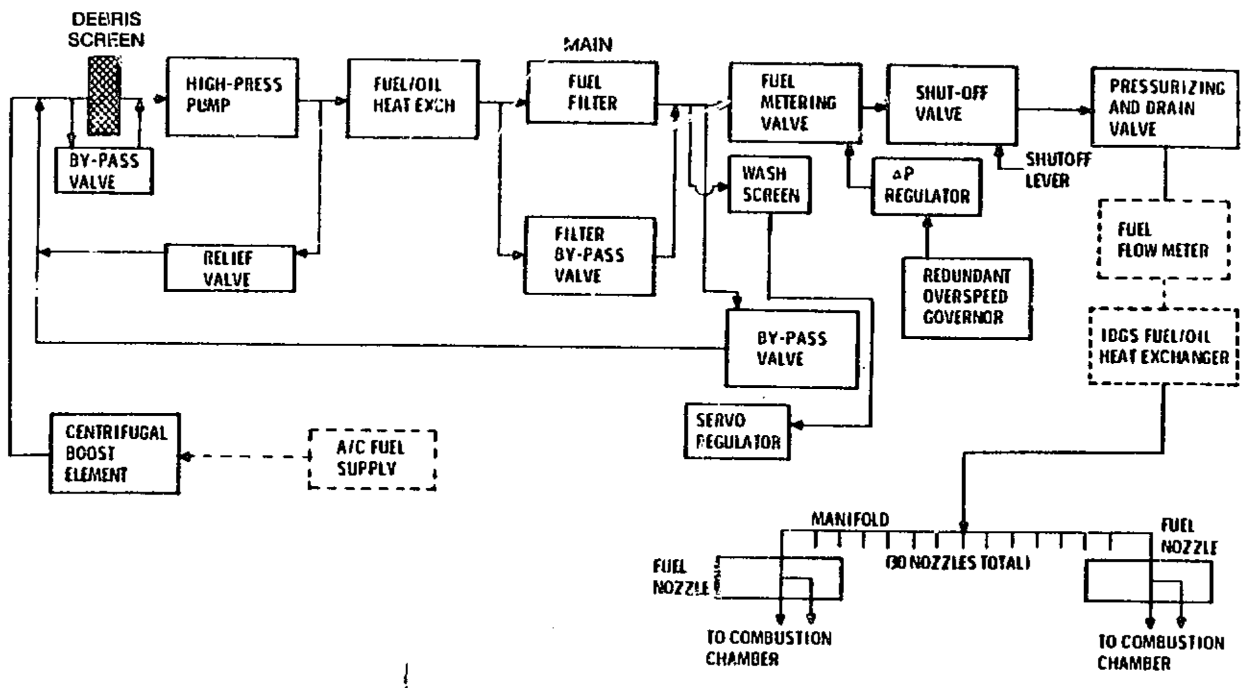
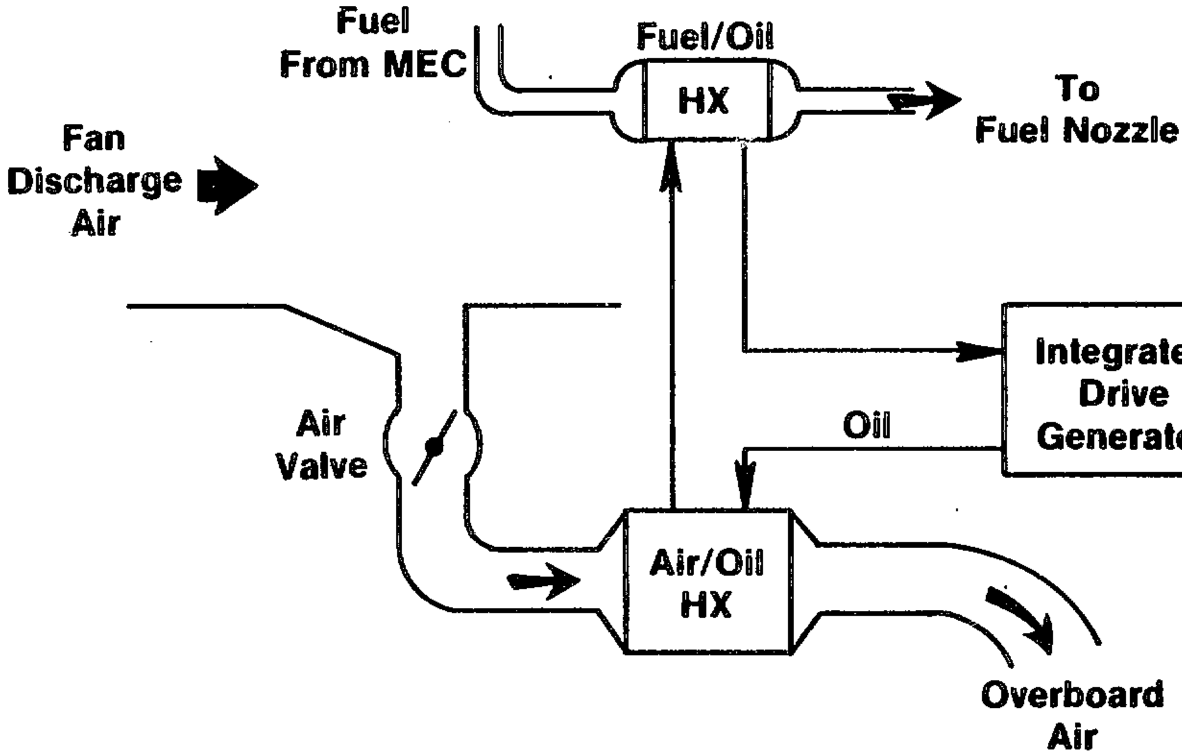


Figure 12. Fuel System Schematic.



- **During Takeoff, Climb and Cruise - Air Valve Closed**
  IDG Oil Heat Goes to Fuel
  0.35% ΔSFC Improvement at Cruise
- **During Idle Descent - Air Valve Open**
  IDG Oil Heat Goes to Air
- **Used on CF6-80A For B-767 and A-310**

Figure 13. IDG Oil Cooling System.

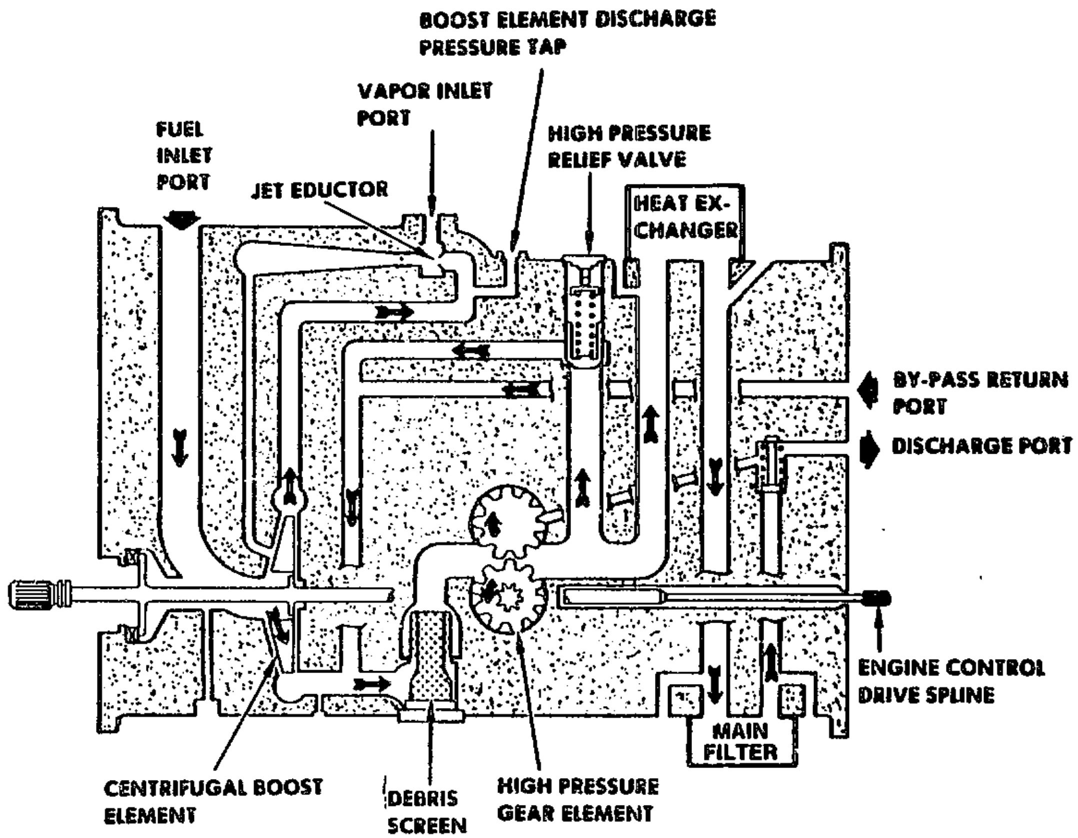


Figure 14. Fuel Pump.

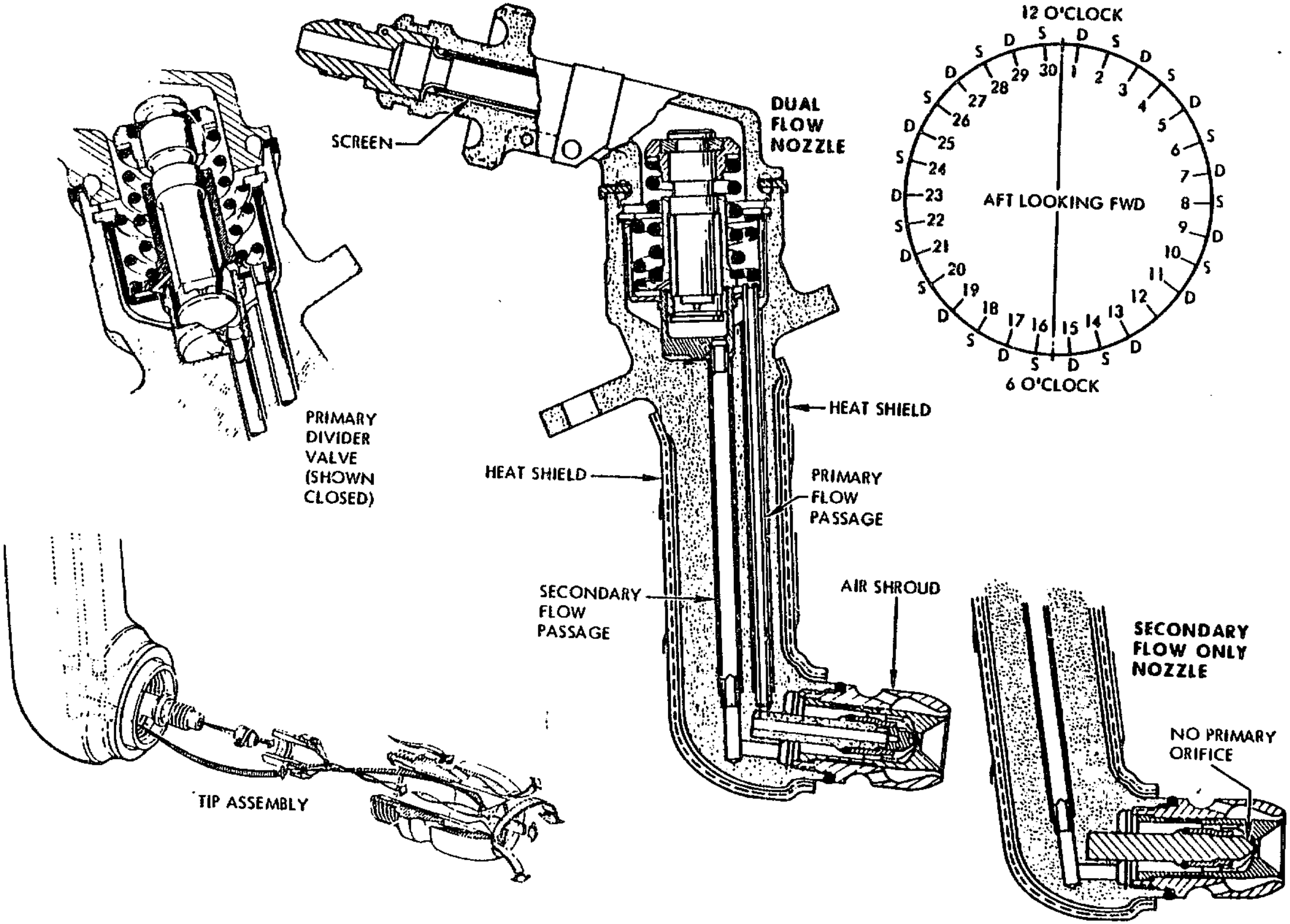


Figure 15. CF6-50 Fuel Nozzles (Pressure Automizing).

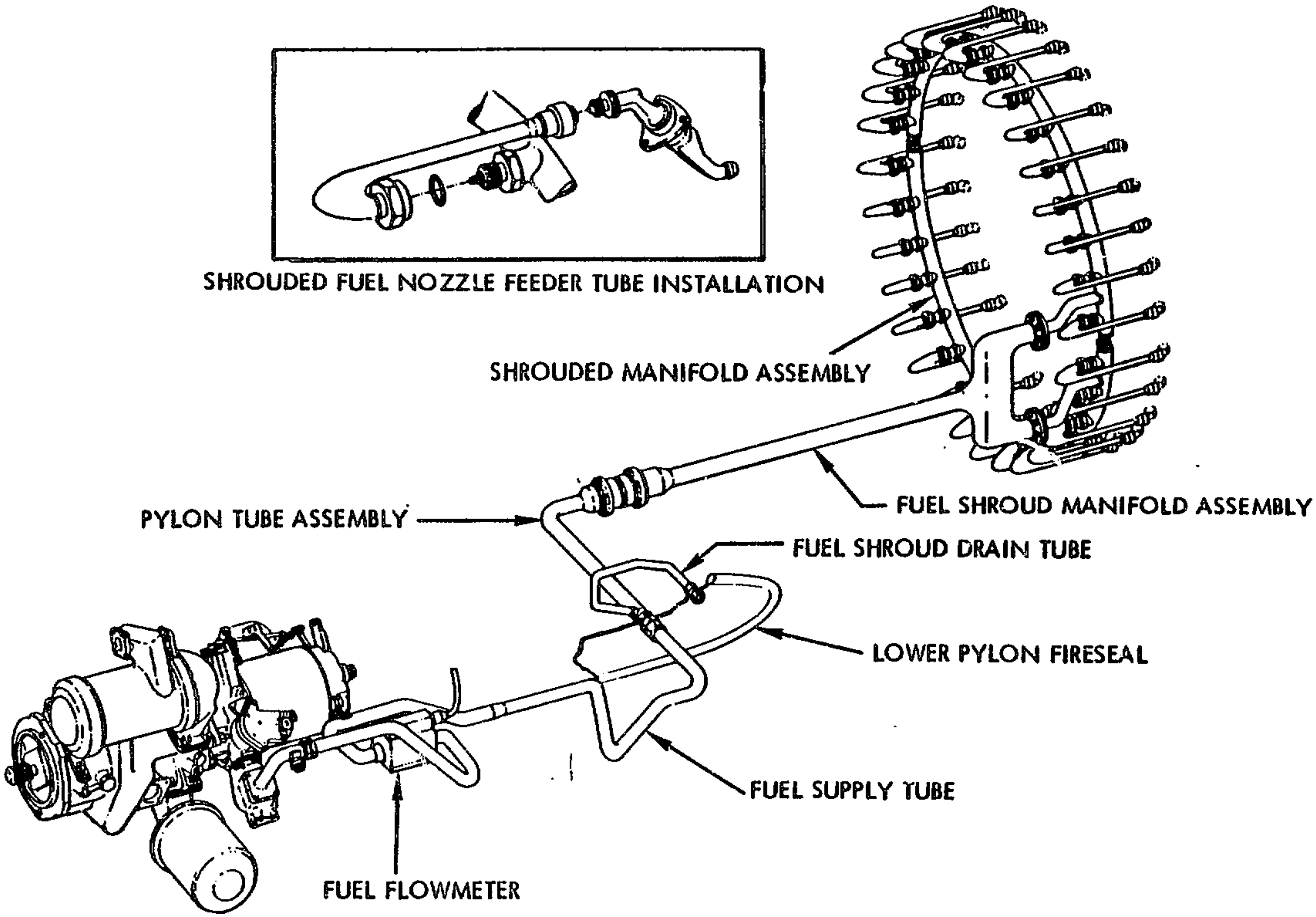


Figure 16. CF6-50 Fuel Nozzles with Valves on Casing.

4.0 ADVANCED SYSTEMS

4.1 INTRODUCTION

The system arrangements and component selections for the advanced systems are keyed to the issue of broadened-property fuels. For the study, three fuel properties were of primary concern:

1. Freezing Point - tank heating consideration
2. Thermal Stability - fuel nozzle consideration
3. Low Lubricity - fuel pump consideration.

The results of the study provide comparisons between three Advanced Systems (A, B and C) and the Baseline System. Figure 17 lists the fuel properties and the approach or method for dealing with these properties. In all cases, tank heating is used to provide fuel freezing protection. Low lubricity problems would be avoided by either the use of low lubricity tolerant materials or the use of centrifugal pumps. Thermal stability problems are addressed by improvements in the fuel nozzle design and by reducing the fuel temperature supplied to the nozzles.

Figures 18 through 21 show, using a common format, the differences between the Baseline and the Advanced Systems. The major features of each system are indicated by these figures. Note that these systems as formulated in the study computer models start with the aircraft auxiliary and No. 2 main tank. System weight comparisons are shown in Figure 22.

4.2 ADVANCED SYSTEM A

In this system, a fuel return line is connected from the engine fuel control to the outboard fuel tank of the corresponding engine. Normally all control bypass flow returns to the tank. This permits a portion of the pump heat and engine lube system heat to be transferred to the fuel tanks. Explicitly, heat from these sources is transferred to the tanks or to the

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Fuel Property	Approach	DC10-30/CF6-80X Baseline	Advanced Systems A	Advanced Systems B	Advanced Systems C
Fuel Freezing Point Jet-B + 5° F = -53° F Spec Jet-A + 5° F = -35° F Study Limit + 5° F = - 12° F	• Tank Heating	• None	• New • Gear Pump Fuel Bypass Recirculation. • Lube and Pump Heat To Tank	• New • Boost Pump Fuel Recirculation • IDG Heat to Tank	• New • Water-Recir.-Loop • Bleed Air Heat to Tank
Lubricity Current = High Study Limit = Low	• Fuel Pump Compatibility	• Conventional	• New • Low Lubricity Gear Material	• New • Low Lubricity Gear Material	• New • Centrifugal
Thermal Stability (Manifold) Avg. Jet-A = 300° F Max Study Limit = 255° F Max	• Fuel Nozzles and Valves Compatibility • Lower Fuel ΔT	• Conventional • High - ΔP • Valves on Casing	• New • Low - ΔP • Valves on Casing • Low Fuel ΔT	• New • Low - ΔP • Valves on Manifold • Low Fuel ΔT	• New • Low ΔP • Remote Single Valve • Low Fuel ΔT

Figure 17. Relationship of Advanced Systems to Fuel Properties.

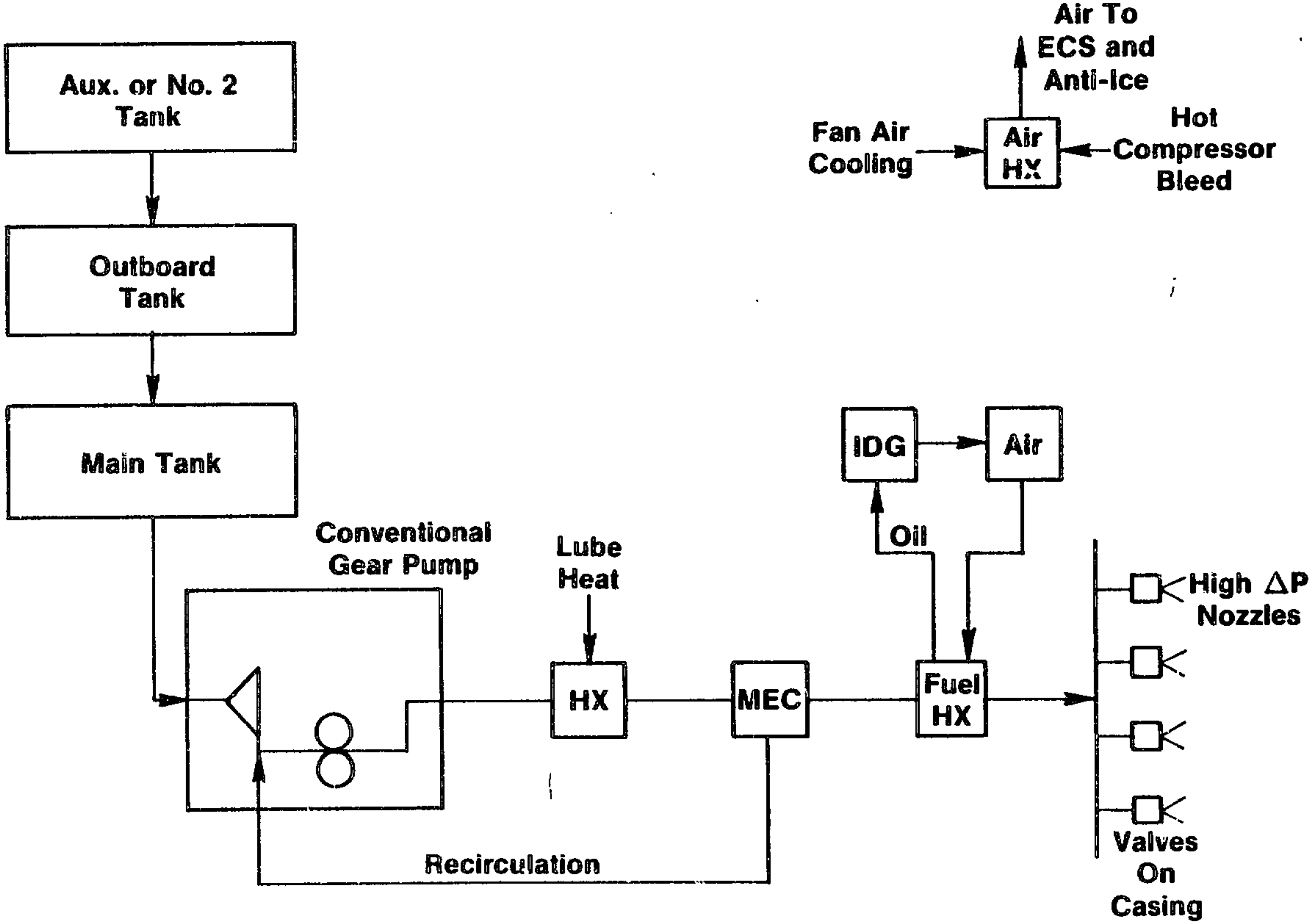


Figure 18. Baseline DC10-30 and CF6-80X.

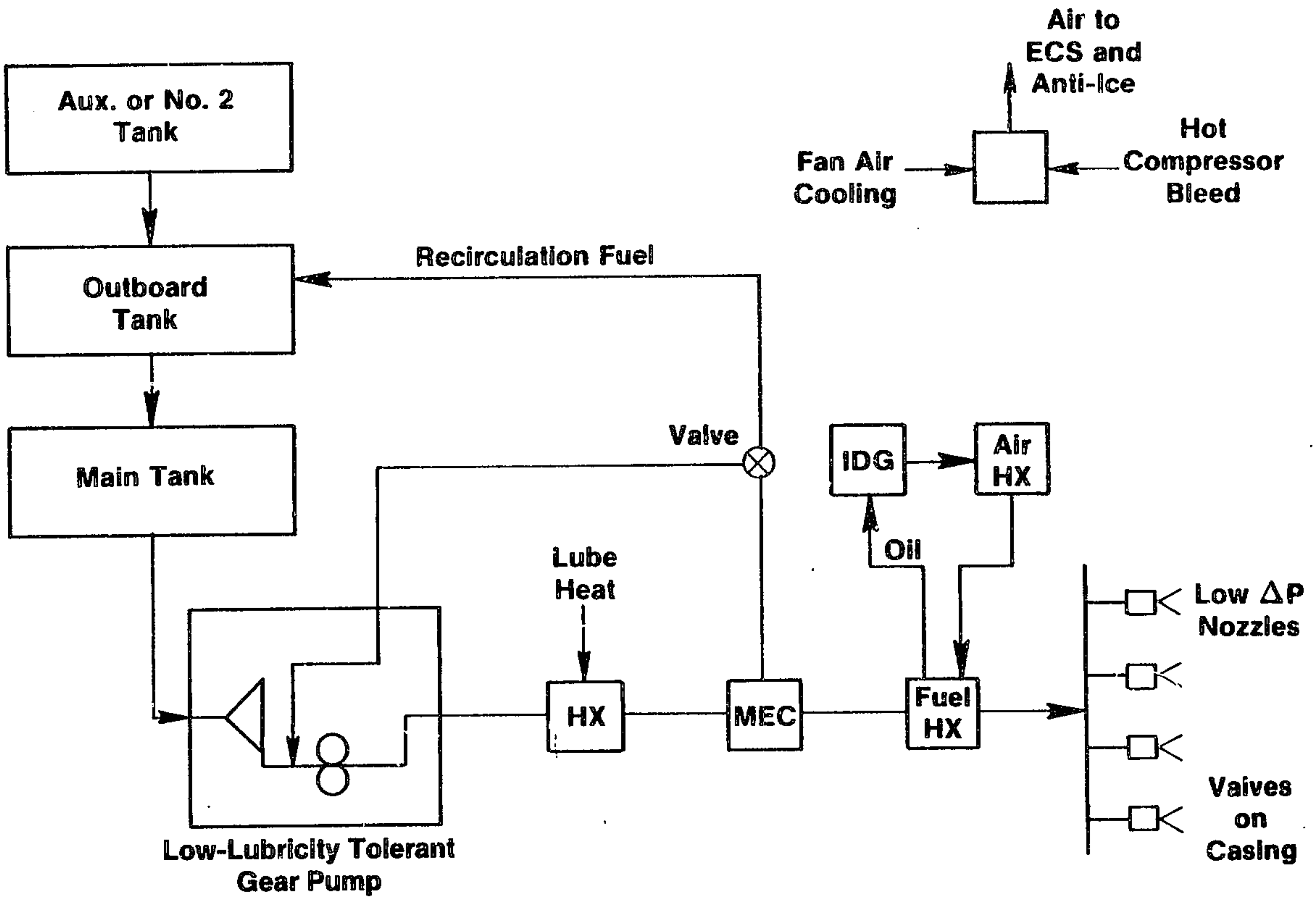


Figure 19. Advanced System "A".

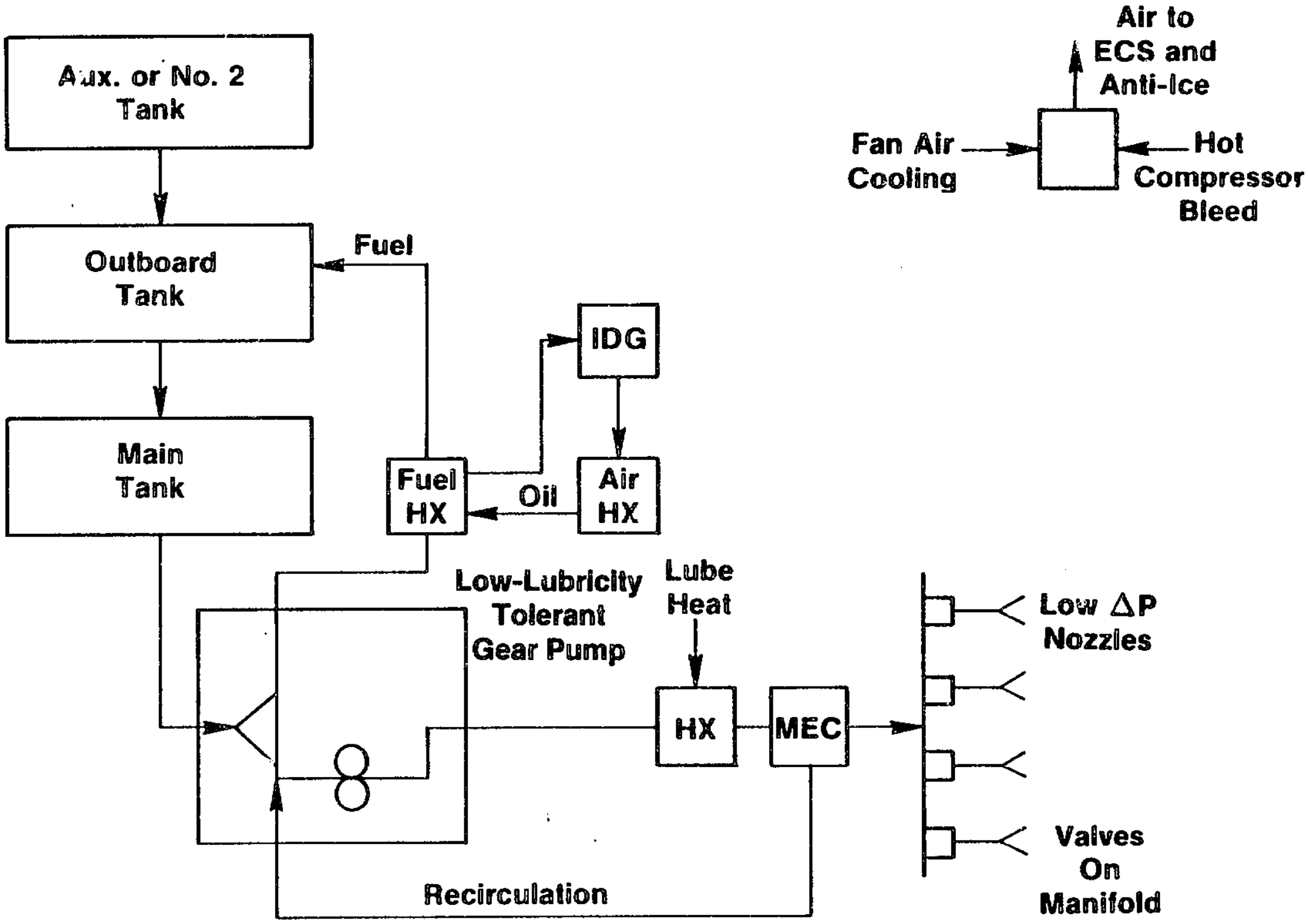


Figure 20. Advanced System "B".

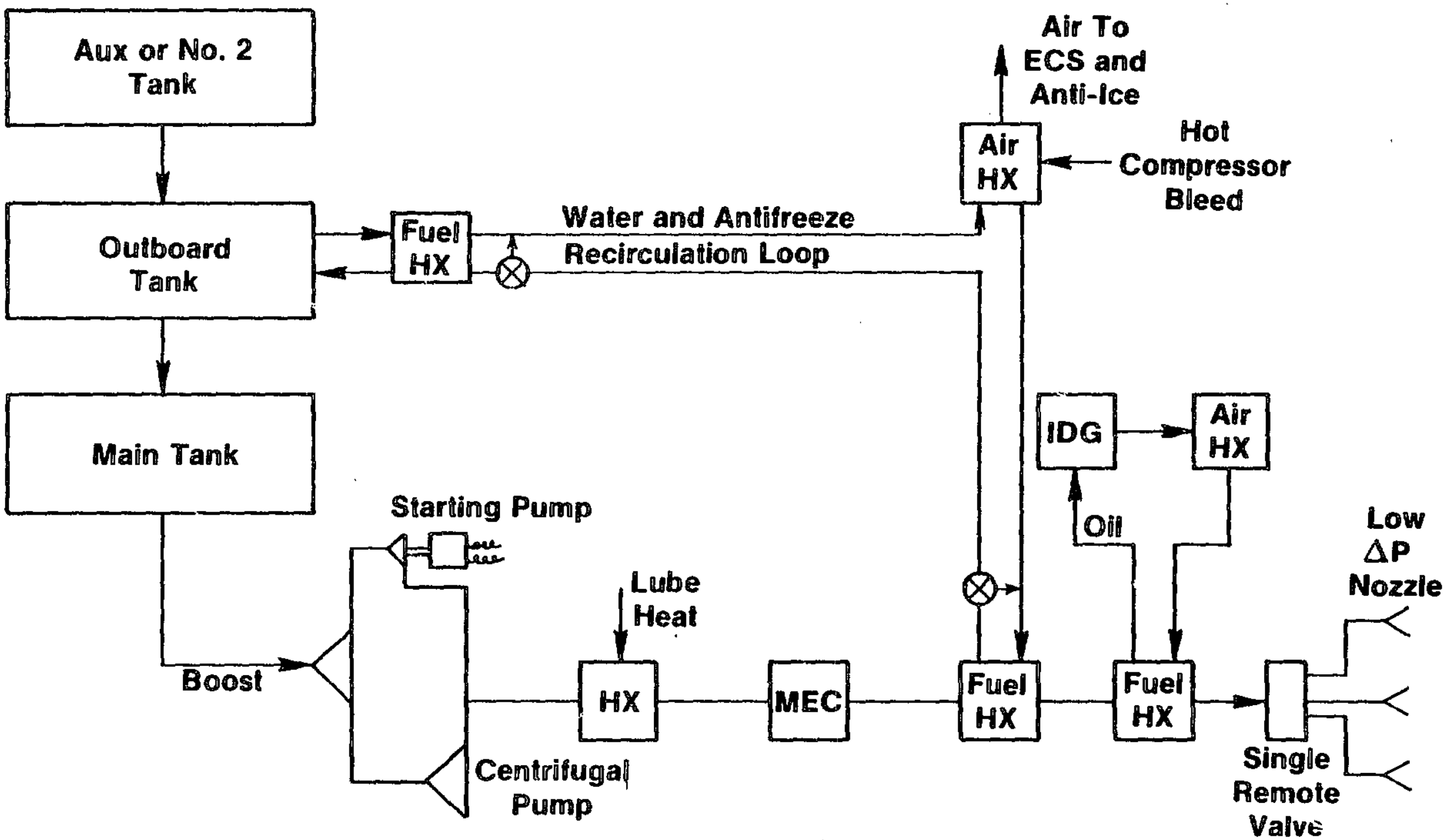


Figure 21. Advanced System "C".

	Fuel Pump	Bleed Air Precooler	Fan Bleed Valve	WHRS Loop	Total
Baseline	39/17.7	62/28.1	14/6.4	—	115/52.2
System A	39/17.7	62/28.1	14/6.4	—	115/52.2
System B	39/17.7	62/28.1	14/6.4	—	115/52.2
System C	29/13.2 Including Start Pump	—	—	157/71.2	186/84.4

Note: These Weight Penalties Increased by 25% in Model to Account for Additional Engine Mount Weight

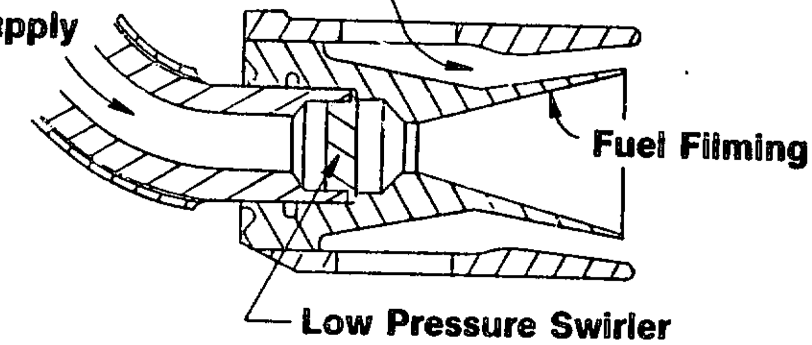
Figure 22. Weight Tradeoffs (Dry Weight, Pounds/Kilograms).

engine combustor in proportion to the ratio of tank return flow to engine burn flow (metered flow). In certain situations such as tank temperature exceeding limits or needing additional fuel icing protection, it becomes necessary to shut off tank return flow. This may be done by cockpit- controlled operation of a valve which causes control bypass flow to return to engine pump interstage (in the normal manner). The reason for suggesting tank return as a normal operational mode is to gain the added benefit of reduced fuel temperature rise in the engine system. This occurs because the fuel temperature rise associated with pumps and lube heat are now (with tank return) chargeable to total pump flow (gear flow) instead of only metered flow. This reduced fuel temperature is advantageous for cooling other systems and operating at lower nozzle temperatures. Fuel cooling of auxiliary systems (such as the IDG) results in better sfc by reduction of air cooling (see Figure 13).

System A uses low ΔP (air atomizing) nozzles with the divider and check valves mounted on the engine casing. This low ΔP nozzle is of a design similar to the nozzles on the General Electric TF34, T700 and CFM56 engines. These air atomizing designs are shown in Figure 23. From a thermal stability standpoint, the advantages of these nozzles are: (1) larger injector ports, (2) more air cooling of the nozzle tip, and (3) lower nozzle ΔP resulting in lower pump pressure rise (less pump heat input). Reduction in nozzle ΔP from the Baseline (high ΔP CF6-50 type) is shown in Figure 24.

For low lubricity considerations, System A uses pump gears made from a carbide matrix material. The gears are dimensionally the same as standard tool steel or nitraloy gears. Various carbide-matrix gears have been and continue to be evaluated by pump manufacturers. Titanium carbide in an iron matrix is one possibility. Tooth bending strength is imparted by the iron. Titanium carbide is hard and self-lubricating because of its hexagonal crystal structure.

TF34 and T700



CFM56

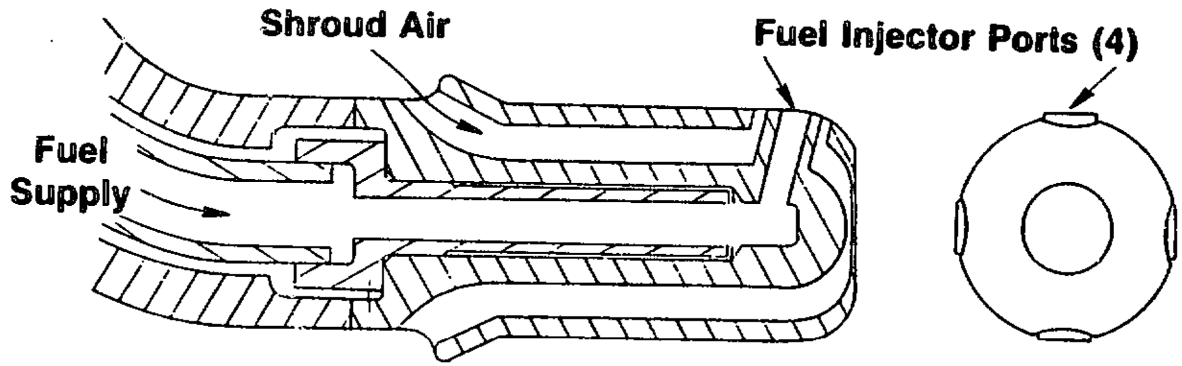


Figure 23. Low ΔP Air Atomizing Nozzles.

① Primary/Secondary Nozzle or Secondary Only Nozzle

② Primary/Secondary Nozzle

③ Secondary Only Nozzle

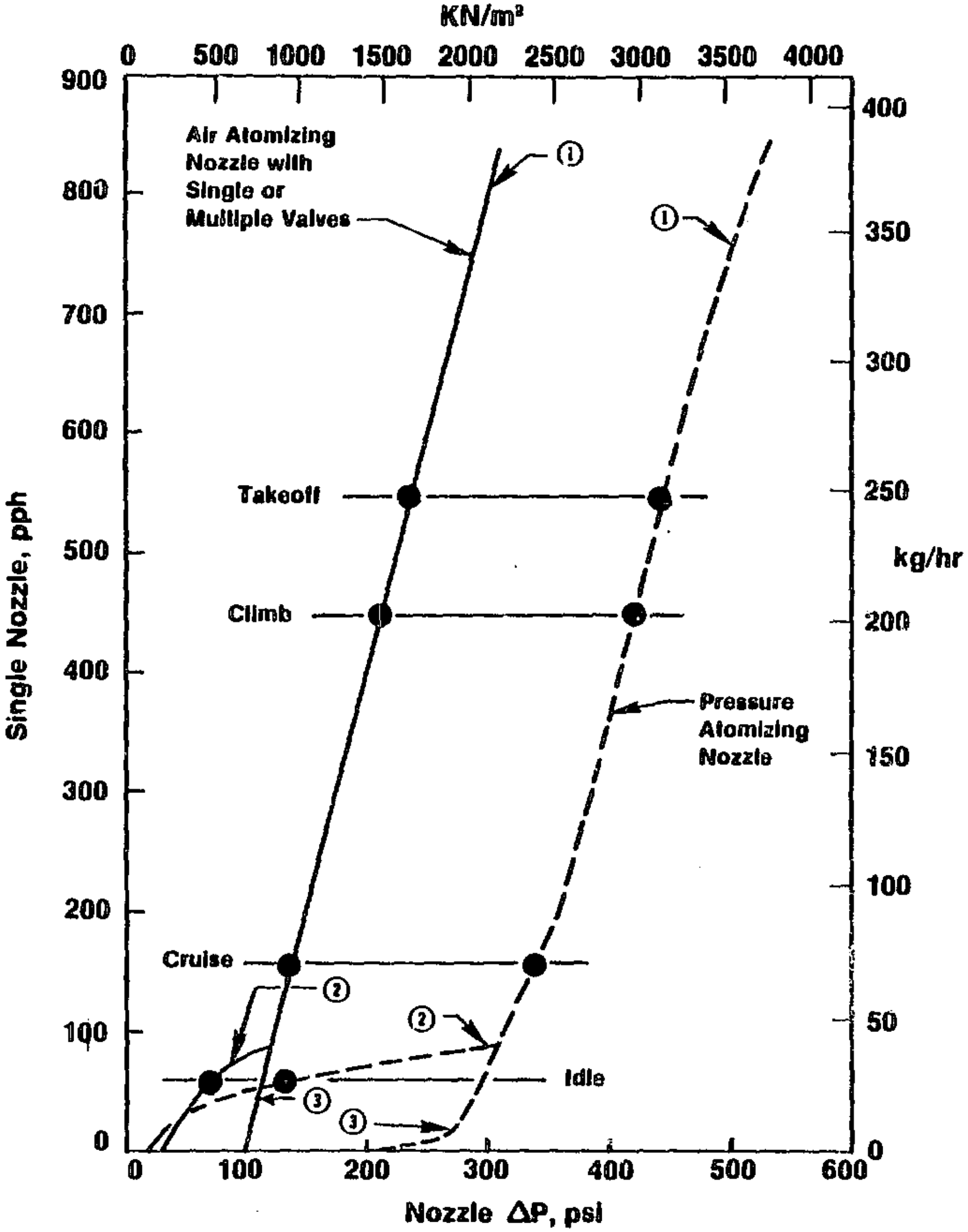


Figure 24. Nozzle ΔP Characteristics.

4.3 ADVANCED SYSTEM B

Advanced System B incorporates a fuel tank return line which receives heat input from the generator (IDG) oil system. The engine fuel pump centrifugal boost stage is oversized to provide additional flow capacity. In effect, the arrangement simply moves the IDG fuel-oil heat exchanger from its normal location (downstream of the fuel control) to the tank return line. The air-oil heat exchanger provides cooling if tank temperature exceeds limits.

The same low ΔP fuel nozzles are used as with System A except that the divider and check valves are located off the engine casing. Valve locations are shown in Figure 25. Secondary flow nozzles are used only at power settings above idle. If the check valves for these nozzles are located on the engine casing, the combination of static fuel and heat influx from the casing [315.6° C (600° F) at valve closure during power reduction] could accelerate coking and affect valve freedom of motion. With these secondary-only valves on the manifold, fuel flowing in the manifold provides a heat sink to cool the valve continuously during engine operation. In addition, the manifold location more effectively isolates the valves from the hot engine casing.

System B uses low-lubricity tolerant pump gear materials the same as System A.

4.4 ADVANCED SYSTEM C

Advanced System C represents the greatest change from the conventional design approach. Figure 26 shows a more complete description of the Waste Heat Recovery System (WHRS) used to heat the fuel tanks. The system uses engine compressor bleed air as the source of heat for tank fuel freezing protection. Normally air is bled from the engine for wing and engine cowl anti-icing and for cabin environmental control. Before the compressor bleed air can be routed away from the engine (to the wings or ECS) it must be cooled. Engine fan bleed air is typically used to cool engine compressor bleed air. A large air-to-air heat exchanger (precooler) is used for this

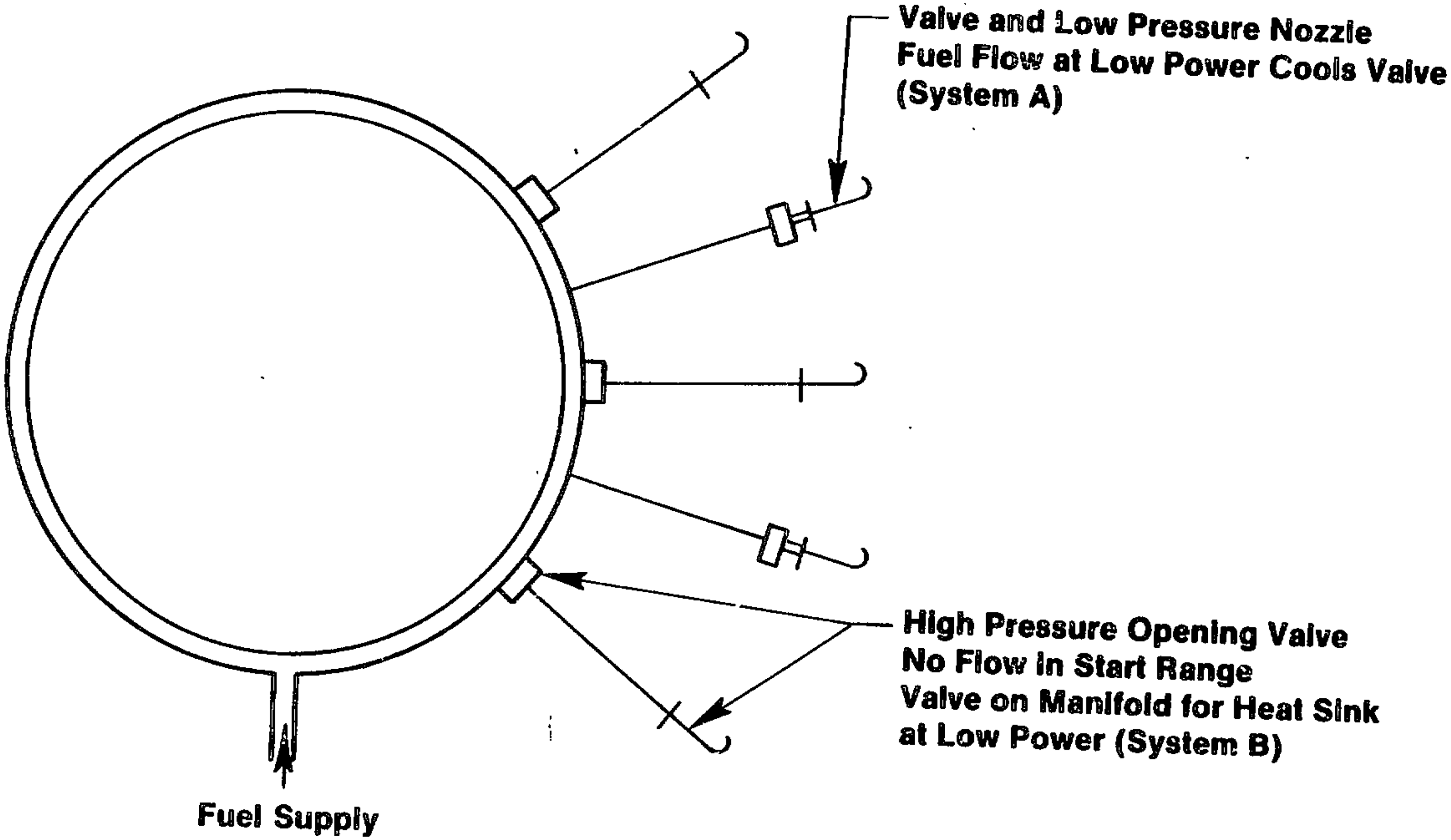


Figure 25. Nozzle Divider Valve Locations.

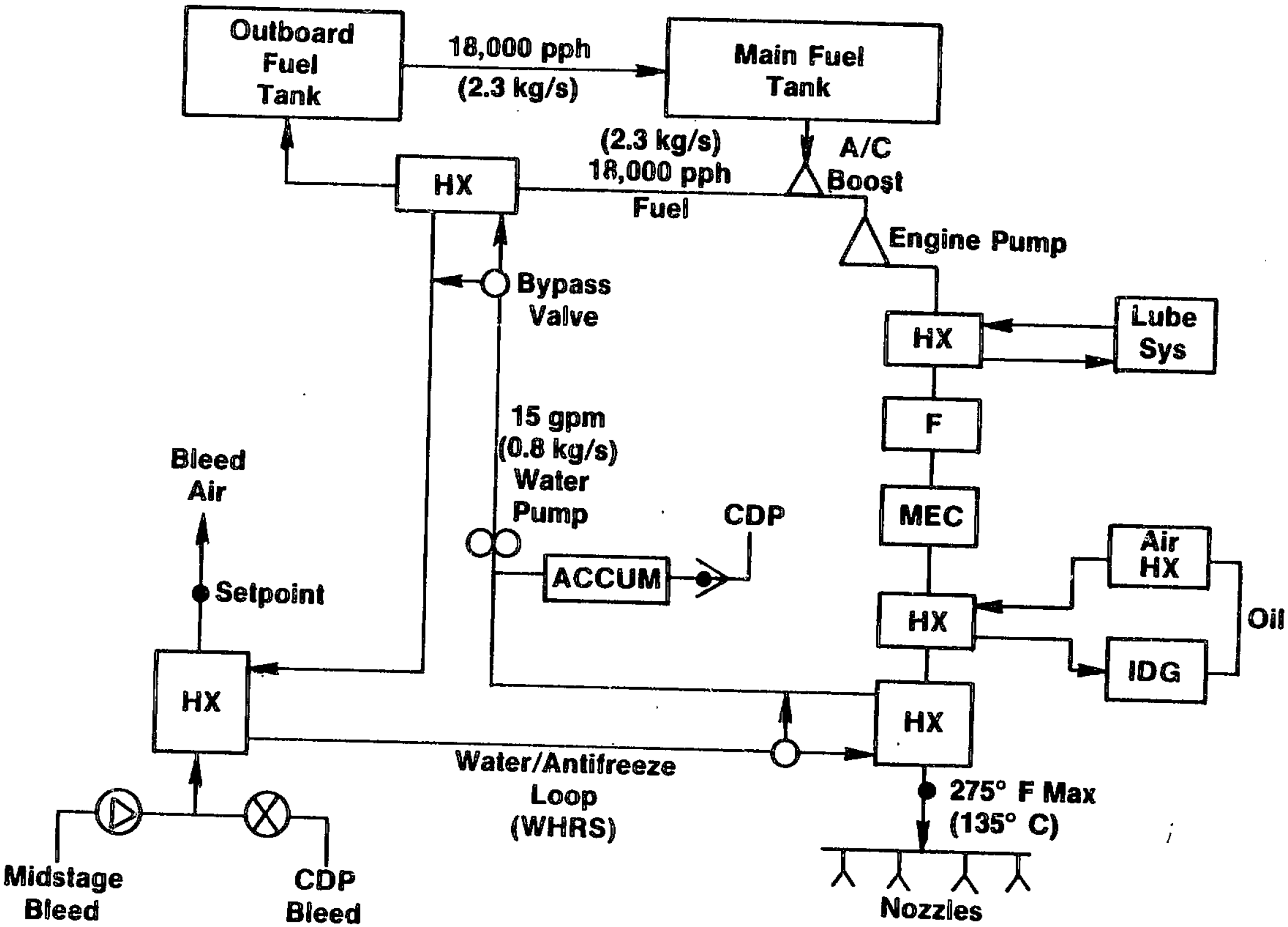


Figure 26. Advanced System C.

purpose. The arrangement can be seen in Figures 8 and 10. In the interest of reduced fuel consumption (lower sfc) the trend is toward less engine bleed extraction for the ECS by means of cabin air recirculation systems. Studies are also in process to eliminate fan bleed (and the precooler) by using selective bleed ports on the engine. Ideally, the bleed air would be taken from the stage of the engine that most efficiently and effectively provides the desired pressure (cabin pressurization needs) and temperature (cabin cooling or heating). If tank fuel heating were not an issue (fuel freezing point remained low), these multi-port bleed systems and other advanced concepts may be preferable to a Waste Heat Recovery System. It should be pointed out, however, that a workable system has yet to be developed which meets these objectives (elimination of fan bleed and precooler).

Given the situation where both sfc and fuel freezing point are significant issues, the WHRS is of particular interest. In this system, as shown in Figure 26, the precooler is eliminated. Either (or both) engine fuel and tank fuel provide the heat sink for compressor bleed air cooling. There are numerable ways such a system can be put together. For this study, an arrangement was chosen which provides a high degree of design flexibility. The jet engine is always viewed as a multi-application product. Consequently, installation differences between different aircraft is a prime consideration. Bleed air lines are typically large in diameter and not routed in close proximity to the engine fuel system. Consequently, a liquid transport system is desired to transfer heat from the engine bleed location to the engine fuel. The desirability of a transport system (as opposed to direct heat transfer) is reinforced by aircraft tank heating and cabin air conditioning considerations. Routing additional fuel lines to and from the tanks is to be avoided if possible. The possibility of fuel leakage into the cabin air system is also undesirable. Both of these safety issues are addressed by use of a liquid transport loop.

The system incorporates a water/anti-freeze heat transfer loop. The anti-freeze may be Dowfrost which is used in aircraft food chillers and is non-toxic in the event of a leak to cabin air. An electric motor pump circulates the water between heat exchangers located at engine compressor bleed ports, engine fuel and tank fuel. Water loop bypass valves automatically control the distribution of heat to either engine or tank fuel and also control the temperature of the bleed air. A fuel recirculation arrangement located near the fuel tanks provides heat transfer between tank fuel and the water. The water system is statically pressurized by engine compressor discharge air (CDP) so as to prevent water boiling at low ambient pressures.

Advanced System C uses a single remotely located fuel nozzle flow divider valve. The arrangement is shown in Figure 27. The valve would be designed to distribute flow to the nozzles (injectors) as a function of upstream supply pressure. This valve would be thermally isolated from the hot casing and would operate at a higher force margin than the typical nozzle divider/check valve. Hence, from a thermal stability point of view, the arrangement is attractive. Low ΔP nozzles are also used. A disadvantage of the arrangement is the need for as many as 30 separate fuel delivery tubes leading from the valve to the nozzles.

System C uses a high speed centrifugal fuel pump and a throttling-type fuel control system. This is similar to the afterburner system on military engines. A separate low-speed boost pump is used to pressurize the inlet to the high pressure pump. The arrangement is shown in Figure 28. Engine starting is accomplished by use of a separate electric-motor-driven centrifugal pump. The entire arrangement is conventional from a component standpoint and similar to existing centrifugal systems used on jet engines (Concorde SST, for example). The particular advantages of a centrifugal pump system are inherent low-lubricity tolerance and low fuel temperature rise at idle flow rates. The fuel control can be either hydromechanical or electronic. The throttling valve (see Figure 28) reduces pump discharge pressure to the value needed to hold a constant ΔP across the metering valve. For the study these valves were assumed to be a flat-plate shear type in order to increase tolerance to low-lubricity fuels. Flat plate (shear valves) can be easily made from hard carbide materials incorporating self-lubricating characteristics similar to low-lubricity tolerant gear pumps. Reference 2 discusses these valves in more detail.

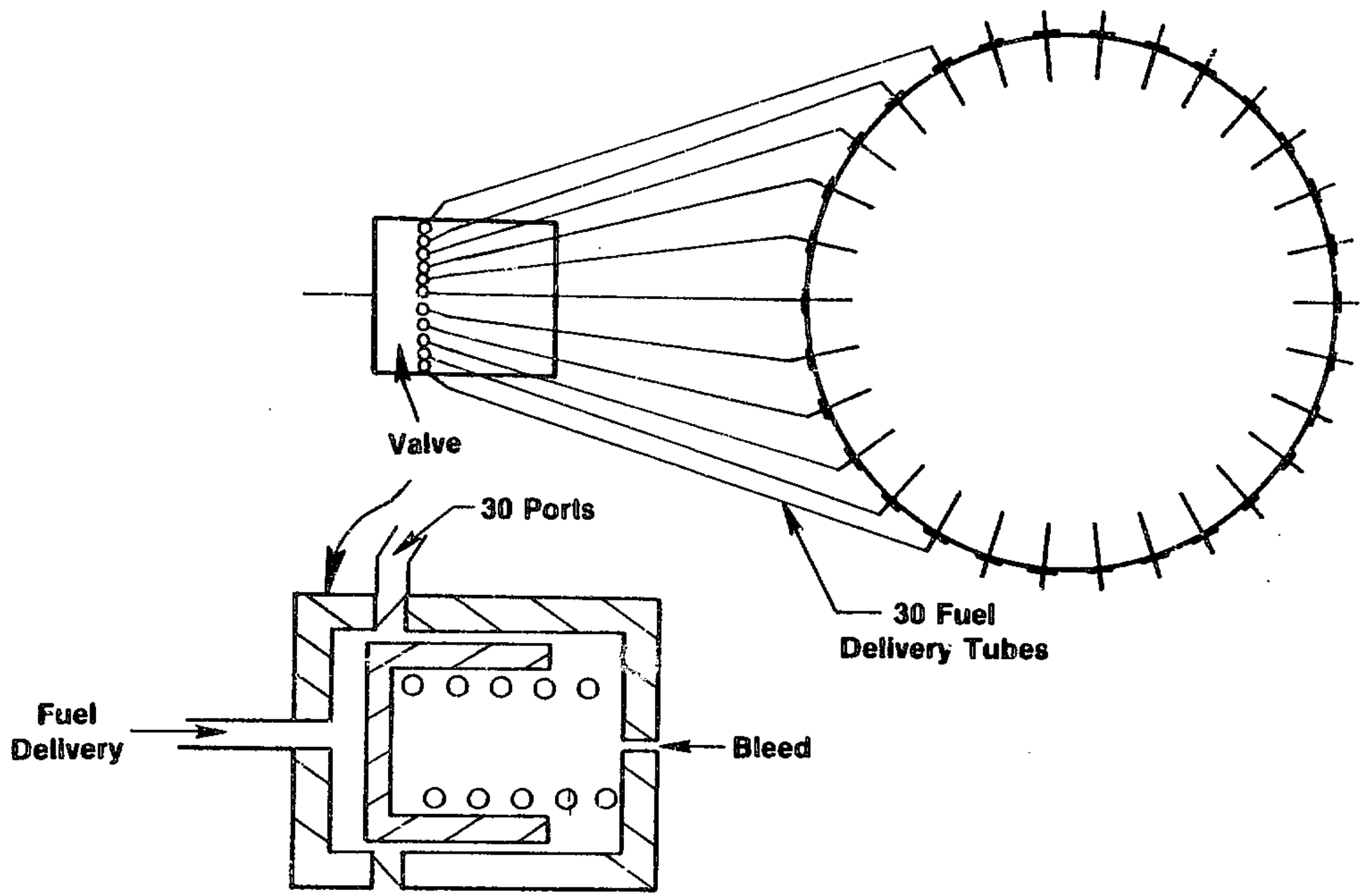


Figure 27. Remote Nozzle Divider Valve.

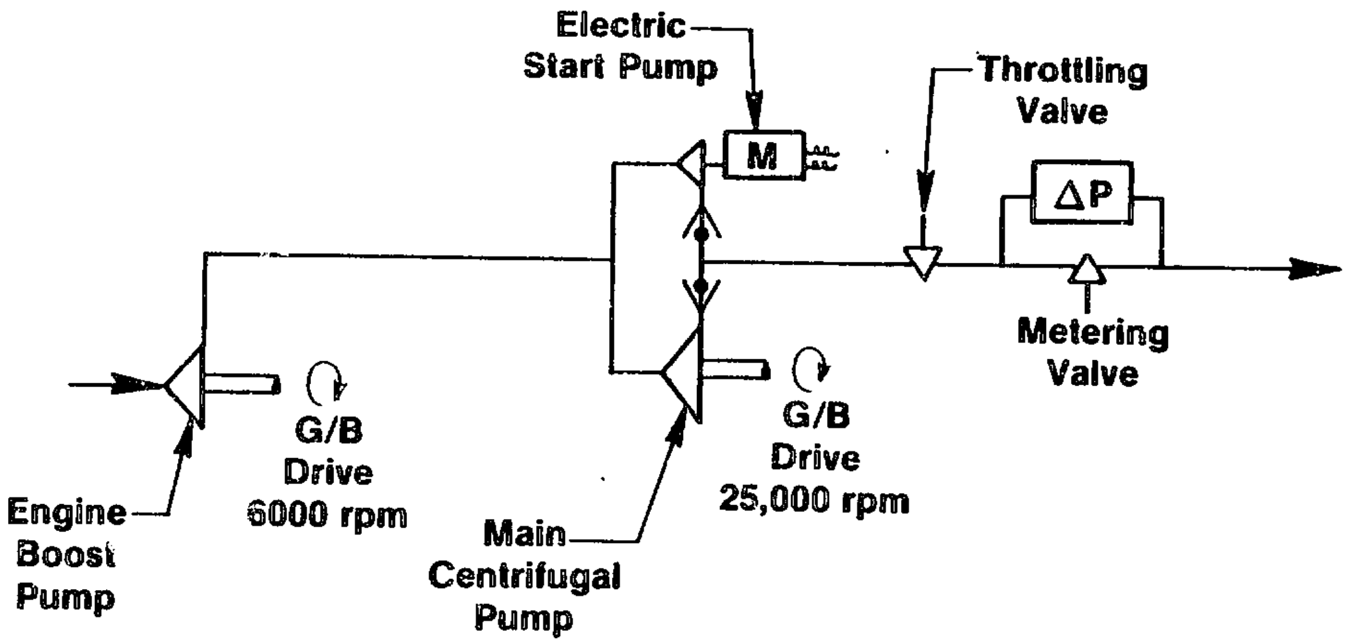


Figure 28. Centrifugal Fuel Pump (Gearbox Driven).

5.0 FUEL PROPERTIES

5.1 FUEL PROPERTY CONTROL

Figure 29 shows how the properties of aviation grade fuel are controlled. In the past there has been a wide acceptable crude selection in the form of petroleum. This wide availability has been coupled with a relatively low airline fuel demand. Selection of the crude source has permitted the desired end result in terms of properties which include aromatics, thermal stability, heating value and viscosity. Ordinary straight distillation processes at the refinery lead to control of boiling range with corresponding control of freezing point and flash point. Airline demand for kerosene-type fuels such as Jet-A has provided a generally good market distribution of the total available crude product. Consequently, market cost factors (competing demand for end product) and actual cost factors (cost to produce aviation spec fuel) have been in harmony.

In the future, it can be expected that there will be a general reduction in the total availability of acceptable crude sources (petroleum) as compared to the past situation. This trend has been evident for several years and can be noted by the heavier, higher aromatic fuels such as those derived from the Alaskan Slope. Figure 30 shows generally what can be expected in the future. It is irrelevant to the study as to when this situation may develop. An aviation fuel property issue may emerge under world economic conditions that reflect the rate of growth (increase in GNP) which has generally existed during the past three decades. Coupled with this increase in economic growth may also be an increase in airline travel as a percentage of the total demand on transportation energy. These conditions (1) reduced selective crude sources, (2) economic growth, and (3) increased airline demand for fuel may lead to a situation where fuel properties have a more deciding influence on fuel cost.

Over the spectrum of potential crude sources there is a general trend away from property control by crude selection. The result is a need for

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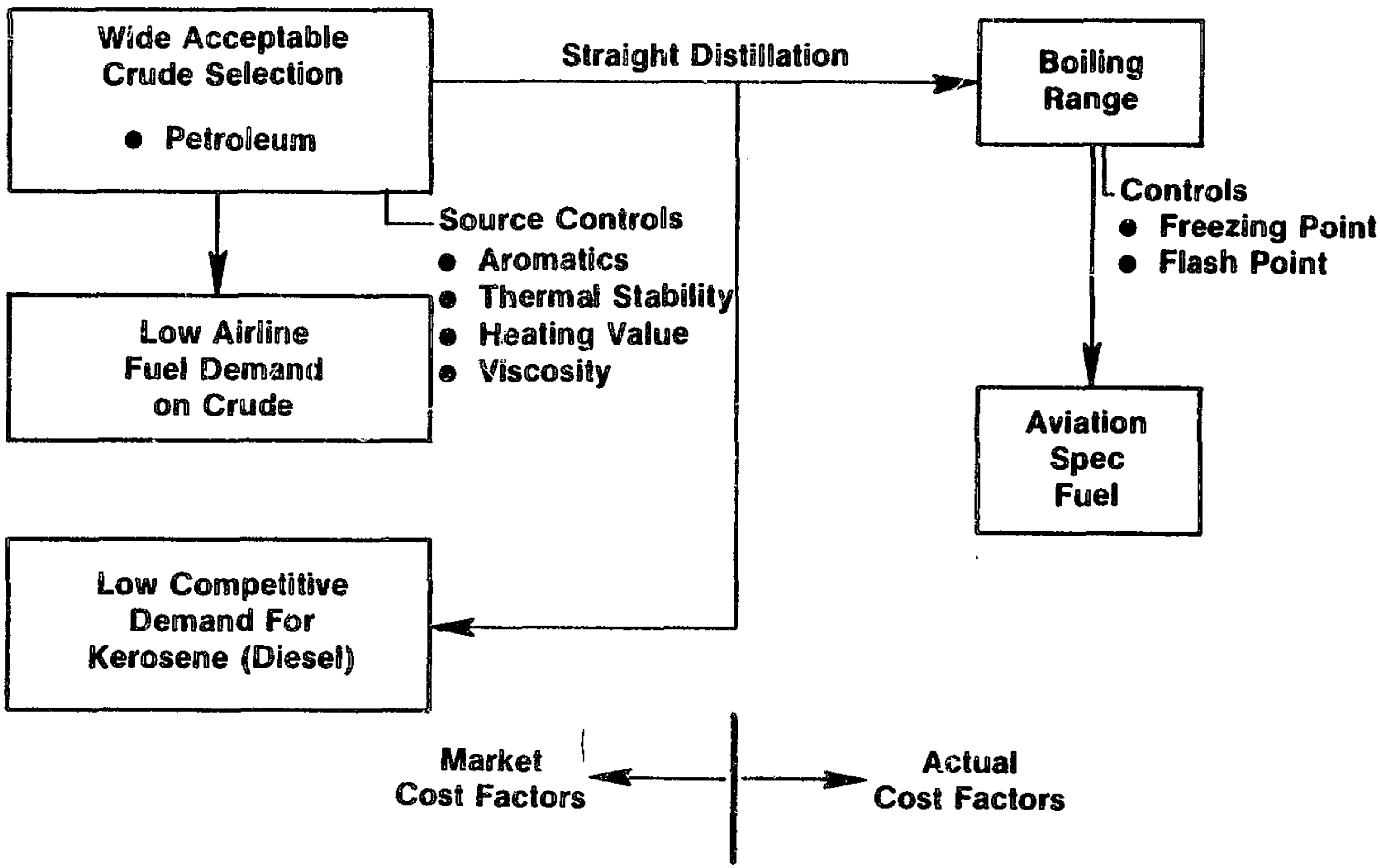


Figure 29. Aviation Fuel - Past Situation.

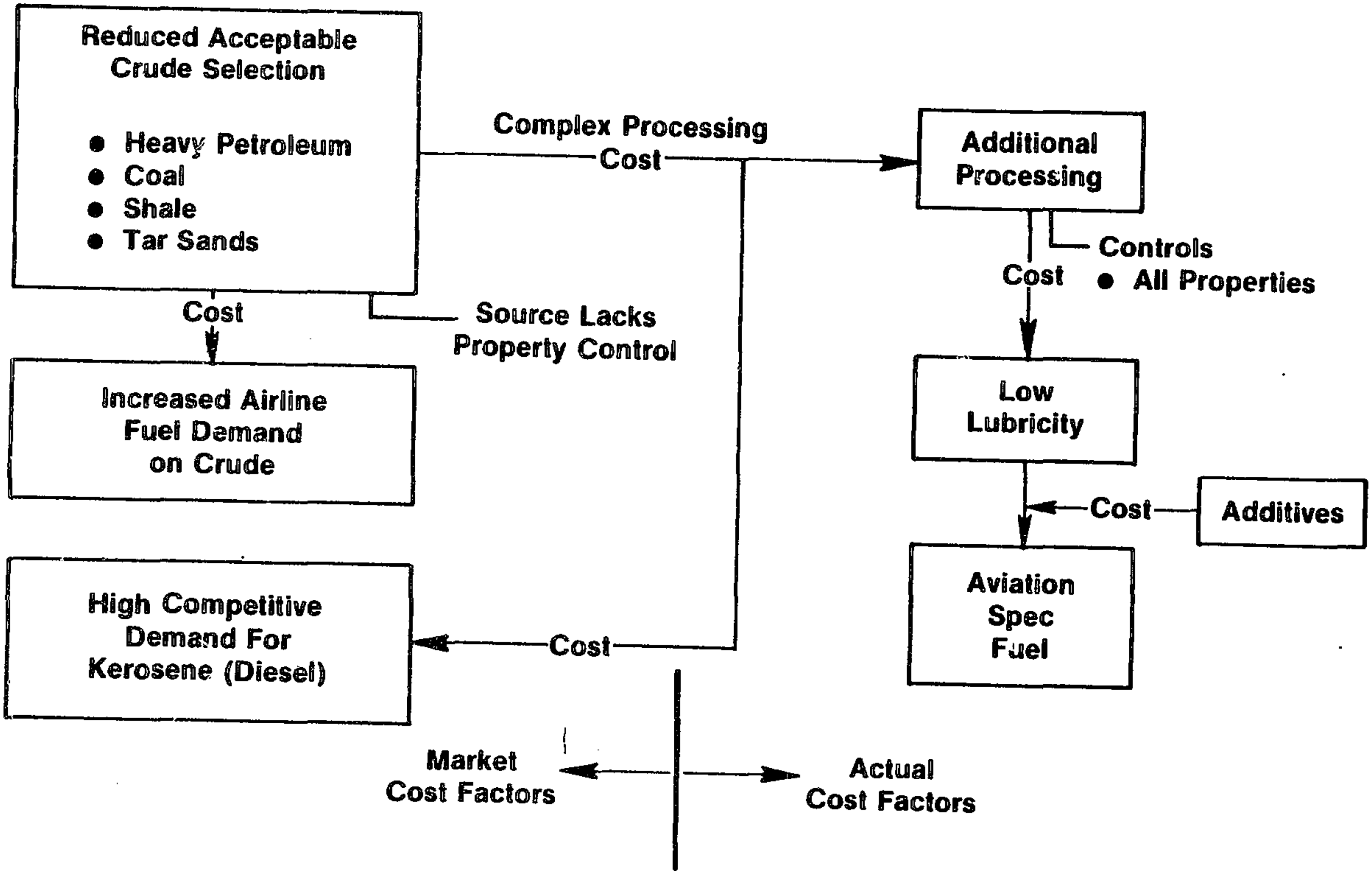


Figure 30. Aviation Fuel Future Situation Increased Aviation Supply at Present Spec Limits.

additional and more complex processing in order to arrive at the desired end result. For example, low lubricity is not presently a significant property issue. Severe hydrotreating removes impurities and hence the natural lubricity of these impurities. At present, however, there are few modern refineries using severe hydrotreating. In cases where aircraft fuel pump failures have occurred because of a lack of fuel lubricity, the problem has been solved by additives such as corrosion inhibitors. Eventually, actual cost factors associated with the production of spec-grade aviation fuel must increase. This is because the aviation grade fuel will no longer be a simple matter of crude selection and simple distillation processing. Adding to an increase in actual cost may be an increase in market cost. This comes about as the demand for kerosene fuel increases. The higher fuel efficiency of diesel engines in automobiles leads to their desirability. In a free market environment, both airlines and automobiles may be competing for essentially the same kerosene product. This would of course be a dramatic change from the past harmonious relationship between kerosene demand and gasoline demand.

Enough is known about future fuels to recognize that a choice may ultimately be made between rigidly defined aviation fuel properties and broadening of these properties. Table 1 shows an assessment of aviation fuel property change which might occur under assumed conditions of world economic growth. Table 2 shows present specification limits for Jet-A and Jet-B fuels. Also shown are limits for the study fuel. These study fuel property values are given here only as a matter of reference. They assume an increase of about 50 percent in aviation fuel yield from the crude sources listed in Table 1 over the next 15 to 20 years. It is irrelevant to the results of this study whether fuel properties change to this degree or only slightly from present-day values. The systems evaluated by this study afford various degrees of property change. Airline operational procedures also are a factor in equating the performance of a system to its fuel property compatibility.

If one assumes that fuel properties will change or that lowering of relative fuel cost would make a property change desirable, the next question is how to accommodate the change from the standpoint of the airline business.

TABLE 1. ESTIMATED FUEL PROCESSING REQUIREMENTS

Source	Freezing Point	Thermal Stability	Flash Point	Viscosity	Aromatic Content	Lubricity	Lower Heating Value
Petroleum Crudes (average)							
1980 - 1990	1	0	0	0	1	0	0
1990 - 2000	2	1	0	1	2	1	2
Synthetic Crudes							
- Tar Sands (1980 -)	3	1	0	1	3	2	3
- Shale (1985 -)	2	2	0	2	2	3	2
- Coal (1990 -)	3	1 - 2	0 - 1	2	4	3	4

Processing Code:

0 - Similar to 1970 Crude - Meets Current Jet-A Specification.

1 - Worse Than 1970, - But Expected to Meet Specification Without Additional Processing

2 - Additional Processing Probably Needed to Meet Specification with Adequate Availability

3/4 - Significant Additional Processing Required to Meet Specification

TABLE 2. FUEL PROPERTY SPECIFICATION LIMITS

	Freezing Point °F/(°C)	Thermal Stability °F/(°C)	Flash Point °F/(°C)	Viscosity at -20° C CS	Aromatics Content Vol. %	Lower Heating Valve BTU/lb (kJ/kg)
Jet-A	-40 Max (-40)	473 Min (245)	100 Min (38)	8.0 Max	25 Max	18,400 Min (42,800)
Jet-B	-58 Max (-50)	473 Min (245)	N/A	N/A	25 Max	18,400 Min (42,800)
Study Fuel*	-17 Max (-27)	428 Min (220)	80 Min (27)	10.5 Max	35 Max	18,300 Min (42,570)

* Estimated 50% Increase in Yield

Table 3 lists several options available to the aircraft user. Ideally, fuel properties and the costs of meeting these property limits is precisely matched against airline profitability and passenger safety. Otherwise, money is being lost, or accidents are too frequent. Assuming this ideal relationship to now exist, each of the fuel properties listed in Table 3 will (if changed) cause a need for a corresponding change in order to preserve this idealized balance. Under these assumptions, flight crew action is inappropriate for any property change. Increased maintenance can only be applied to the economic side of the issue (not the safety consideration) if the result is a direct change to aircraft performance or reliability. That is, if an increase in maintenance is necessary to accommodate satisfactory aircraft performance or reliability, and therefore not jeopardize safety, only economics are affected. Operational planning influences both economics and safety if freezing point is increased or heating value is decreased.

Freezing point, thermal stability and lubricity are the properties from Table 3 which are most meaningfully addressed from an aircraft/engine fuel system standpoint. The other properties are involved more with the engine combustor (viscosity, aromatic content, and heating value) or fuel handling safety (flashpoint). In the study, freezing point was considered from two points of view: (1) operational consideration and (2) design consideration. Thermal stability was considered both from a design and maintenance standpoint. Lubricity was considered only from a design standpoint.

5.2 OPERATIONAL CONSIDERATION OF FREEZING POINT

Figure 31 shows how fuel freezing point is addressed by the airline. The airline captain responsible for the safety of the aircraft does not know what the exact freezing point* of the fuel is during any particular flight. He knows, however, the fuel type and its specification limits. He also knows and has available the aircraft flight manual which describes any limitations associated with cold fuel operation. He assumes based on his flight engineer's observation of fuel tank temperature (usually one measure of bulk

*Temperature at which last waxy solids melt when the fuel is heated.

TABLE 3. APPROACH TO FUEL PROPERTY ISSUES

	Design	Maintenance	Operational Planning	Flight Crew Action
Freezing Point	X	—	X	—
Thermal Stability	X	X	—	—
Flash Point	X	—	—	—
Viscosity	X	—	—	—
Aromatic Content	X	X	—	—
Heating Value	X	—	X	—
Lubricity	X	—	—	—

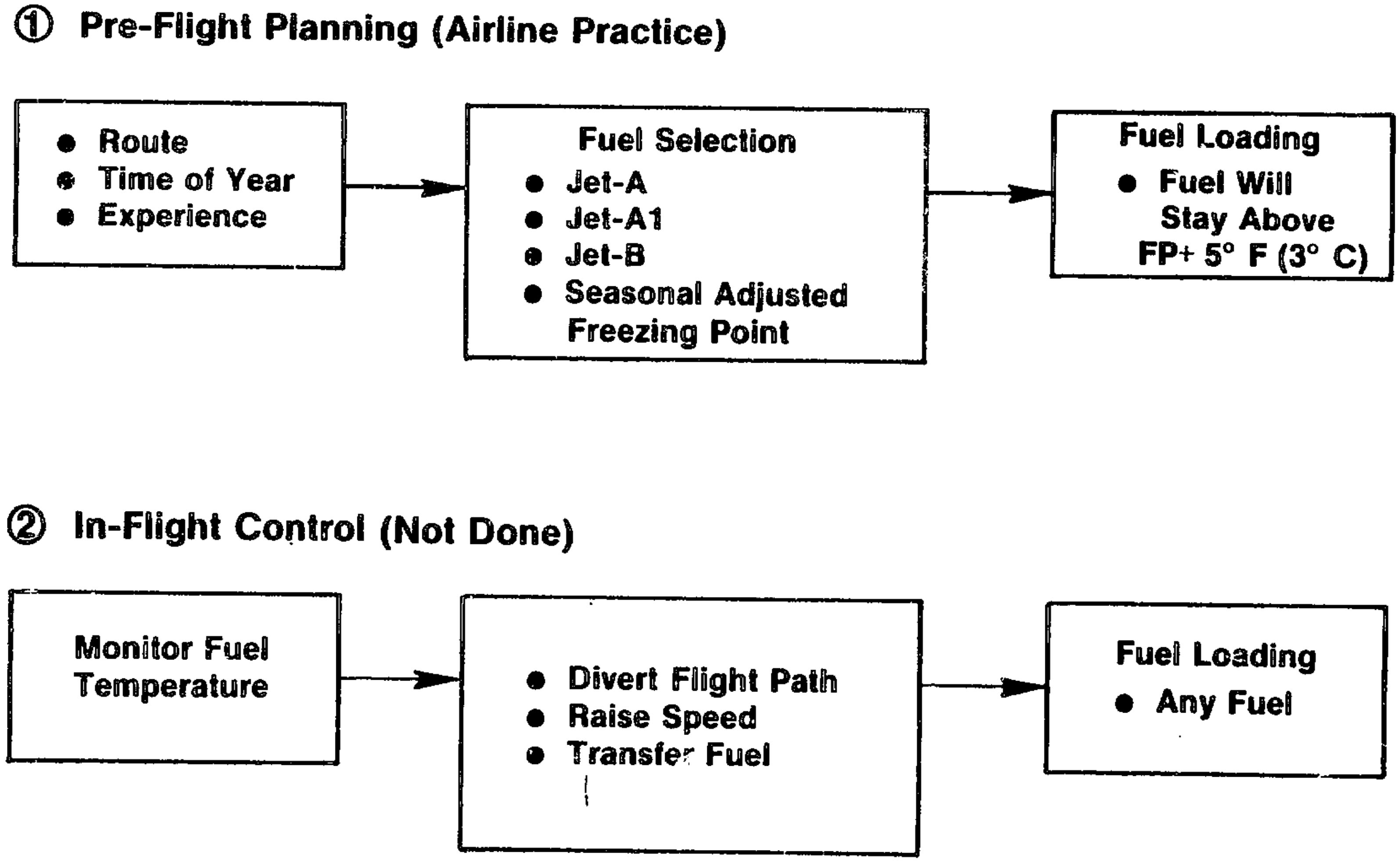


Figure 31. Freezing Point Operational Options.

temperature in one tank) that all fuel is available except that which is consumed as the flight progresses. Typically, the aircraft flight manual will permit operation to the fuel specification maximum freezing point plus 3° C (5° F). With present day fuel properties, it would be a rare occurrence to reach this limit. Figure 32 goes further to show airline practice with respect to fuel freezing point. By using a grade of fuel (Jet-A1 or Jet-B) with a lower freezing point, the airline is able to stay clear of potential fuel freezing problems.

In the future, this situation may change. Such change may be predicated on economic factors such as fuel cost relative to fuel properties. The following factors can be considered:

- Increased probability of freezing point influence during certain flights.
- Meaningful cost trade-off for fuel selection.
- More advanced computer techniques available for en route weather forecasting and fuel temperature forecasting.

The factor involving en route forecasting was used in this study to predict what might happen in terms of fuel tank temperature. Figure 33 shows the approach to operational planning that an airline might use in the future. For this study, the analytical approach was as follows:

1. A flight forecasting technique was developed in a manner which might be similar to that used by an airline. The objective of the forecast was to obtain fuel tank temperature.

2. The baseline aircraft and engine was flown by computer simulation through the forecast air temperature and route structure.

3. Each Advanced system was in turn flown through the same forecast flight.

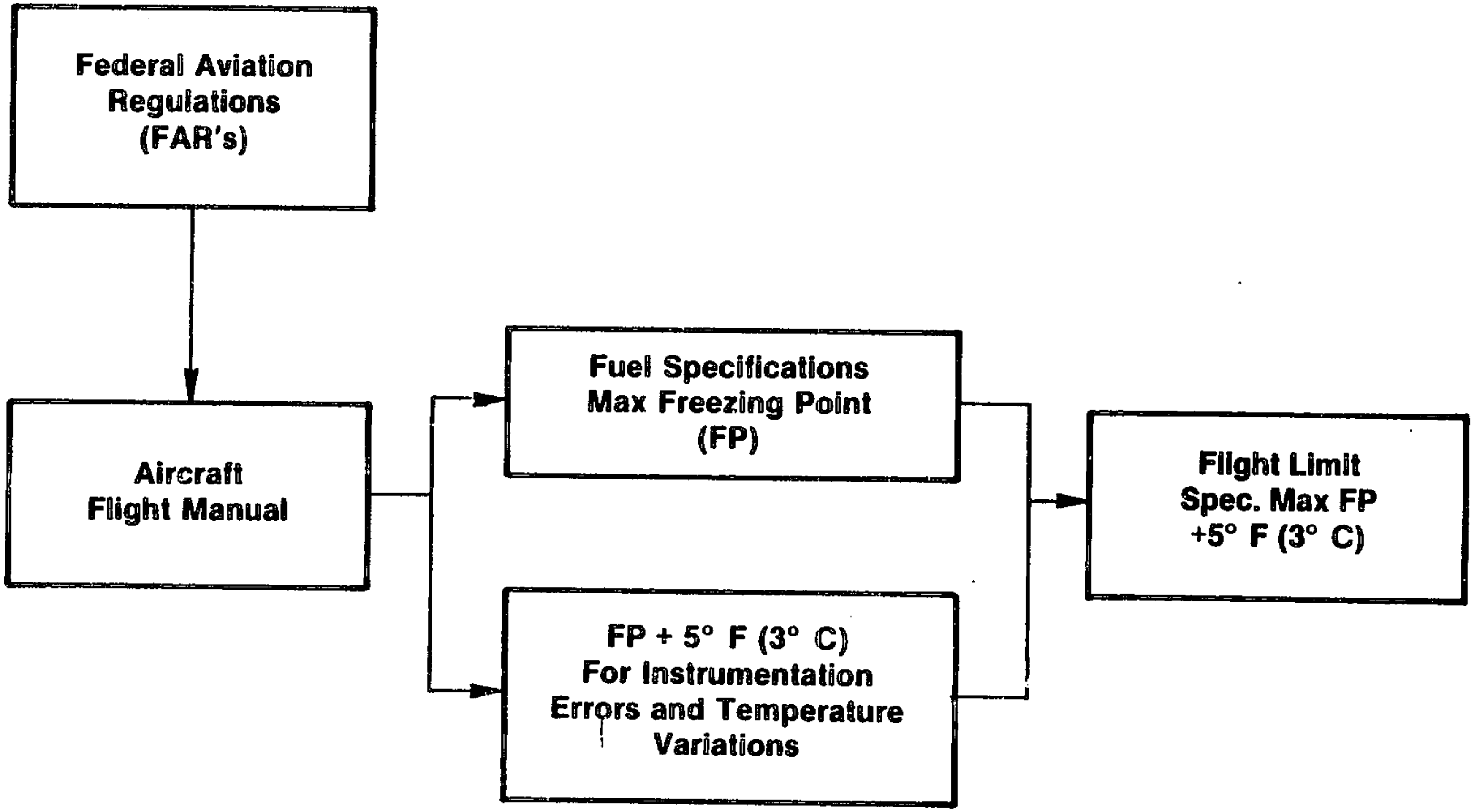


Figure 32. Freezing Point Current Operation Requirements.

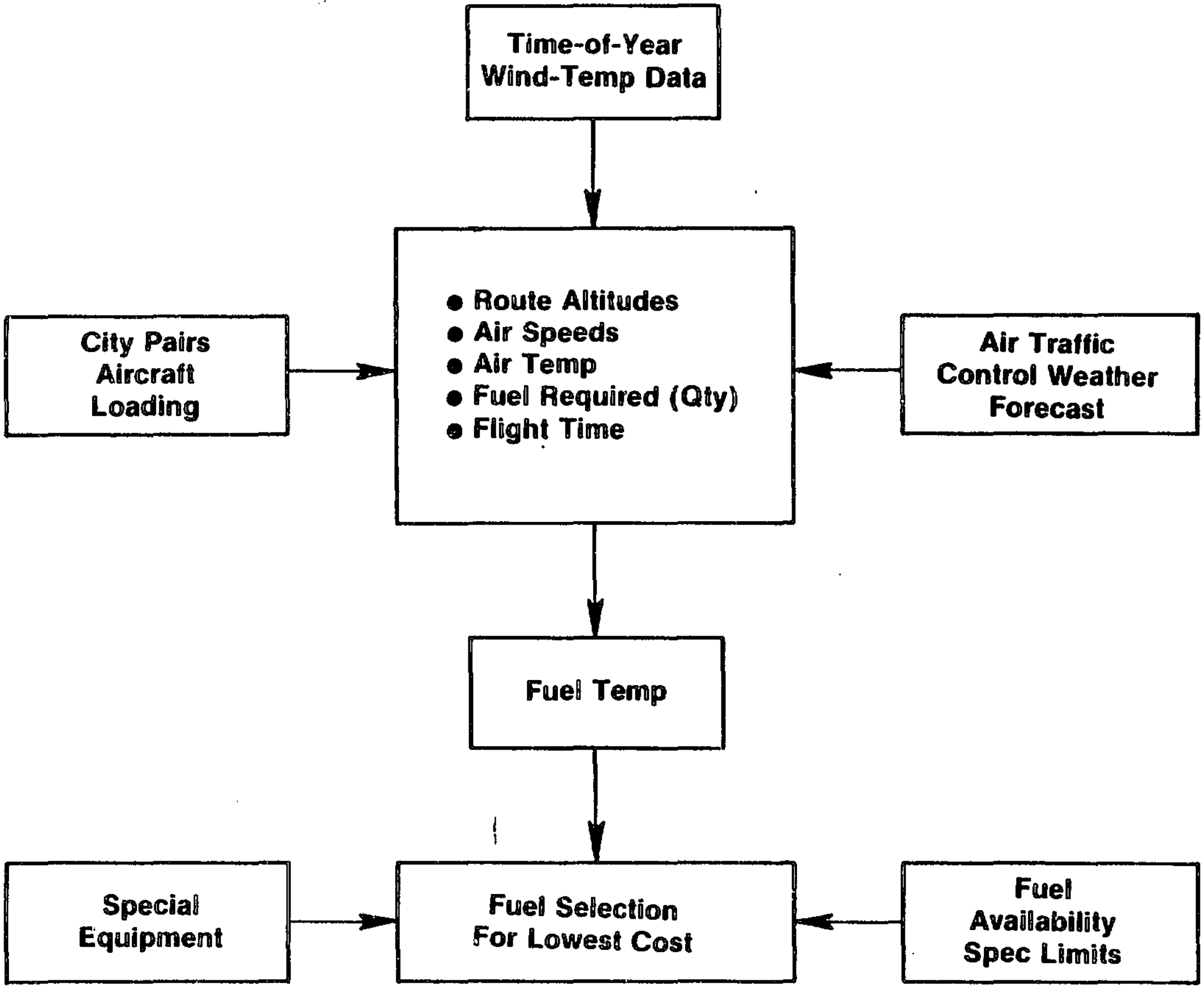


Figure 33. Operational Planning for Lowest Fuel Cost.

6.0 METHOD OF ANALYSIS AND FLIGHT DEFINITIONS

6.1 THERMAL MODEL

A computer model was formulated to represent the baseline aircraft and engine. Using common formulations as appropriate, additional models were prepared for the advanced systems. These models were extensions of the General Electric CF6-80 engine-family heat model used to predict engine fuel, lubrication and generator oil temperatures. In the CF6-80 application, the validity of the model has been verified by engine ground and flight test data such as for the Boeing 767/General Electric CF6-80A. The models follow thermodynamic 1st-Law expression of the energy continuity throughout the aircraft and engine fuel systems and thermodynamically interconnected oil and air systems.

Figure 34 for the baseline model shows a simplified description of the model. Fuel from the aircraft auxiliary or number 2 tank (inboard tanks) is pumped to the main engine outboard tank. The temperature of these supply tanks changes as the flight progresses. Heat (Q) is added by the tank fuel transfer pump. In the outboard tank heat (Q_A) is transferred to air flowing over the wing. Fuel flows from the outboard tank overfill valve to the main tank. More heat transfer occurs to air over the main tank wing area. Engine meter flow (WFE) is pumped through a main tank boost pump to the engine. The mass of fuel in the main tank (M) decreases. In the engine, fuel is pumped through the engine lube system heat exchanger. Excess pump flow is throttled with corresponding temperature increase (Q). IDG heat is added to the metered fuel and then more throttling and temperature rise occurs at the fuel nozzles.

Figures 35, 36 and 37 show the typical arrangement for fuel return to the aircraft tanks. In order to suppress the cooldown rate of the outboard tank, tank return is made to the outboard. This results essentially in a recirculation loop from the main tank to the engine fuel system to the outboard tank then back to the main tank.

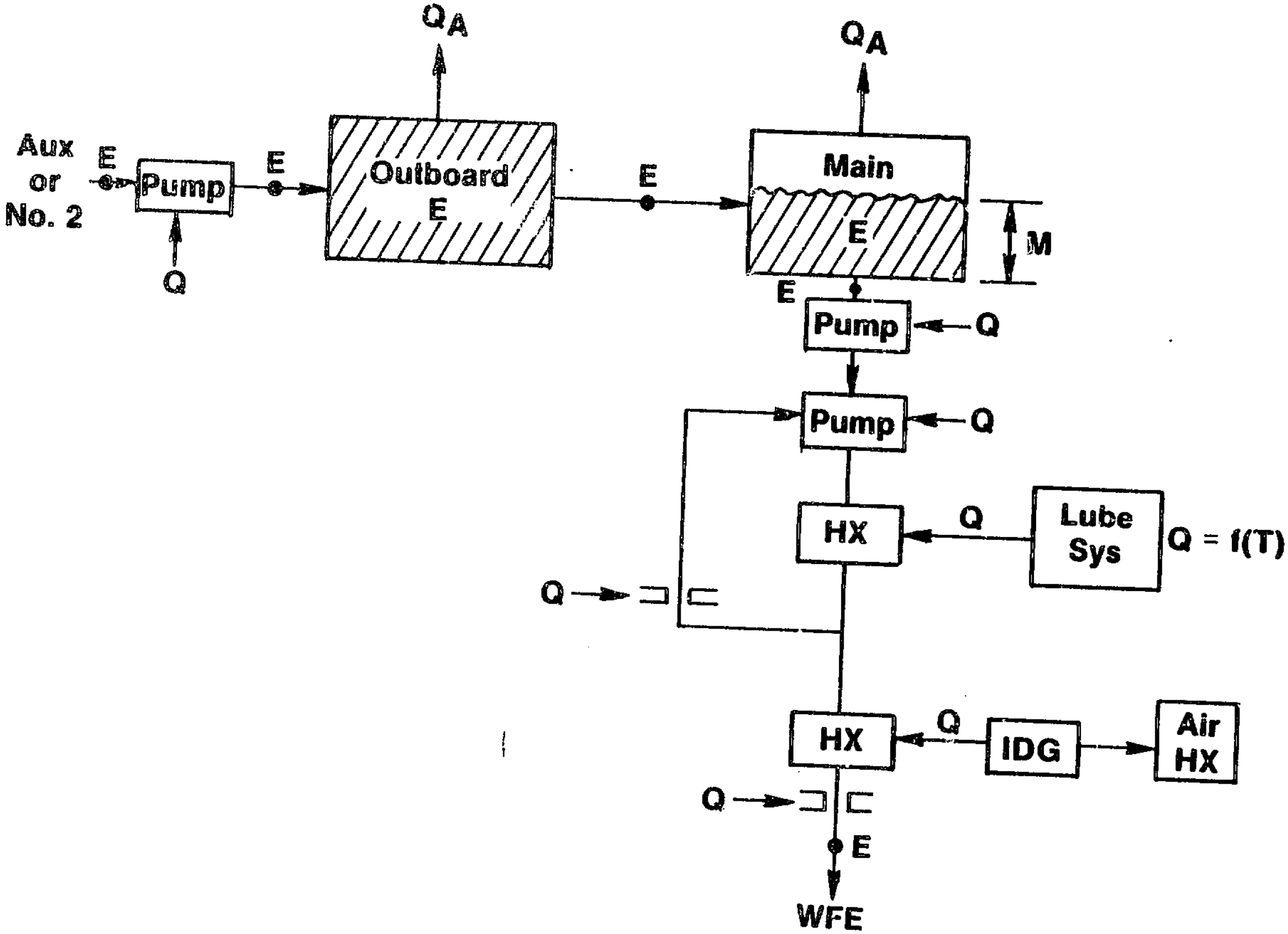


Figure 34. Energy Transfer - Baseline.

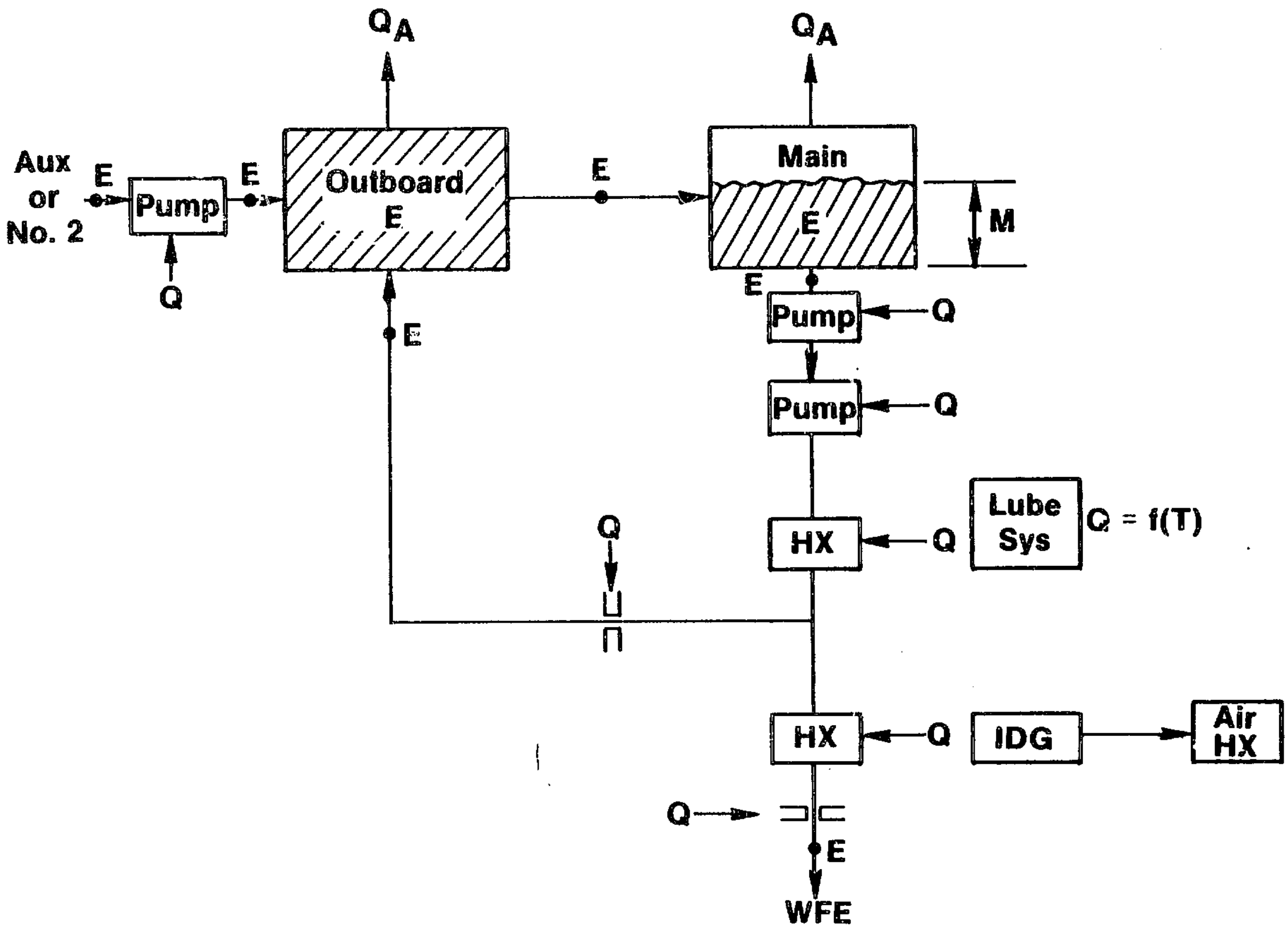


Figure 35. Energy Transfer - System A.

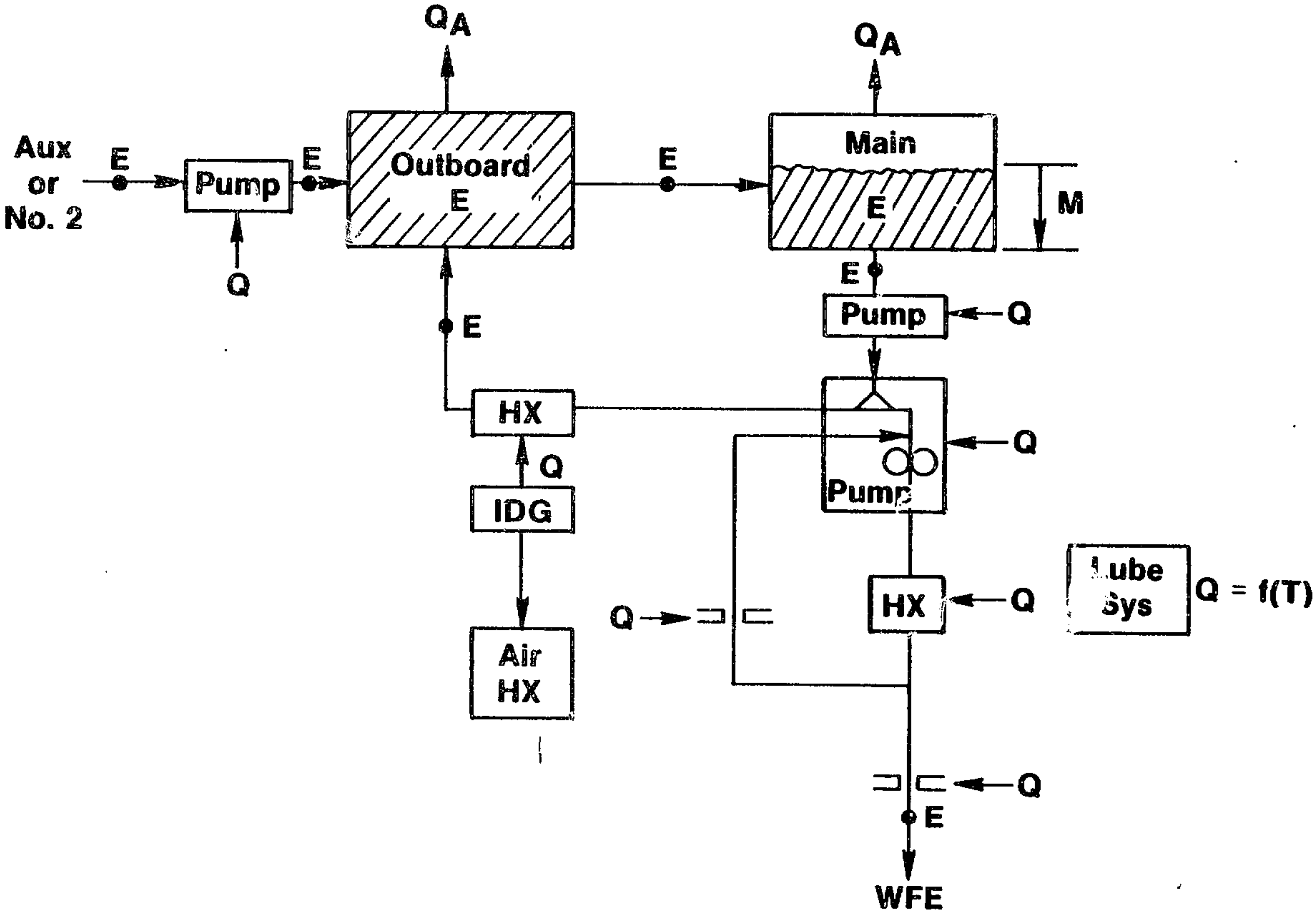


Figure 36. Energy Transfer - System B.

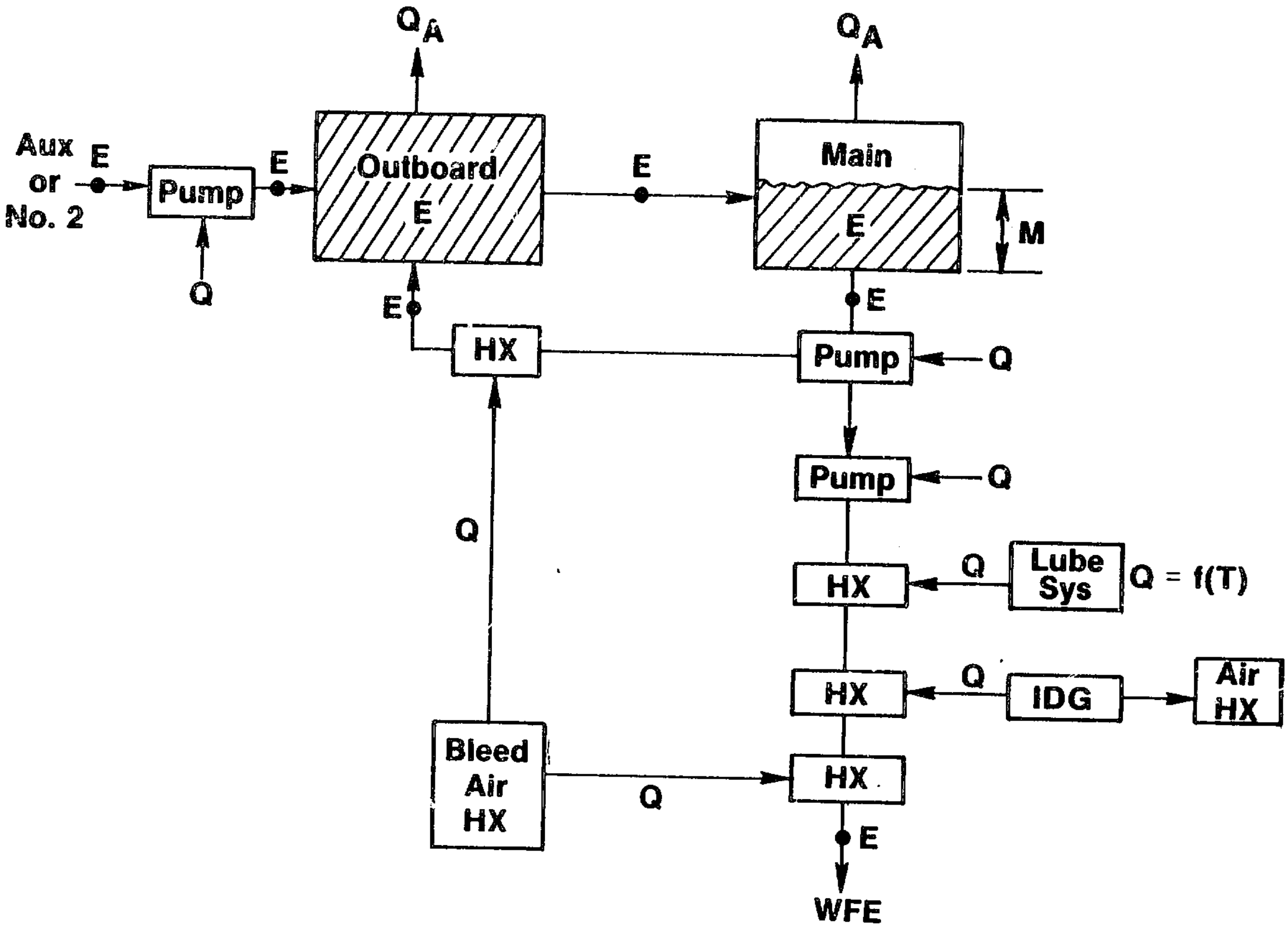


Figure 37. Energy Transfer - System C.

Figure 38 shows the basic thermodynamic considerations involved with the various fuel tanks. Fuel mass may be either constant or changing at different times during the flight. Total thermal energy (total BTU of thermal energy in tank) and specific energy (BTU per pound of fuel in tank) are accounted for in the model. Figure 39 shows the component energy exchanges which occur in the system. Total thermal energy of the flowing fuel is bookkept in the manner shown. Note that throttling results in an increase in total thermal energy since pressure energy is expended in the constant enthalpy process.

Figure 40 shows the heat transfer mechanism occurring in the tanks. Minor effects such as radiation are not included. Fuel in the tank exchanges thermal energy with air outside the wing by the process of forced convection in the wing boundary layer air film. Air film convection is predominant over other heat transfer modes in the tank (liquid to tank walls for example). The tank wall and the fuel bulk temperature are identical in the model. The air temperature involved with the heat transfer process is the wing boundary layer temperature which is the recovery temperature (T_R). Note that recovery temperature is lower than total temperature since stagnation occurs only at the leading edge of the wing. Air heat transfer properties are calculated from the air film temperature which is a function of wall (metal) temperature and recovery temperature.

Table 4 lists the steps used to calculate the tank-to-air heat transfer rate. Fuel volume affects the heat transfer area by means of both wetted internal surface areas and conduction through the tank stringers.

The thermal model calculates temperatures, pressures, flows, heat transfer rates, and sfc effects at one-minute intervals throughout the flight. Tank temperature determination is crucial to the accuracy of the results since virtually all other systems conditions are influenced by the engine fuel inlet temperature. Figure 41 shows how the tank temperature is determined. Tank fuel temperature (T_2) is the temperature of the bulk fuel at the end of each one-minute interval. Note that bookkeeping of total thermal energy (E_2) and fuel mass (M_2) form the basic thermodynamic statement of accountability.

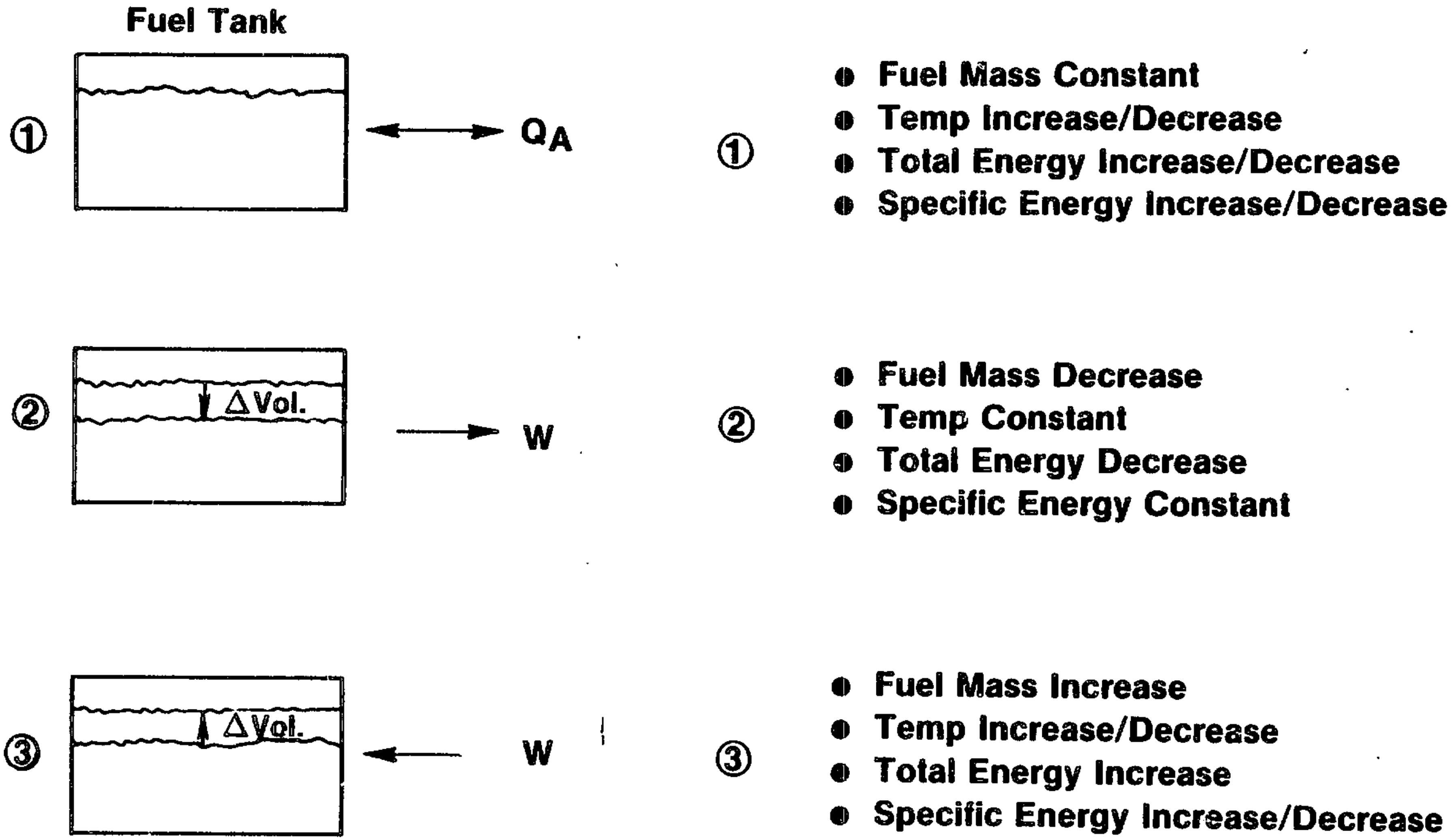
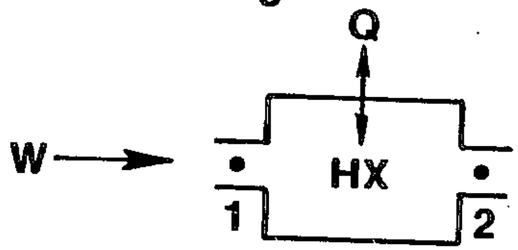


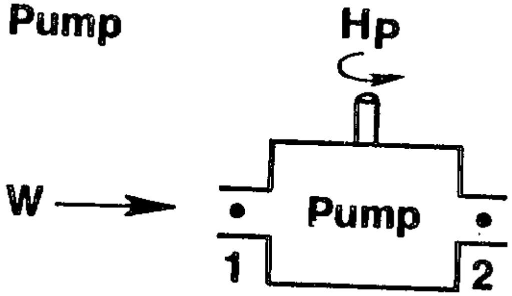
Figure 38. Basic Thermodynamic Considerations for Tanks.

① **Heat Exchanger**



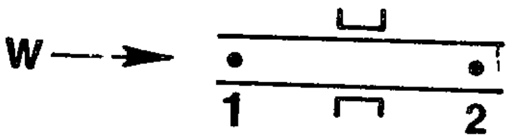
- $W_2 = W_1$
- $P_2 = P_1$
- $E_2 = E_1 + Q$

② **Pump**



- $W_2 = W_1$
- $P_2 > P_1$
- $E_2 = E_1 + HP - \Delta P\ (GPM)/1714$

③ **Throttling (Pressure Drop)**



- $W_2 = W_1$
- $P_2 < P_1$
- $E_2 = E_1 + \Delta P\ (GPM)/1714$

Figure 39. Basic Thermodynamic Considerations for Components.
E = Total Thermal Energy (BTU)

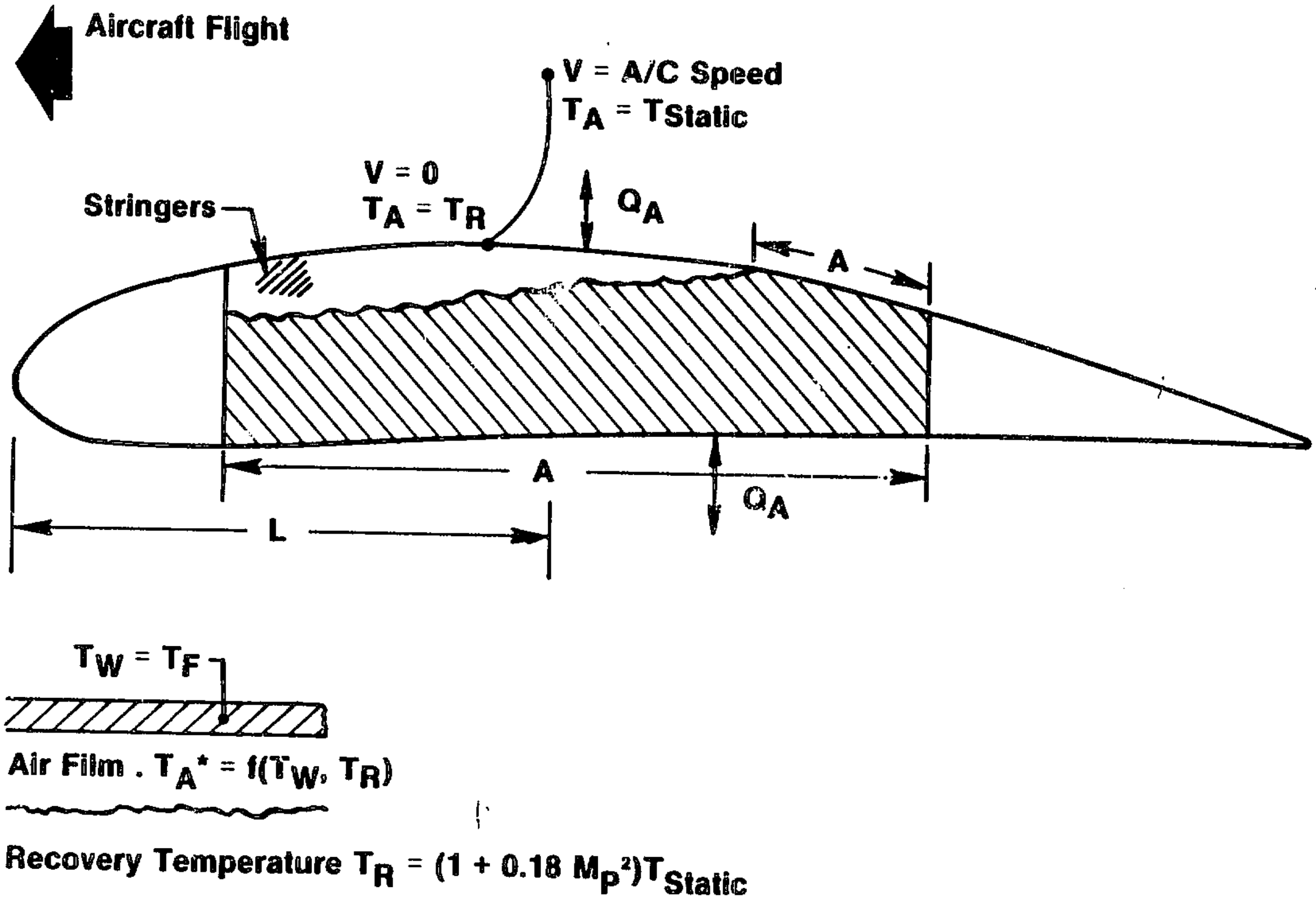


Figure 40. Tank Heat Transfer to Air.

TABLE 4. TANK HEAT TRANSFER TO AIR

① **Define:**

- **Inboard or Outboard Tank - For Tank Slenderness**
- **100% Fuel Volume - Tank Capacity ft^3**
- **Wing Cord at Tank - For Air Reynolds Number**

② **Find:**

- **Actual Fuel Volume (Level) - ft^3**
- **Fuel Tank Wetted Area - Function of % Vol., Inboard/Outboard, A/C Size**
- **Area Increase for Stringer Contact With Unwetted Area - K_1**
- **Air Film Temperature and Air Film Coefficient - U**

③ $Q_{Air} = UAK_1 (T_F - T_R)$

For One-Minute Interval Time ① To Time ②

$$\text{Total Energy in Tank} = M\,(AT + BT^2/2)$$

$$\text{Energy Added/Removed By Flow} = W\,(AT + BT^2/2)$$

$$\text{Energy Added/Removed By Heat Transfer} = Q$$

$$\text{Total Energy } E_2 = E_1 - \Sigma\left[W(AT + BT^2/2)\right] - Q$$

$$\text{Mass } M_2 = M_1 - \Sigma W$$

$$\text{Specific Energy } E'_2 = E_2/M_2$$

$$\text{Temperature } T_2 = \frac{-A + \sqrt{A^2 + 2BE'}}{B}$$

Figure 41. Tank Temperature Determination.

6.2 MISSION DEFINITIONS

In order to evaluate the differences between the baseline and advanced systems, it was necessary to simulate four flight missions of the DC-10-30 aircraft. These missions were:

1. A one-day-per-year long-range cold environment flight originating from a cold airport which results in the coldest fuel in the aircraft wing tanks during cruise. The proximity of the temperature of tank fuel to fuel freezing point shows the effect of this fuel property on aircraft operational capability.

2. A one-day-per-year short-range hot environment flight originating from a hot airport which results in the hottest fuel in the aircraft wing tanks at the initiation of idle descent. This results in the hottest fuel normally in the engine fuel and lubrication systems. Fuel thermal stability would influence the effect of these hot fuel temperatures on fuel injector coking.

3. A nominal (50 percent probability) flight at nominal environmental and airport temperatures. This flight serves as the primary basis for assessing economic factors and sfc when system and component changes are considered for resolution of the problems presented by fuel properties.

4. An emergency condition with low fuel reserves. This analysis was needed to assess the likelihood of excessive tank temperature caused by the tank heating system.

All of the mission analysis work was performed using computer models. Figure 42 shows the analysis flowchart. Tables 5 and 6 list the procedures.

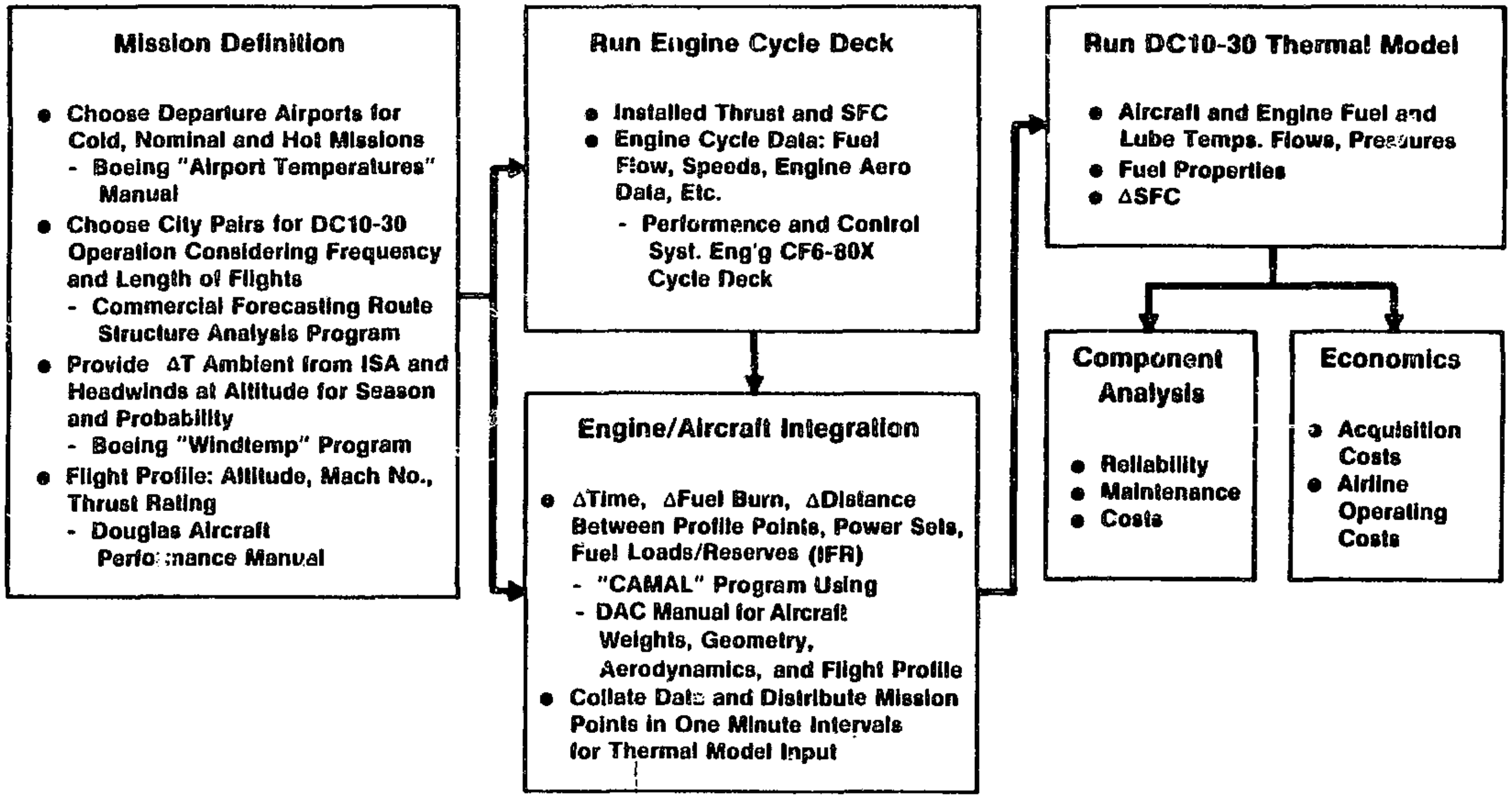


Figure 42. Analysis Flowchart.

TABLE 5. DEFINING FLIGHTS

1 **Define Fuel Loading Temperature**

- **From GE/TBC CF6-80/767 Requirements**
- **One-Day-Per-Year Hot = 100° F (38° C), Nominal = 60° F (16° C)**
  One-Day-Per-Year Cold = 0° F (-18° C)

2 **List Possible Departure Airports Using TBC "Airport Temperatures"**

• **Cold**	**160 Listings**	**-20 to -78° F (-29 to -61° C) Winter Lows**
• **Nominal**	**50 Listings**	**Most Frequent City-Pairs**
• **Hot**	**100 Listings**	**>115° F (46° C) Summer Highs**

3 **List DC10-30 Airline Departures Using "Airline Route Structure Analysis Program"**

- **August 1981 Route Data**
- **Screen For Flight Length and Destination Airport**
- **List Possible City-Pairs**

4 **Cross-Check Departure Airports with City-Pairs**

- **List Possible Flights**

TABLE 5. DEFINING FLIGHTS (CONCLUDED)

5 Define Cruise Conditions Based on DC10-30 Flight Manual

- Altitudes and Air Speeds

6 Define Altitude Temperatures and Head Winds Using TBC "Windtemp" Program

- Average Values at Cruise Altitudes
- One-Day-Per-Year and Nominal Probabilities

7 Selected Flights

- Actual DC10-30 Scheduled Flight
- Actual Routing
- Probable Fuel Loading Temp
- Departure Airport Temp Consistent with Fuel Temp
- Actual Flight Profile
- Probable Air Temp and Head Winds

TABLE 6. OBTAINING CYCLE DATA.

Known:

- **Cruising Altitude**
- **Cruising Altitude Temperatures**
- **Cruise Air Speeds**
- **Still Air Miles**

① Define Remainder of Flight Profile From DC10-30 Flight Manual

- **Taxi, Takeoff, Climb, Step-Climb, Descent, Approach, Land, Taxi**

② Define Altitude Temperature Profile Based on Departure, Cruise, Destination Temperatures

③ Find Fuel Burn From Commercial Aircraft Mission Analysis (CAMAL) Program

④ Define Takeoff Fuel Load and Payload Based on Fuel Burn, FAR Reserves, and Landing Weight Limits

⑤ Run Engine Cycle Deck - Store in Memory Bank for Thermal Model Access

6.2.1 AIRPORT TEMPERATURES

The first step was to identify world-wide airports from which the aircraft might be departing. Boeing "Airport Temperatures" (Reference 5) was used to establish a list of departure airports which would have a likelihood of cold, nominal, or hot fuel loading temperatures to be used in the study. Figure 43 shows, for example, the surface temperature at Helsinki, Finland. Using coldest zero-probability surface temperatures, more than 160 cold-day departure airports were identified. Helsinki has a -33.9° C (-29° F) February low temperature. Other locations had temperatures ranging from -28.9° C (-20° F) to -61.1° C (-78° F) (Upper Canada during January). Surface temperatures at 50% probability were also listed to arrive at a likely choice of departure airports for cold flights with cold on-loaded fuel. Similar departure airport lists were constructed for nominal and hot departure airports using both zero and 50% probabilities. The nominal flight with 50 listed airports considered the most frequent flight routes. For the hot flight, Phoenix to Las Vegas was chosen. Phoenix has a 47.8° C (118° F) high temperature. Eighteen DC-10-30 airports have highs in excess of 43.3° C (110° F). Over 100 world-wide airports have highs above 46.1° C (115° F).

6.2.2 COMMERCIAL FORECASTING ROUTE STRUCTURE ANALYSIS (CFRSA)

The next step was to determine for all the departure airports which ones operate DC-10-30 aircraft. Figure 44 shows airline route guide data for August 1, 1981, for flights originating from Gatwick airport, London, England. This official airline operation data is updated in the GE CFRSA program every three months. Gatwick was one of the departure airports on the list for nominal flights. DC-10-30 flights were identified using CFRSA and the departure airport listings for cold, nominal and hot surface air temperatures. Screening of airport city-pairs was also based on flight length. As shown in Figure 44, CFRSA uses great circle statute miles.

SURFACE RELIABILITY TEMPERATURE IN DEGREES FAHRENHEIT FOR GIVEN PROBABILITIES OF NOT BEING EXCEEDED

HAY RIVER CANADA — LATITUDE 6051N — LONGITUDE 11546W — ELEVATION 543 — AIRPORT CODE YHY

PROB	DEC	JAN	FEB	1QT*	MAR	APR	MAY	2QT	1HF**	JUN	JUL	AUG	3QT	SEP	OCT	NOV	4QT	2HF	ANN
0	-60	-62	-59	-62	-53	-40	-12	-53	-62	18	29	20	18	4	-15	-41	-41	-41	-62
50	-7	-12	-9	-9	3	23	41	22	[illegible]	53	60	57	56	47	33	10	30	43	25
75	6	1	5	5	15	34	52	37	25	60	68	65	64	56	45	20	43	54	40
85	12	7	11	11	21	39	57	44	[illegible]	65	71	68	68	60	51	25	49	59	47
95	24	19	24	24	32	49	67	57	[illegible]	73	78	75	76	68	03	35	61	70	61
100	54	49	56	56	60	74	92	92	[illegible]	95	96	93	96	89	92	59	92	96	96
ADM***	2	-2	2	1	14	33	50	32	17	61	70	56	65	55	40	7	37	52	34

HELENA, MONTANA, USA — LATITUDE 4636N — LONGITUDE 11159W — ELEVATION 3873 — AIRPORT CODE HLN

PROB	DEC	JAN	FEB	1QT*	MAR	APR	MAY	2QT	1HF**	JUN	JUL	AUG	3QT	SEP	OCT	NOV	4QT	2HF	ANN
0	-29	-42	-36	-42	-30	1	17	-30	-42	31	35	32	31	21	10	-39	-39	-39	-42
50	25	18	24	22	31	44	53	42	32	59	68	66	64	57	46	32	45	55	44
75	33	27	33	32	40	53	61	52	44	68	75	74	72	65	54	40	56	65	56
85	37	32	38	36	44	57	64	57	50	72	79	77	75	69	58	44	61	70	62
95	45	40	46	45	52	65	72	66	61	80	83	85	84	77	65	51	71	79	74
100	65	62	68	68	73	86	90	90	90	100	102	103	103	96	84	70	95	103	103
ADM***	34	28	34	32	42	56	65	54	43	71	84	82	79	71	59	42	57	68	56

HELSINKI, FINLAND — LATITUDE 6019N — LONGITUDE 02458E — ELEVATION 167 — AIRPORT CODE HEL

PROB	DEC	JAN	FEB	1QT*	MAR	APR	MAY	2QT	1HF**	JUN	JUL	AUG	3QT	SEP	OCT	NOV	4QT	2HF	ANN
0	-22	-27	-29	-29	-18	0	21	-10	-29	32	39	37	32	25	14	-4	-4	-4	-29
50	28	22	20	23	25	36	47	36	30	57	61	59	59	51	42	33	42	51	40
75	32	27	26	28	31	43	54	45	41	64	67	65	65	56	46	37	49	59	50
95	34	30	29	31	34	47	58	50	46	67	70	67	68	59	49	39	53	63	55
95	38	35	35	36	40	53	64	59	56	73	75	73	74	64	53	42	60	70	65
100	47	47	45	49	54	70	81	81	81	89	89	86	89	77	63	51	77	89	89
ADM***	35	27	26	29	30	41	54	42	36	64	67	65	65	56	46	36	46	56	46

*1QT--FIRST QUARTER DEC-JAN-FEB

**1HF--FIRST HALF YEAR DEC--MAY

***ADM--AVERAGE DAILY MAXIMUM

Figure 43. Airport Temperatures.

AIRLINE ROUTE STRUCTURE ANALYSIS - REPORT ARSJ01
FLIGHT ITINERARY ANALYSIS

NUMBER OF FLIGHTS PER WEEK

LGW LONDON, ENGLAND, (U.K.)-GATWICK ARPT

DATA-AS-OF 09-01-81
REPORT DATE 12-09-81

				FLIGHT ITINERARY											
TYPE OF AIRCRAFT	ALN	FLT	FREQ	ORIG	DIST	STOP	DIST	STOP	DIST	STOP	DIST	STOP	DIST	STOP	TOTAL DIST
DC10-30	BR	231	6	LGW	4217	ATL									4217
DC10-30	BR	232	6	ATL	4217	LGW									4217
DC10-30	BR	245	7	LGW	4841	IAH									4841
DC10-30	BR	246	7	IAH	4841	LGW									4841
DC10-30	BR	253	4	LGW	4754	DFW									4754
DC10-30	BR	254	4	DFW	4754	LGW									4754
DC10-30	BR	267	4	LGW	4207	STL									4207
DC10-30	BR	268	4	STL	4207	LGW									4207
DC10-30	BR	361	2	LGW	3084	LOS									3084
DC10-30	BR	362	3	LOS	3084	LGW									3084
DC10-30	BR	363	4	LGW	2744	KAN	516	LOS							3260
DC10-30	BR	364	1	ACC	248	LOS	3084	LGW							3332
DC10-30	BR	365	1	LGW	3084	LOS	248	ACC							3332
DC10-30	BR	366	3	LOS	516	KAN	2744	LGW							3260
DC10-30	BR	368	1	LOS	248	ACC	3145	LGW							3393
DC10-30	BR	373	1	LGW	3084	LOS									3084
DC10-30	BR	373	1	LGW	3084	LOS									3084
DC10-30	BR	374	1	LOS	516	KAN	2744	LGW							3260
DC10-30	BR	375	1	LGW	3145	ACC									3145
DC10-30	BR	376	1	LOS	3084	LGW									3084
DC10-30	BR	376	1	LOS	3084	LGW									3084
DC10-30	BR	381	4	DXB	3397	LGW									3397
DC10-30	BR	382	4	LGW	3397	DXB									3397
DC10-30	BR	661	1	LGW	755	MAD									755
DC10-30	BR	662	1	MAD	755	LGW									755
DC10-30	BR	663	1	LGW	958	LIS									958
DC10-30	BR	664	1	SCL	706	EZE	1237	GIG	5731	LGW					7674
DC10-30	BR	665	1	LGW	4960	SSA									4960
DC10-30	BR	666	1	SSA	4960	LGW									4960
DC10-30	BR	671	1	LGW	4645	CCS	638	BOG	1172	LIM					6455
DC10-30	BR	672	1	LIM	828	UIO	1083	CCS	4645	LGW					6553
DC10-30	BR	675	1	LGW	4645	CCS	1250	GYE	705	LIM					6600
DC10-30	BR	676	1	LIM	1172	BOG	638	CCS	4645	LGW					6455
DC10-30	GK	10	7	LGW	3458	JFK									3458
DC10-30	GK	11	7	LGW	4430	MIA									4430
DC10-30	GK	12	7	MIA	4430	LGW									4430
DC10-30	GK	15	7	LGW	4430	MIA									4430
DC10-30	GK	16	7	MIA	4430	LGW									4430
DC10-30	GK	20	7	JFK	3458	LGW									3458
DC10-30	GK	30	7	LGW	3458	JFK									3458
DC10-30	GK	40	7	JFK	3458	LGW									3458
DC10-30	GK	50	7	LGW	3458	JFK									3458
DC10-30	GK	51	3	LGW	3086	BGR	1385	TPA							4471
DC10-30	GK	52	3	TPA	1385	BGR	3086	LGW							4471

Figure 44. Airline Route Structure Analysis Program.

6.2.3 ENVIRONMENTAL ANALYSIS

The Boeing "Windtemp" program (Reference 6) was then used to complete the screening on the basis of cruising altitude environmental temperature and geographical routing. Figure 45 shows the list of cold flight DC-10-30 aircraft city-pairs which were analyzed using Windtemp. All results in the Windtemp computer program are computed in terms of nominal or 50% probabilities based on accumulation of world-wide weather reporting. For three winter months the average temperatures at 39,000 feet over the great circle route between Helsinki and Seattle is ISA (International Standard Atmosphere) minus 3.8° C (7° F), or -56.1° C - 3.8° C = -60° C (-69° F -7° F = -76° F). The standard deviation from this value based on original data is ± 5° C (9° F). Assuming normal statistical distribution, two standard deviations would be appropriate for one-day-per-year. Hence, the average route temperature at 39K is -60° C -2(5° C) = -70° C (-76° F -2(9° F) = -94° F).

It is important to note that this is the altitude "average" static temperature. This value was arrived at in Windtemp using 200 nautical mile temperature nodes between Helinski and Seattle. At 39K, the outside air temperature will vary from this average, both warmer and colder.

Numerous factors affect tank cooldown rate:

- Ambient temperature
- Mach number
- Initial fuel loading temperature
- Fuel tank location
- Fuel transfer rate and schedules
- Tank size, shape, and internal design
- Fuel quantity
- Wing shape
- Altitude step changes
- Direction of flight

- **Cold Flights**
- **Possible DC10-30 City-Pairs**

Selected City-Pair Hel-Sea

```
WINDS AND TEMPS INPUT

     0    1    1    1    1   20    5   18   10   19   10    6    6
35000               450                      2    6              2    0  00000020
BGR LGW                                                                  00000110
DEN LGW                                                                  00000120
ANC NRT                                                                  00000210
ANC SEL                                                                  C0000220
ANC CPH                                                                  00000230
ANC BRU                                                                  00000240
ANC ORY                                                                  00000250
SVO FRA                                                                  00000310
SVO LHR                                                                  00000320
SVO TAS                                                                  00000330
SVO KBL                                                                  00000340
TAS SVO                                                                  00000410
TAS FRA                                                                  00000420
KBL FRA                                                                  00000510
KBL CDG                                                                  00000520
HEL YUL                                                                  00000610
HEL JFK                                                                  00000620
HEL SEA                                                                  00000630
YEG AMS                                                                  00000710
YUL AMS                                                                  00000810
YUL ZRH                                                                  00000820
YUL MXP                                                                  00000830
YUL HEL                                                                  00000840
YUL FCO                                                                  00000850
YWG YVR                                                                  00000910
YWG AMS                                                                  00000920
YYZ YYC                                                                  00001010
YYZ YVR                                                                  00001020
YYZ AMS                                                                  00001030
YYZ FRA                                                                  00001040
YYZ MXP                                                                  00001050
YYZ FCO                                                                  00001060
YYZ HNL                                                                  00001070
YVR YWG                                                                  00001110
YVR YYZ                                                                  00001120
YVR HNL                                                                  00001130
YVR LIM                                                                  00001140
YYC YYZ                                                                  00001210
YYC AMS                                                                  00001220
9                                                                        00010000
```

Figure 45. Windtemp Input.

When these factors are considered along with the fact that the aircraft type and airline routing do not necessarily correspond to a worst case transport aircraft scenario, it is evident that results such as these are "typical," not "worst case." Hence in a "typical" sense, the objective became one of comparative results, not absolute results. In other words, if it were possible to show by analysis that the fuel in the left outboard reserve tank of the DC-10-30 flying from Helinski to Seattle reached exactly -40° C (-40° F) at exactly 2 hours after takeoff exactly once each year, this result would depend on precise statistical analysis of all relevant factors and even then would not represent the one-day-per-year or worst case for the airline industry. Consequently, a significant issue is the coldest fuel temperature which can be reached based on the possibility of cold ambient exposure <u>somewhere</u> along the route. For this reason, the city-pair or route average ambient temperature used to analyze other aspects of commercial aircraft mission analysis was also a logical choice for the analysis of tank cooldown rate and tank temperature. This method was in fact the only one available which would consider a large number of mission options and provide consistency in the method of analysis.

The Windtemp program also provided route-average headwinds and tailwinds. Winds were computed in the same manner as temperatures using 200 nautical-mile node points along the route to find the statistical city-pair average wind component. Wind was then added to or subtracted from great circle distance to find the air miles used to determine flight time and fuel burn.

6.2.4 AIRCRAFT AND ENGINE ANALYSIS

Before the thermal model could be run, it was necessary to determine the exact flight profile and engine power settings and then obtain the engine cycle data. This involved consideration and analysis of a number of factors and the utilization of the Commercial Aircraft Mission Analysis (CAMAL) program.

Fuel loading was determined based on intercontinental or domestic IFR fuel reserve requirements and takeoff/landing gross weight limits. The DC-10-30 flight manual and cruise conditions from Windtemp (altitude, temperature, winds) were used to construct the flight profile. During descent or climb transients, engine power setting adjustments were calculated at 0.5 to 2.0 minute intervals. These points were later fitted to constant one-minute intervals used in the thermal model.

Tables 7 and 8 show the flight selection results. Figures 46 and 47 show geographical locations for these flights. With the exception of the hot flight (Phoenix to Las Vegas), these are actual DC-10-30 ticket guide routes. The hot flight was assumed to be representative of a short hop for a wide-body jet although the DC-10-30 is not routed for this particular flight.

6.2.5 EMERGENCY CONDITION WITH LOW FUEL RESERVES

To consider this issue, it was assumed that all of the systems would continue to transfer heat to the fuel tanks in spite of whatever tank temperature occurred. The result would indicate the need for diverting heat input from the aircraft tanks.

The flight scenario assumed that the DC-10-30 approaches Phoenix to land with 37.8° C (100° F) temperature fuel in all tanks. For this emergency, fuel reserves are below minimum but still adequate to abort the Phoenix Landing and divert to Las Vegas. This is well within the design/performance intent of the aircraft. Fuel has already been transferred from the outboard tanks to the mains as the aircraft approaches Phoenix. There is only 400 pounds of fuel in the outboard tanks. All engines are drawing fuel from the mains and tank heating is being returned to the outboard and then to the mains as is necessary for the operation of the advanced system.

TABLE 7. SELECTED FLIGHTS.

Flight		Nominal	Cold	Hot
City Pair		Gatwick, London to Kennedy, New York (LGW --- JFK)	Helsinki, Finland to Seattle, Washington (HEL --- Sea)	Phoenix, Arizona to Las Vegas, Nevada (PHX ——— LAS)
Delta T_{Amb} from ISA/Probability		+2° F (+1° C)/50%	-25° F (-14° C)/ 1 Day Per Year	+34° F (+19° C)/ 1 Day Per Year
Winds at 50% Probability	(Knots)	-37 (-69 km/hr)	-13 (-24)	+3 (+6)
Great Circle Distance	(NM)	3005 (5570 km)	4140 (7670)	222 (411)
Equivalent Still Air Distance	(NM)	3275 (6070 km)	4263 (7900)	220 (408)
Cruise Altitudes(s)	(ft)	35K' (10.7 km) Initial Cruise Step Climb to 39K' (11.9 km)	35K' (10.7) Initial Cruise Step Climb to 39K' (11.9 km)	20K' (6.1 km)
Reserve Fuel Requirements		FAR International	FAR International	Max Fuel Load Possible Without Exceeding Max Landing Weight
Payload		60% of Max	60% of Max	40% of Max

TABLE 8. FLIGHT TEMPERATURES.

Flight	Nominal	Cold	Hot
City-Pair	LGW —— JFK	HEL —— SEA	PHX —— WAS
Max Alt	39K' (11.9 km)	39K' (11.9 km)	20K' (6.1 km)
Month	Jan	Annual	July
ISA Temp	-69° F (-56° C)	-69° F (-56° C)	-6° F (-21° C)
ΔT Amb (50% Prob)	+2° F (+1° C)	-7° F (-4° C)	+4° F (+2° C)
2 σ (One Day Per Year)	—	-18° F (-10° C)	+30° F (+17° C)
Alt Temp	-67° F (-55° C)	-94° F (-70° C)	+28° F (-2° C)

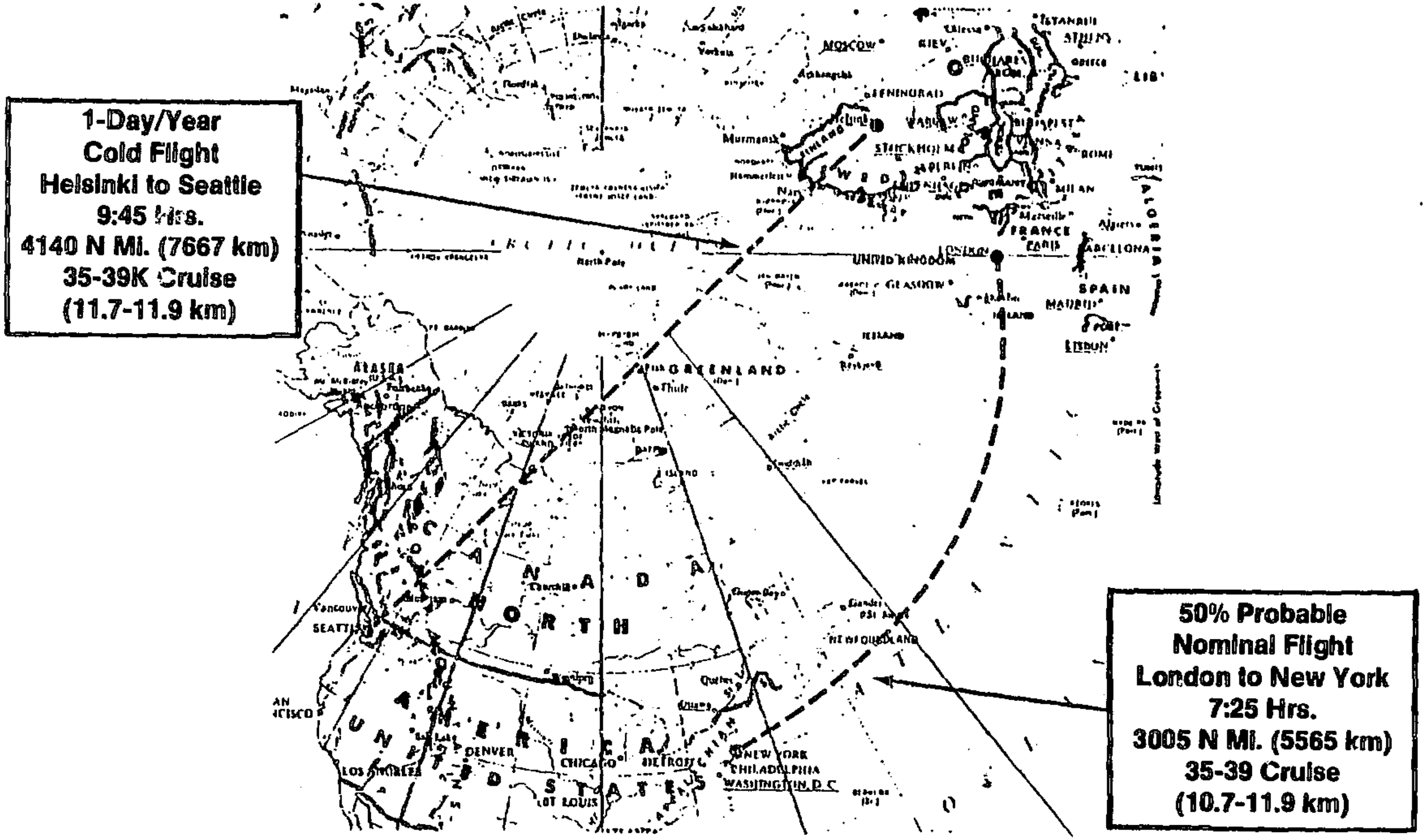


Figure 46. Nominal and Cold Flights.

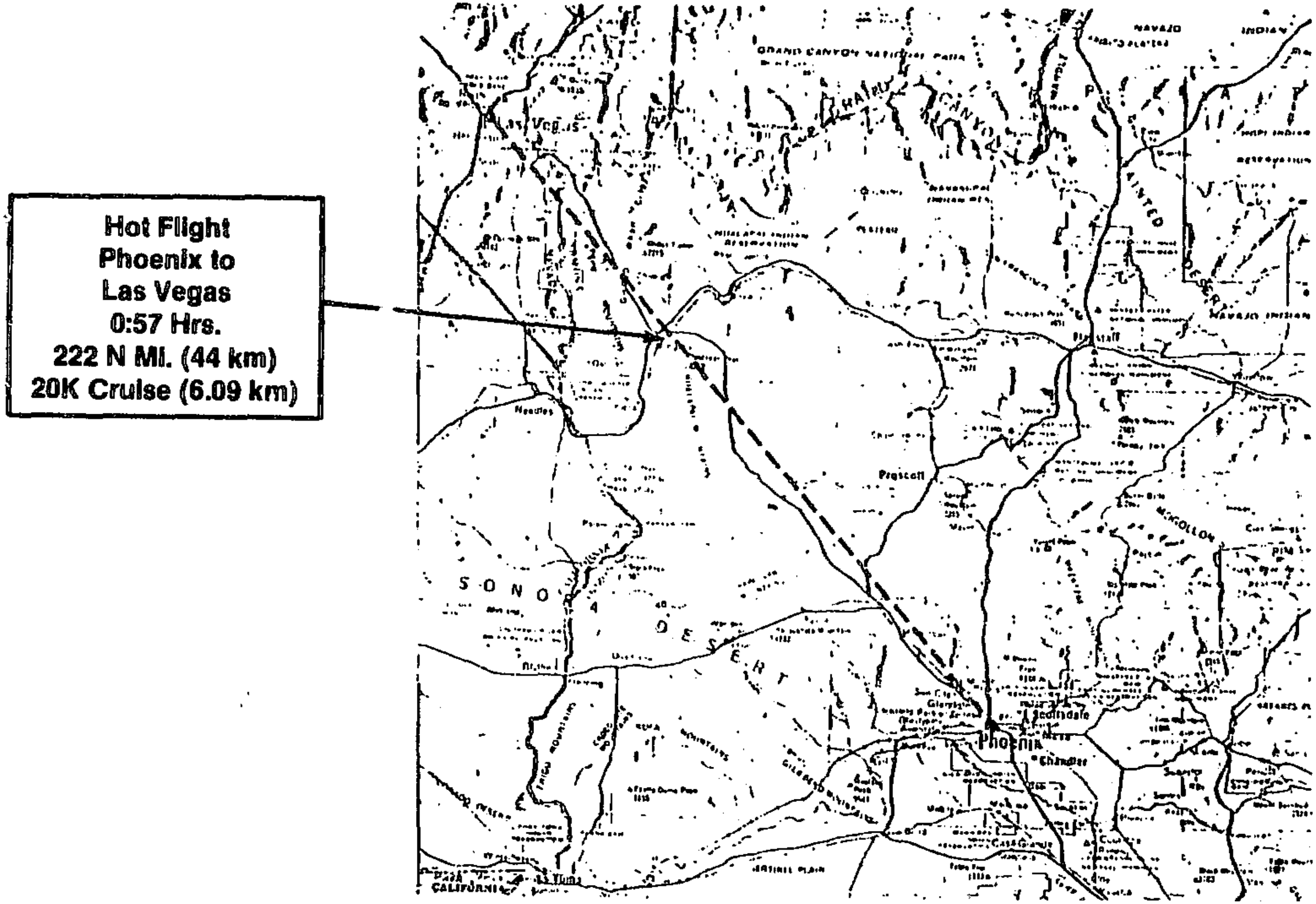


Figure 47. Hot Flight.

7.0 ACCURACY OF RESULTS

7.1 INTRODUCTION

This section of this report discusses accuracy of the mission analysis and thermal model results. Comparison is made to previous work sponsored by NASA-Lewis concerning aircraft fuel tank temperatures.

7.2 FLIGHT AMBIENT TEMPERATURE EFFECT

In the present study, minimum altitude ambient static temperature for the cold flight was determined to be -70° C (-94° F) at 11,887 m (39,000 feet). In a previous NASA-Lewis sponsored study reported in NASA CR-135198 (Reference 4), the air temperature during a similar cold flight (over polar region) was essentially as shown in Figure 48. In this figure, the temperature (T_{amb}) was assumed to occur in the step fashion as shown. The change was more gradual as reported in CR-135198. Note that the coldest temperature of -72.2° C (-98° F) occurs at 322 minutes into the flight. The corresponding air recovery temperature (T_R) which influences tank temperature is also shown in Figure 48. For these air temperatures, the bulk fuel temperature of the main and outboard tanks were calculated to be those shown in Figures 49 and 50. It is significant to note that for all practical purposes the tank fuel temperature reaches air recovery temperature. In other words, it is reasonable to assume from an operational point of view, that knowledge of ambient static temperature and aircraft Mach number (basis for recovery temperature) are all that is needed for determination of worst-case (coldest) tank temperature. As to whether or not worst-case static air temperature is -72.2° C (-98° F) or -70° C (-94° F) during the flight is probably a matter of conjecture. Consequently, the results which will be discussed later in this report should be considered general in nature since absolute values of aircraft tank temperature are defined and valid only to the extent of the assumptions made in the course of analysis, i.e., absolute answers do not exist.

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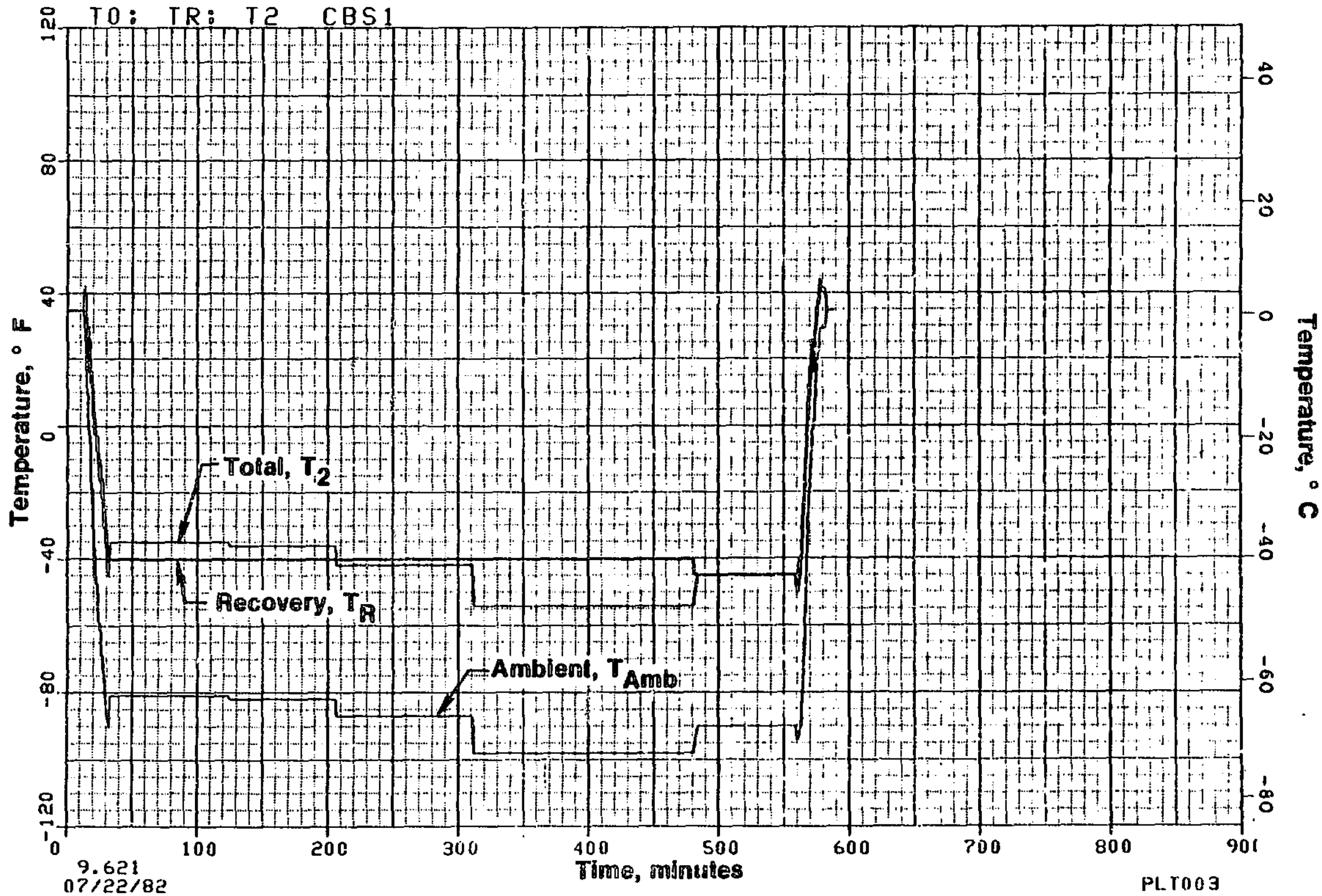


Figure 48. Cold Flight Air Temperature Based on NASA CR-135198.

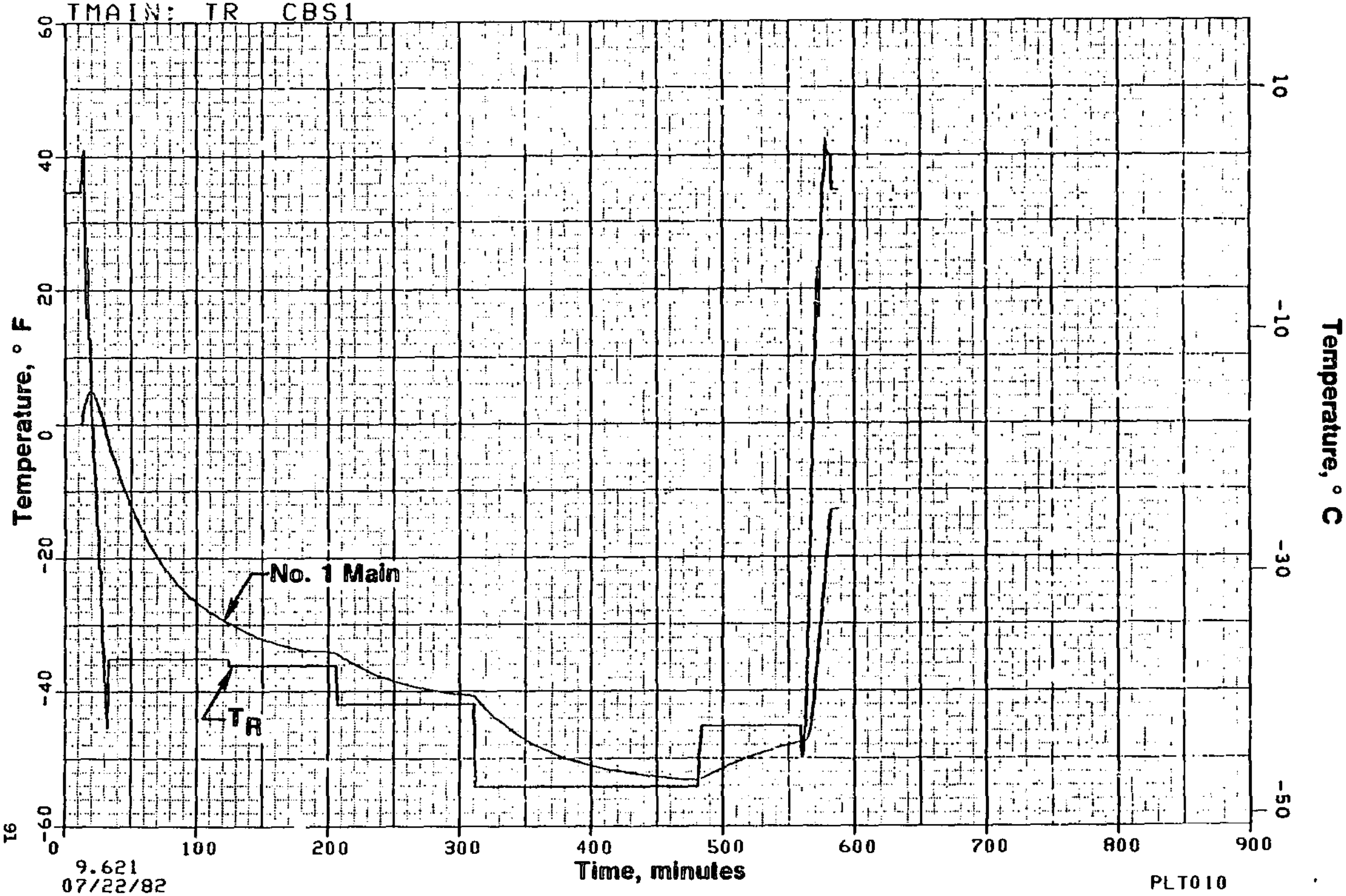


Figure 49. Baseline - Cold Flight No. 1 Main Tank Temperature Based on NASA CR-135198.

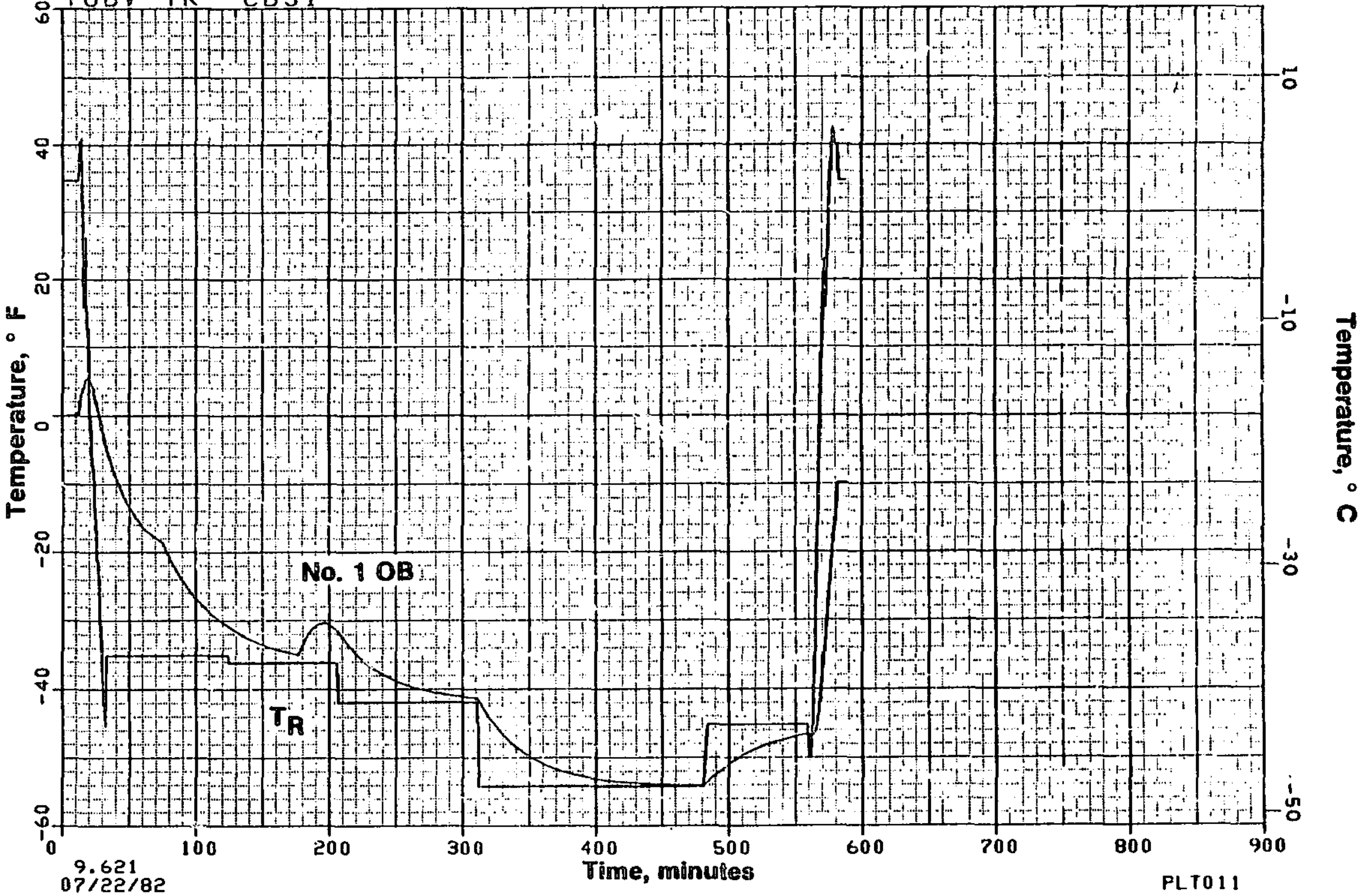


Figure 50. Baseline - Cold Flight No. 1 Outboard Tank Temperature Based on NASA CR-135198.

7.3 ENERGY CHECK

Figure 51 illustrates the thermal energy balance used to check the validity of the thermal model. Shown here are energy transfers (Q_{air}, HP, Q_{lube}, Q_{IDG}, Q_{BLD}) which add or remove thermal energy to or from the flowing thermodynamic system. Figure 52 shows the accountability of these energy transfers with respect to one-minute-interval changes in the energy level of the system (E of the system). This is simply a statement of continuity with respect to energy change in the fuel tanks. Change in tank fuel mass (fuel weight) is included in the values of E_1 and E_2. Figure 53 shows results of this energy check for a typical flight. What appears as a single line is actually two lines falling on top of each other. One is the summation of energy transfers (Q, HP, etc.) during the one-minute interval. The other is the change (E) of the tank. Note that these calculations were performed after the system thermal balance was completed and hence are not an identity to the basic method of calculation.

A second means for checking the analysis involved the energy exchange across the engine fuel pump and heat exchanger. This is shown in Figures 54 and 55. Heat input (Q loss and Q lube) were calculated external to the fuel system. Then the results of this energy summation were compared to the energy equivalent to the fuel temperature which resulted from iterative analysis. Figure 55 shows the agreement between results. It was concluded therefore that the thermal model results were accurate in terms of formulation.

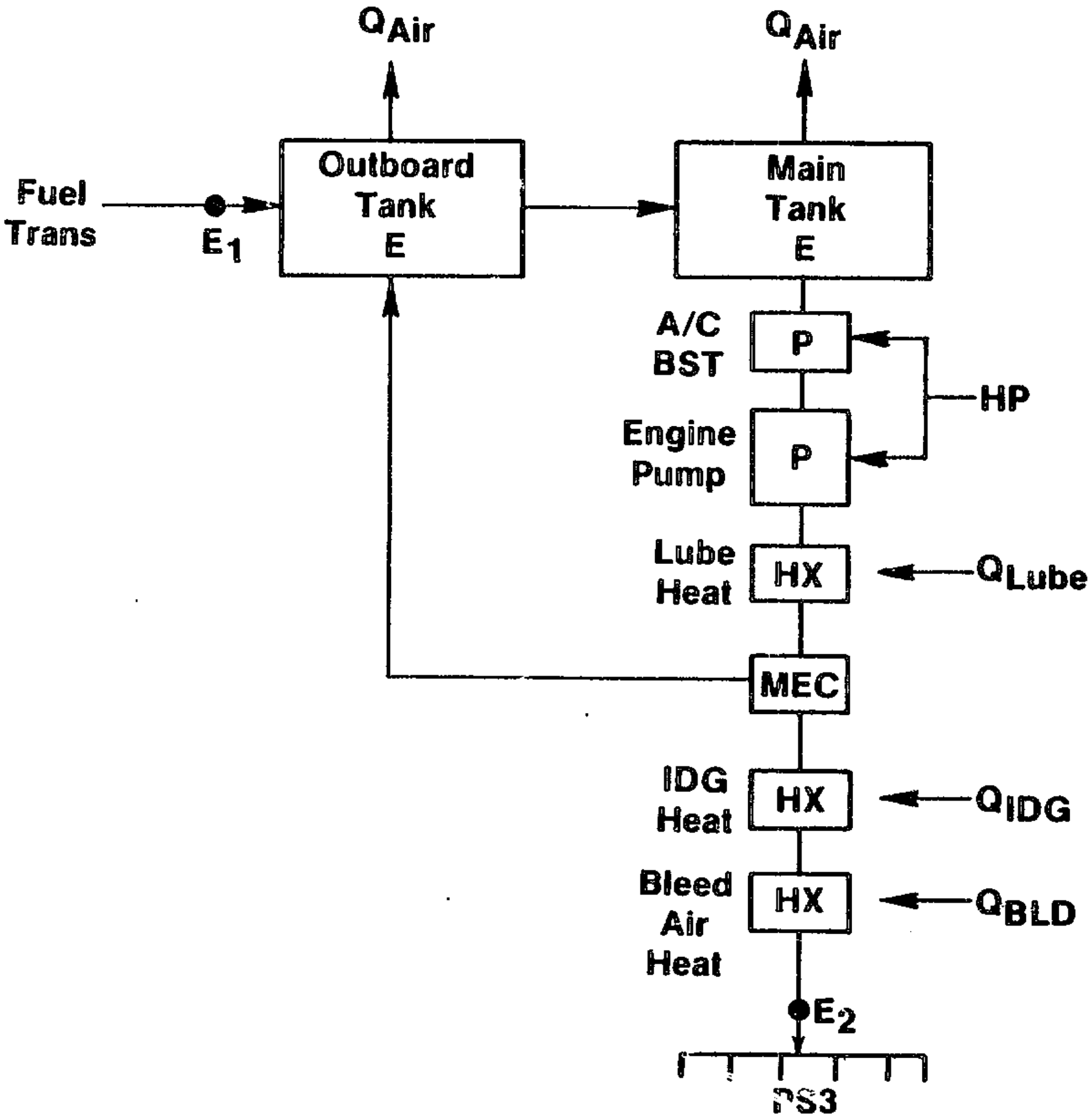


Figure 51. System Energy Check - 1st Law of Thermodynamics.

For Each Minute of Flight -

- **Energy Accumulated by Fuel Tanks**

  $= \Sigma$ **Energy Into System** $-$ Σ **Energy Out of System**

- $\Delta E = E_1 - Q_A + H_P + Q_{Lube} + Q_{IDG} + Q_{BLB} - E_2$

- **E = Thermal Energy + Pressure Energy**

Figure 52. System Energy Check - 1st Law of Thermodynamics.

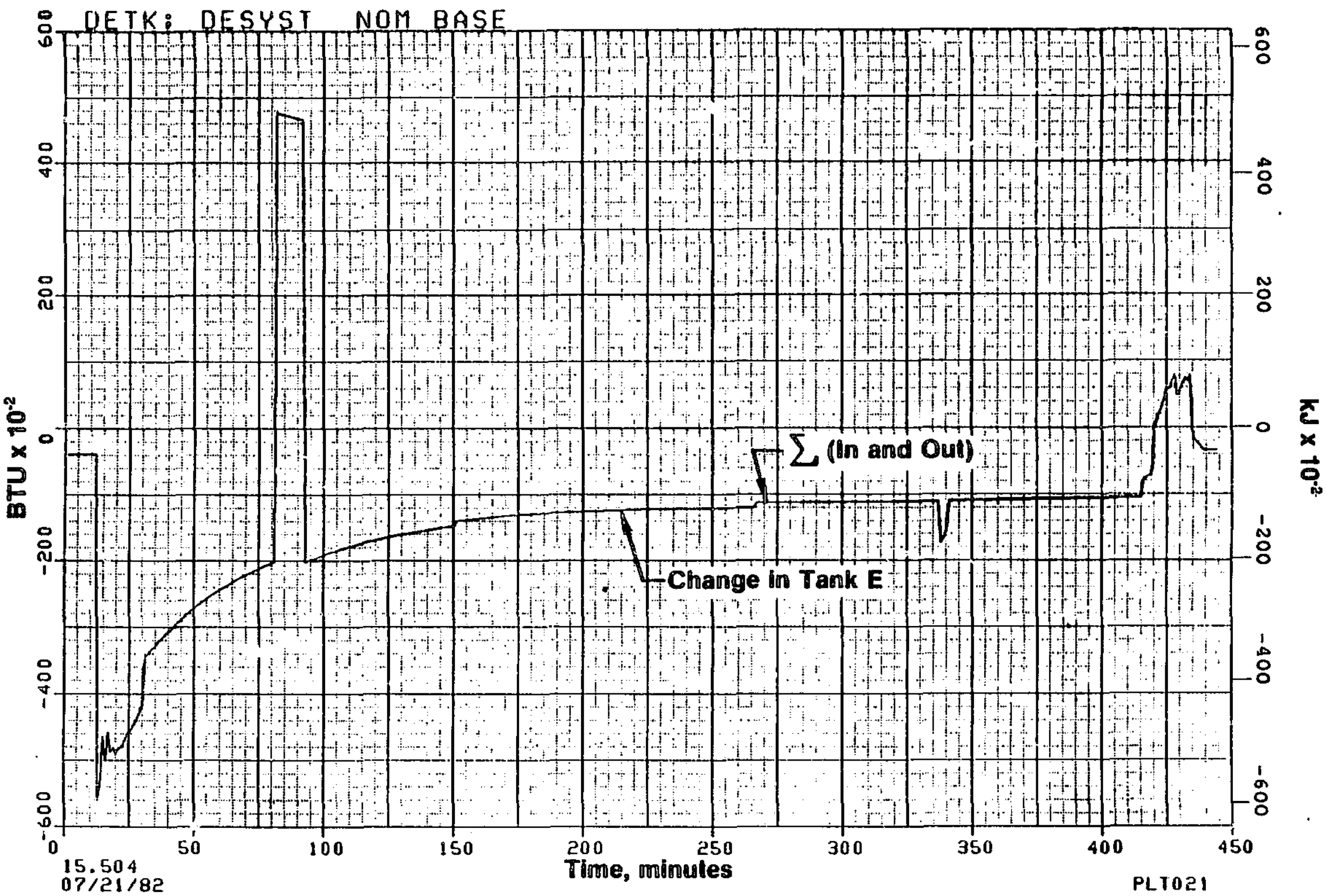
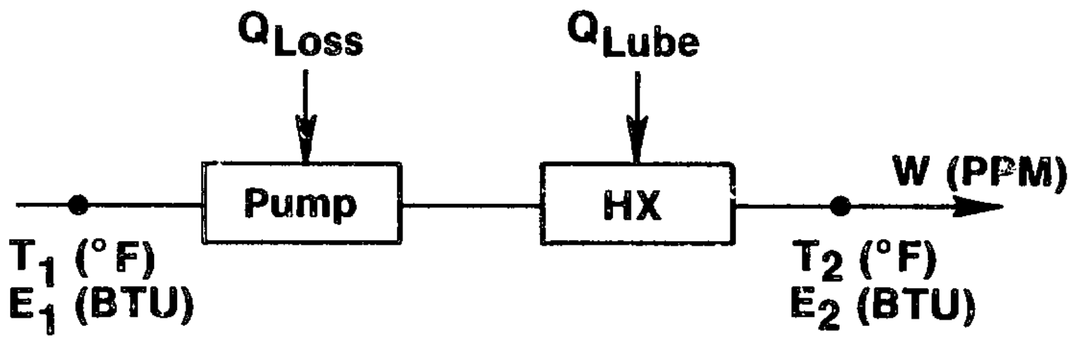


Figure 53. Baseline - Nominal Flight Total System Energy Check.



$$Q_T = Q_{Loss} + Q_{Lube}$$

$$Q_T = E_2 - E_1$$

$$E = W\left(AT + \frac{BT^2}{2}\right)$$

$$Q_T = WC_P\,(T_2 - T_1)$$

$$C_P = f\left(\frac{T_2 + T_1}{2}\right)$$

Figure 54. Energy Transfer Check (BTU/Min).

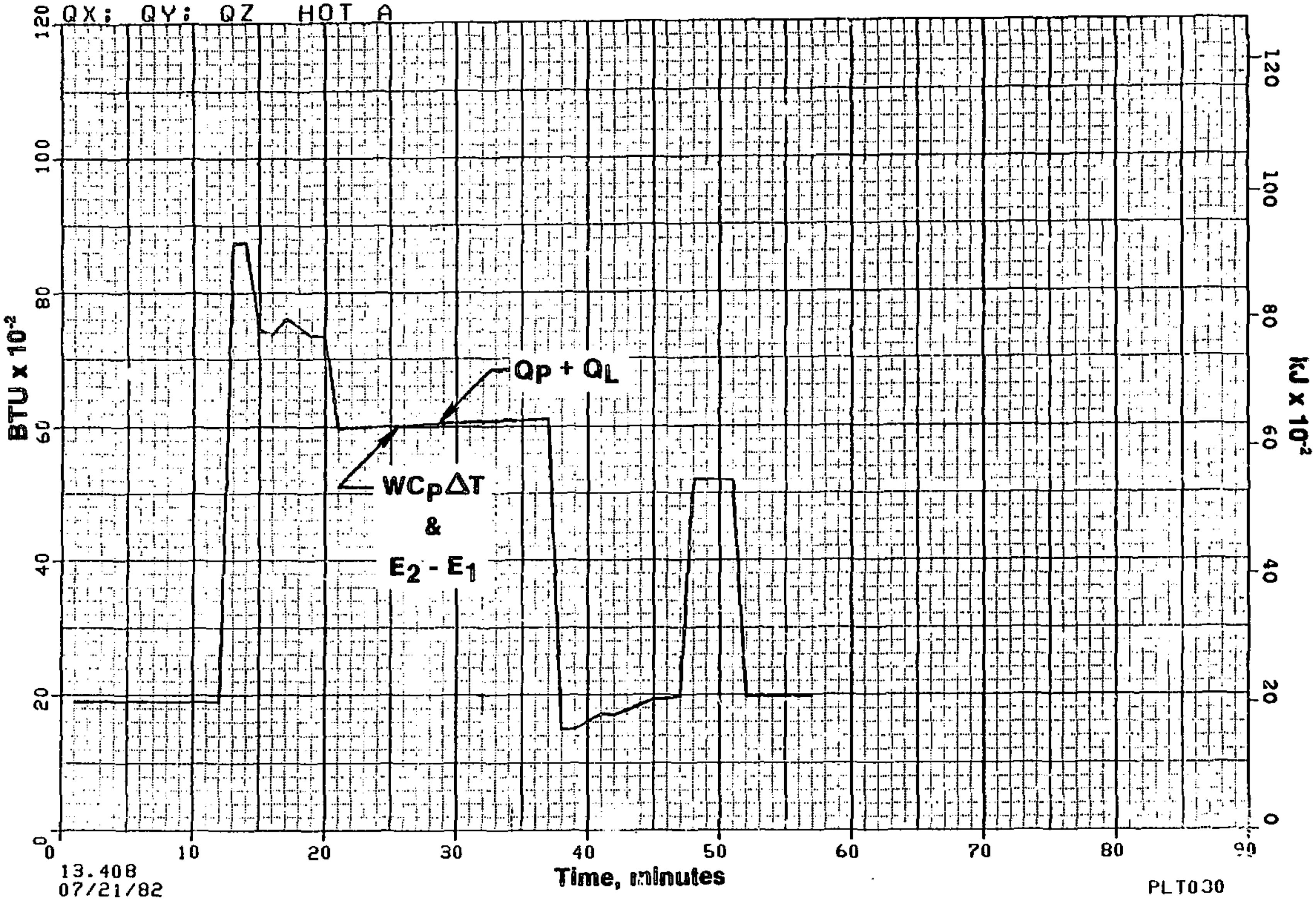


Figure 55. System A - Hot Flight Fuel Pump and Lube HX Energy Check.

8.0 RESULTS OF FLIGHT STUDIES

8.1 INTRODUCTION

Three DC-10-30 flights were evaluated by computer analysis. These flight simulations were designated Cold, Nominal and Hot. The flights were duplicated for the baseline and three advanced systems. With the extensive modeling used for the study, it was possible to generate a great deal of computer plotted data. Only a portion of this data has been included with this report. The selection of these data is intended to illustrate general feasibility of the alternative systems. Special computer runs were made to determine fuel residence time in the engine system and to assess emergency low-fuel reserve conditions.

8.2 FLIGHT DEFINITION RESULTS

Figures 56 through 70 define the flights in terms of distance, time, altitude, air speed, engine thrust and engine metered fuel flow. These definitions are the same for all of the systems studied. In all cases, the flight starts when the aircraft begins its taxi-out for takeoff and ends with taxi-in. Engine fuel burn is accumulated in the computer routine so that total block-to-block fuel burn is known for each flight and each system. The computer calculates all parameters at one-minute intervals during the flight. During both the cold and nominal flights, the aircraft climbs and levels off at 10,668 m (35,000 feet). Later in the flight it makes a step-climb to 11,887 m (39,000 feet). For the hot flight (Phoenix to Las Vegas), the cruise altitude is 6,096 m (20,000 feet).

8.3 FUEL TANK TEMPERATURES

Fuel tank temperature is of particular concern from the standpoint of fuel freezing. In the advanced systems which all involve tank heating, hot fuel could also be a concern. Later in this report the question of low fuel reserves and excessive tank heating is discussed.

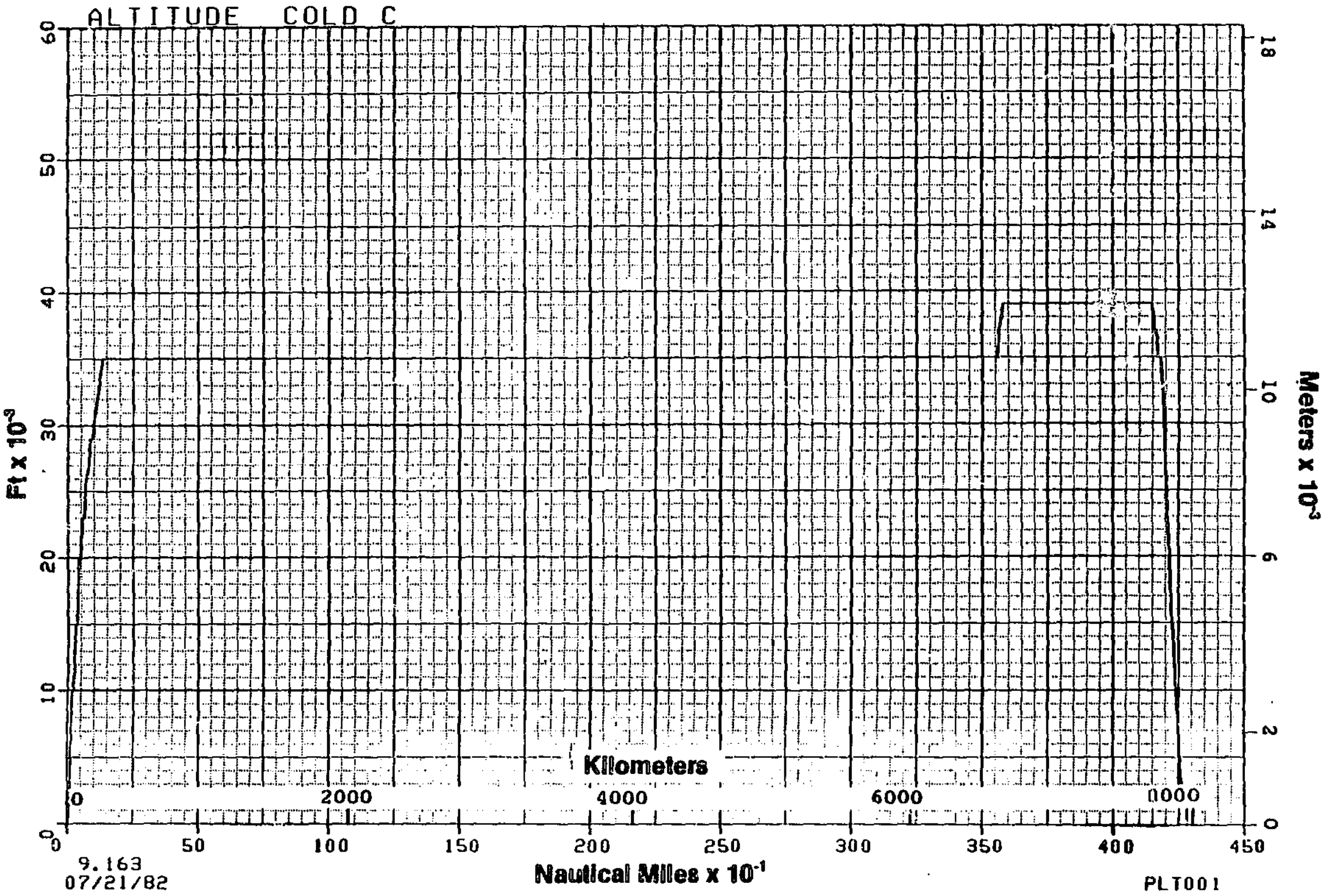


Figure 56. Cold Flight Altitude Versus Distance

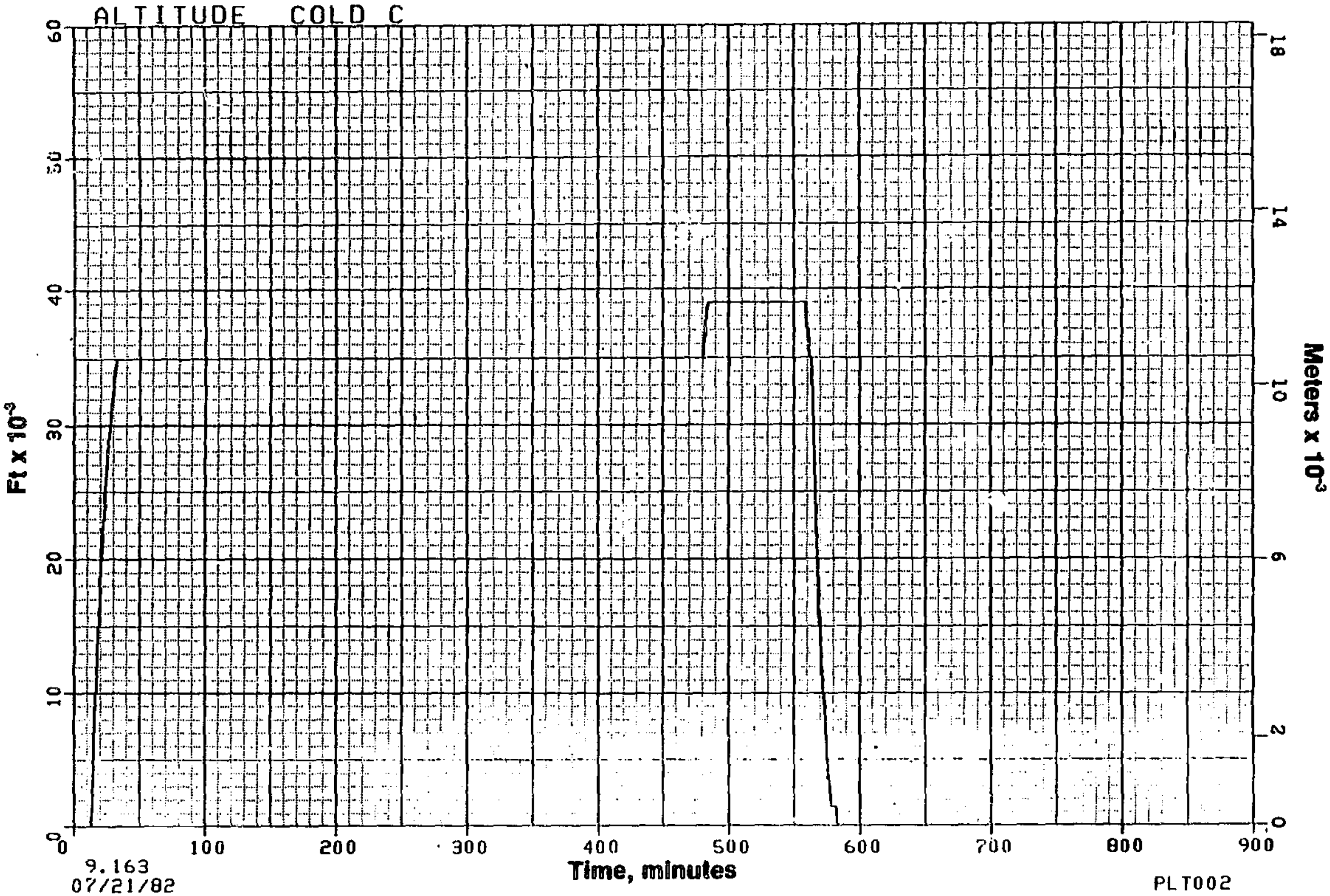


Figure 57. Cold Flight Altitude Versus Time.

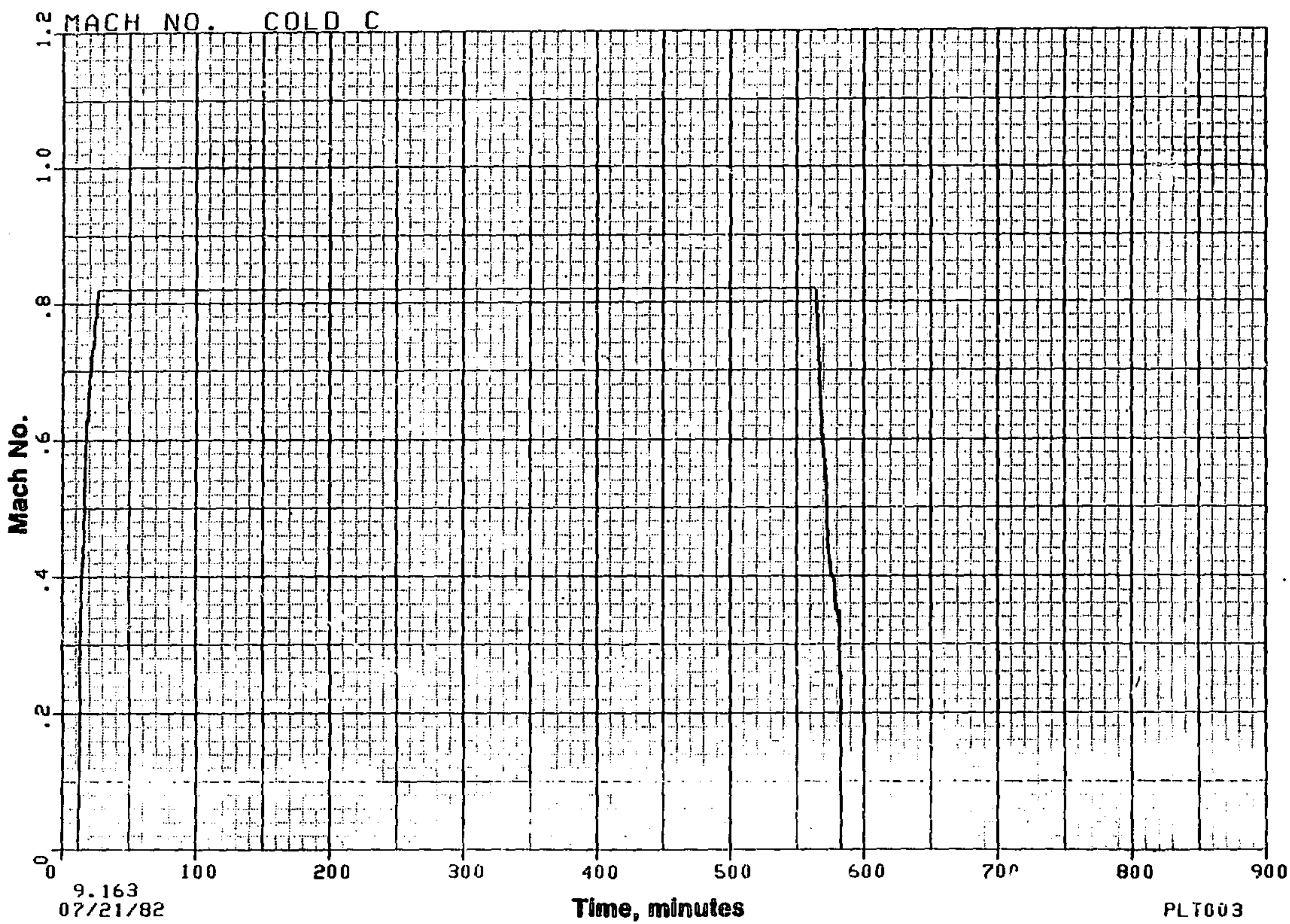


Figure 58. Cold Flight Mach Number.

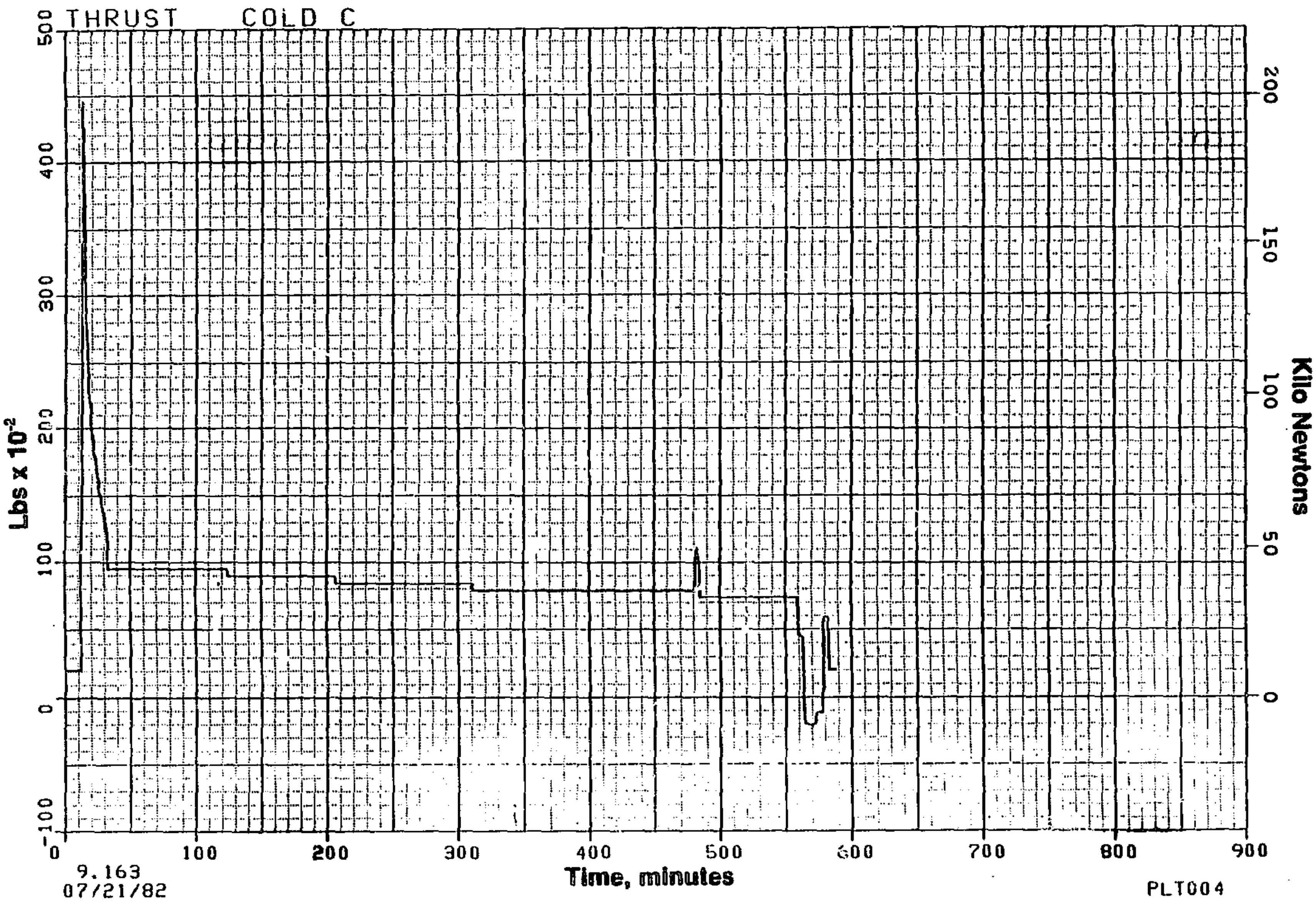


Figure 59. Cold Flight Installed Thrust.

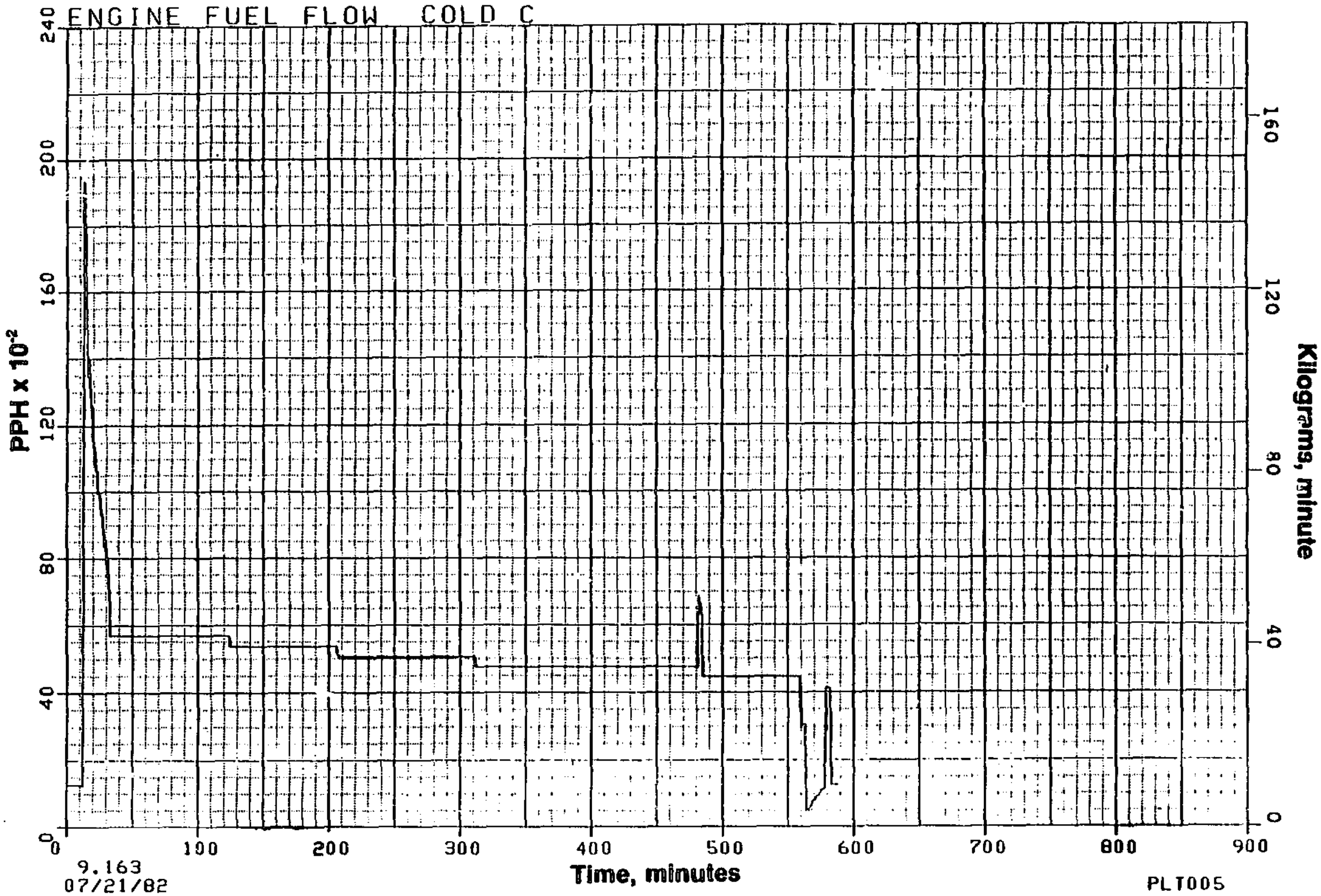


Figure 60. Cold Flight Engine Fuel Flow.

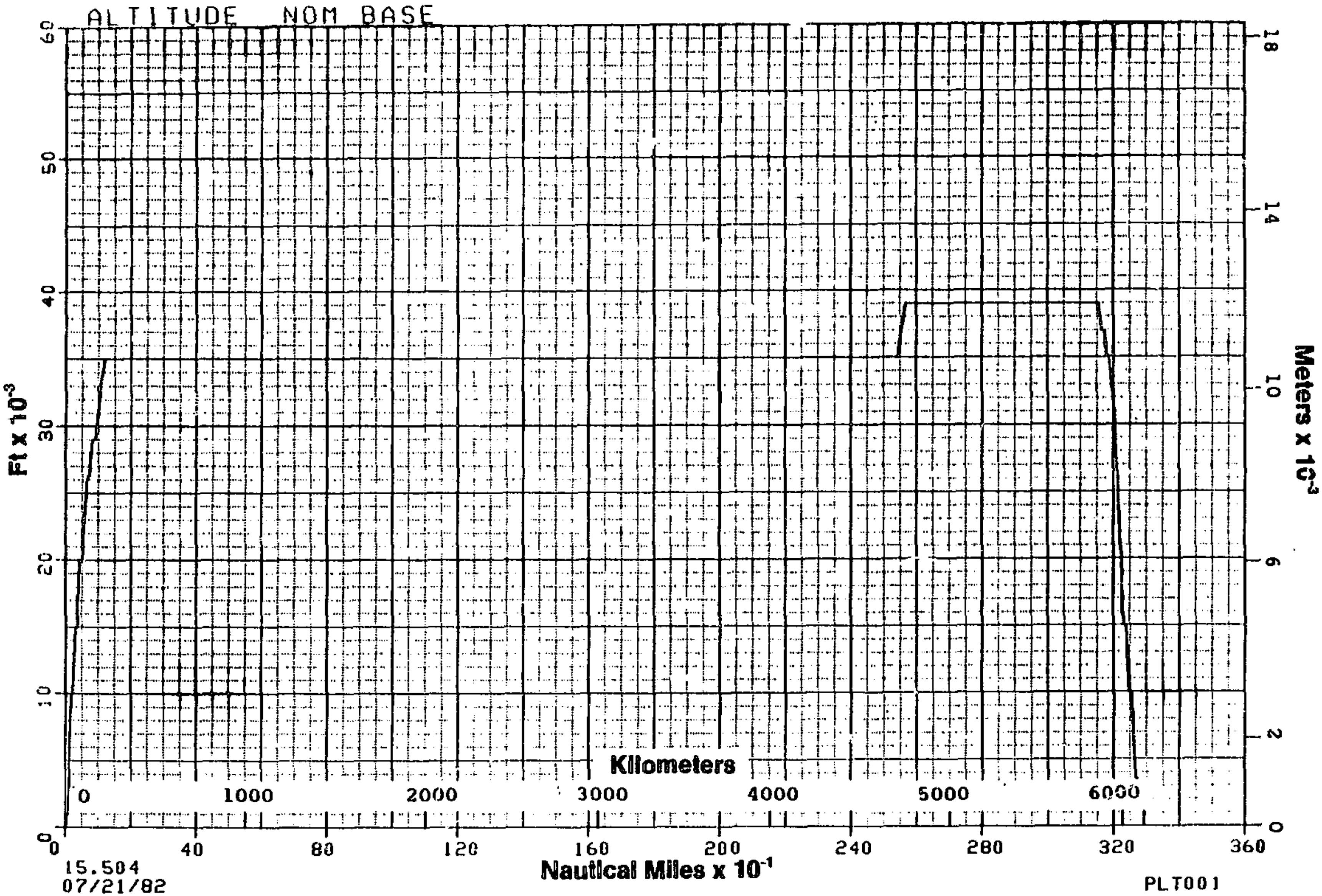


Figure 61. Nominal Flight Altitude Versus Distance.

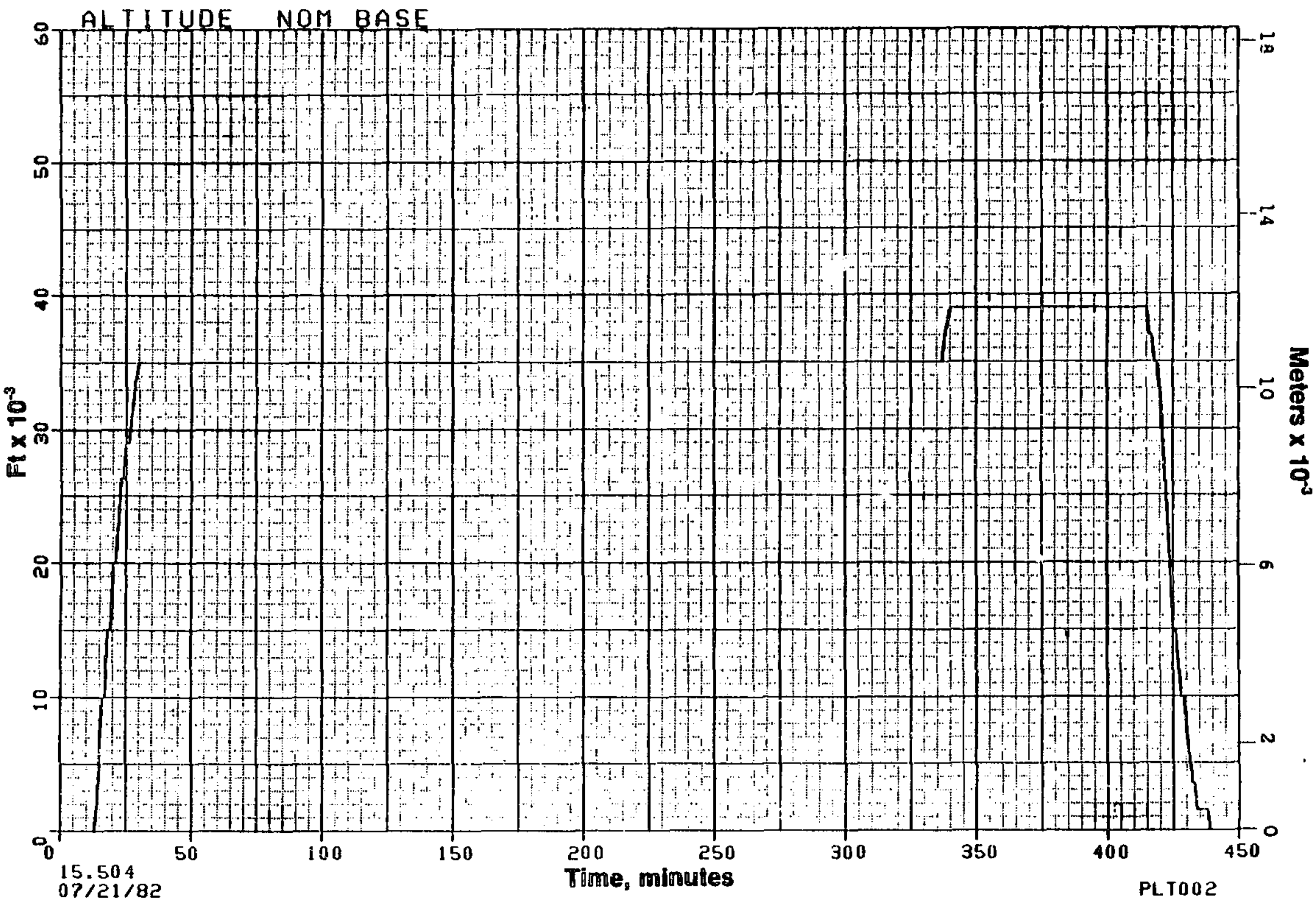


Figure 62. Nominal Flight Altitude Versus Time.

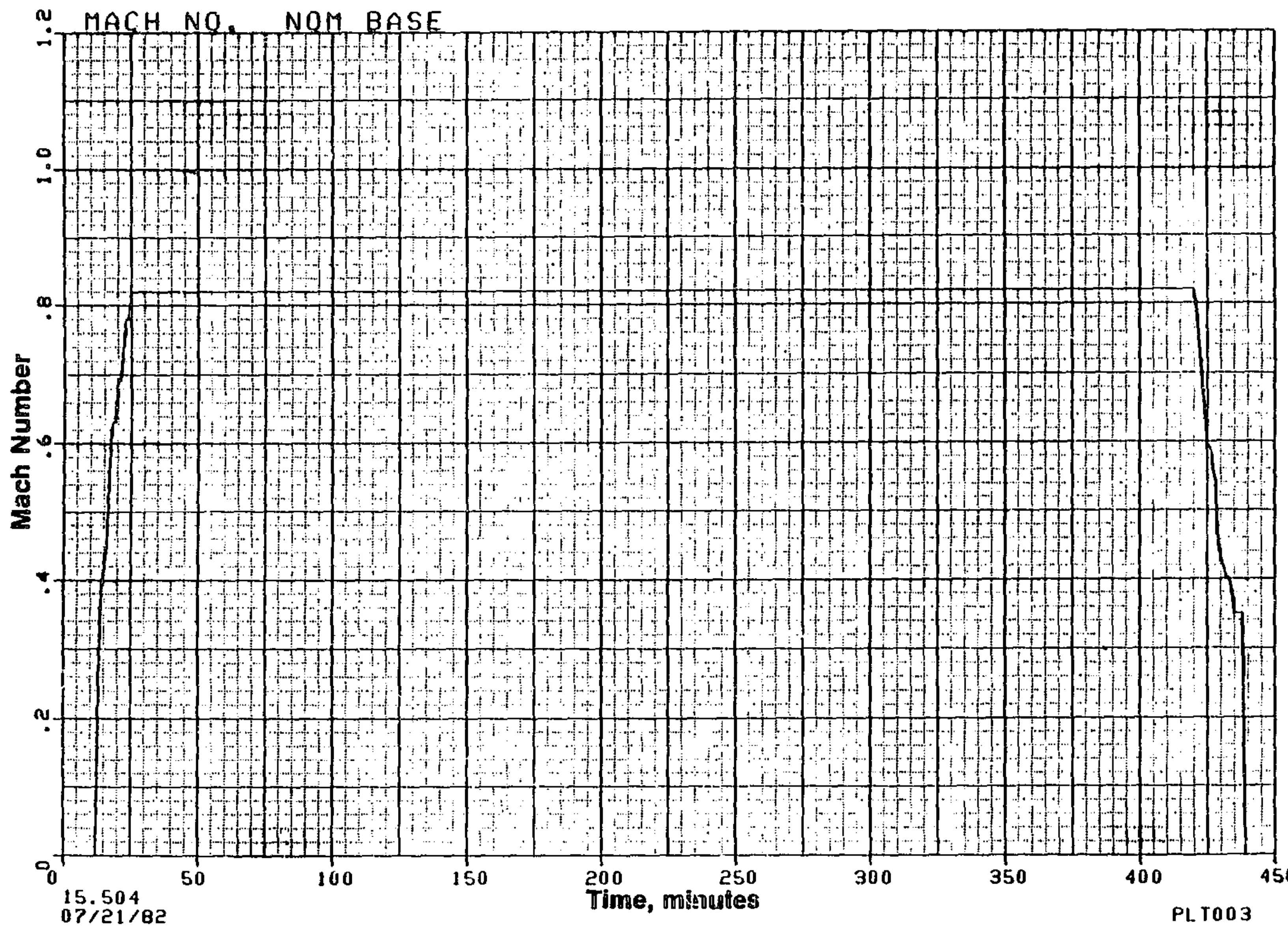


Figure 63. Nominal Flight Mach Number.

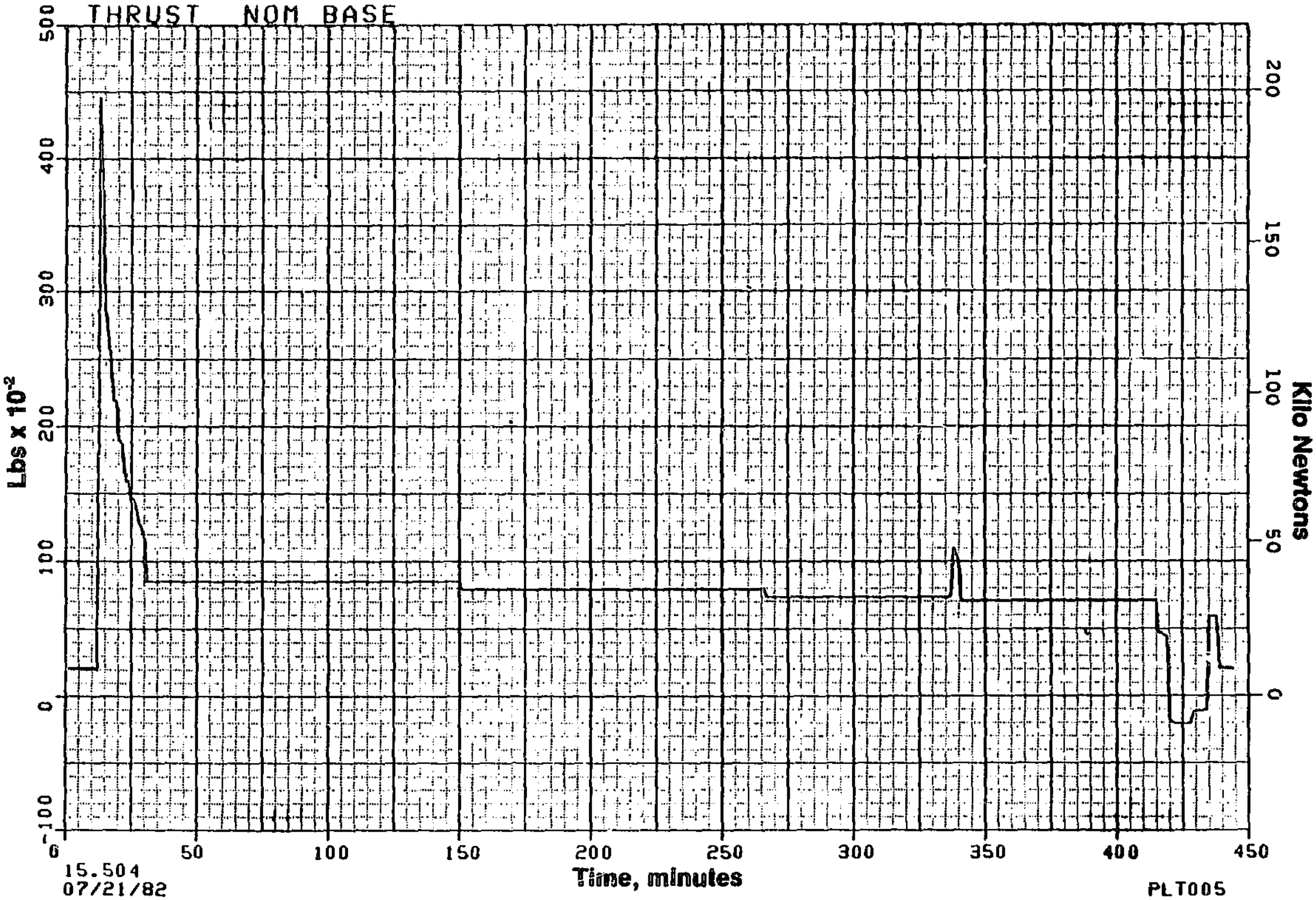


Figure 64. Nominal Flight Installed Thrust.

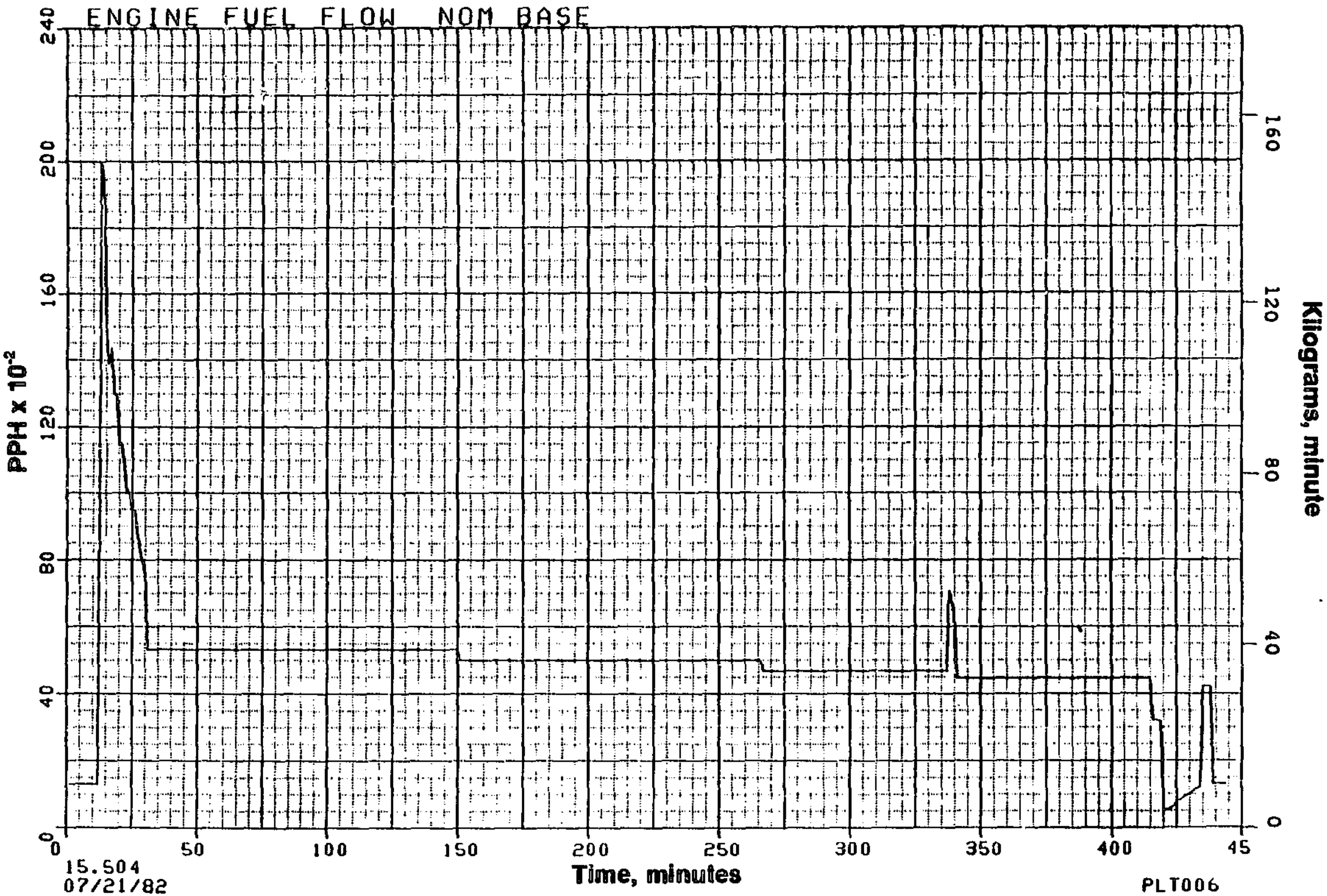


Figure 65. Nominal Flight Engine Fuel Flow.

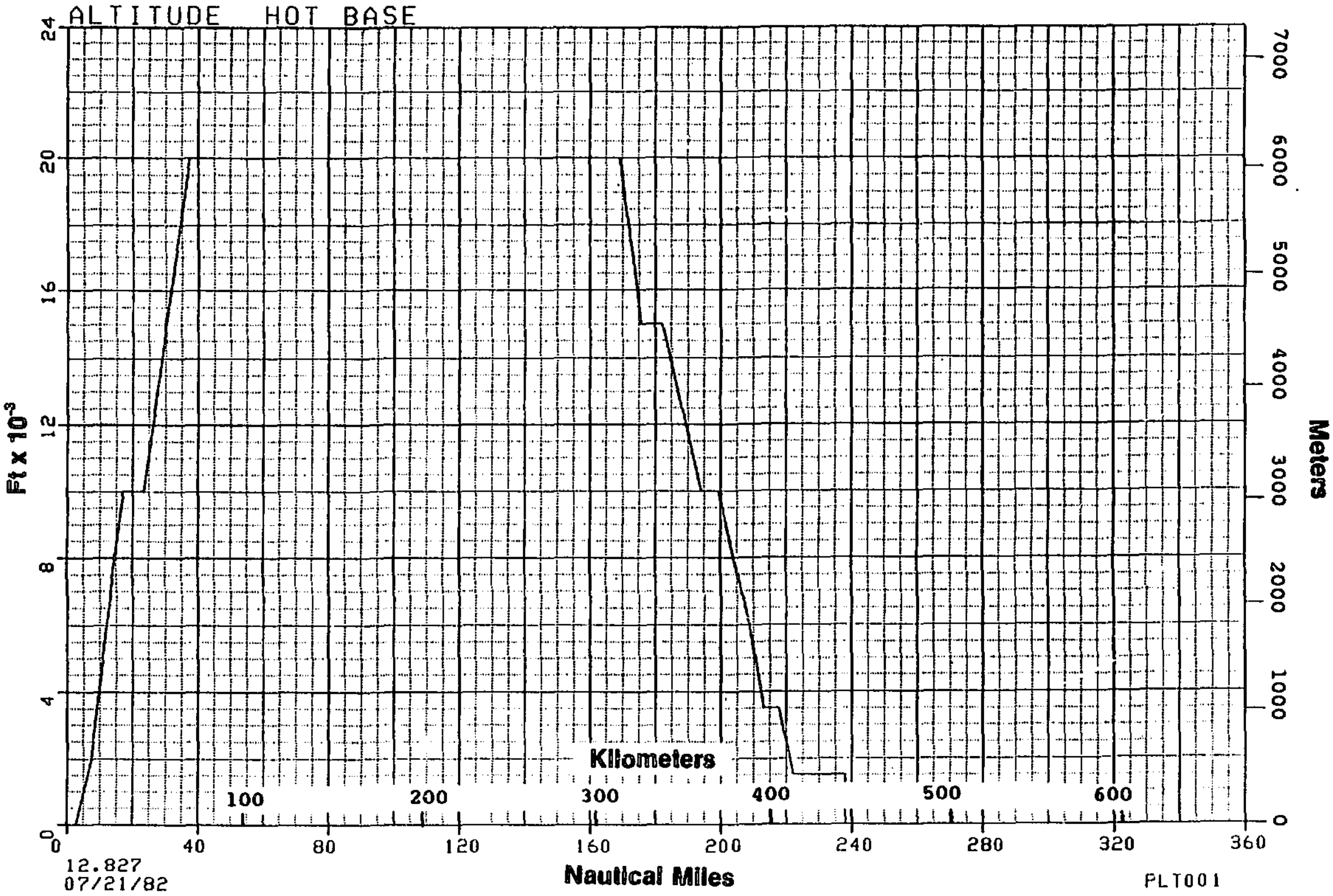


Figure 66. Hot Flight Altitude Versus Distance.

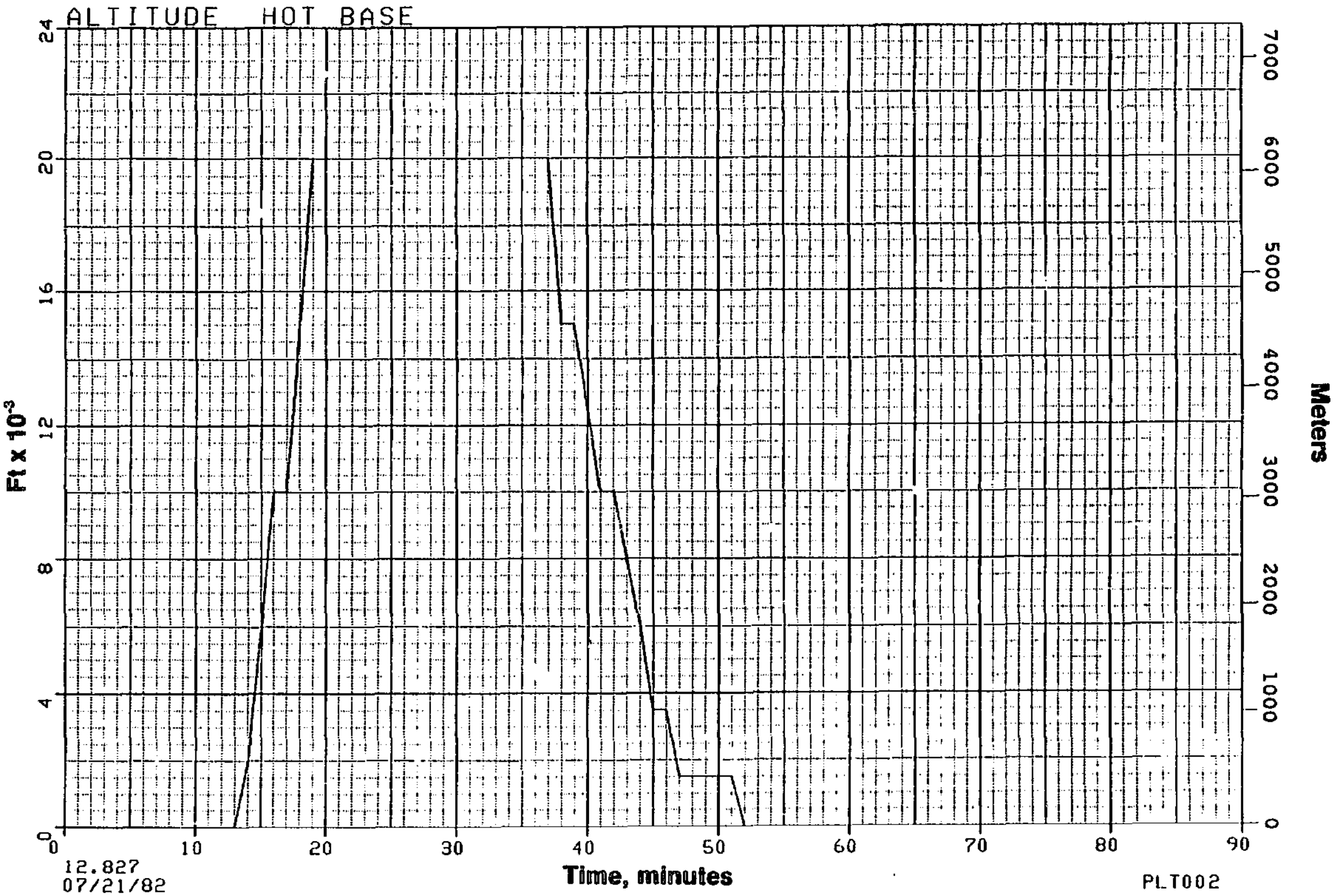


Figure 67. Hot Flight Altitude Versus Time.

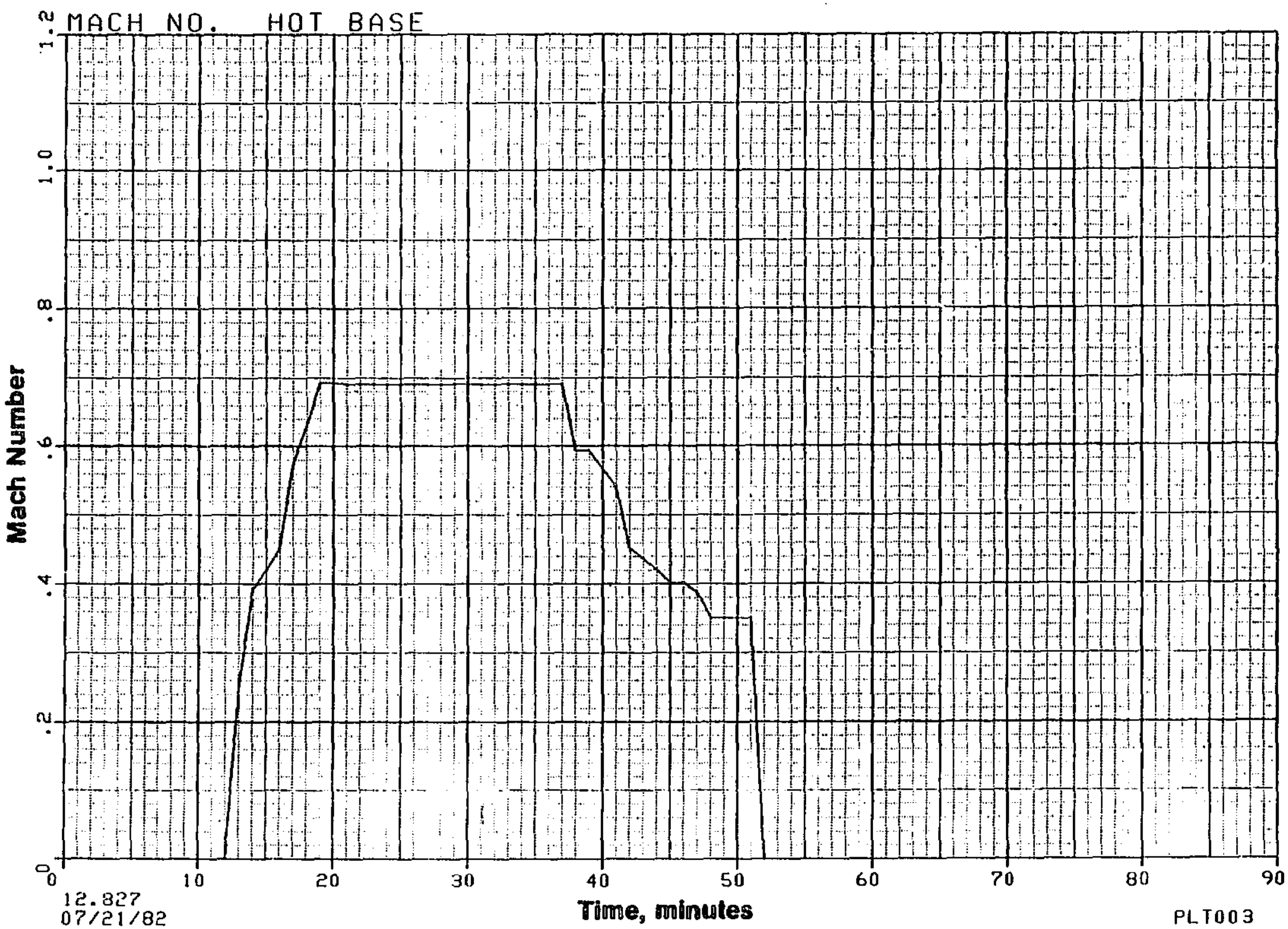


Figure 68. Hot Flight Mach Number.

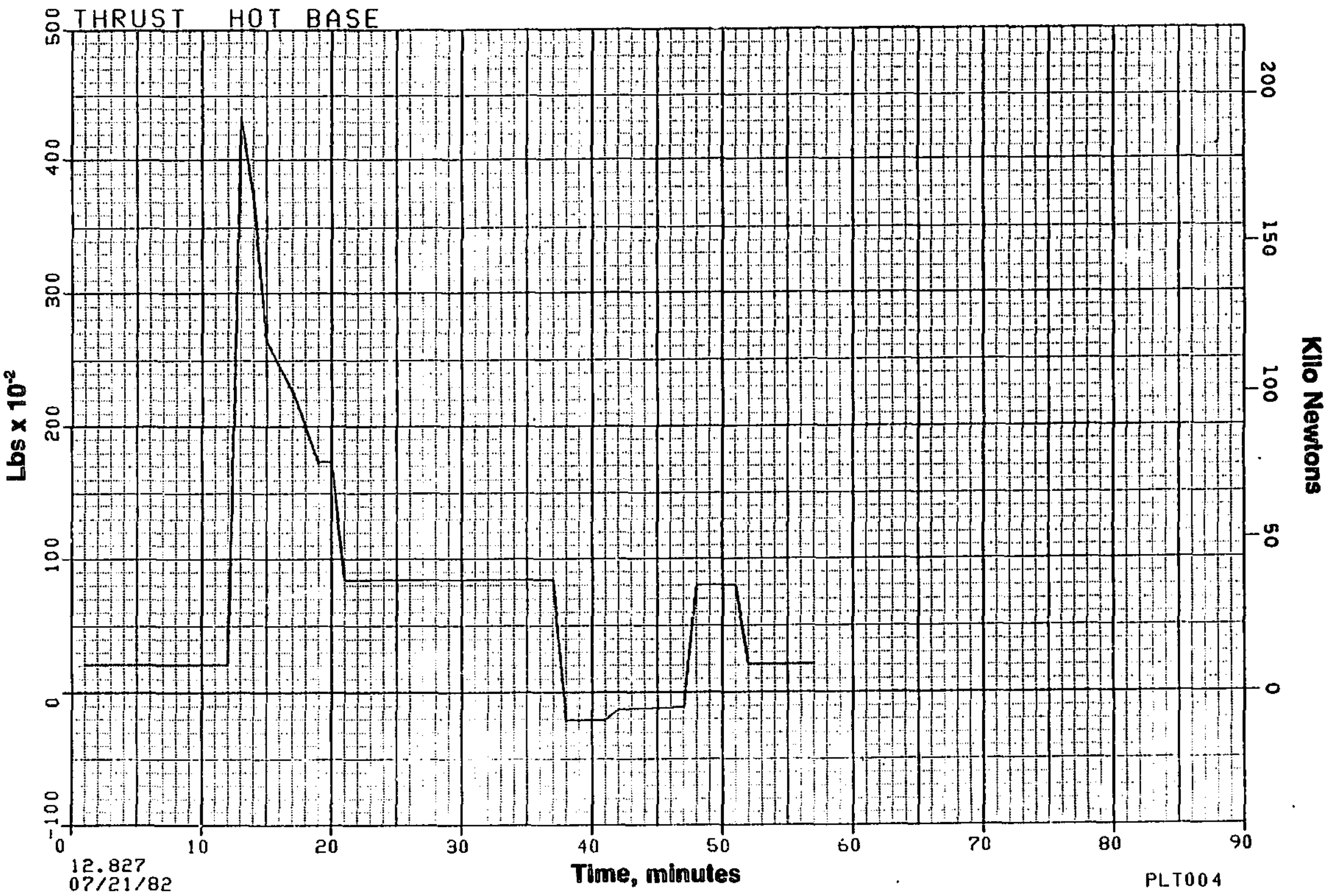


Figure 69. Hot Flight Installed Thrust.

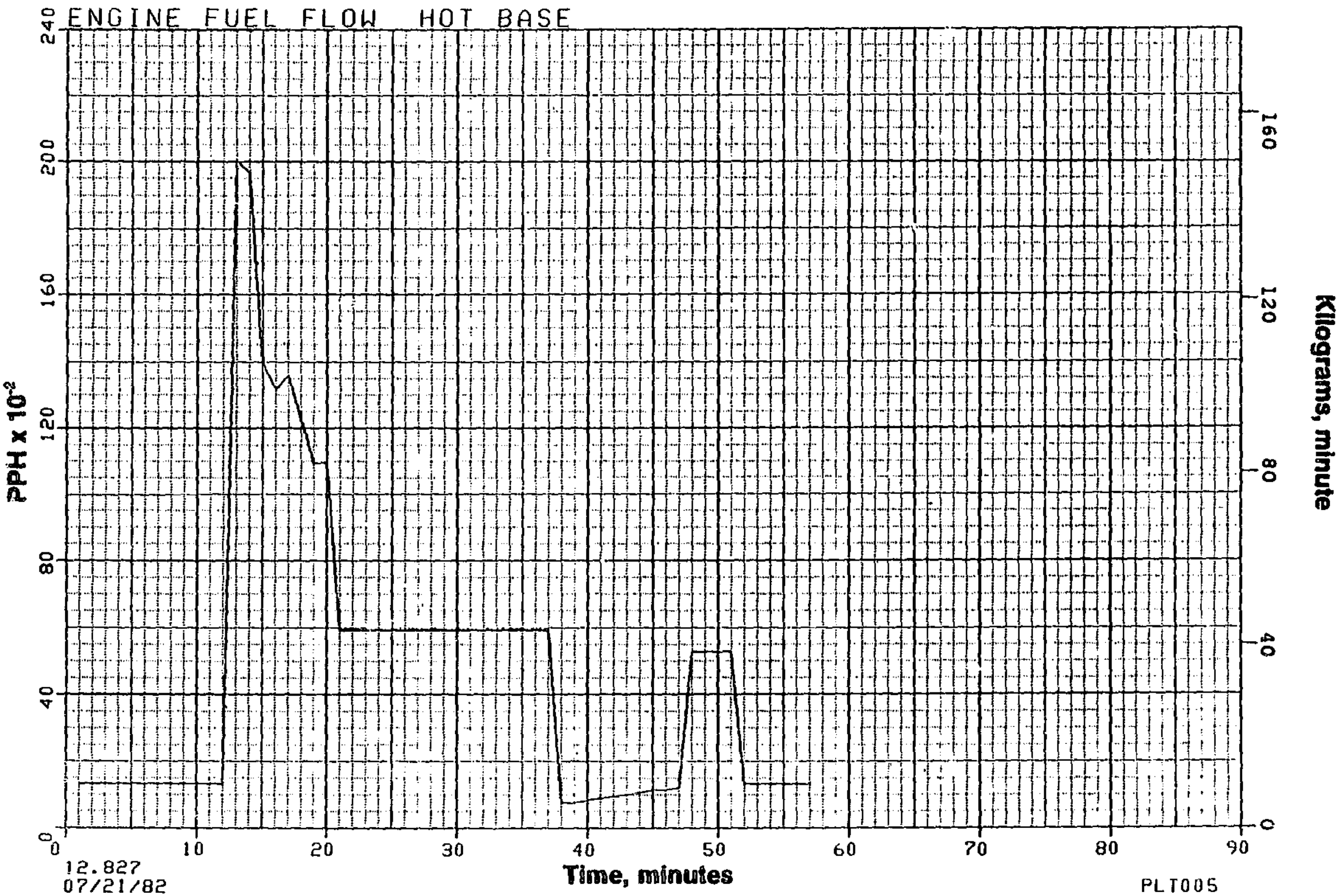


Figure 70. Hot Flight Engine Fuel Flow.

Ambient air temperature and aircraft Mach Number determine the air total temperature and the wing boundary layer recovery temperature. These results are shown in Figures 71 through 73. Figure 71 shows that the recovery temperature (T_R), which is the heat sink temperature for tank cooling, is about 2.8° C (5° F) colder than total (stagnation) temperature (T_2). The coldest value for T_R is -45.6° C (-50° F) at 11,887 m (39,000 feet) and 0.82 Mach number. At zero air speed and the same altitude and statistical probability, the tank heat sink temperature is -70° C (-94° F) (T_{amb}). Consequently, a 27.2° C (49° F) spread in temperature exists between static (T_{amb}) and total (T_2) temperature. This suggests that the analytical choice for the heat sink temperature (T_R for this study) and aircraft speed have decided influence on the results.

During the nominal flight the results shown in Figure 72 are T_{amb} of -55.6° C (-68° F), T_R of -29.4° C (-21° F) and T_2 of -26° C (-15° F). Assuming the validity of these absolute results, Jet-A fuel with a -40° C (-40° F) maximum freezing point should experience little difficulty in a -29° C (-21° F) heat sink environment. The hot flight yields a 17.2° C (63° F) recovery temperature. In total, these results indicate that from a one-day-per-year cold to one-day-per-year hot extreme, the DC-10-30 aircraft flies in a tank temperature heat sink environment varying from -45.5° C (-50° F) to 17° C (63° F). The nominal flight sees -29.4° C (-21° F). Statistically this suggests a probability toward cold temperatures in the -17.8° C (0° F) to -40° C (-40° F) range.

Tank cooling is a far more complicated issue than air temperature and fuel level in an aircraft such as the DC-10. Fuel management has a decided effect on the cooldown rate. In order to appreciate this, note the results shown in Figures 74 and 75. Figure 74 shows for the long-range cold flight how the different tank levels vary. The number 1 outboard tank level does not change until the end of the flight. This is not a static condition, however, since fuel from the auxiliary or number 2 tank flows to the outboard main before flowing to the main tank which feeds the engine. Rate of tank cooldown is strongly influenced by tank effective heat transfer area. This variation

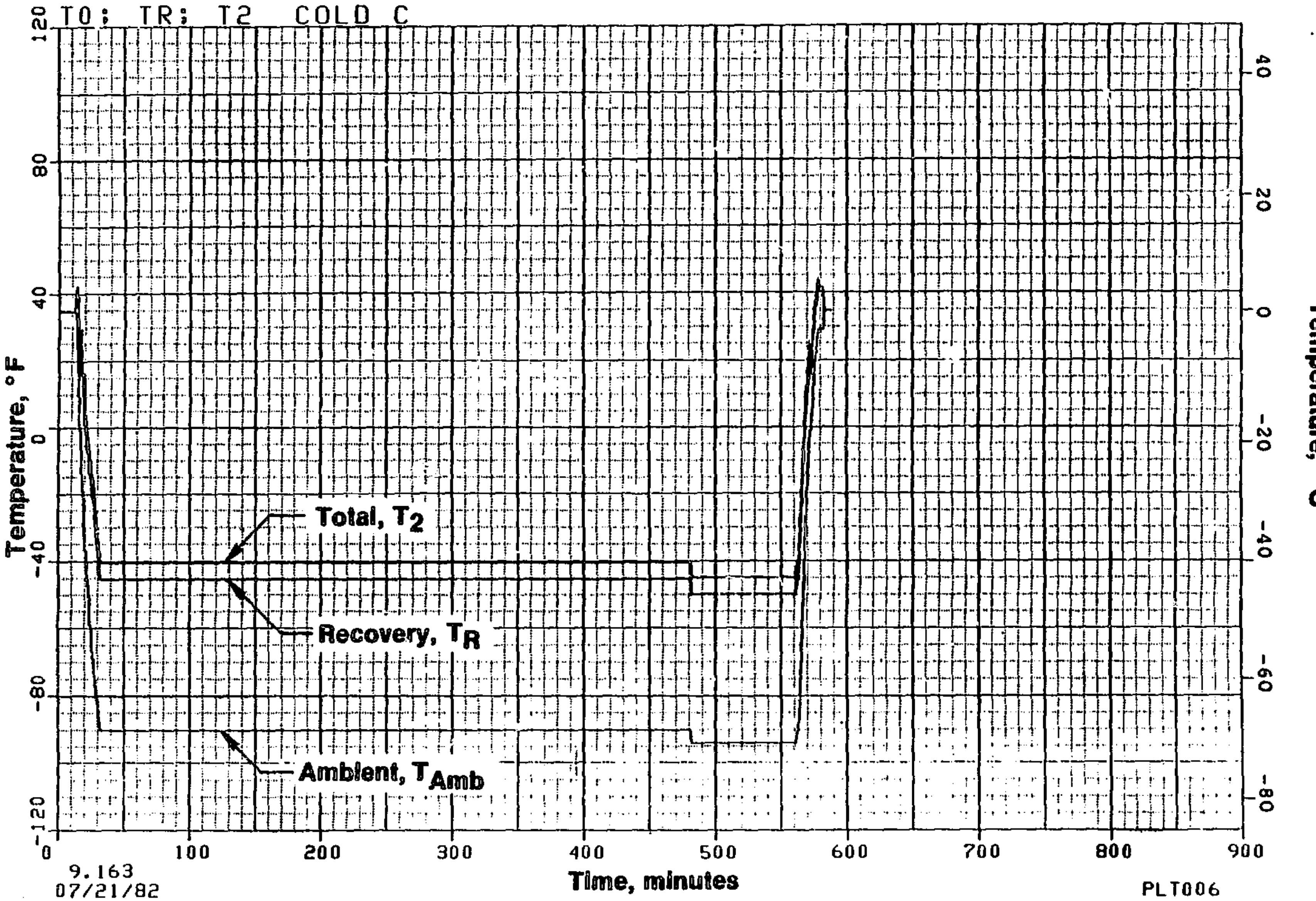


Figure 71. Cold Flight Air Temperatures.

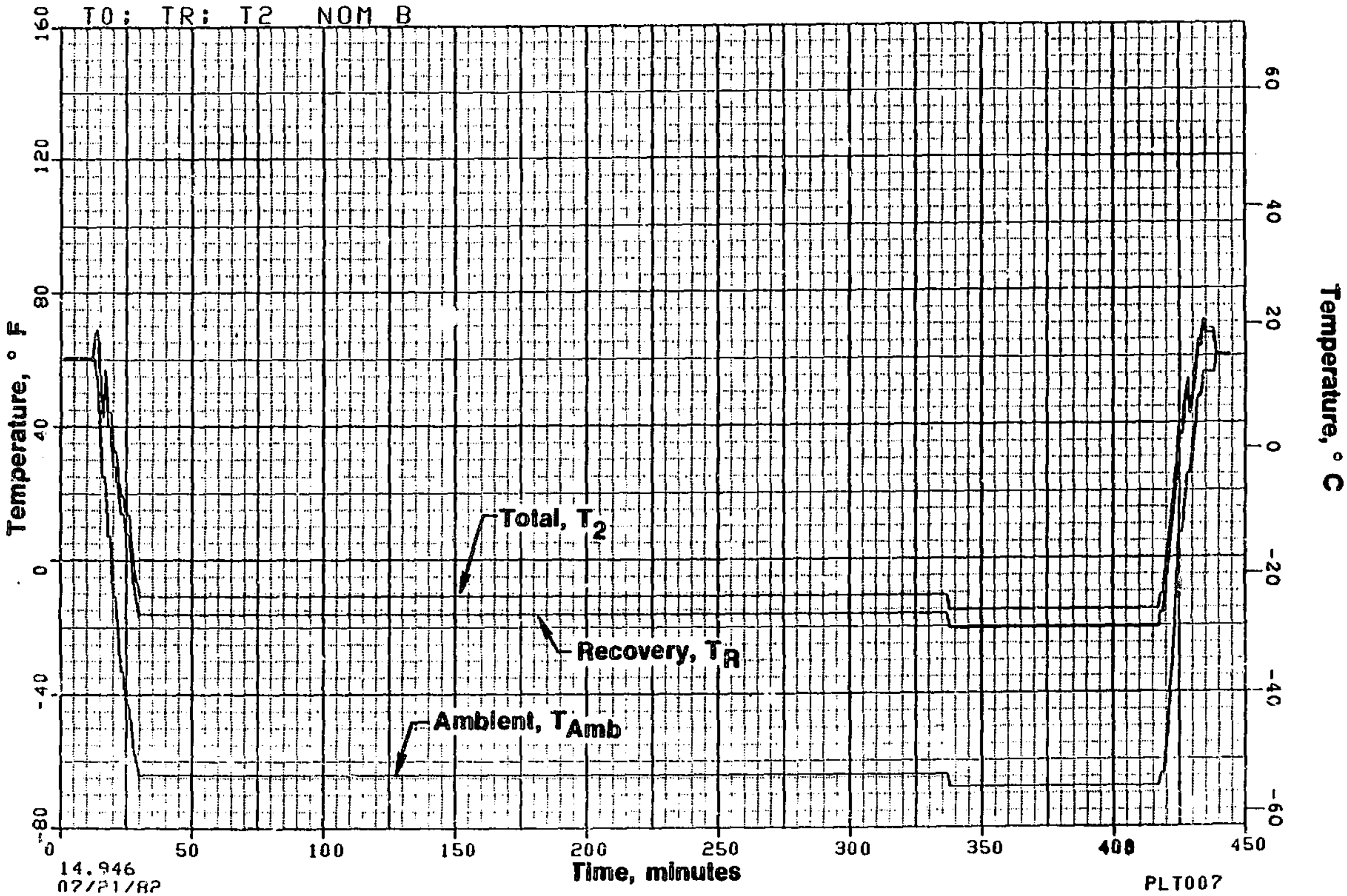


Figure 72. Nominal Flight Air Temperatures.

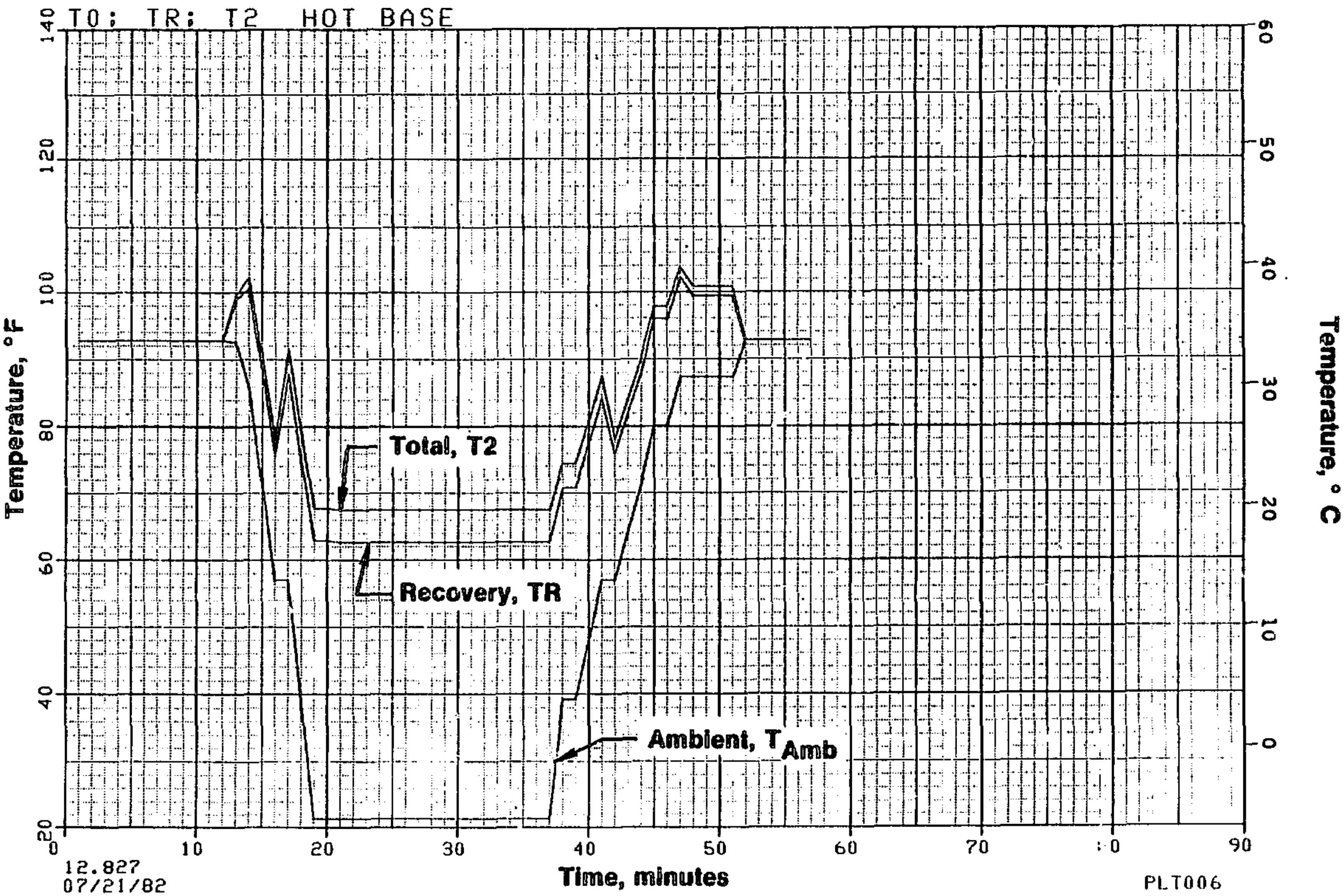


Figure 73. Hot Flight Air Temperatures.

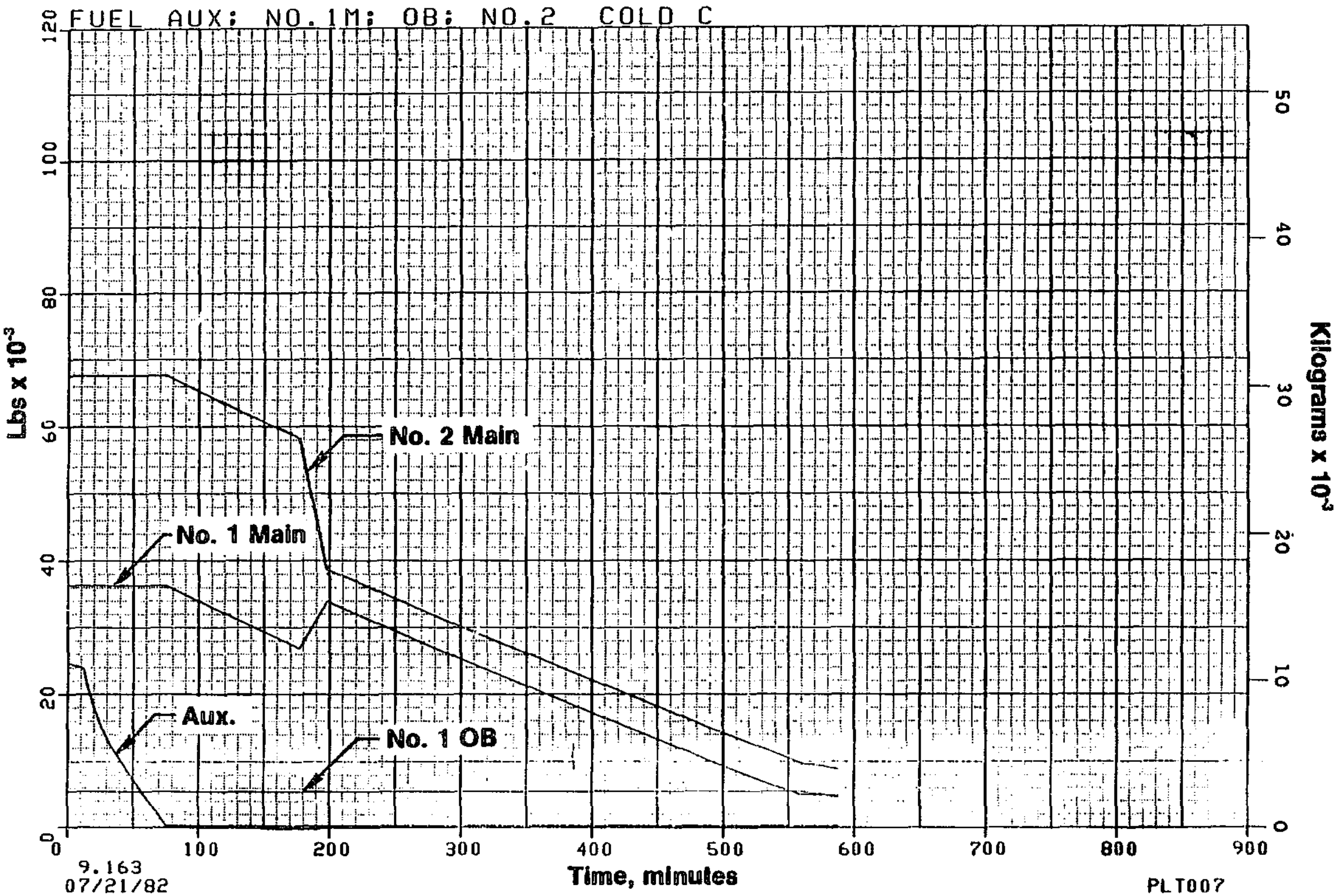


Figure 74. Cold Flight Tank Fuel Level.

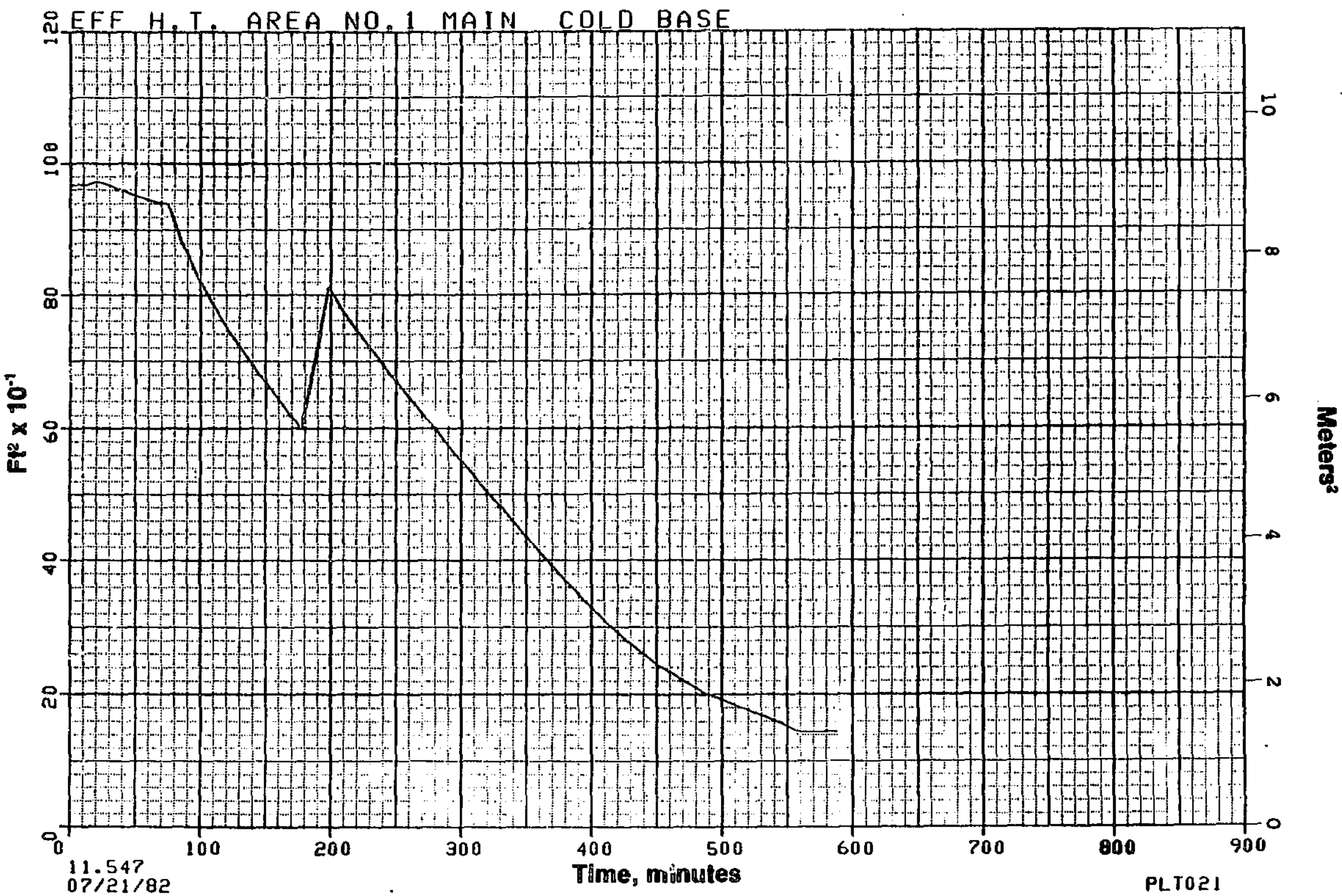


Figure 75. Cold Flight No. 1 Main Tank Heat Transfer Area.

for the number 1 main tank is shown in Figure 75. The shape of this curve is indicative of fuel management activities during the flight. Similar results for the nominal and hot flights are shown in Figures 76 and 77.

Figures 78 through 81 show the resulting fuel tank temperatures during the cold flight with the Baseline system.

As might be expected, the outboard tank is the fastest to cool down. This is seen in Figure 81 where at 178 minutes into the flight, the bulk fuel temperature has reached -42.2° C (-44° F). This is within less than 1.1° C (2° F) of the recovery heat sink temperature, T_R. For all practical purposes, the bulk fuel has reached its lowest temperature within the first third of the flight. The outboard tank appears at first to be of primary concern from a low fuel temperature standpoint. This is not necessarily the case when considering the performance of the Advanced systems and reinforces the point that fuel management has a decided influence on tank temperatures.

Figures 82 through 87 show how the advanced systems affect tank temperature during the cold flight. At this point it is necessary to point out that these results were obtained assuming no change to the DC-10-30 electrical or pneumatic (ECS) systems. For System B using IDG heat, the electrical load is 68 KVA (75 percent load on a 90 KVA generator). Additional electrical load could be demanded with corresponding increase in heat available to the fuel tanks. ECS air bleed is without wing or cowl anti-ice and at the standard 223.3° C (434° F) precooler setpoint for the DC-10-30 design. This means that for System C only a small portion of the available engine bleed heat is being utilized. This is shown in Figures 88 and 89. Bleed flow would more than double with wing anti-ice which would increase the available heat. As shown in Figure 89, very little temperature drop occurs from 8th stage bleed which is used for the study to the nominal setpoint of 223.3° C (434° F). Consequently, it should not be concluded from these results that System C lacks tank heating capability. In fact, a lower setpoint than 223.3° C (434° F), switch to 14th stage (compressor discharge) or more bleed air demand would provide additional tank heating capability

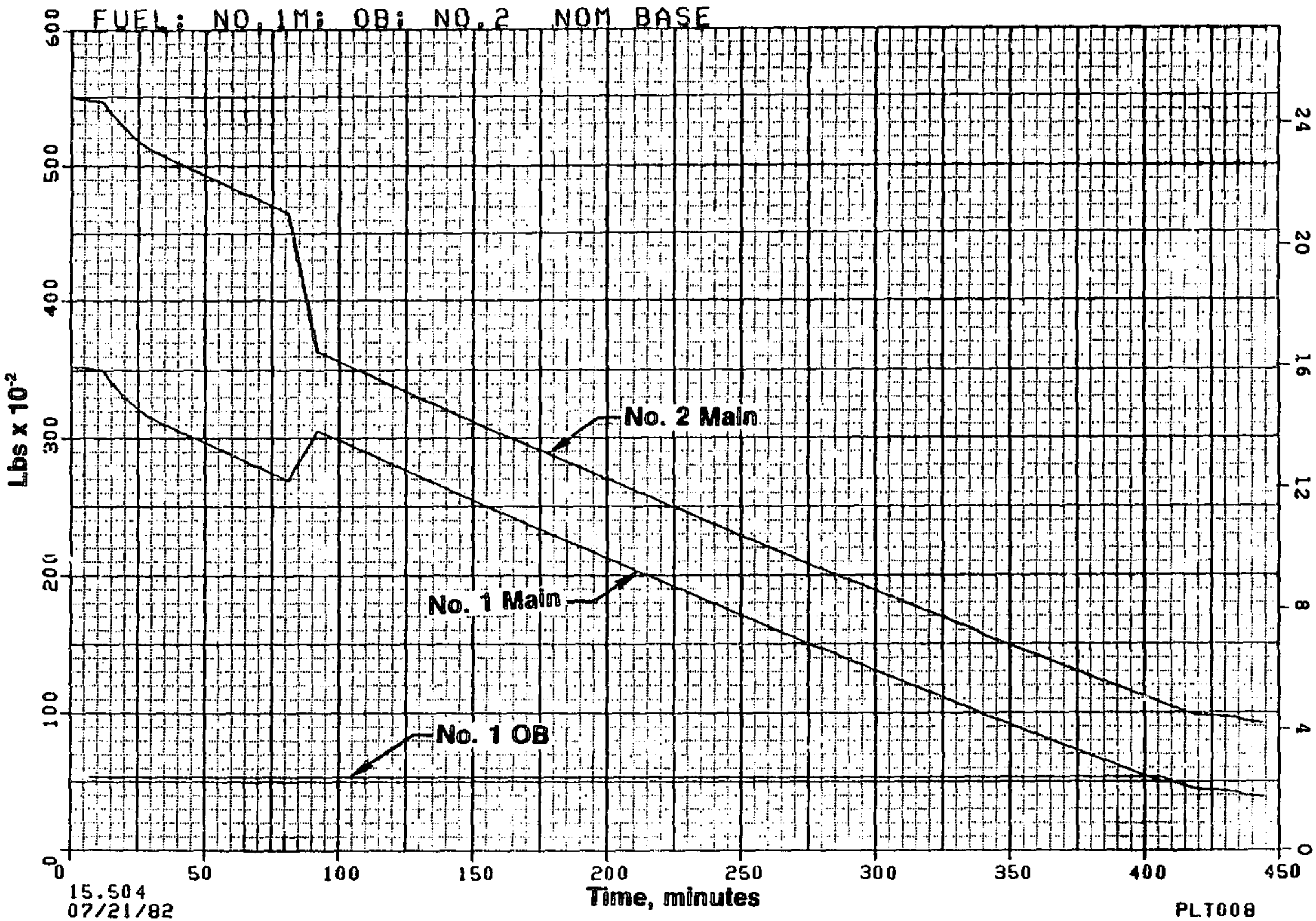


Figure 76. Nominal Flight Tank Fuel Levels.

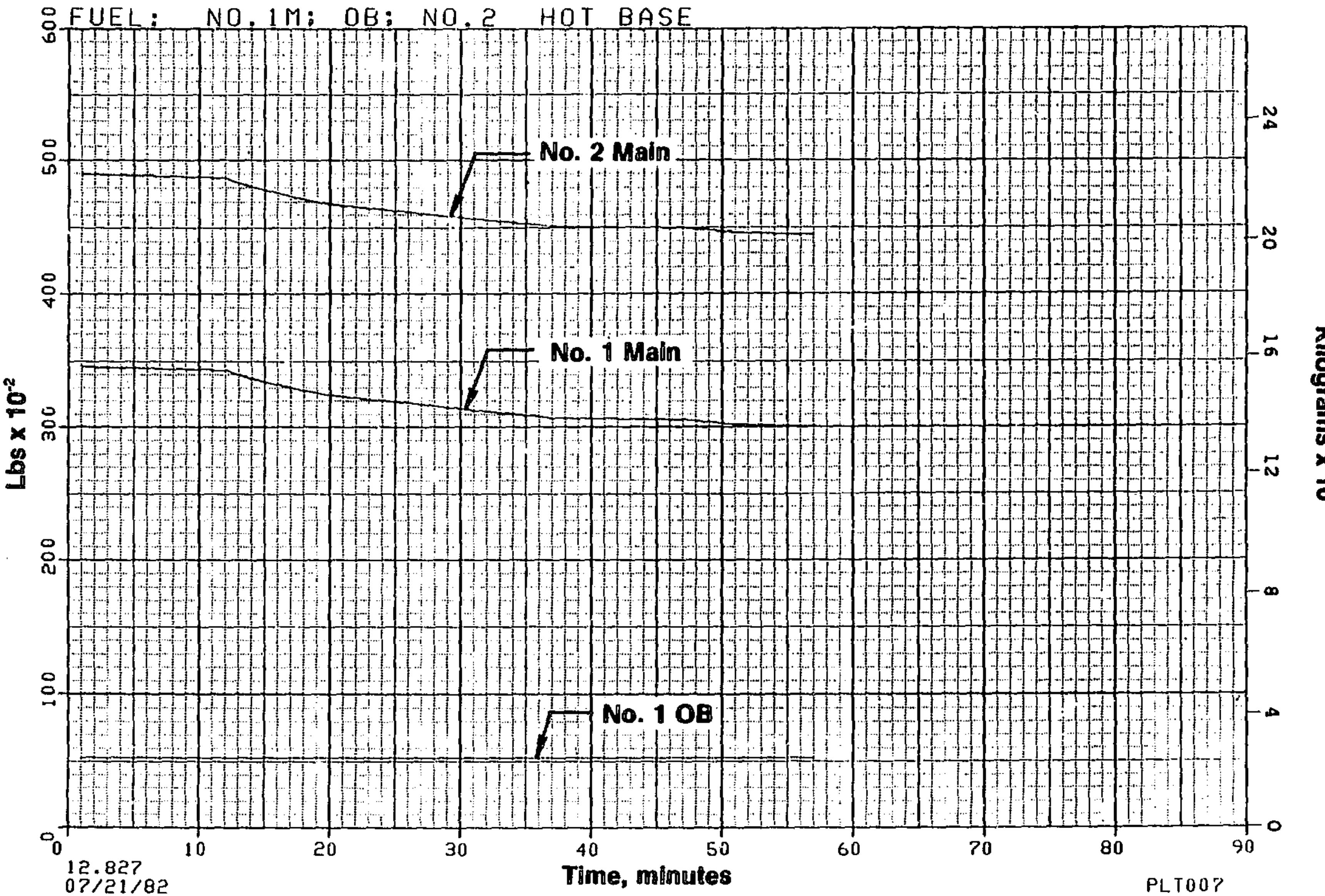


Figure 77. Hot Flight Tank Fuel Levels.

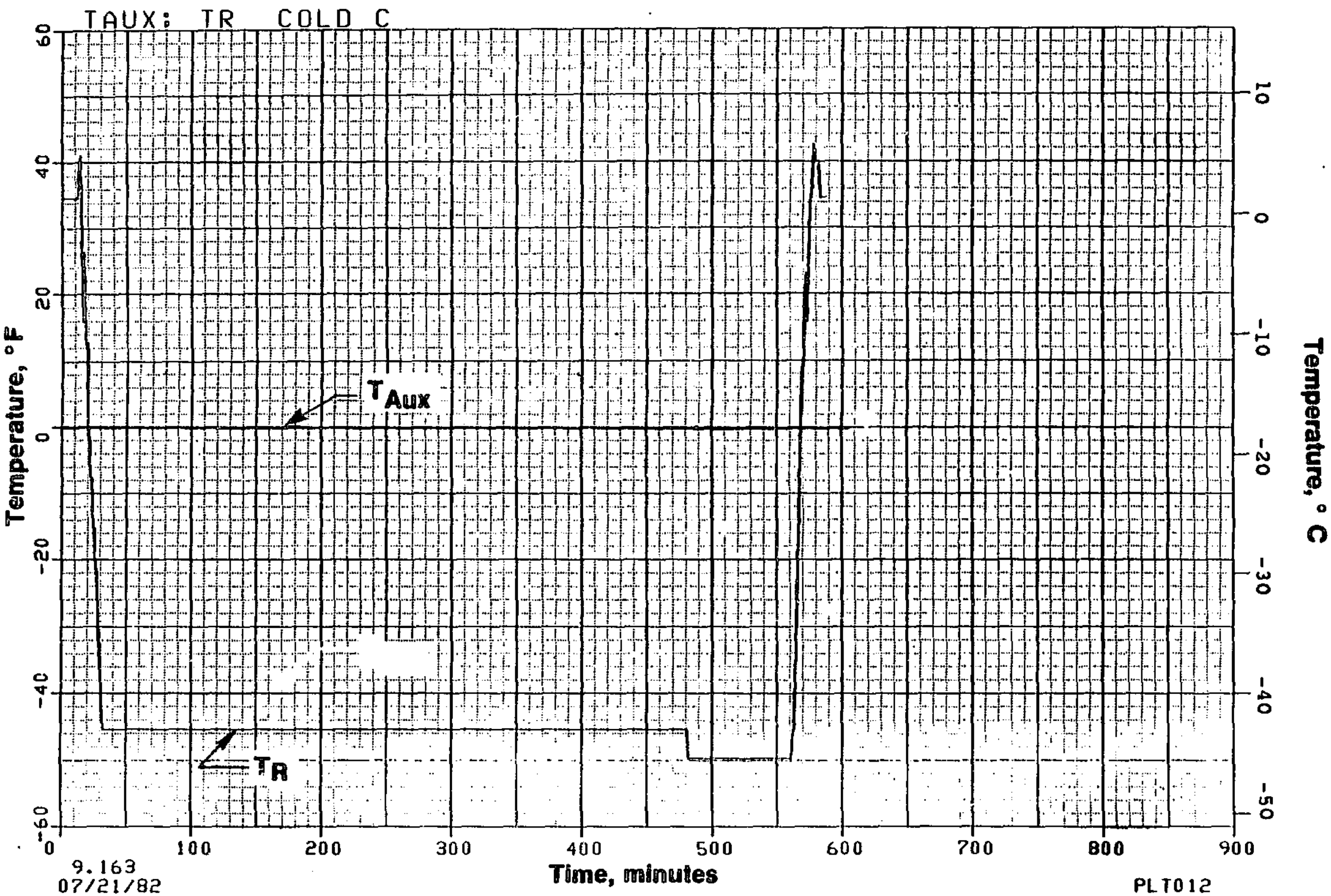


Figure 78. Cold Flight Auxiliary Tank Temperature (For All Systems).

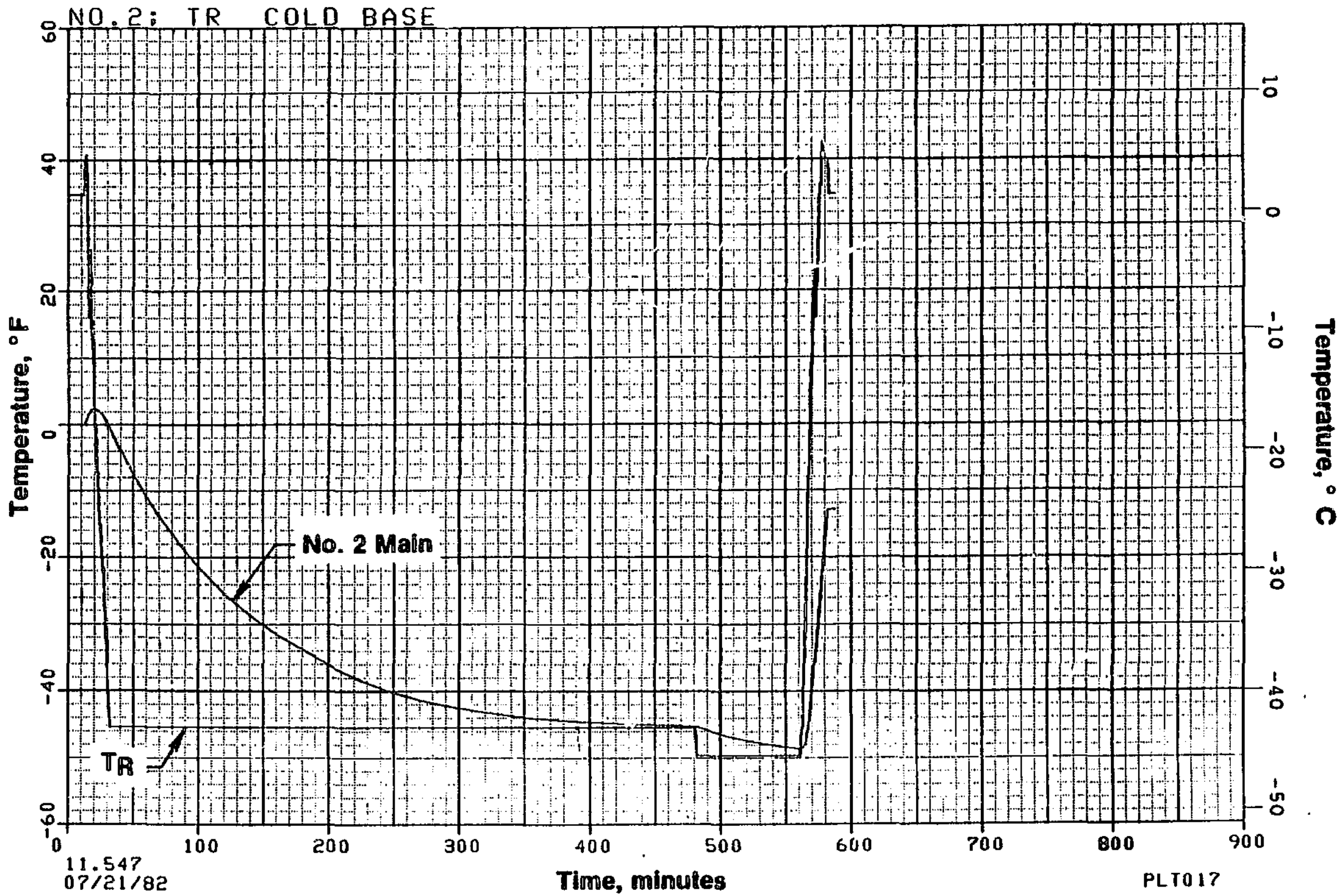


Figure 79. Baseline - Cold Flight No. 2 Main Tank Temperature.

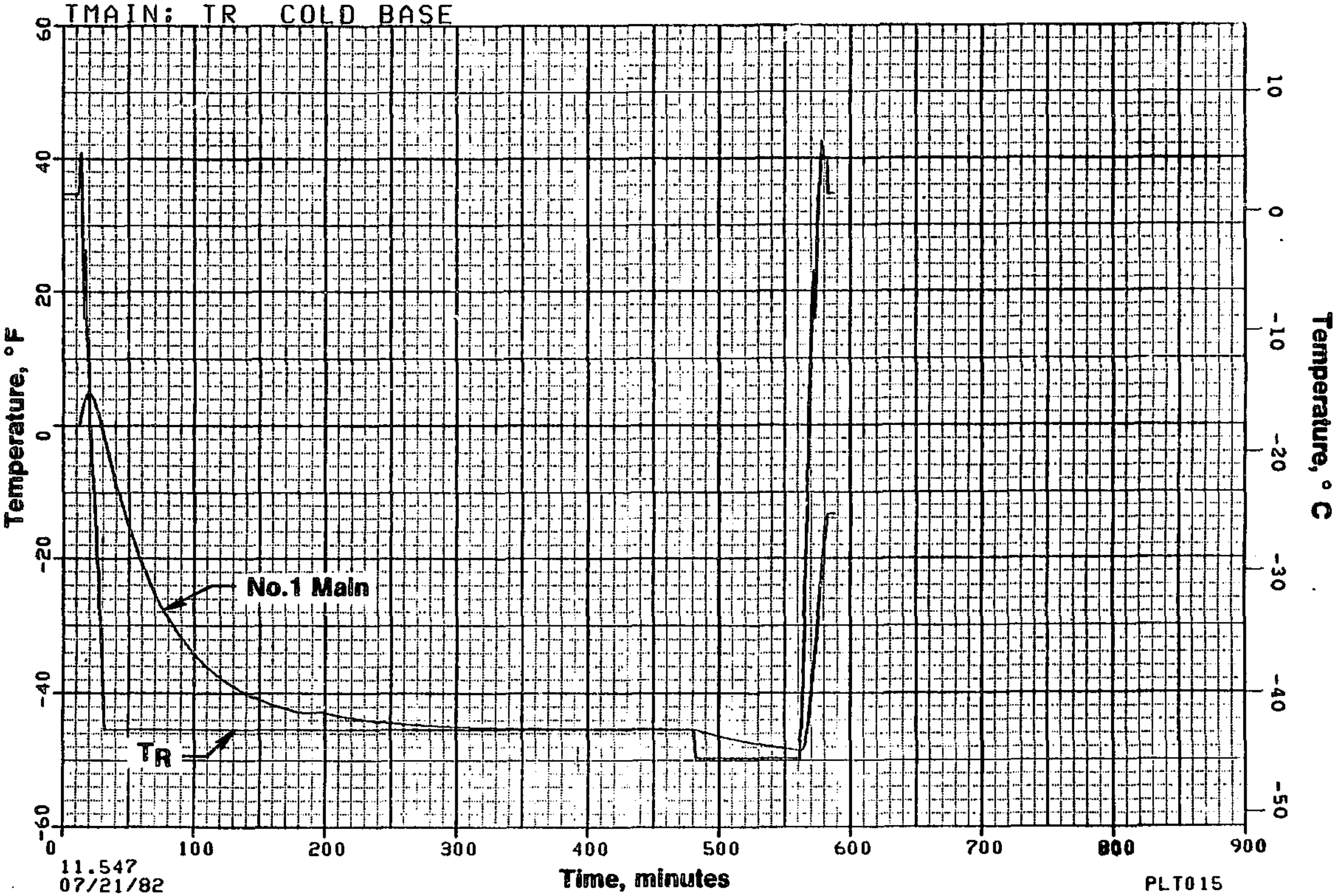


Figure 80. Baseline - Cold Flight No. 1 Main Tank Temperature.

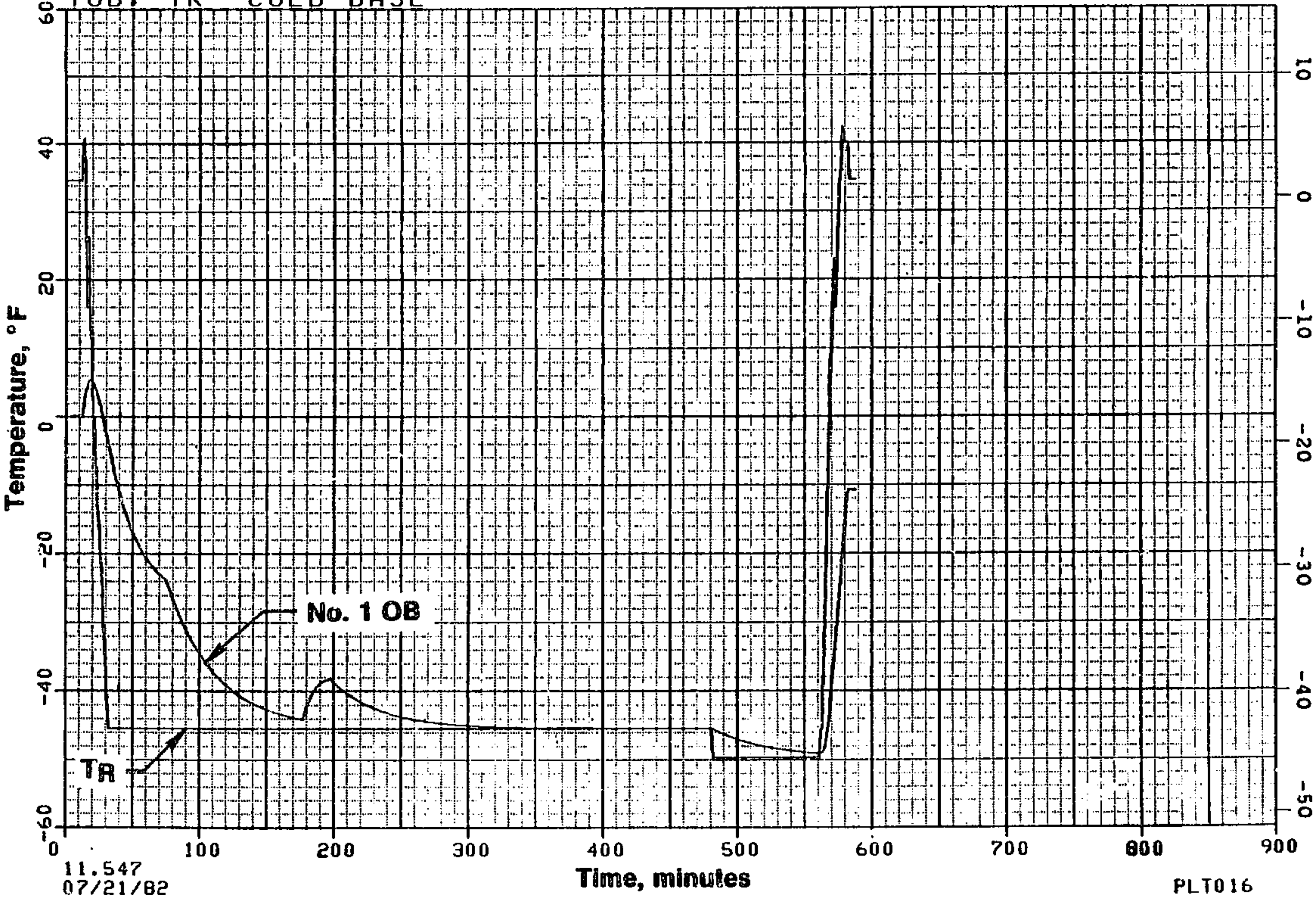


Figure 81. Baseline - Cold Flight No. 1 Outboard Tank Temperature.

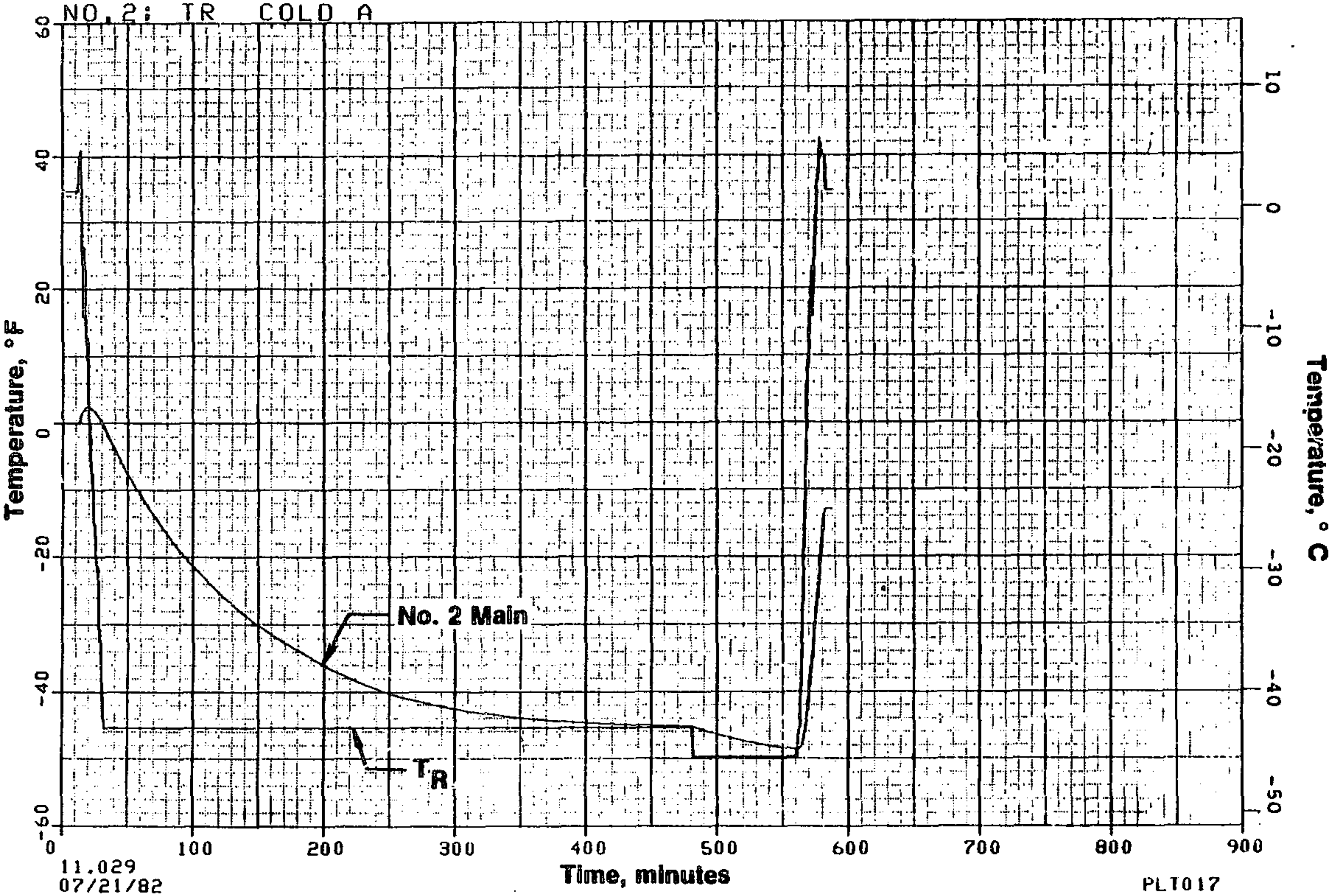


Figure 82. System A - Cold Flight No. 2 Main Tank Temperature.

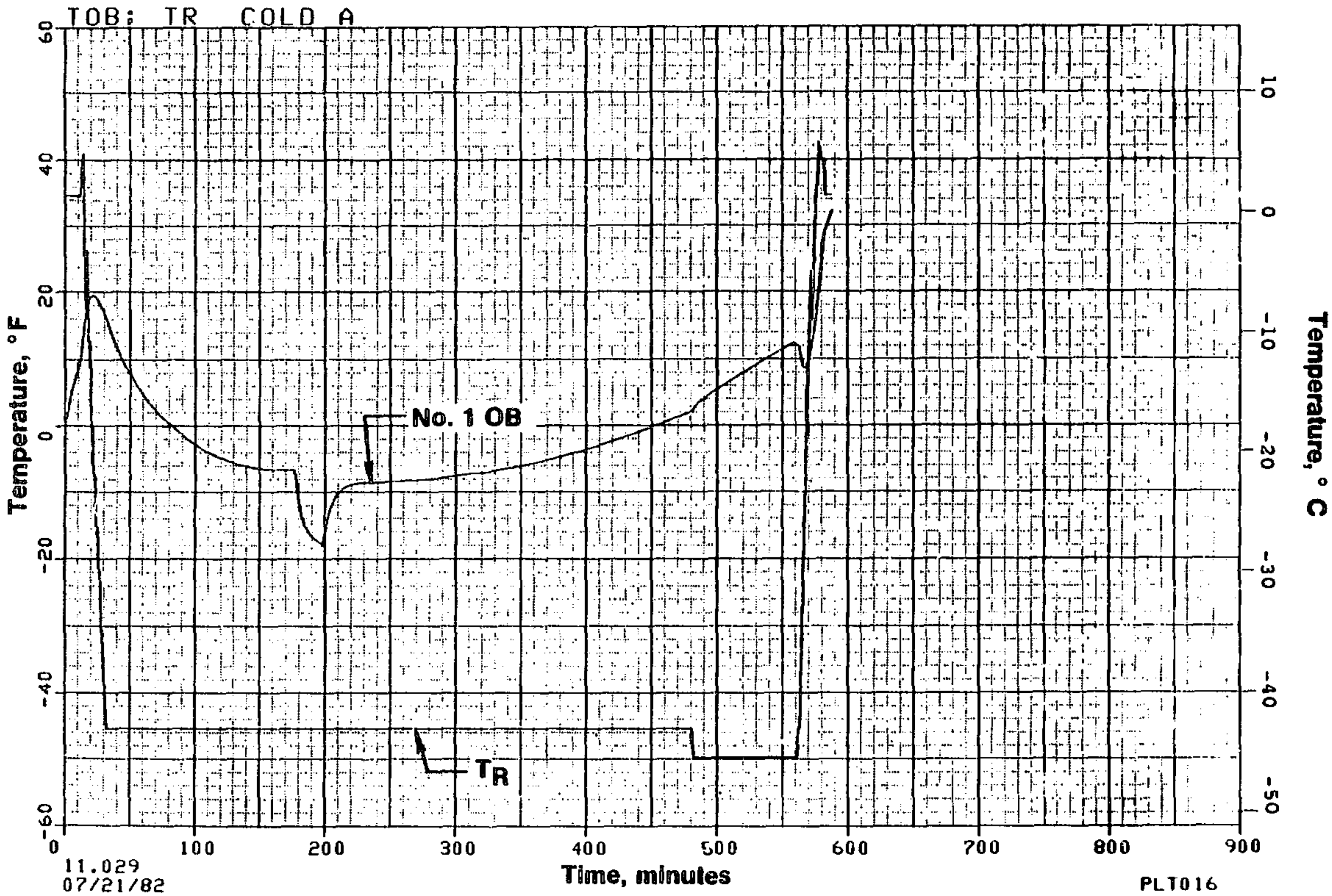


Figure 83. System A - Cold Flight No. 1 Outboard Tank Temperature.

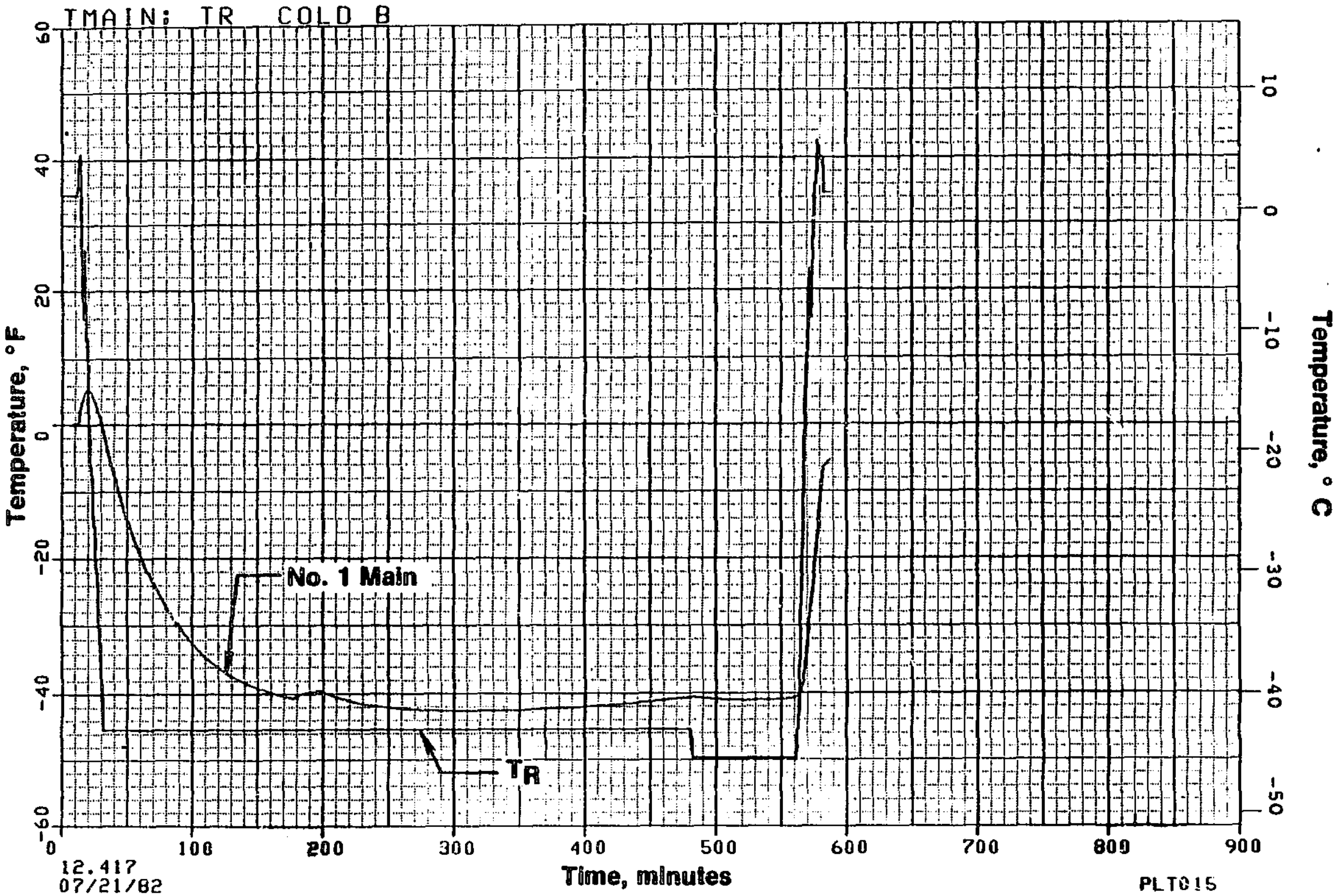


Figure 84. System B - Cold Flight No. 1 Main Tank Temperature.

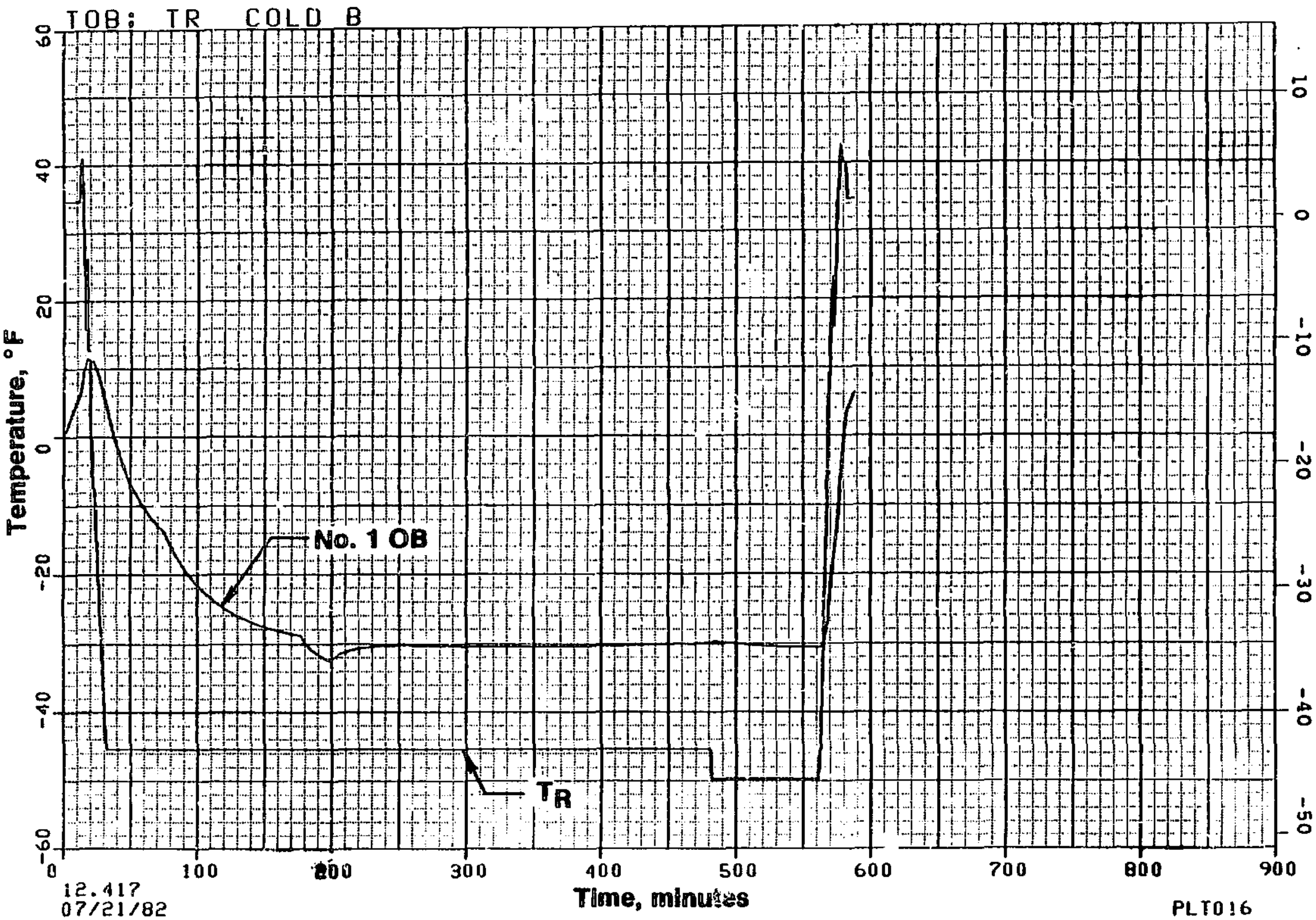


Figure 85. System B - Cold Flight No. 1 Outboard Tank Temperature.

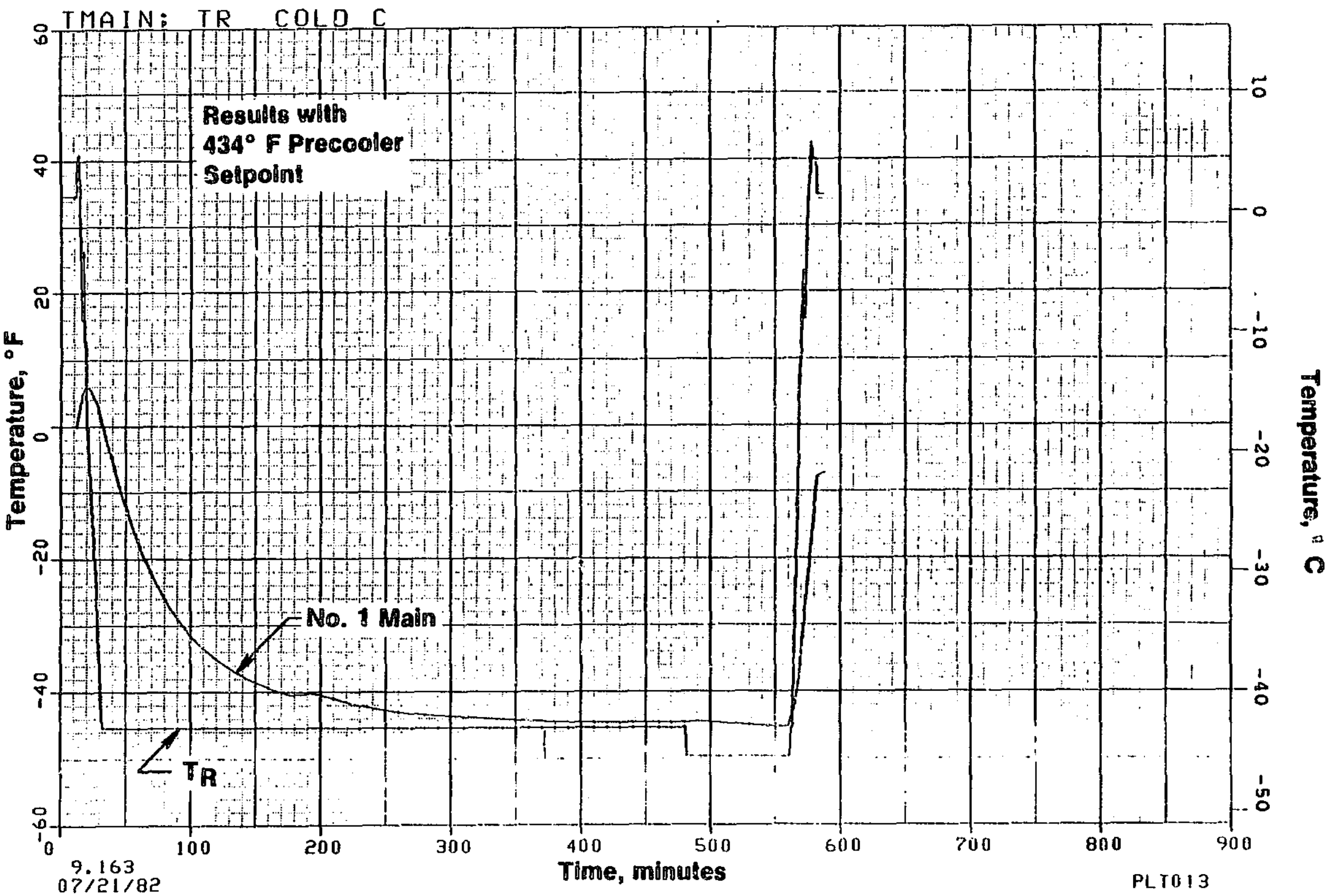


Figure 86. System C - Cold Flight No. 1 Main Tank Temperature.

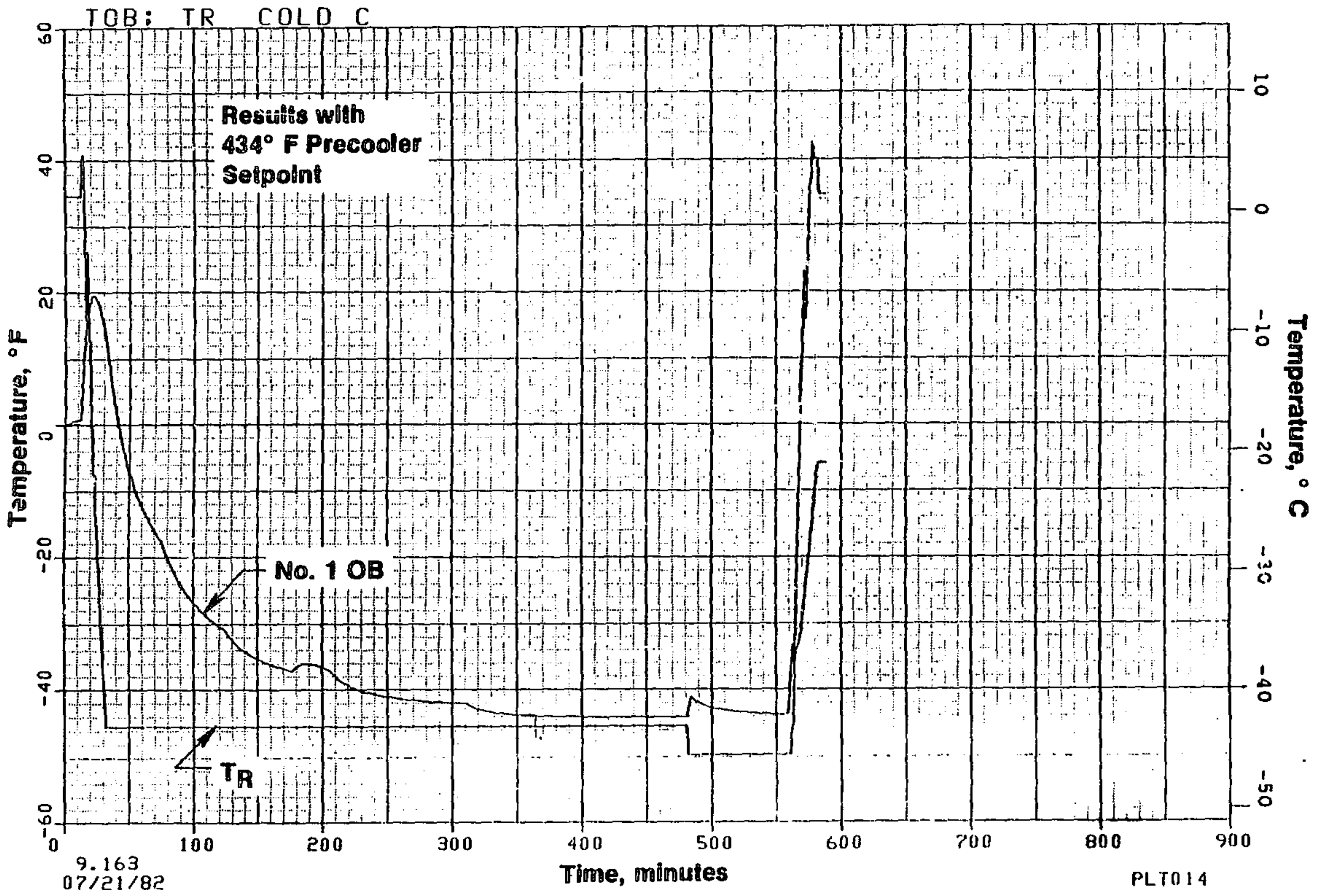


Figure 87. System C - Cold Flight No. 1 Outboard Tank Temperature.

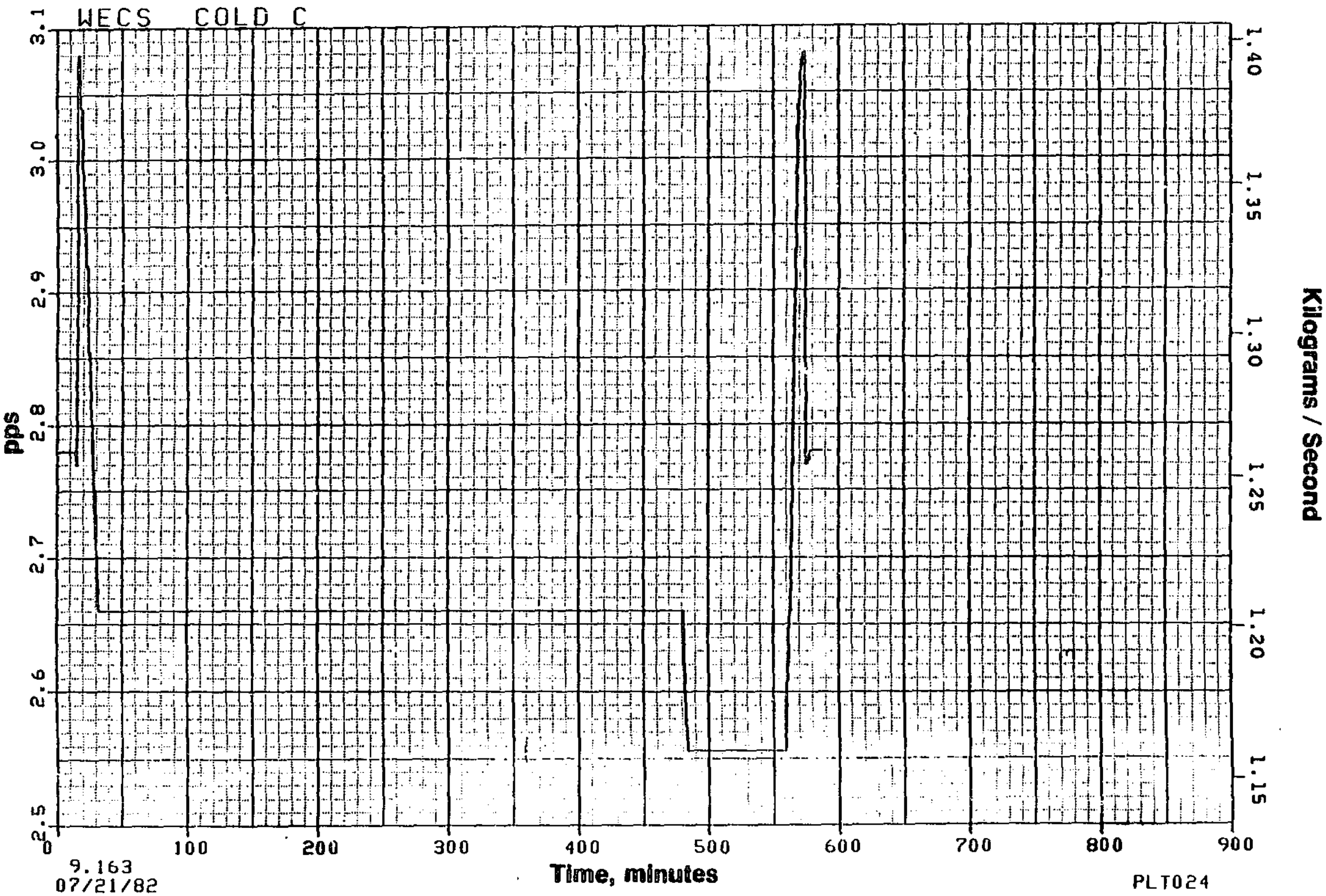


Figure 88. Cold Flight ECS Bleed Air Flow.

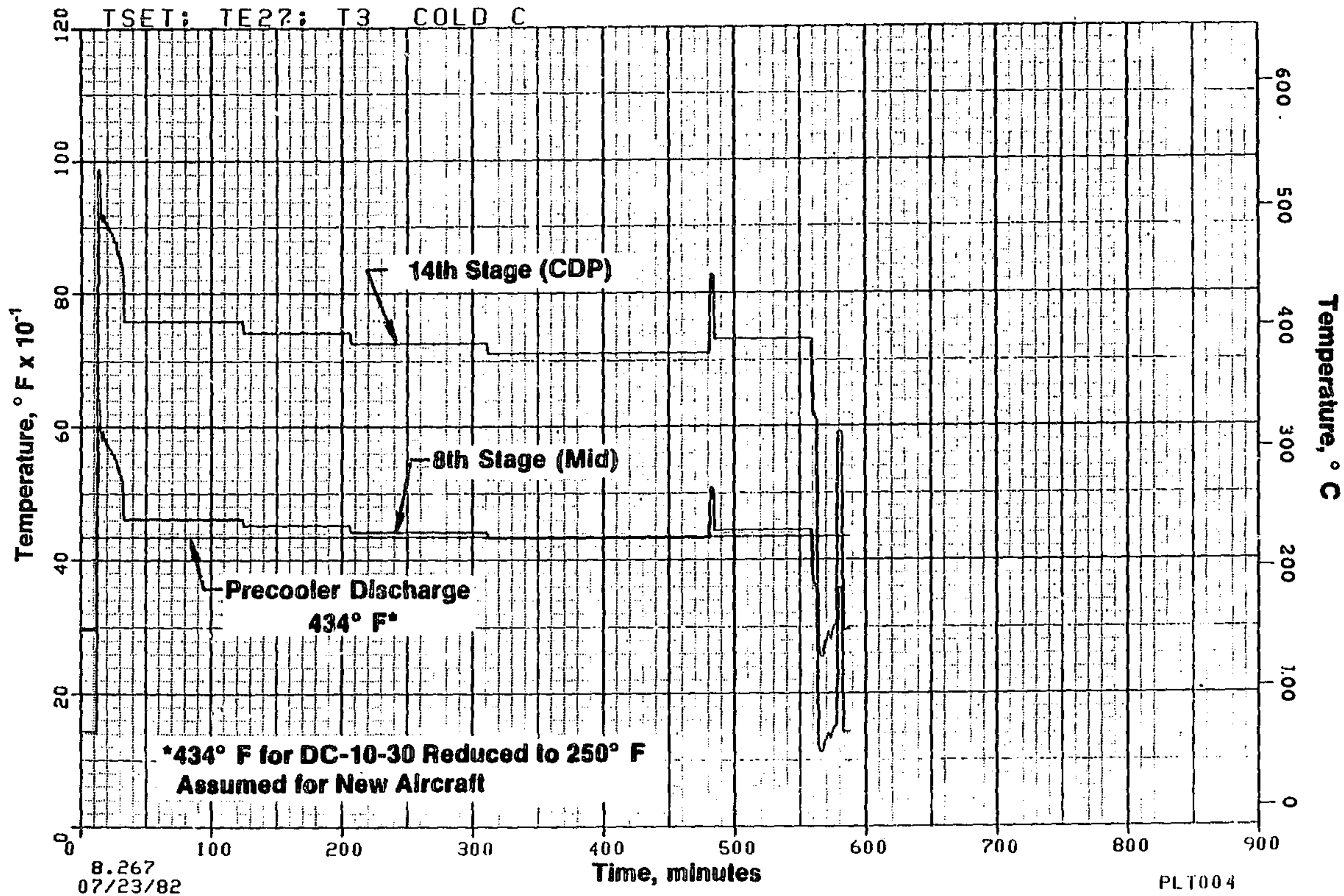


Figure 89. System C - Cold Flight ECS Bleed Air Temperatures and Precooler Setpoint.

since the available heat is a function of the flow rate and temperature difference. To illustrate this point, additional computer runs were made for the cold flight using a 121.1° C (250° F) precooler setpoint which increased the temperature difference and thus the available heat. These results are shown in Figures 90 and 91. Although not specifically evaluated for the DC-10-30, a 121.1° C (250° F) air supply to the ECS is considered acceptable for cabin heating. Table 9 summarizes the cold flight tank heating analysis.

Tank fuel temperature results for the hot flight are shown in Figures 92 through 99. Tables 10 and 11 summarize significant results for nominal and hot flights.

8.4 ENGINE TEMPERATURES

Several engine fluid system temperatures are of interest. Again, it must be pointed out that the present study did not attempt to refine system control parameters. The objective in terms of numerical results was to model each system on the basis of existing parameters, associated with the DC-10-30 and the CF6-80X.

Fuel system ice protection is an issue which must be addressed so long as anti-icing inhibitor is not required by the fuel specification.--This is presently the case with commercial grade jet fuels. Figure 100 shows the baseline results during the one-day-per-year cold flight. Main filter inlet temperature is the main concern from the standpoint of fuel icing. It is the first fine-micron filter in the fuel system and could block in the presence of water (or ice) at temperatures below 0° C (32° F). Although filter bypass is provided on all General Electric engines, the customary design requirement is to assure that ice blockage does not occur. Note that the filter temperature is well above 0° C (32° F) during the baseline cold flight. On the CF6 family of engines, fuel heating is provided by engine lube system heat rejection. Figure 101 shows the corresponding baseline oil temperatures which are above the 32.2° C (90° F) limit desired during steady state operation. Figures 102 through 108 show corresponding cold flight results for the advanced systems.

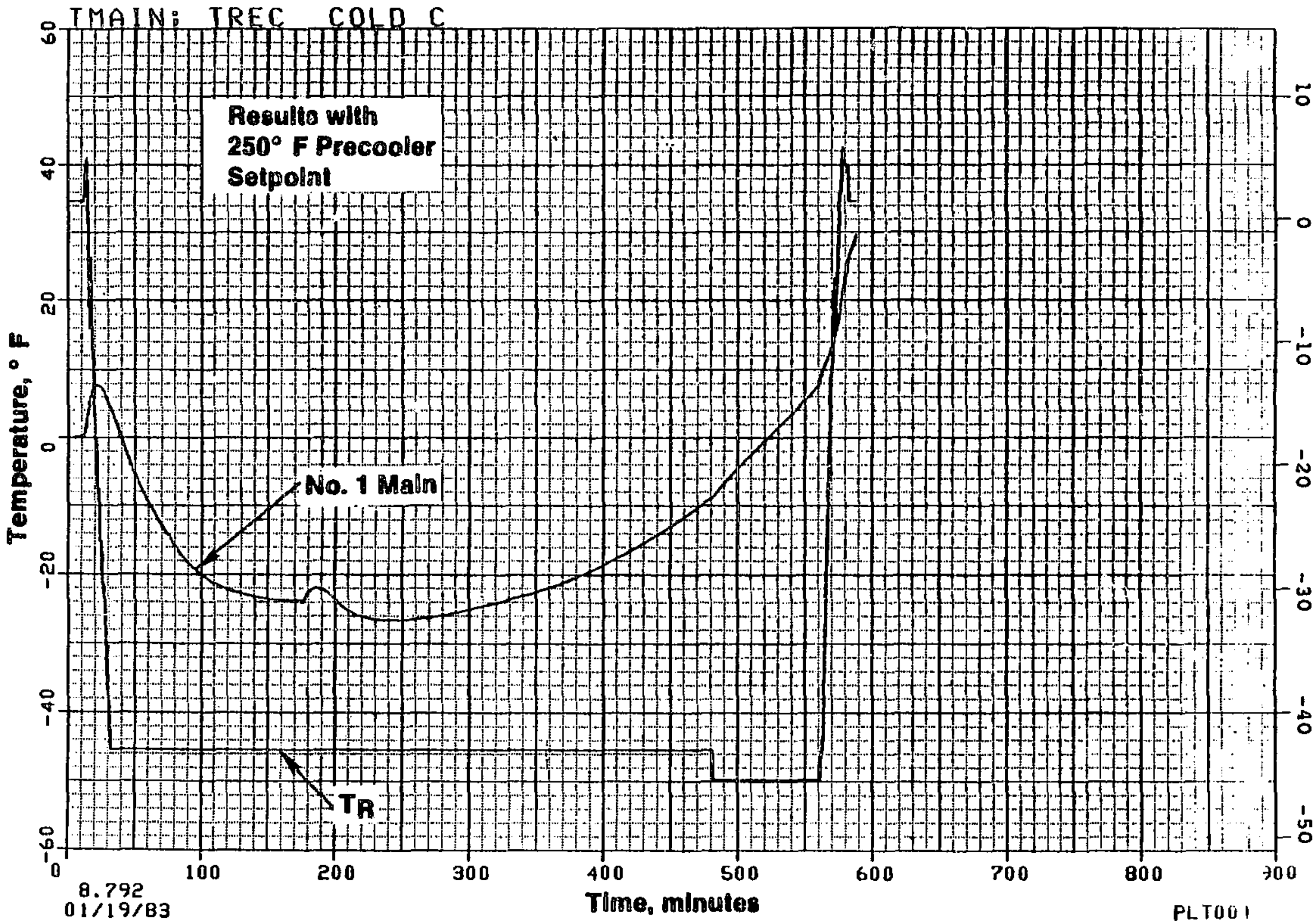


Figure 90. System C - Cold Flight No. 1 Main Tank Temperature.

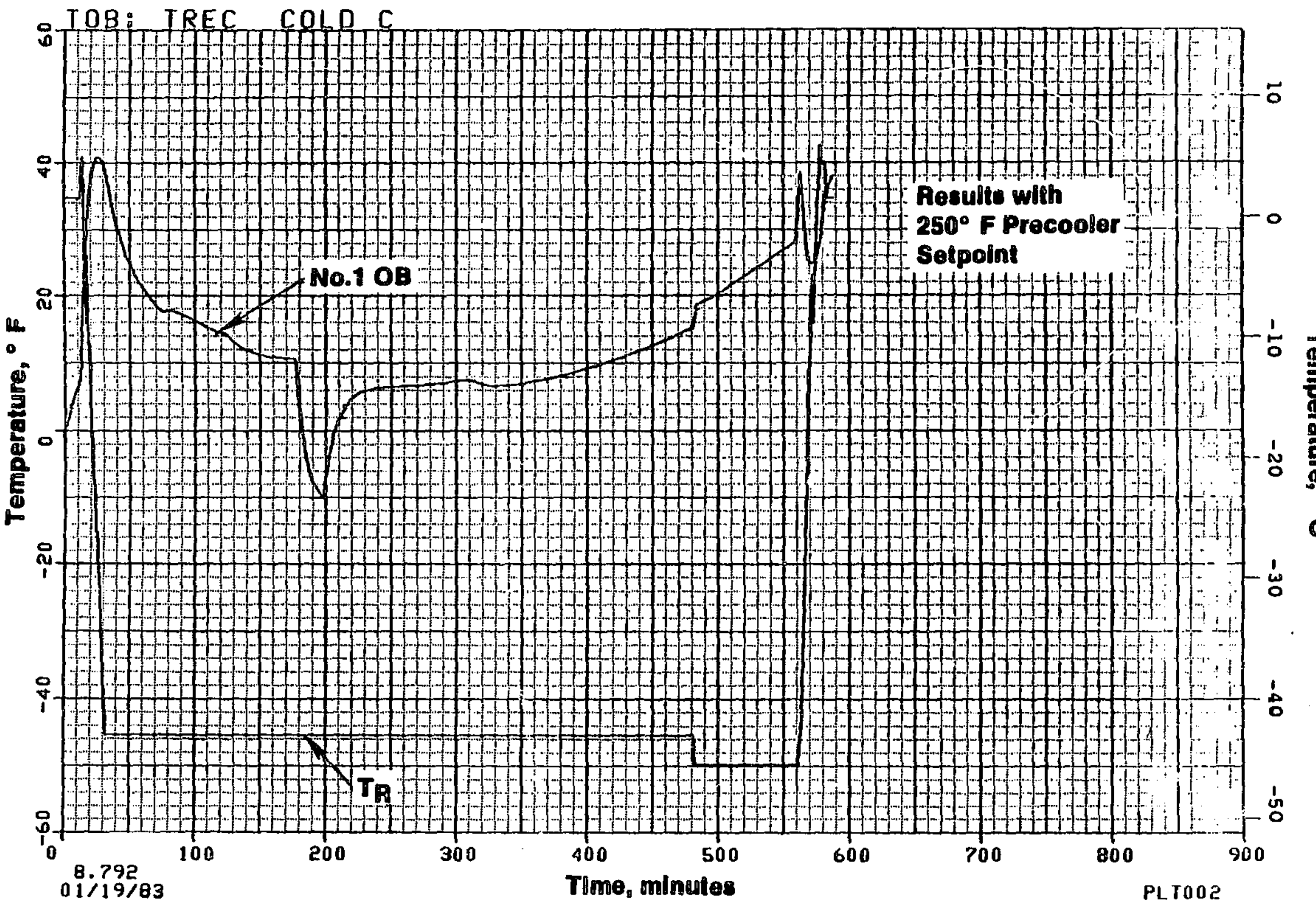


Figure 91. System C - Cold Flight No. 1 Outboard Tank Temperature.

TABLE 9. COLD FLIGHT TANK TEMPERATURES
MINIMUM DURING FLIGHT - °F (°C)

	Baseline	System A	System B	System C**
No. 2 Main	-49 (-45)	*	*	*
No. 1 Main	-49 (-45)	-29 (-34)	-43 (-42)	-26 (-32)
No. 1 Outboard	-49 (-45)	-18 (-28)	-32 (-36)	-10 (-23)

Fuel Loading Temperature = 0° F (-18° C)

Spec Max Freezing Point +5° F (+3° C)

Jet-B = -53 (-47)

Jet-A = -35 (-37)

Study Fuel = -12 (-24)

Minimum Air Temperature

T_{Amb} **= -94 (-70)**

T_R **= -50 (-46)**

T_2 **= -45 (-43)**

* No Advanced Systems on No. 2 Engine

** System C With 250° F (121° C) Precooler Setpoint

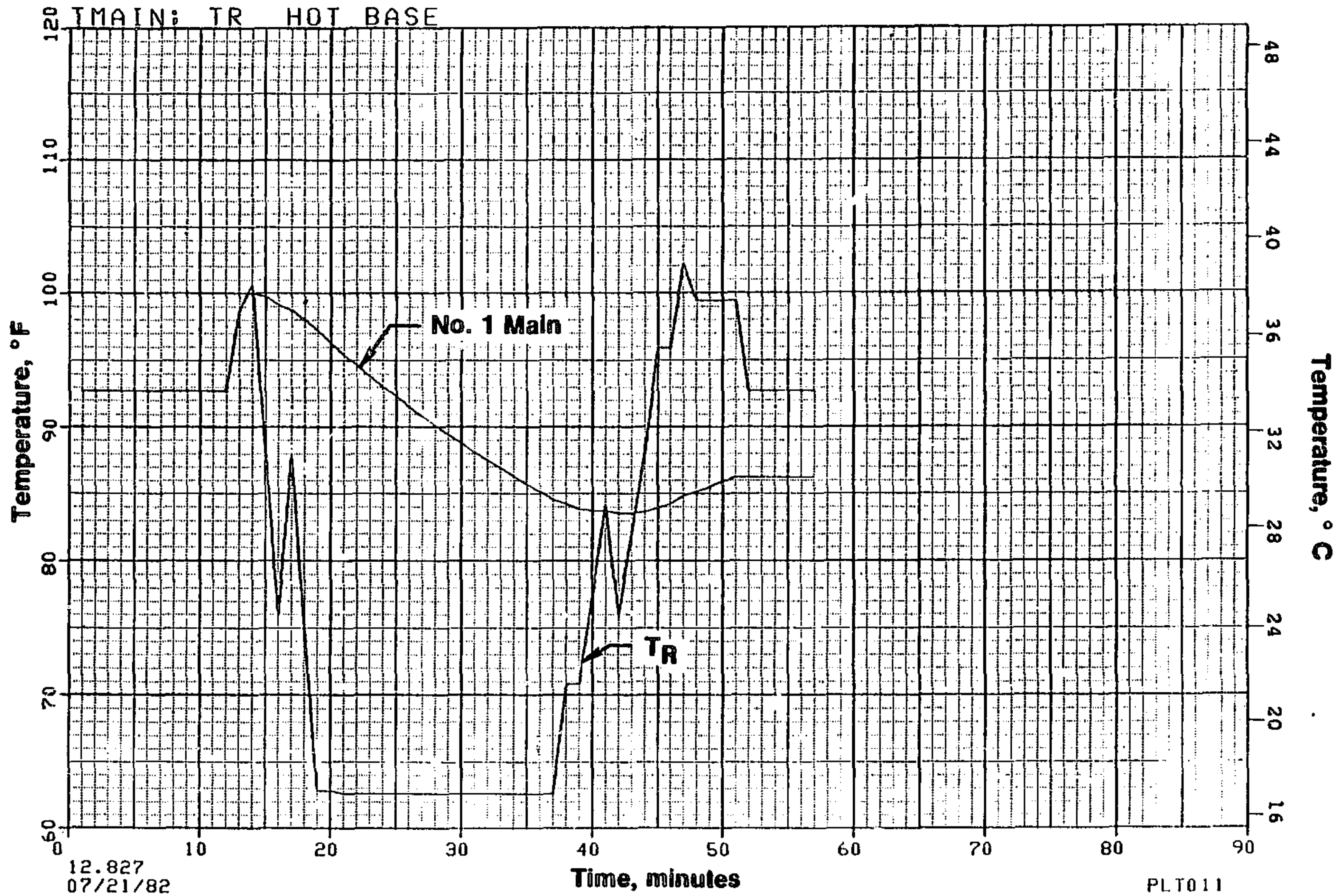


Figure 92. Baseline - Hot Flight No. 1 Main Tank Temperature.

Figure 93. Baseline - Hot Flight No. 1 Outboard Tank Temperature.

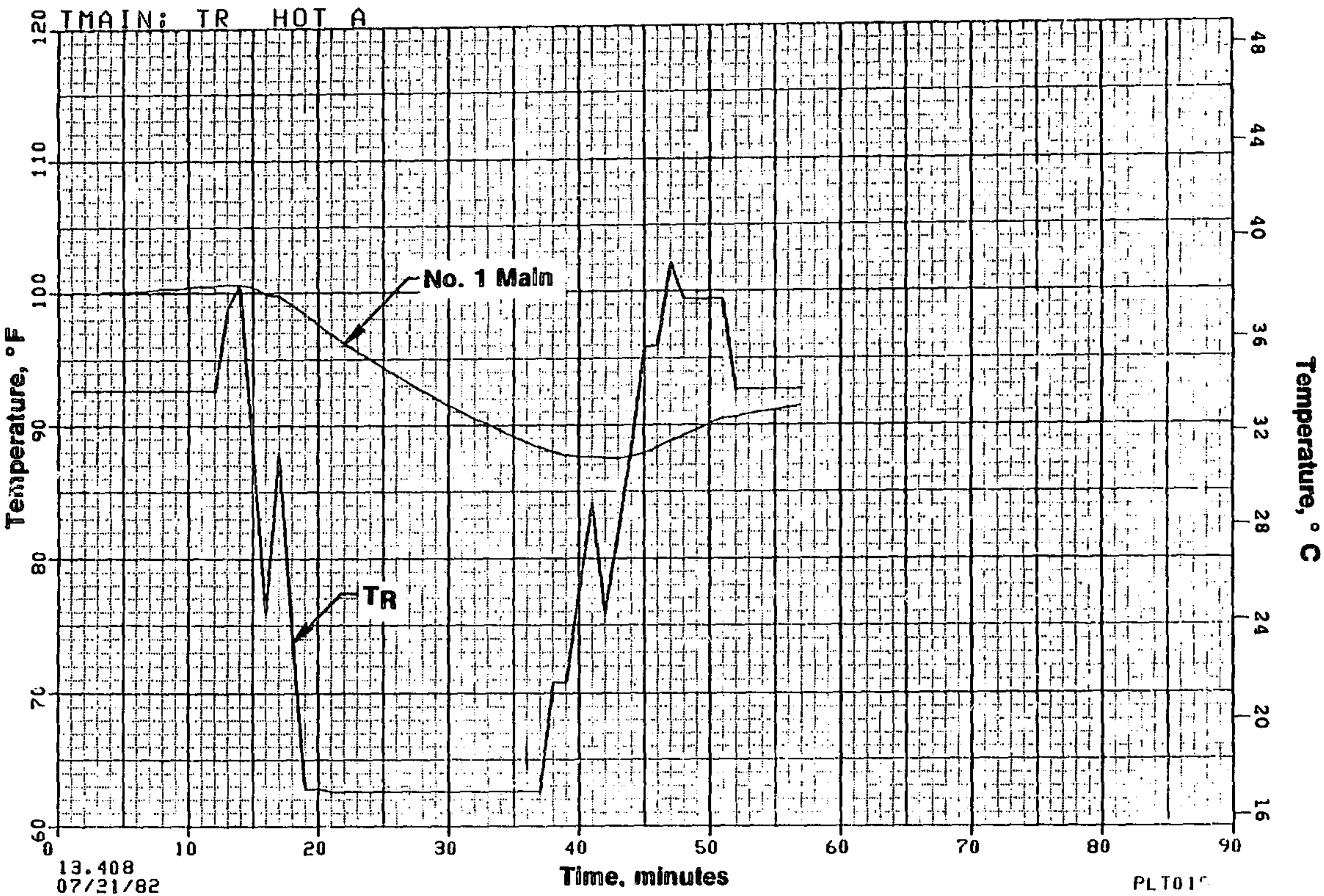


Figure 94. System A - Hot Flight No. 1 Main Tank Temperature.

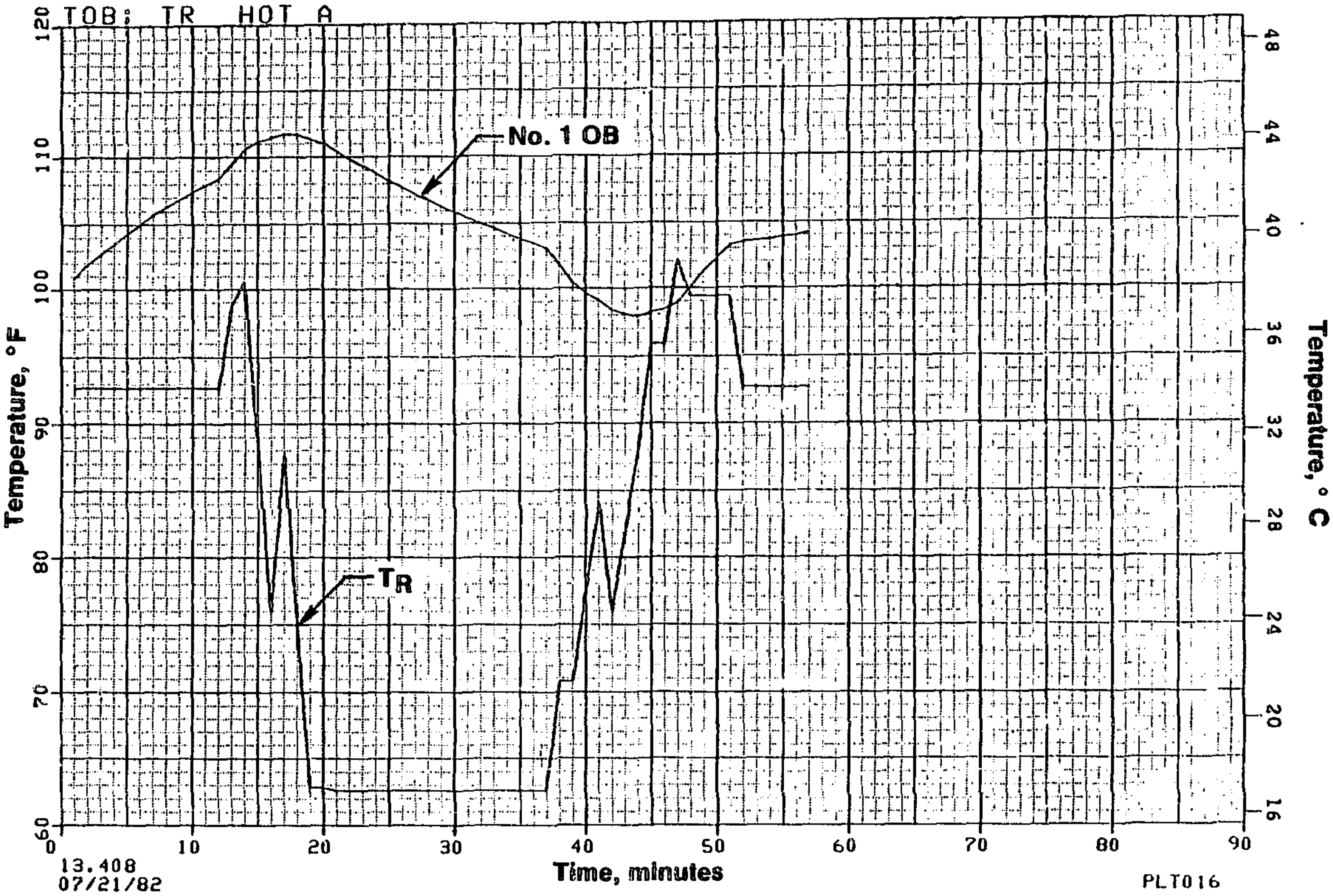


Figure 95. System A - Hot Flight No. 1 Outboard Tank Temperature.

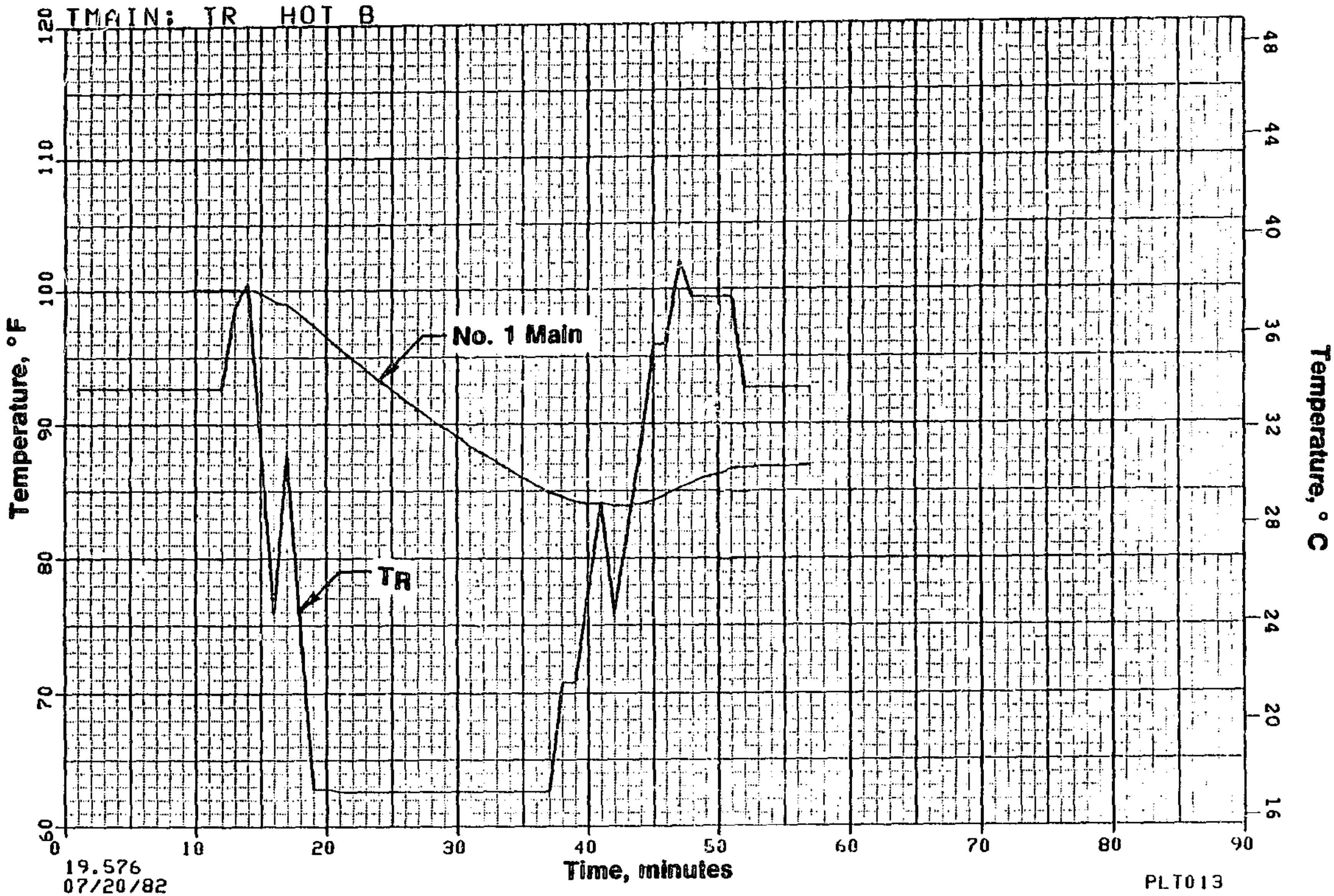


Figure 96. System B - Hot Flight No. 1 Main Tank Temperature.

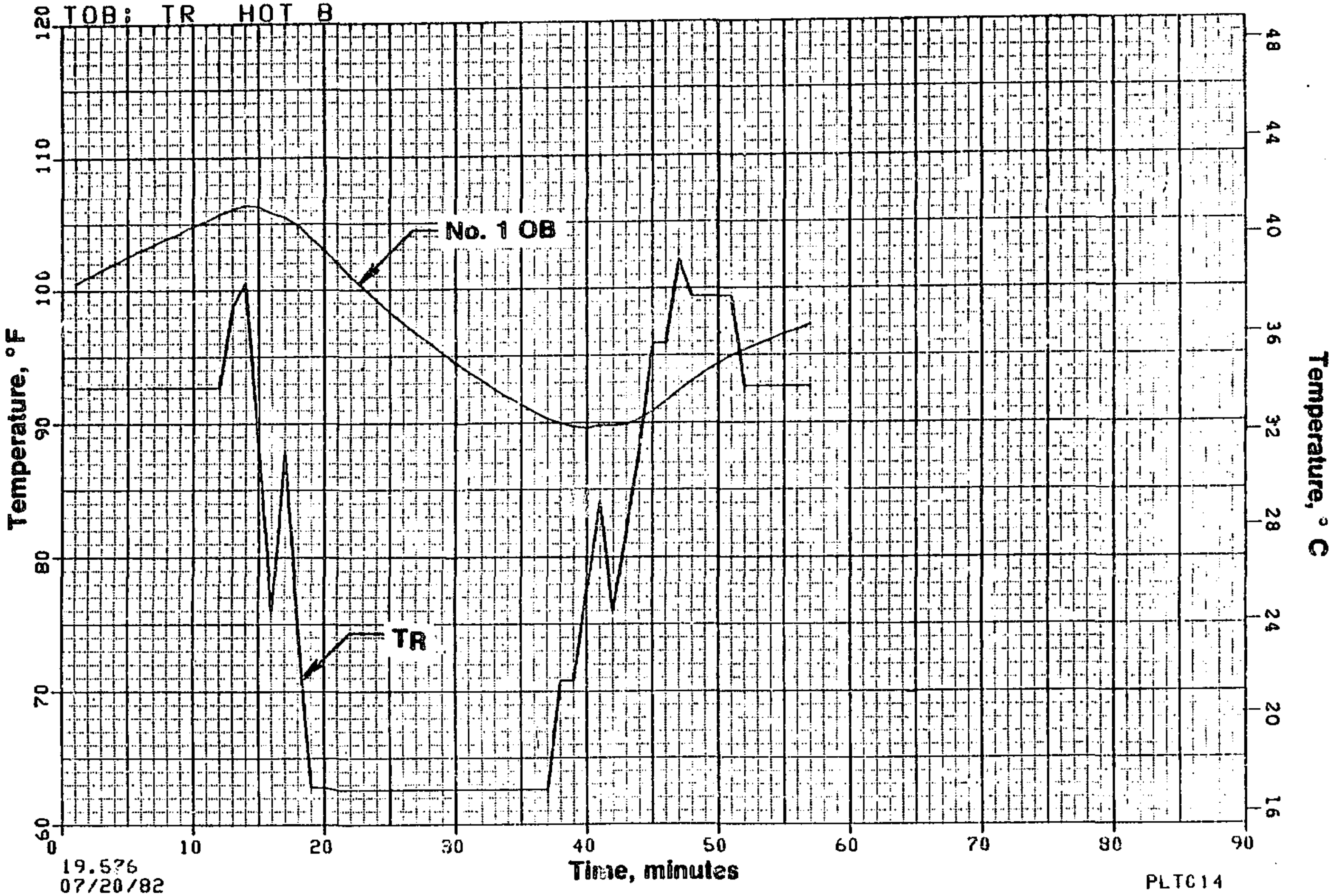


Figure 97. System B - Hot Flight No. 1 Outboard Tank Temperature.

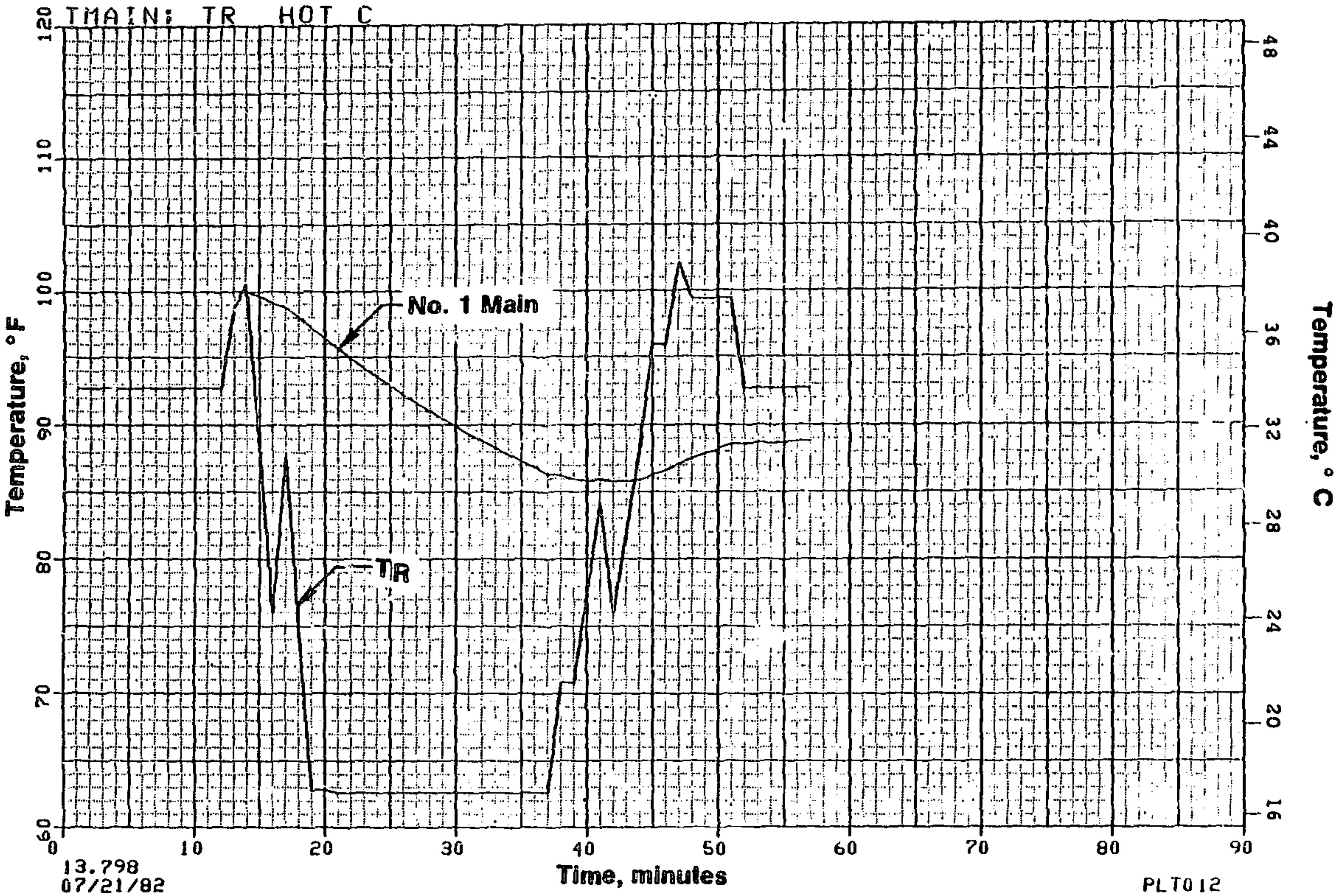


Figure 98. System C - Hot Flight No. 1 Main Tank Temperature.

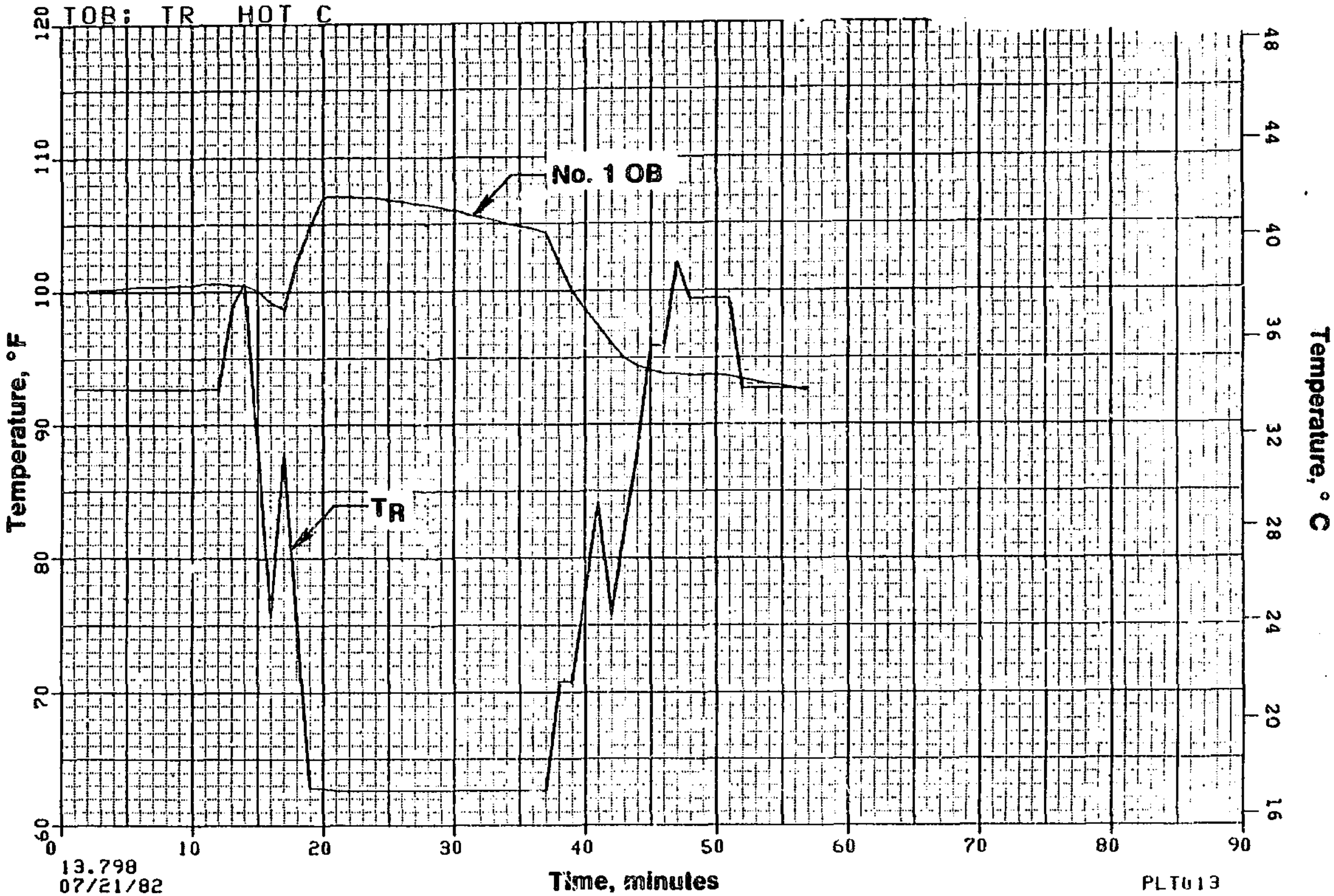


Figure 99. System C - Hot Flight No. 1 Outboard Tank Temperature.

TABLE 10. NOMINAL FLIGHT TANK TEMPERATURES
MINIMUM DURING FLIGHT – °F (°C).

	Baseline	System A	System B	System C
No. 2 Main	-19 (-28)	*	*	*
No. 1 Main	-19 (-28)	+8 (-13)	-12 (-24)	-18 (-28)
No. I Outboard	-20 (-29)	+26 (-3)	0 (-18)	-18 (-28)

Fuel Loading Temperature = 60° F (16° C)

Spec Max Freezing Point +5° F (+3° C)

Jet-B = -53 (-47)

Jet-A = -35 (-37)

Study Fuel = -12 (-24)

Minimum Air Temperture

T_{Amb} = -68 (-56)

T_R = -21 (-29)

T_2 = -15 (-26)

*No Advanced Systems on No. 2 Engine

TABLE 11. HOT FLIGHT TANK TEMPERATURES
MINIMUM DURING FLIGHT – °F (°C).

	Baseline	System A	System B	System C
No. 2 Main	+89 (32)	*	*	*
No. 1 Main	+83 (28)	+87 (31)	+84 (29)	+86 (30)
No. 1 Outboard	+79 (26)	+98 (37)	+89 (32)	+92 (33)

Fuel Loading Temperature = 100° F (38)

Spec Max Freezing Point +5° F (+3° C)

Jet-B = -53 (-47)

Jet-A = -35 (-37)

Study Fuel = -12 (-24)

Minimum Air Temperture

T_{Amb} = +21 (-6)

T_R = +62 (17)

T_2 = +67 (19)

*No Advanced Systems on No. 2 Engine

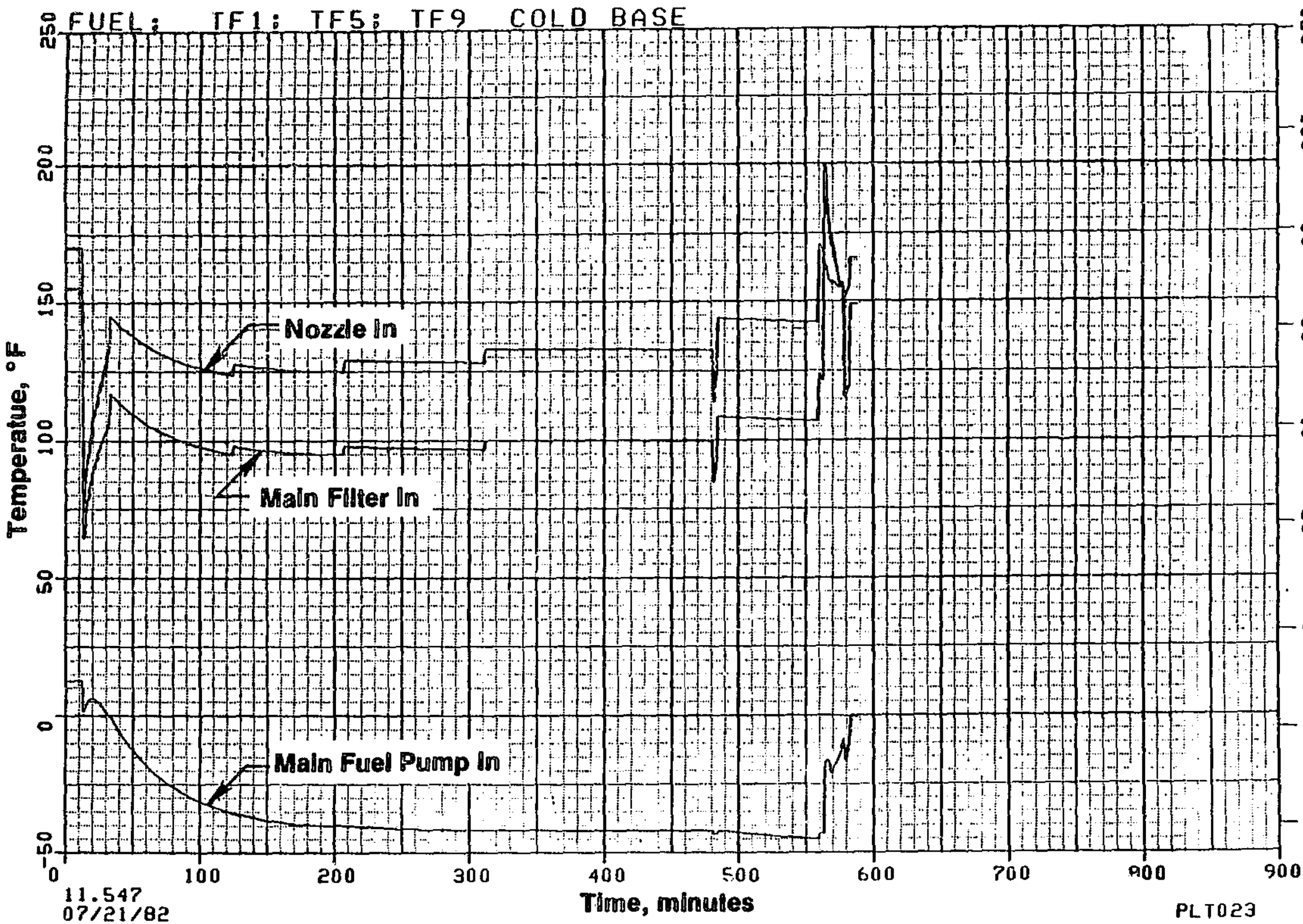


Figure 100. Baseline - Cold Flight Engine Fuel Temperatures.

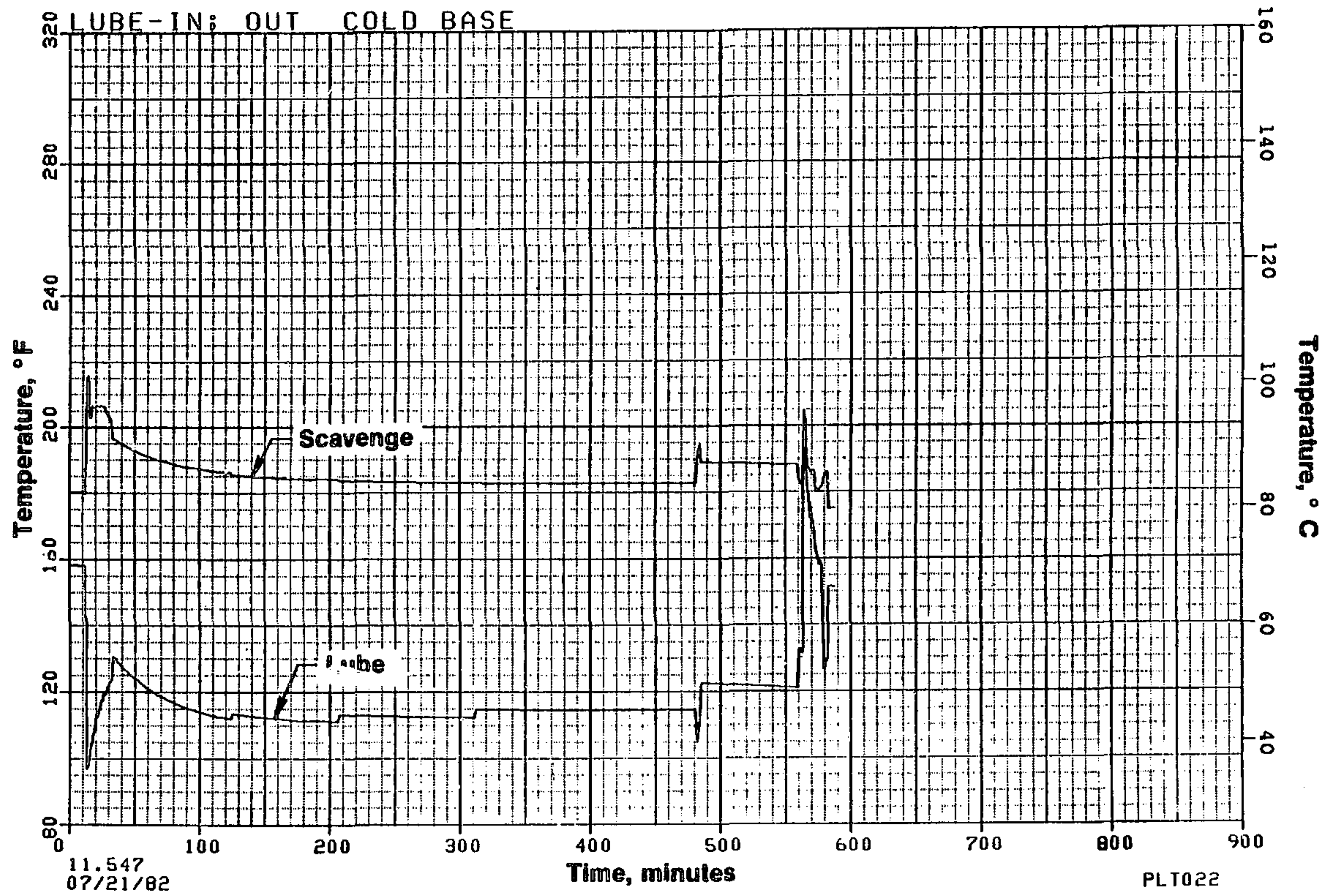


Figure 101. Baseline - Cold Flight Engine Lube and Scavenge Oil Temperature.

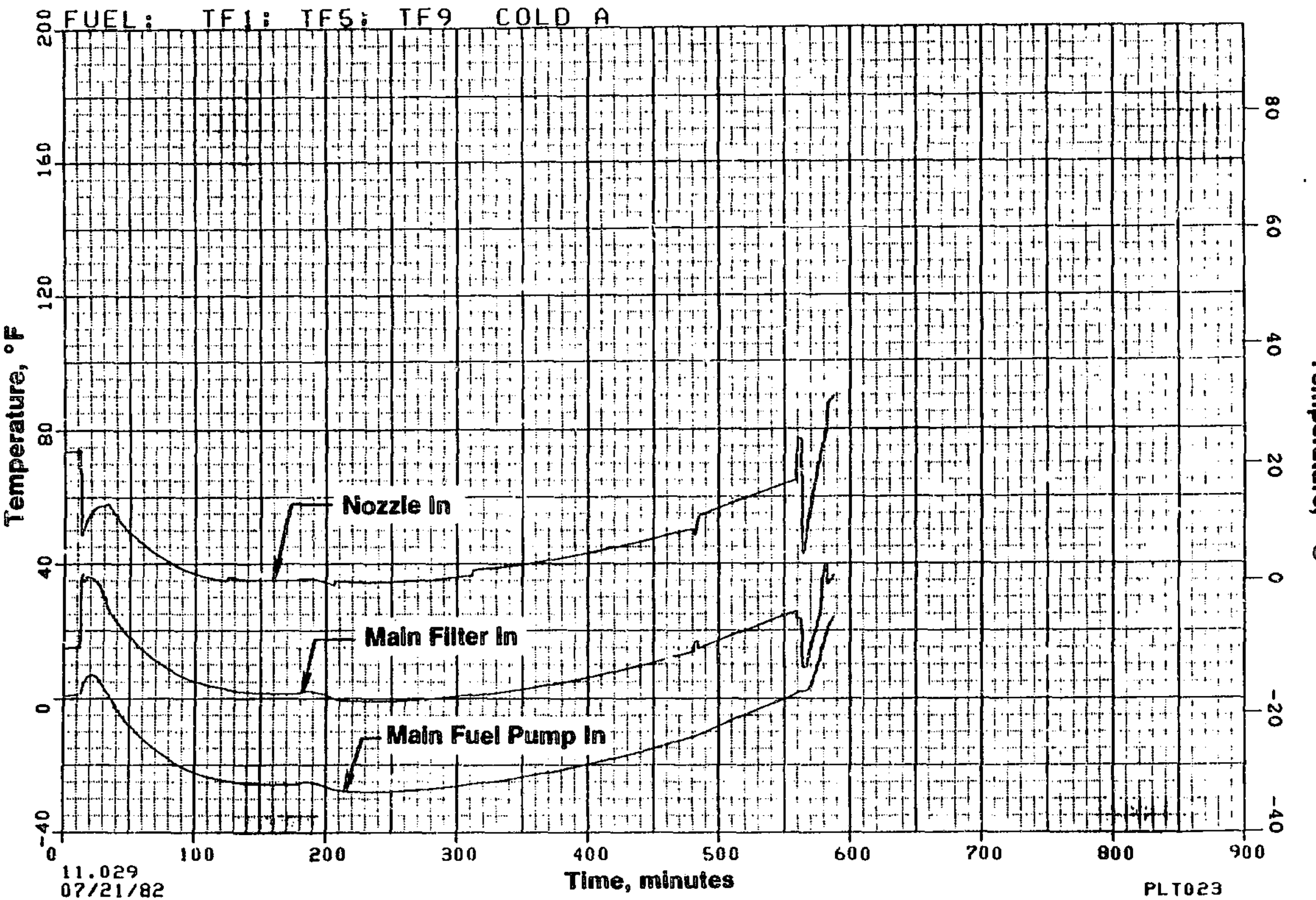


Figure 102. System A - Cold Flight Engine Fuel Temperatures.

Figure 103. System A - Cold Flight Engine Lube and Scavenge Oil Temperature.

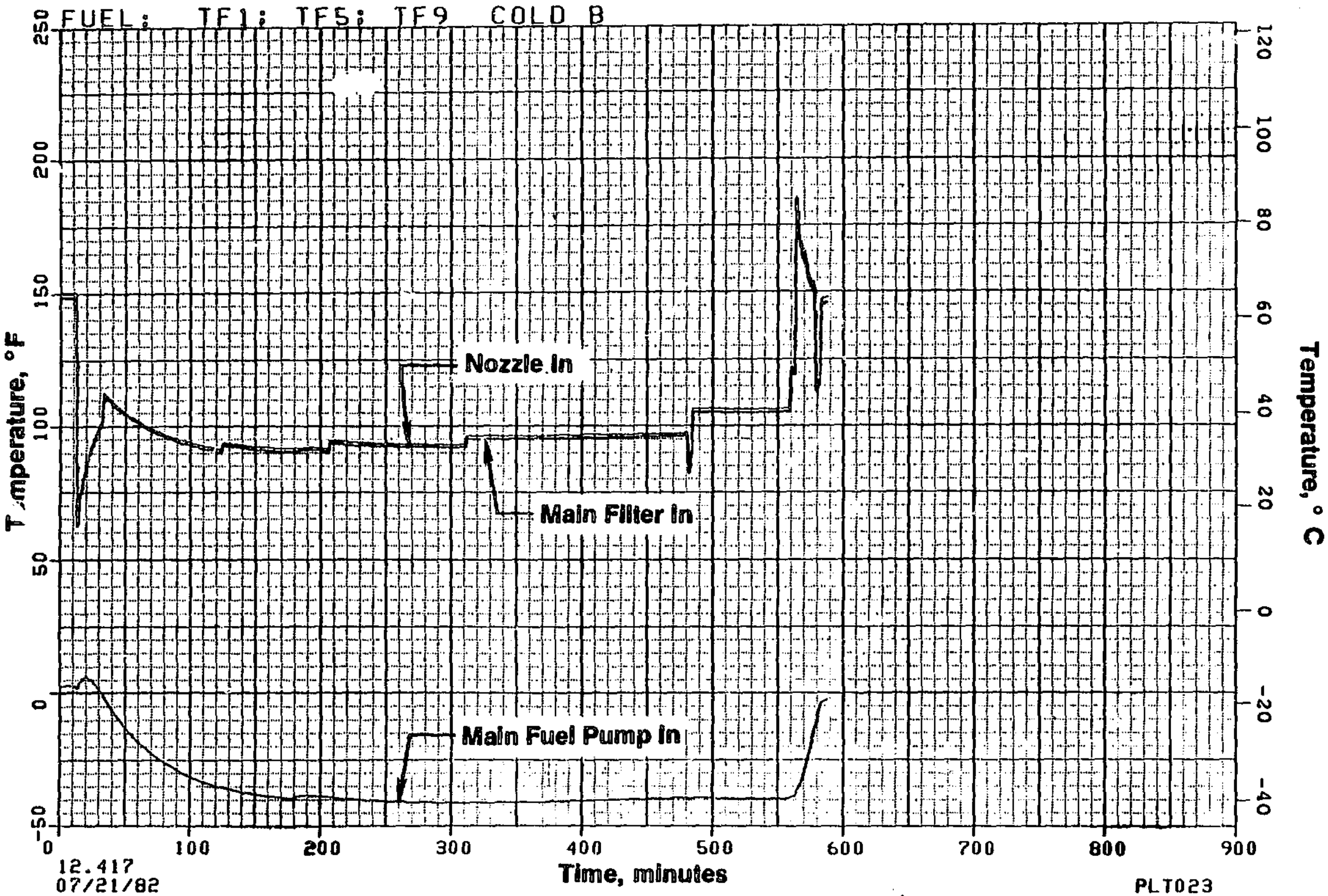


Figure 104. System B - Cold Flight Engine Fuel Temperature.

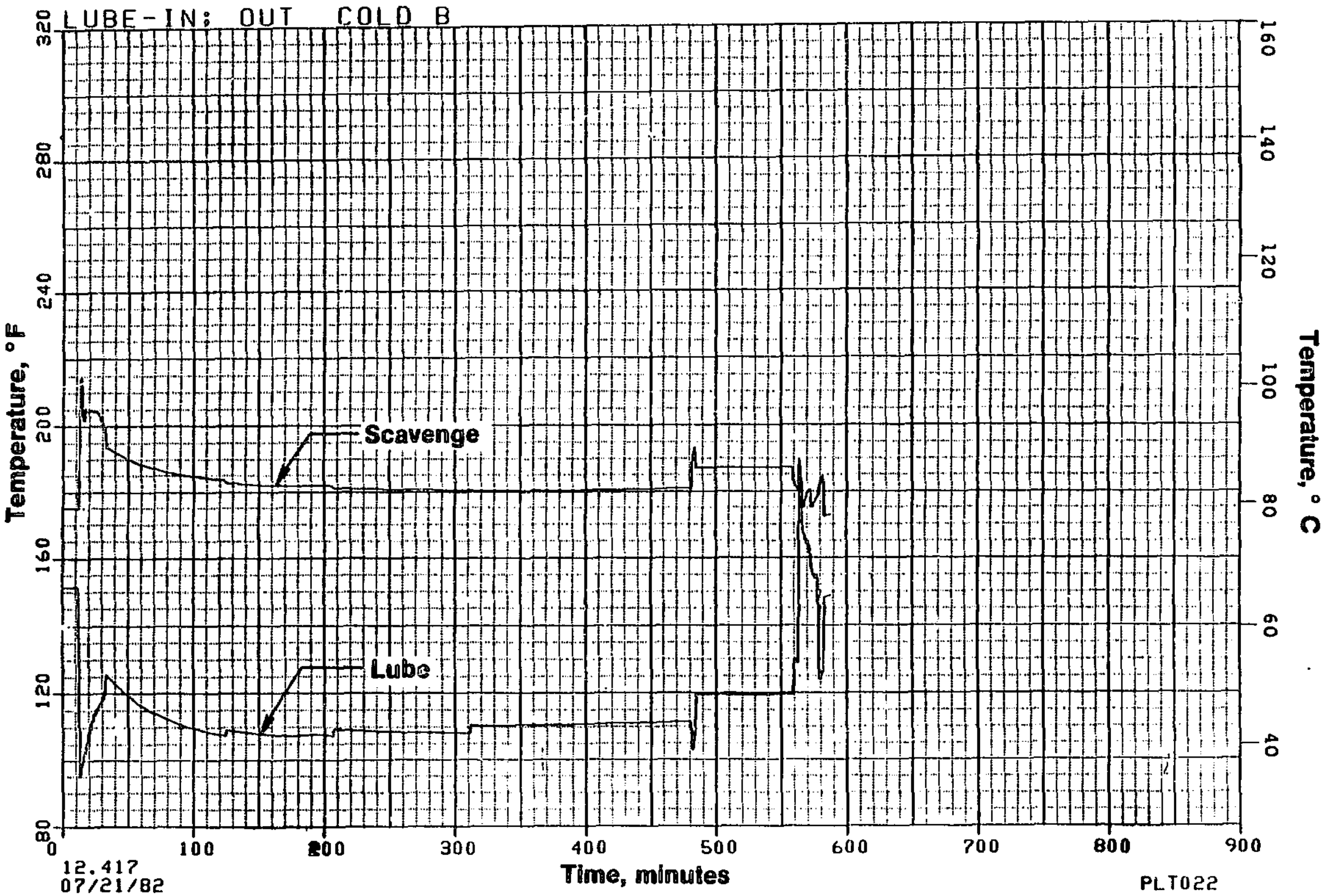


Figure 105. System B - Cold Flight Engine Lube and Scavenge Oil Temperature.

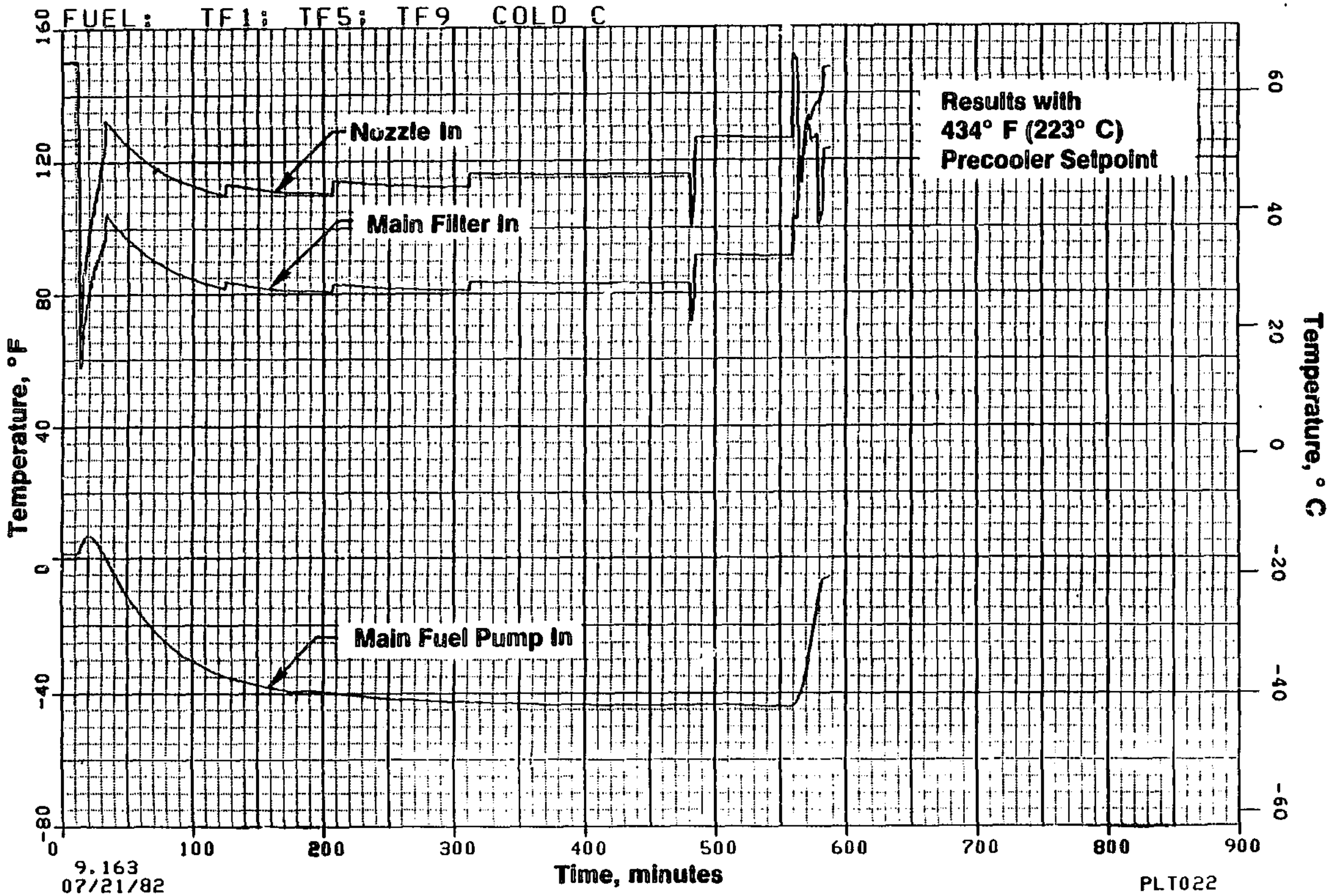


Figure 106. System C - Cold Flight Engine Fuel Temperatures.

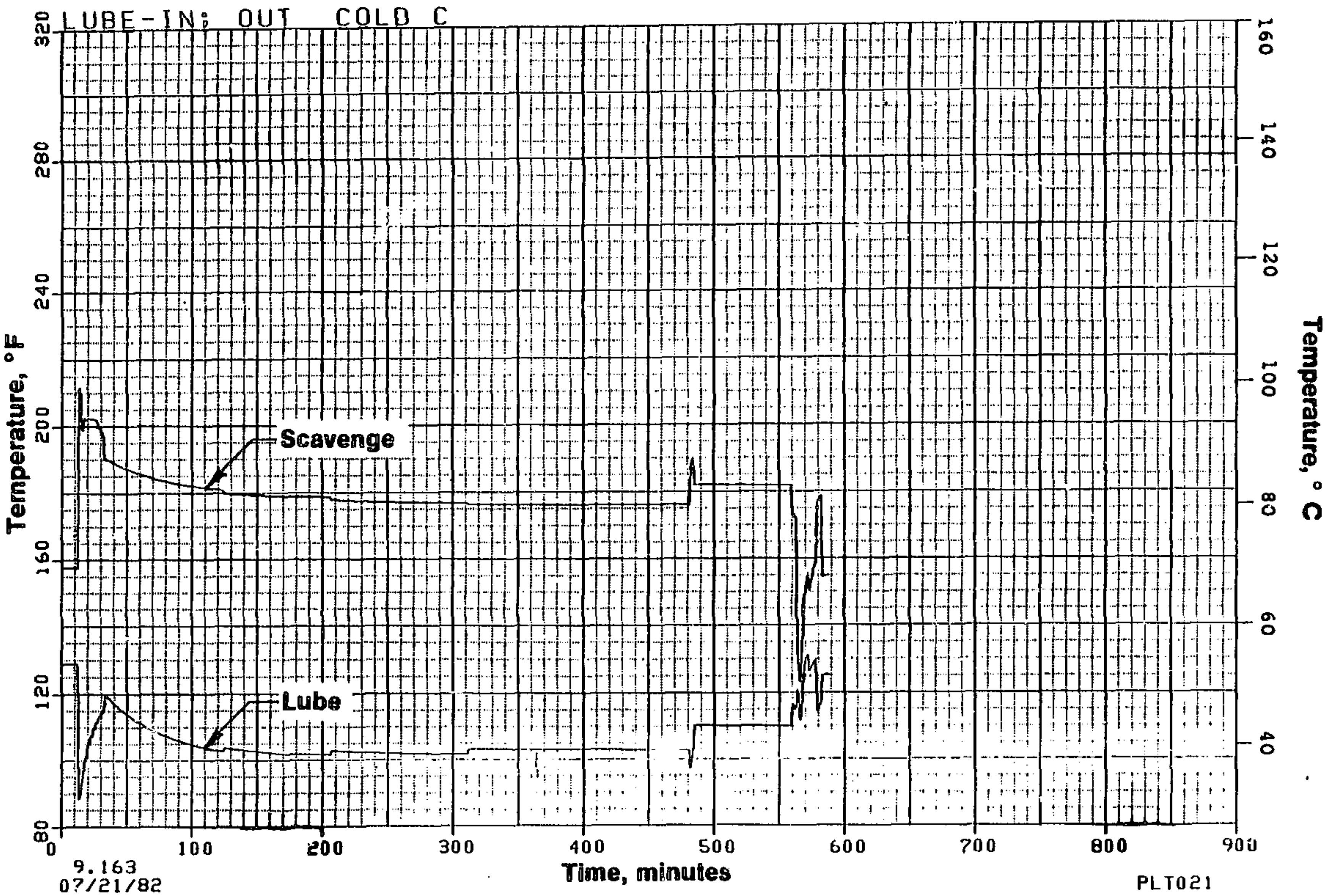


Figure 107. System C - Cold Flight Engine Lube and Scavenge Oil Temperature.

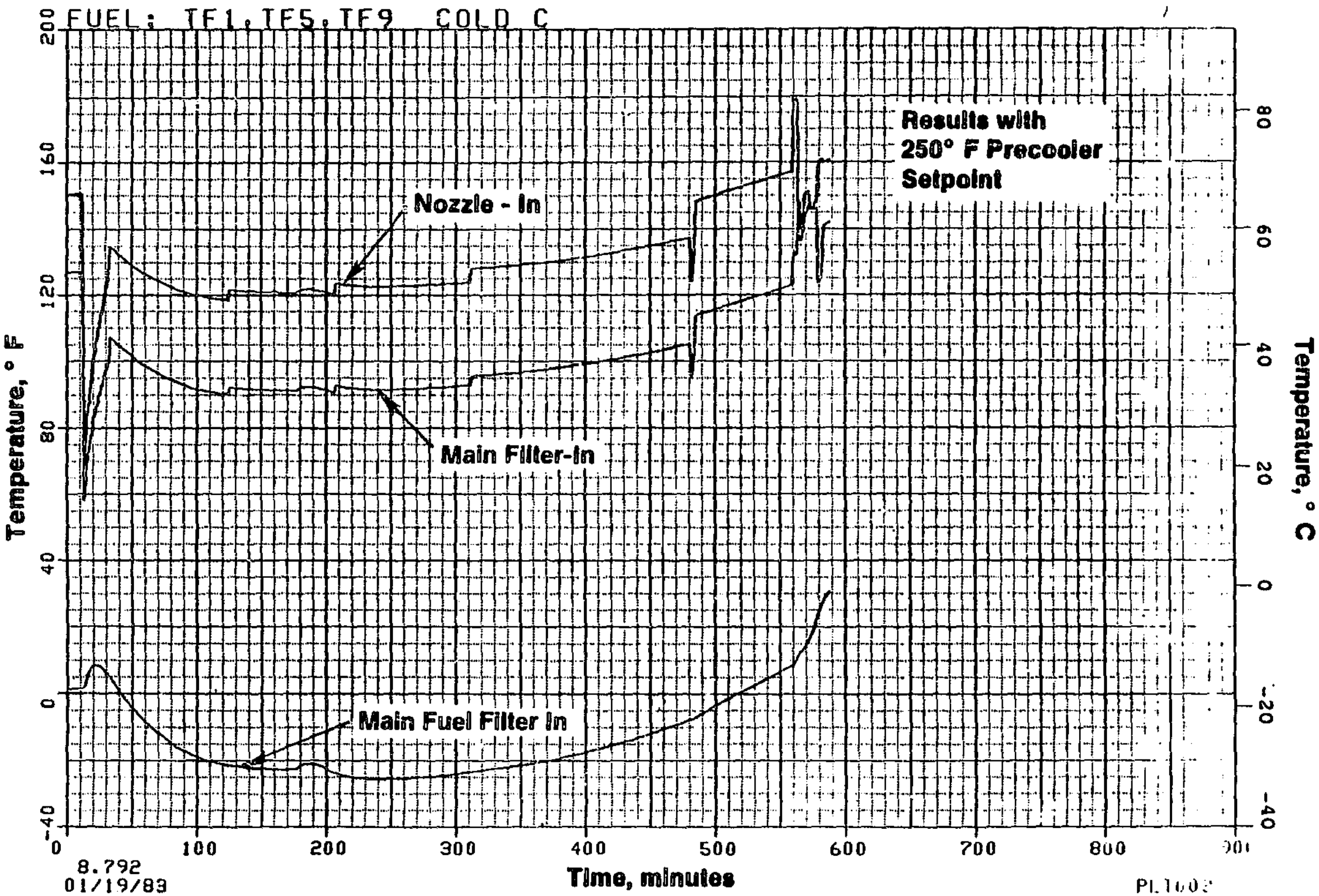


Figure 108. System C - Cold Flight Engine Fuel Temperature.

Fuel and lube oil temperatures of particular interest are shown in Table 12. From an ice protection and engine lube temperature standpoint, all of the results are acceptable except for Advanced System A. With System A, the fuel flow to the engine corresponds to engine gear pump flow and this is too high a flow rate for the available lube system heat. The resolution to this problem is simple, however, in that return of control bypass flow to main pump interstage would produce the same cold flight results as the baseline. This option, however, raises an issue concerning the choice between tank heating and engine fuel ice protection. Both cannot be satisfied at the same time. The acceptability of the situation and particularly whether engine lube temperature levels are acceptable with this tank heating approach needs further consideration. Note that the low oil temperature result would occur with System A regardless of the means for fuel ice protection.

With respect to hot fluid temperatures in the engine systems, the engine pump inlet, main fuel control, fuel nozzles and scavenge oil are the primary concerns. Figures 109 through 116 show these results for both nominal and hot flights. Tables 13, 14, 15, and 16 summarize the key results. As a cross-section of normal flight conditions (nominal and one-day-per-year extreme), the results are acceptable in all regards. Systems B and C show higher fuel nozzle temperatures than those for the baseline but this could be resolved by control mode optimization. Advanced System B includes an air-to-oil heat exchanger; but this heat exchanger was not activated during these flight simulations. Its use during descent would lower nozzle temperatures without significant effect on sfc. System C has the capability to place more heat into the fuel tank than elected for this study. A 135° C (275° F) setpoint for switching heat from engine meter fuel to tank fuel was assumed in the model.

To further consider the issue of hot fuel in the engine system, special runs were made to determine fuel residence time during the nominal and hot flights. Figure 117 shows a breakdown by zones of the Baseline system. The computer model was modified to calculate average fuel temperature and thermal residence time in four zones of the airframe fuel feed system and engine.

TABLE 12. FUEL AND ENGINE LUBE OIL TEMPERATURE MINIMUMS DURING FLIGHT - °F (°C).

- **Main Fuel Filter Inlet Temperature**
- **Ice Protection Limit = 32° F (0° C)**

	Baseline	System A	System B	System C
Cold Flight	65 (18)	-1 (-18)	62 (17)	58 (14)
Nominal Flight	118 (48)	35 (2)	116 (47)	102 (39)
Hot Flight	157 (69)	97 (36)	155 (68)	152 (67)

TABLE 12. FUEL AND ENGINE LUBE OIL TEMPERATURE MINIMUMS DURING FLIGHT - °F (°C) (Concluded).

- **Engine Lube Oil Temperature**
- **Baseline Normal Minimum = 90° F (32° C)**

	Baseline	System A	System B	System C
Cold Flight	96 (36)	17 (-8)	95 (35)	89 (32)
Nominal Flight	133 (56)	48 (9)	130 (54)	123 (51)
Hot Flight	177 (81)	103 (39)	175 (79)	168 (76)

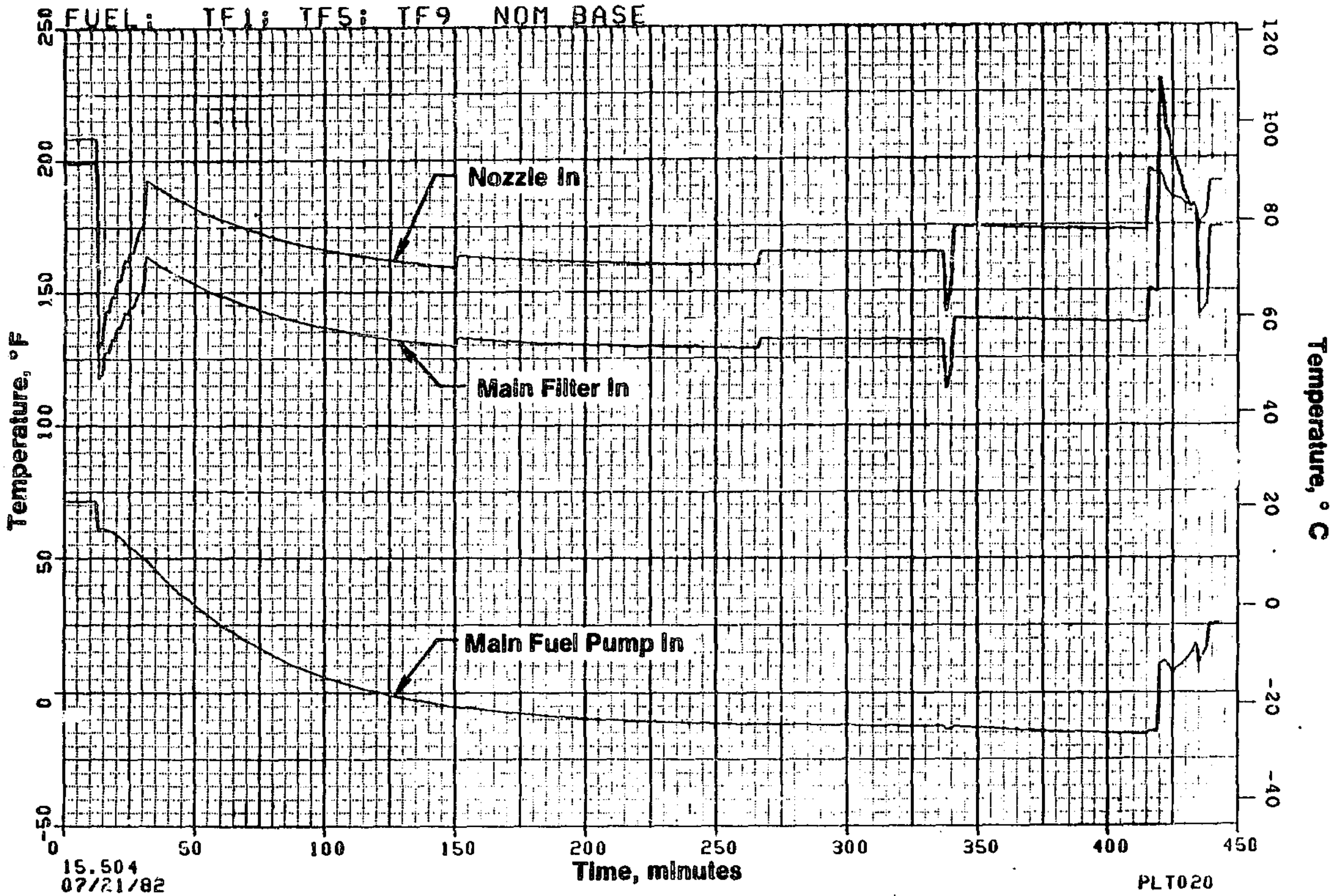


Figure 169. Baseline - Nominal Flight Engine Fuel Temperatures.

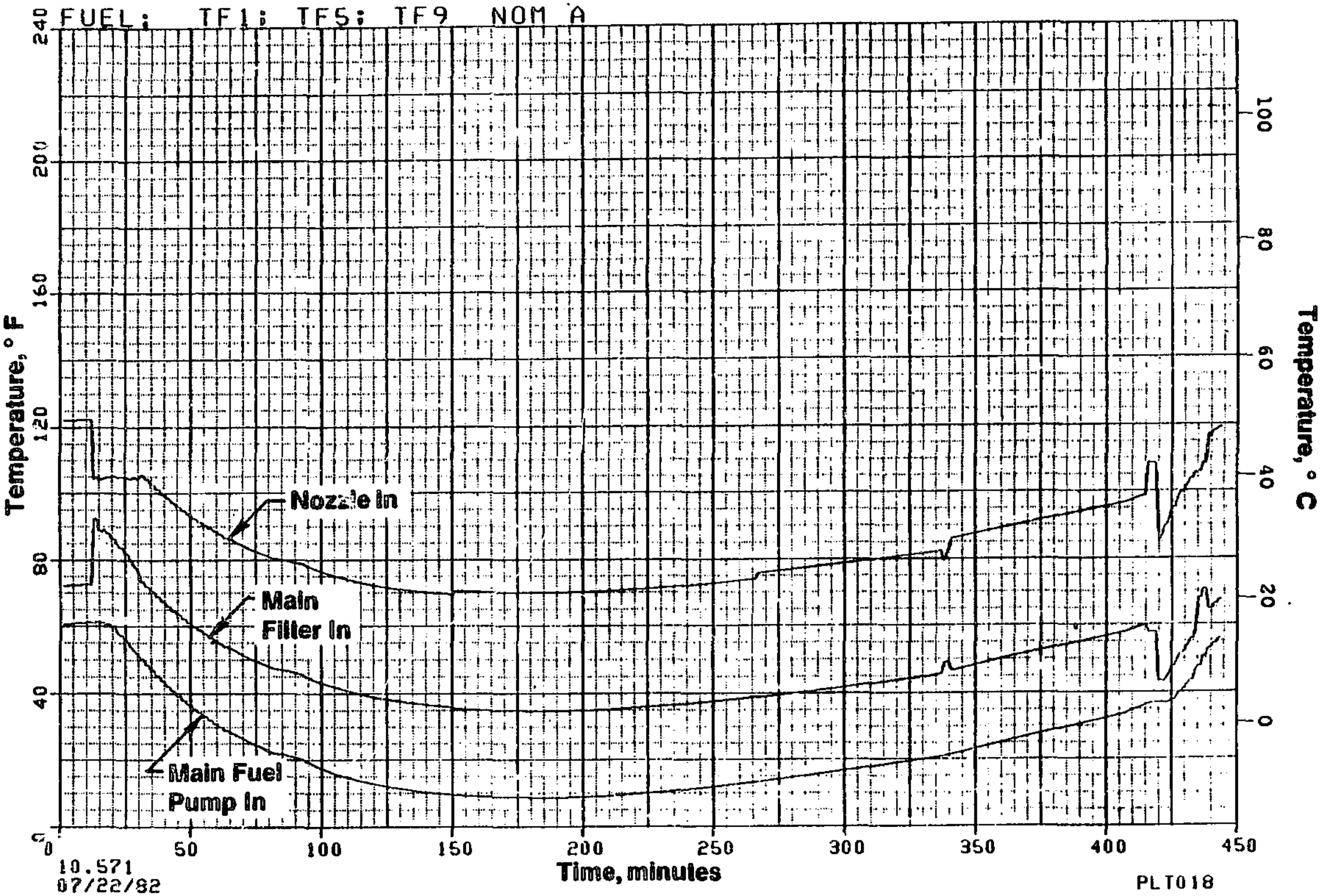


Figure 110. System A - Nominal Flight Engine Fuel Temperatures.

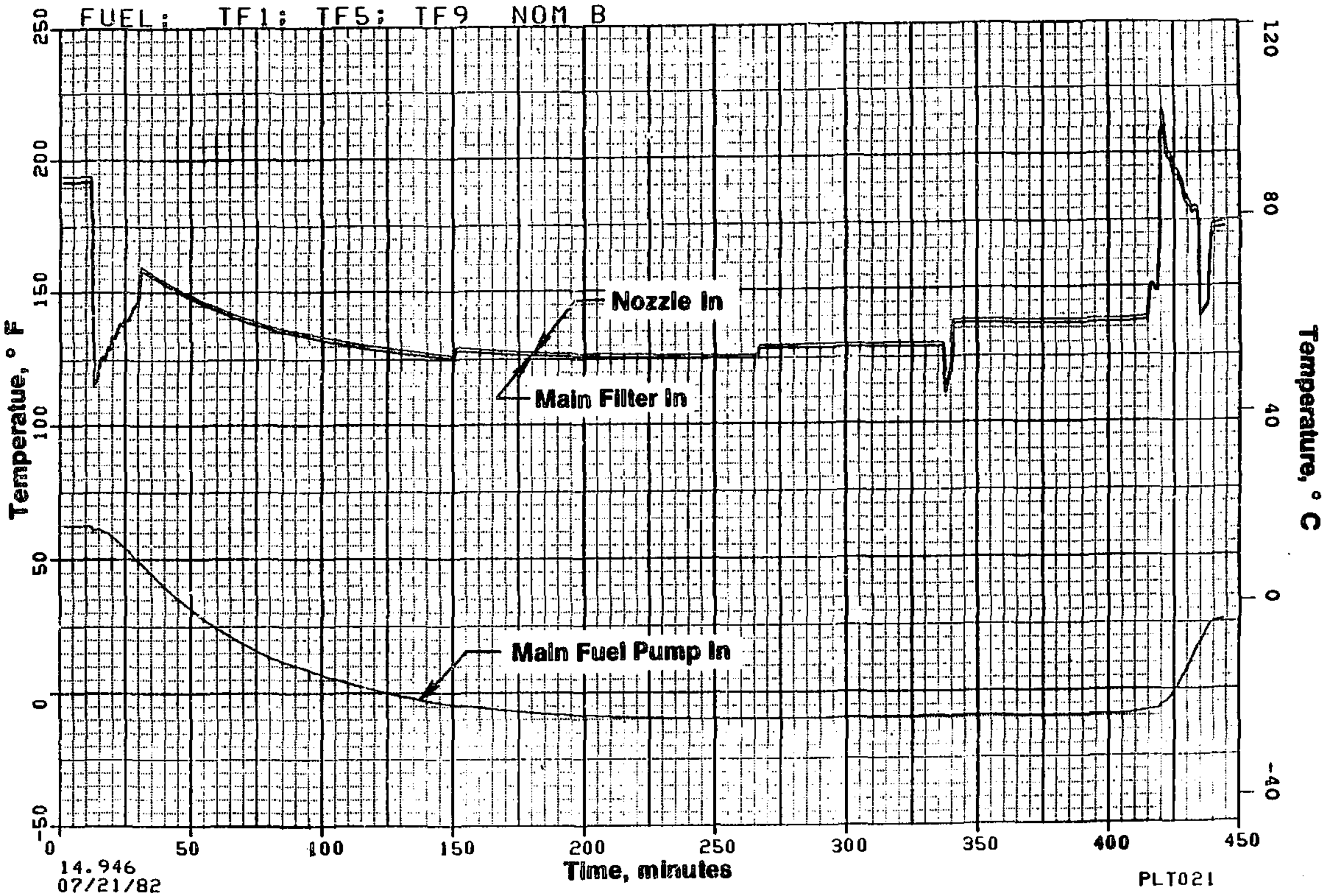


Figure 111. System B - Nominal Flight Engine Fuel Temperature.

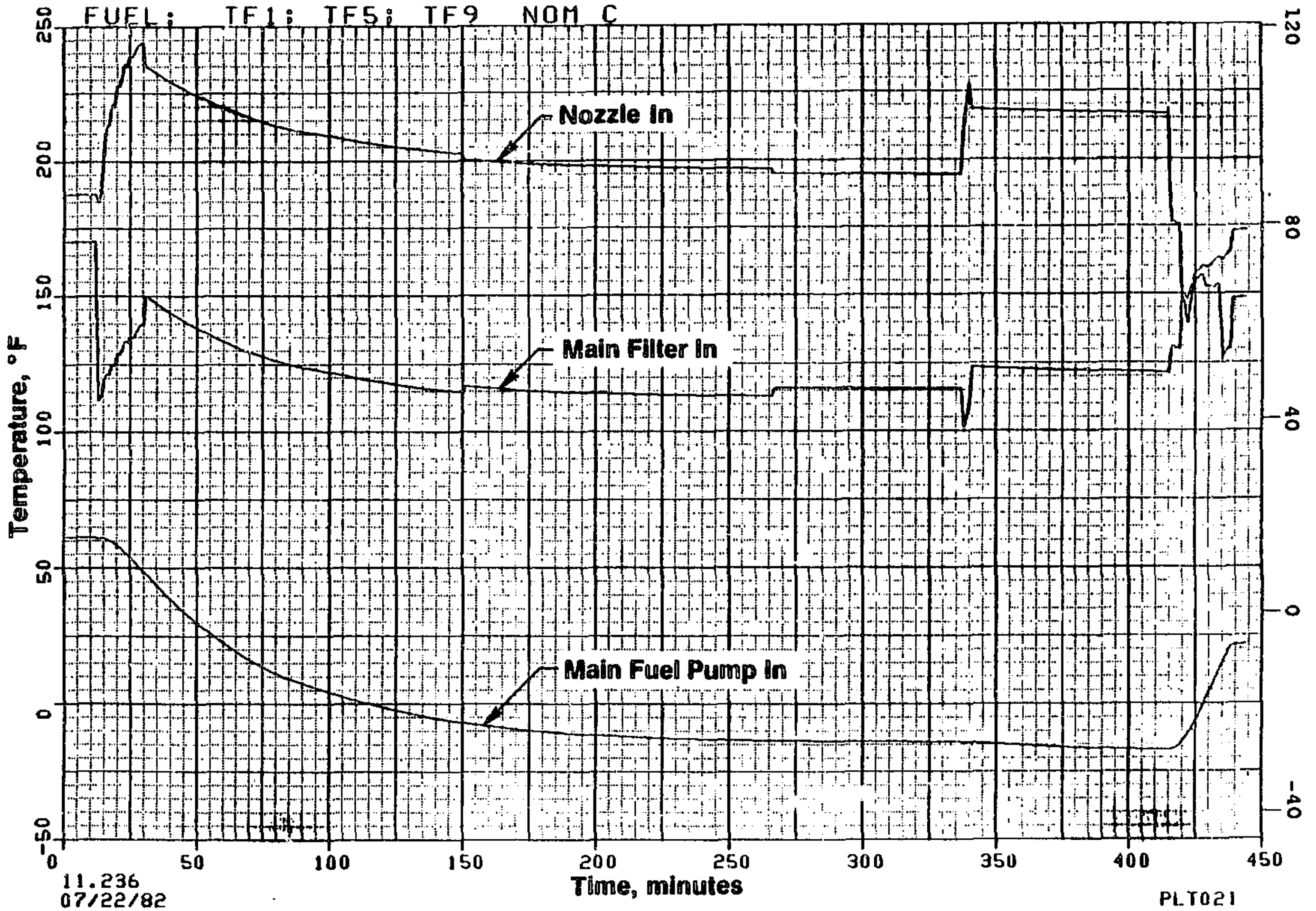


Figure 112. System C - Nominal Flight Engine Fuel Temperatures.

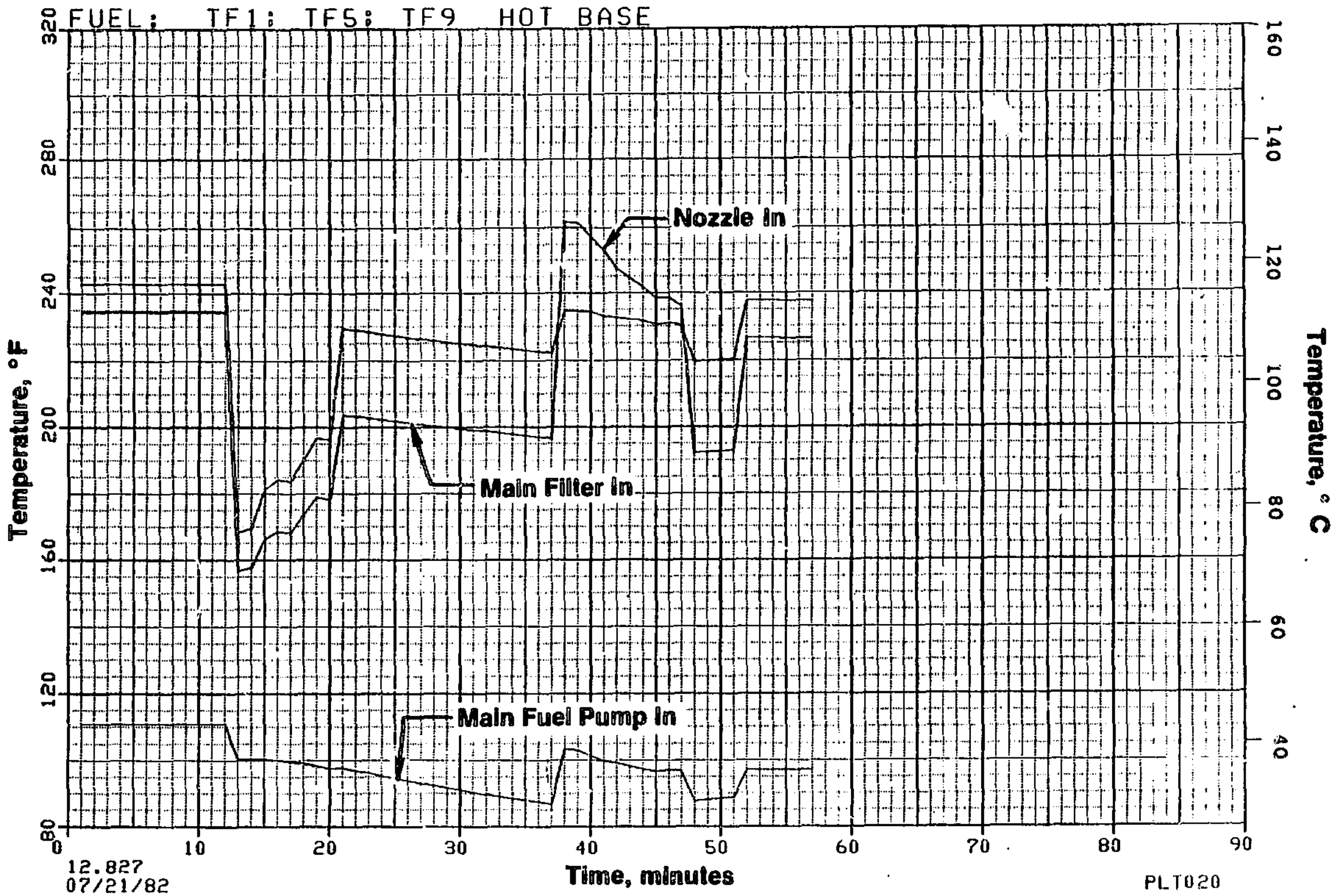


Figure 113. Baseline - Hot Flight Engine Fuel Temperature.

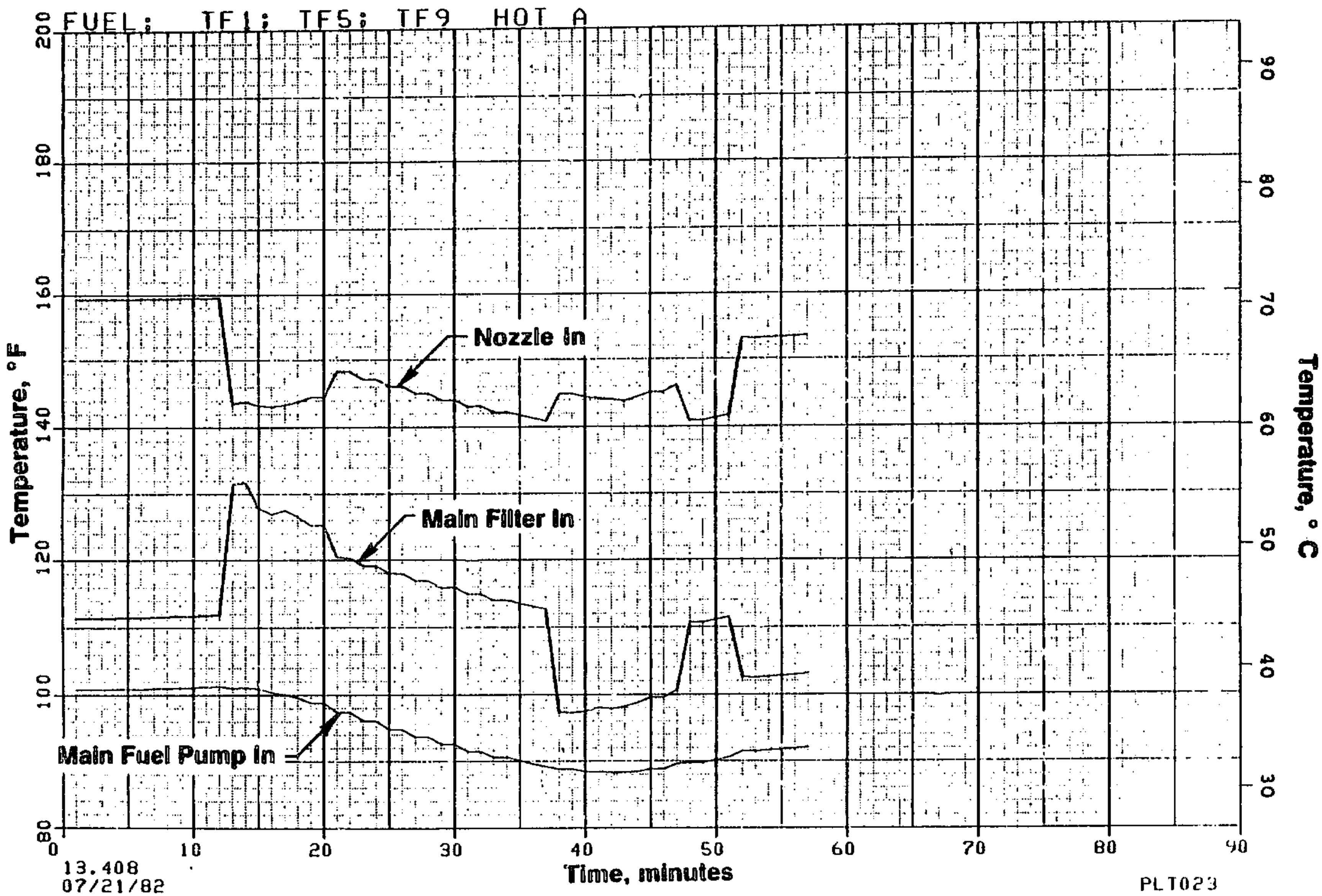


Figure 114. System A - Hot Flight Engine Fuel Temperatures.

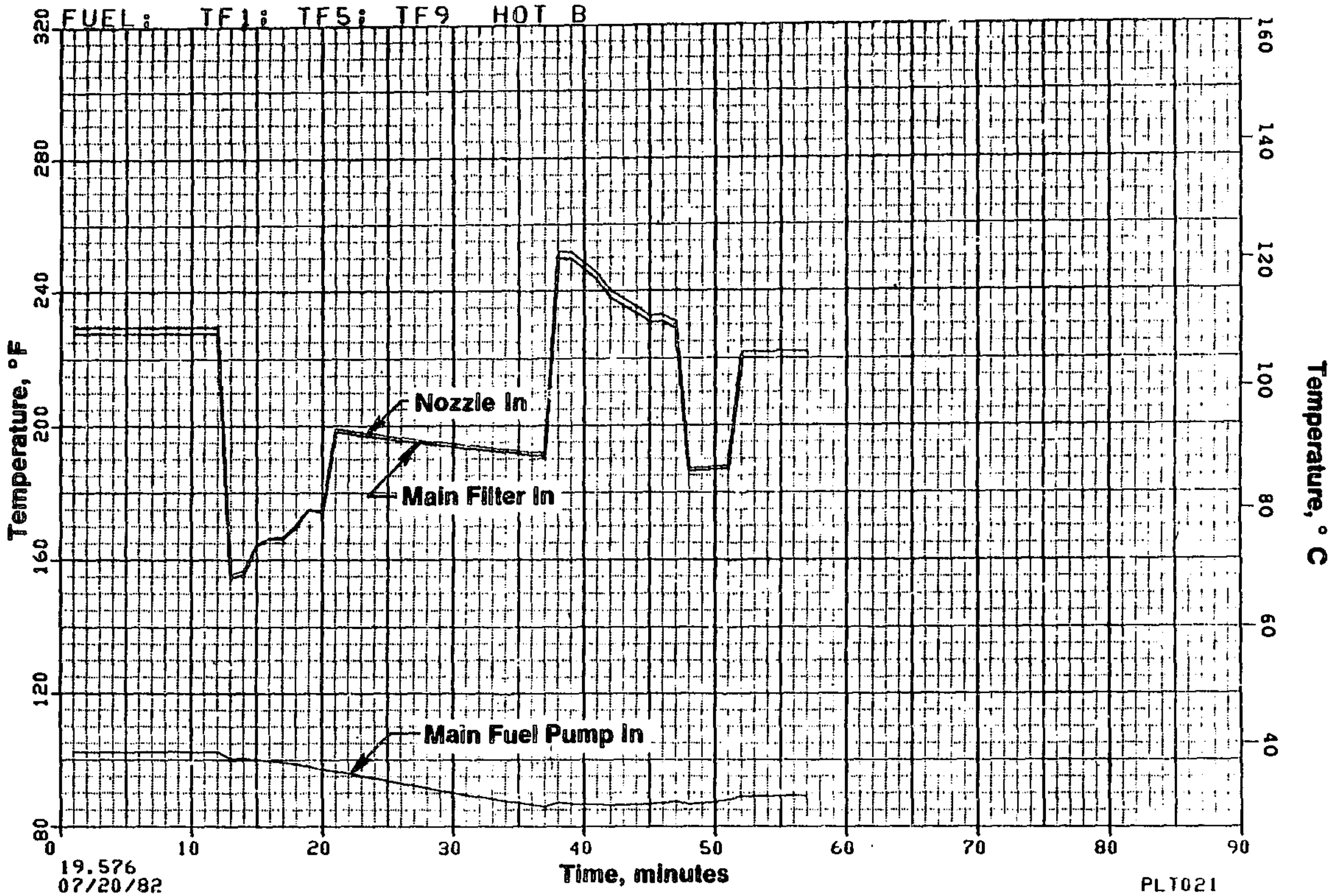


Figure 115. System B - Hot Flight Engine Fuel Temperatures.

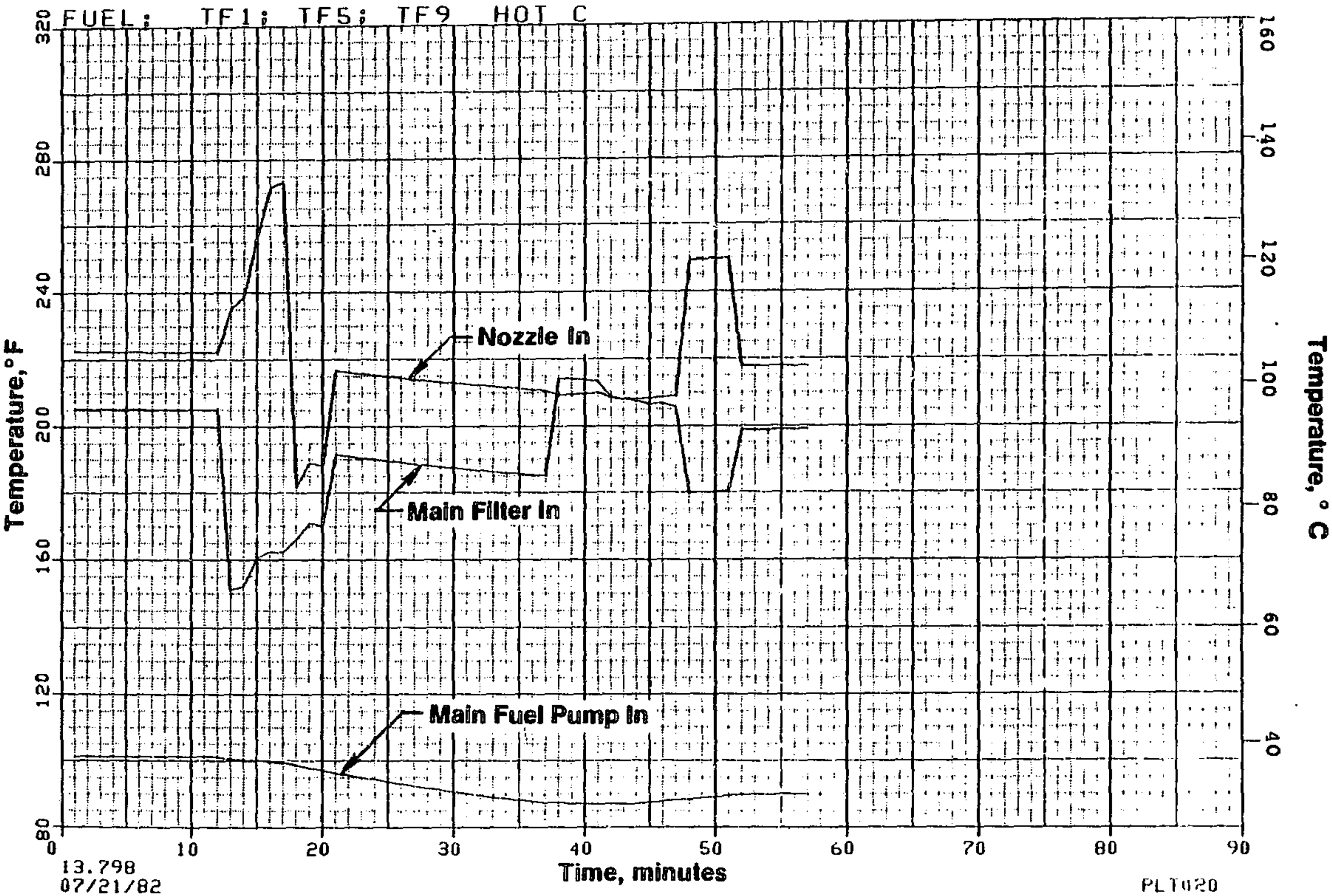


Figure 116. System C - Hot Flight Engine Fuel Temperatures.

TABLE 13. MAIN FUEL PUMP INLET TEMPERATURE MAXIMUM DURING FLIGHT - °F (°C).

	Baseline	System A	System B	System C
Cold Flight	12 (-11)	24 (-4)	6 (-14)	7 (-14)
Nominal Flight	72 (22)	62 (17)	62 (17)	62 (17)
Hot Flight	111 (44)	101 (38)	102 (39)	102 (39)

Model Spec Limit

Jet-A = 140° F (60° C)

Jet-B = 120° F (49° C)

TABLE 14. FUEL CONTROL (MEC) FUEL TEMPERATURE MAXIMUM DURING FLIGHT - °F (°C).

	Baseline	System A	System B	System C
Cold Flight	200 (93)	40 (4)	186 (86)	147 (64)
Nominal Flight	230 (110)	92 (33)	216 (102)	170 (77)
Hot Flight	262 (128)	132 (56)	250 (121)	214 (101)

Baseline Normal Maximum = 300° F (149° C)

TABLE 15. NOZZLE FUEL INLET TEMPERATURE MAXIMUM DURING FLIGHT — °F (°C).

	Baseline	System A	System B	System C
Cold Flight	172 (78)	90 (32)	186 (86)	152 (67)
Nominal Flight	208 (98)	122 (50)	216 (102)	243 (117)
Hot Flight	243 (117)	160 (71)	252 (122)	273* (134)

Baseline Nozzle Limit

Jet-A = 300° F (149° C)

Study Fuel = 255° F (124° C)

***ECS Bleed Air Heat Switches to Tank Hx at 275° F (135° C)**

TABLE 16. ENGINE SCAVENGE OIL TEMPERATURE MAXIMUM DURING FLIGHT - ^{o}F (^{o}C).

	Baseline	System A	System B	System C
Cold Flight	216 (102)	77 (25)	215 (102)	212 (100)
Nominal Flight	253 (123)	241 (116)	252 (122)	248 (120)
Hot Flight	287 (142)	274 (134)	286 (141)	282 (139)

Baseline Limits

Normal Max = 275° F (135° C)

Red Line = 350° F (177° C)

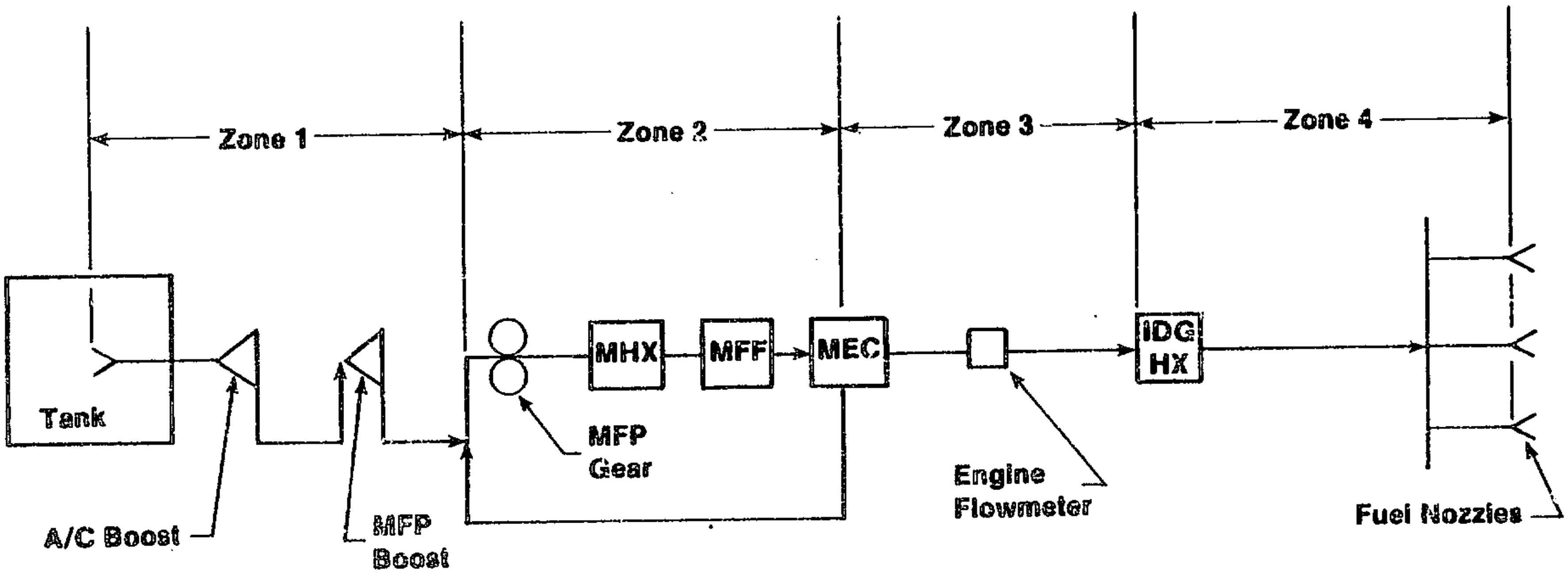


Figure 117. Fuel Residence Zones - Baseline Thermal Model.

Zone 1 is from the No. 1 tank aft boost pump through the engine boost impeller. Zone 2 is from the boost impeller discharge through the fuel control (MEC) bypass valve. The calculations for Zone 2 include the average number of times the fuel recirculates in the pump gear stage. Zone 3 is from the MEC bypass valve to the IDG fuel/oil cooler. Finally, Zone 4 is through the remainder of the fuel system and fuel nozzle. Note that these are bulk fuel temperatures. In the fuel nozzle, for example, the surface fuel film temperature would be higher. The fluid volume for each zone is as follows:

Zone	Volume - m^3 (ft^3)
1	0.03 (0.94)
2	0.0014 (0.05) gear + .007 (0.24) bypass
3	0.003 (0.10)
4	0.002 (0.07)

Based on volume, residence time was calculated from volumetric fuel flow.

The results for the Baseline nominal flight are shown in Figures 118 through 121. For the Baseline hot flight the results are shown in Figures 122 through 125. Figure 119A, etc., provides an expanded scale for residence time. Discrete fuel temperatures and flight profile definitions may be obtained from the results presented previously. It is somewhat surprising to note the long period of time it takes for the fuel to move through the system. For example, Figure 122 for Zone 1 hot flight shows that during takeoff it takes 8 seconds for the fuel to reach the engine gear pump after leaving the tank aft boost pump. During idle descent, it takes 220 seconds, almost 3 minutes. In addition to fuel thermal stability considerations, these model results also suggest other areas of interest such as:

- Engine start/relight time from a drained system.
- Quantity of fuel drainage after shutdown.
- Fuel spillage after closing the emergency fuel shutoff valve.
- Engine run time with an incorrectly positioned fuel feed valve.

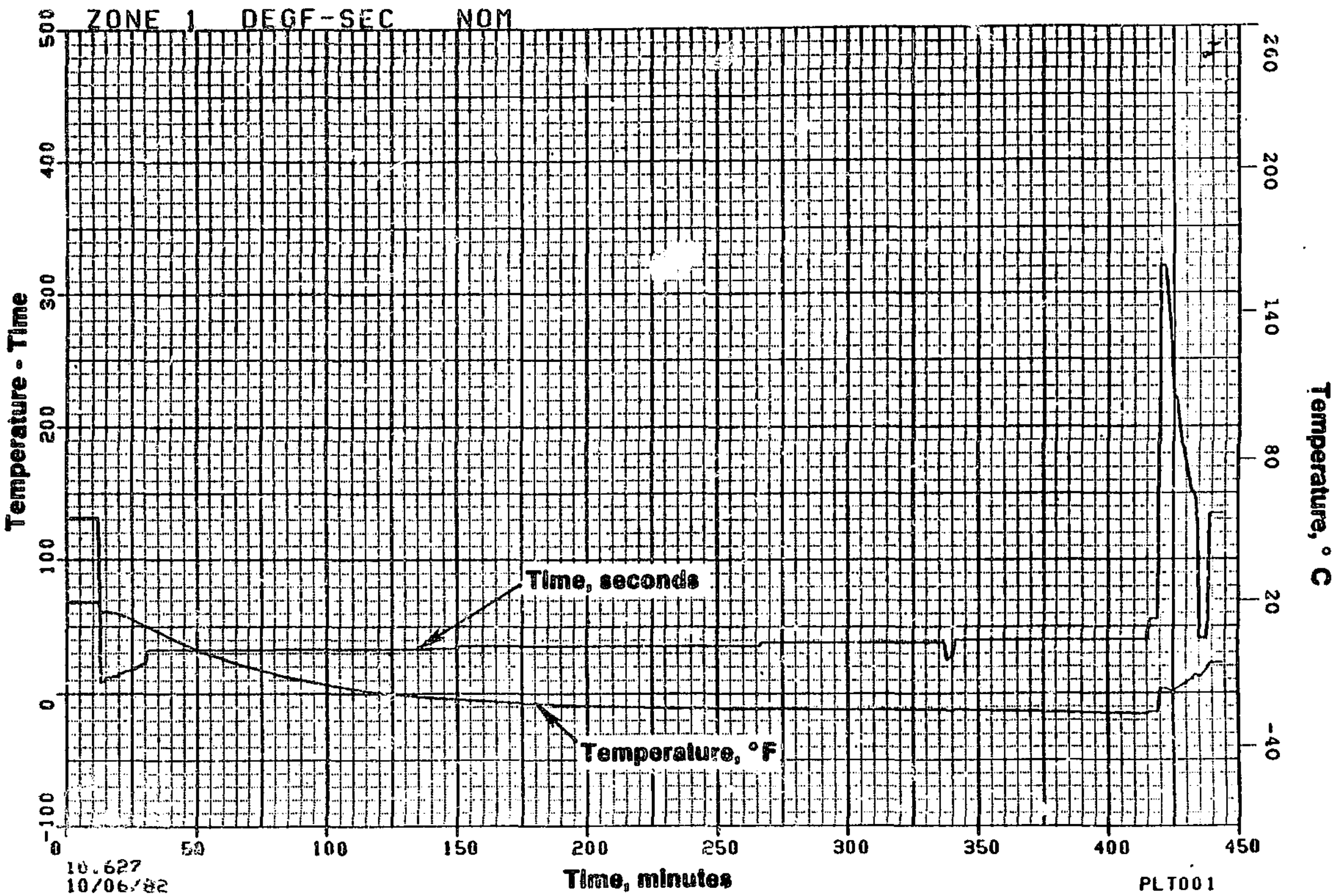


Figure 118. Zone 1 Residence Time and Temperature - Nominal Flight.

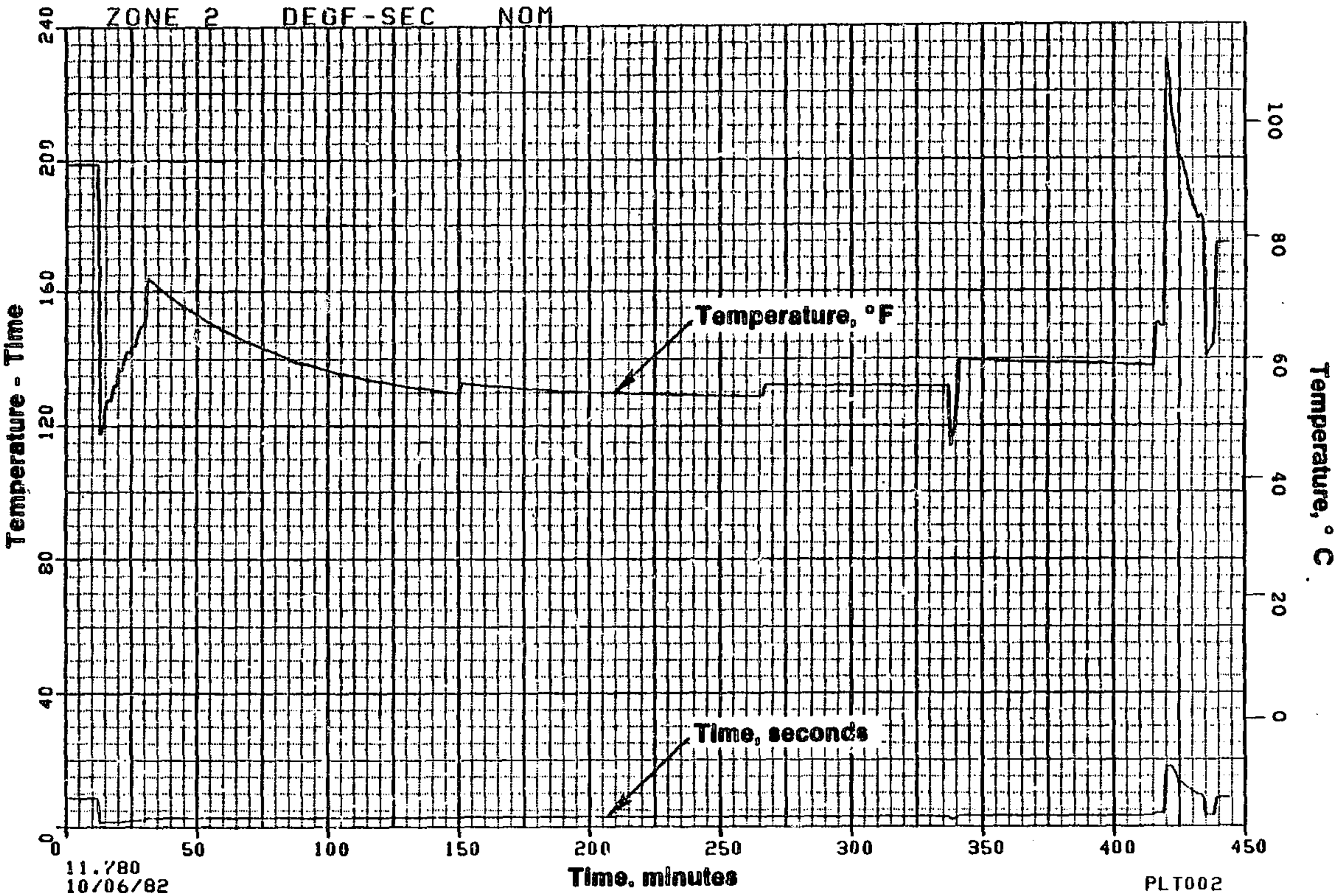


Figure 119. Zone 2 Residence Time and Temperature - Nominal Flight.

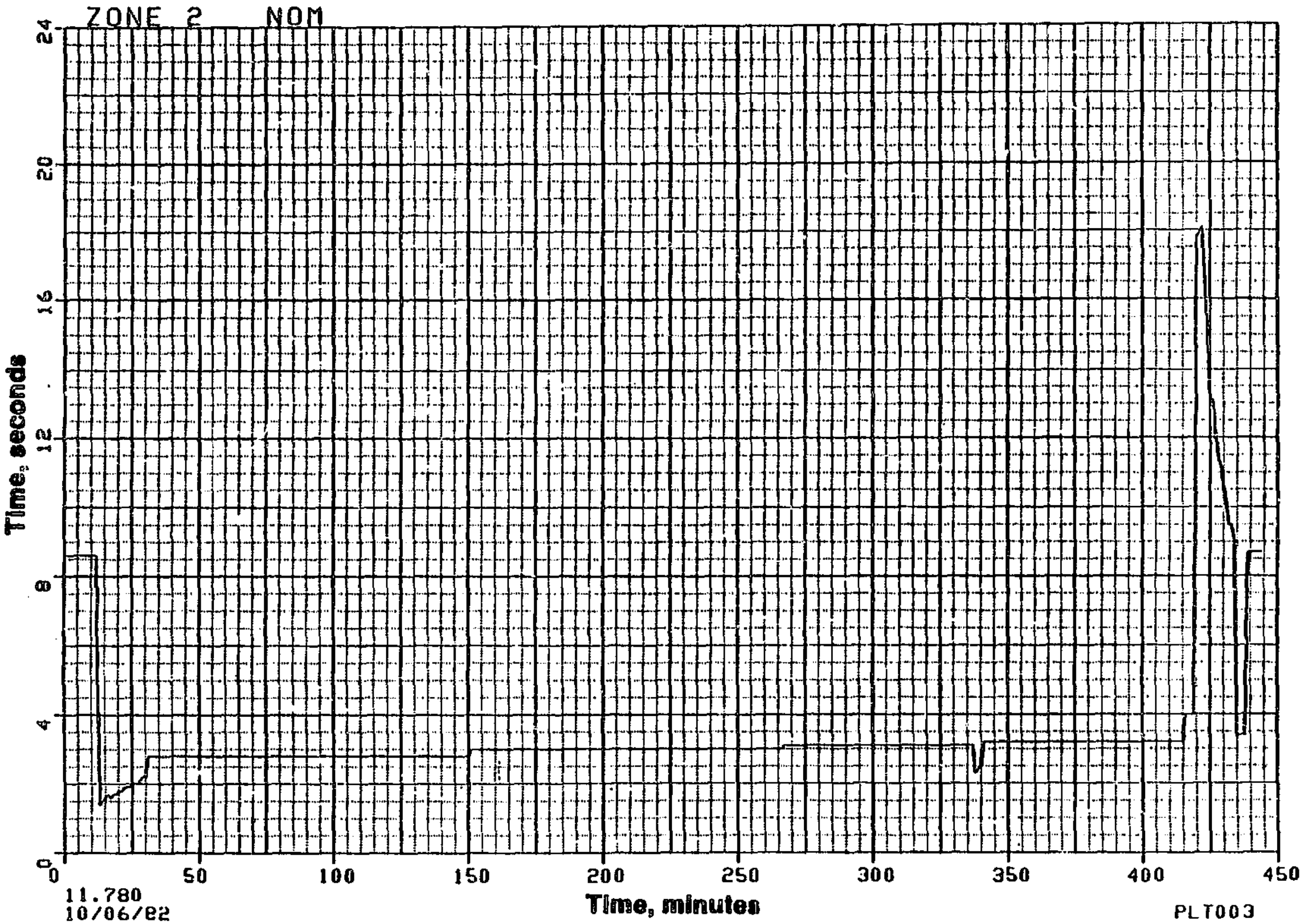


Figure 119a. Zone 2 Residence Time - Nominal Flight.

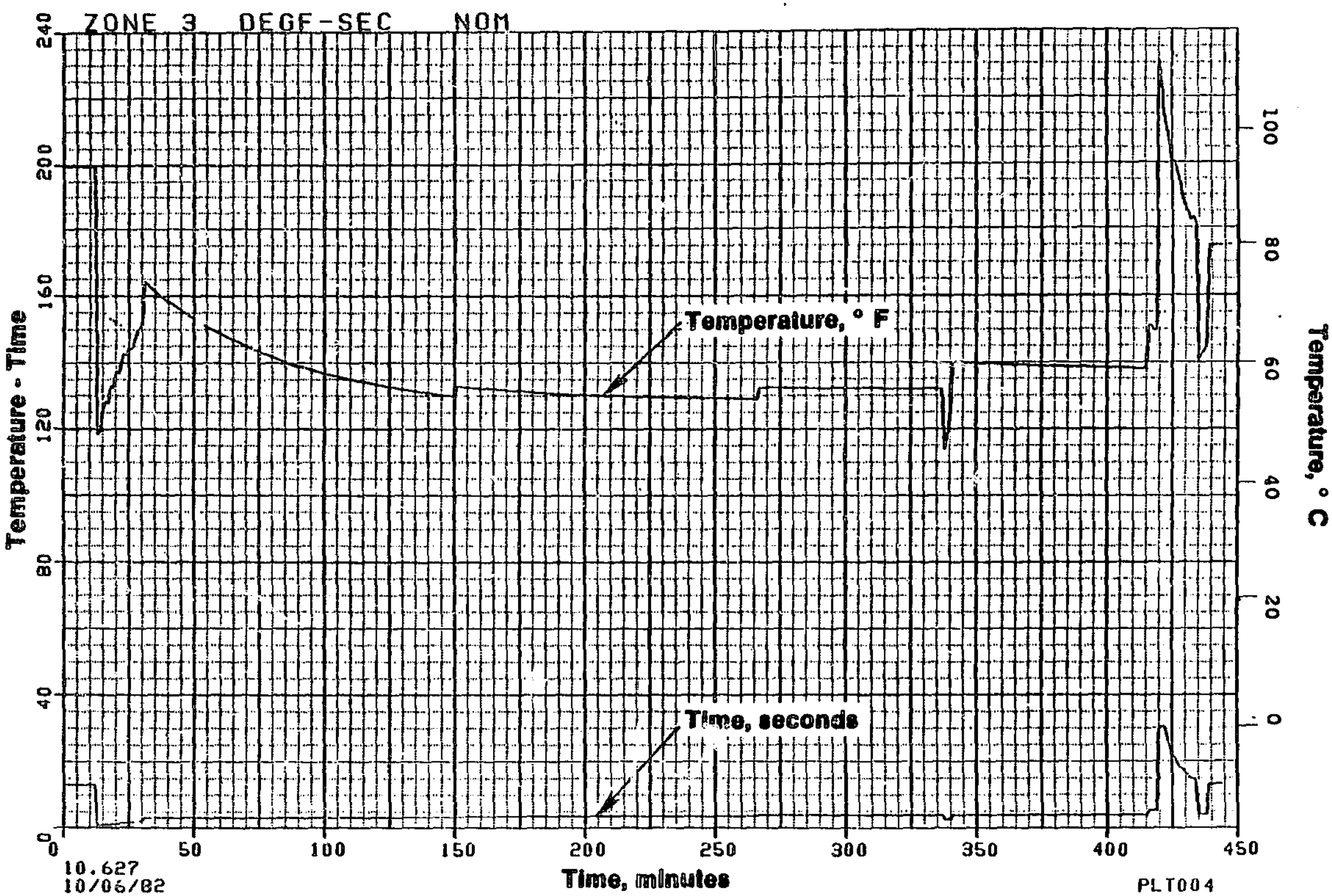


Figure 120. Zone 3 Residence Time and Temperature - Nominal Flight.

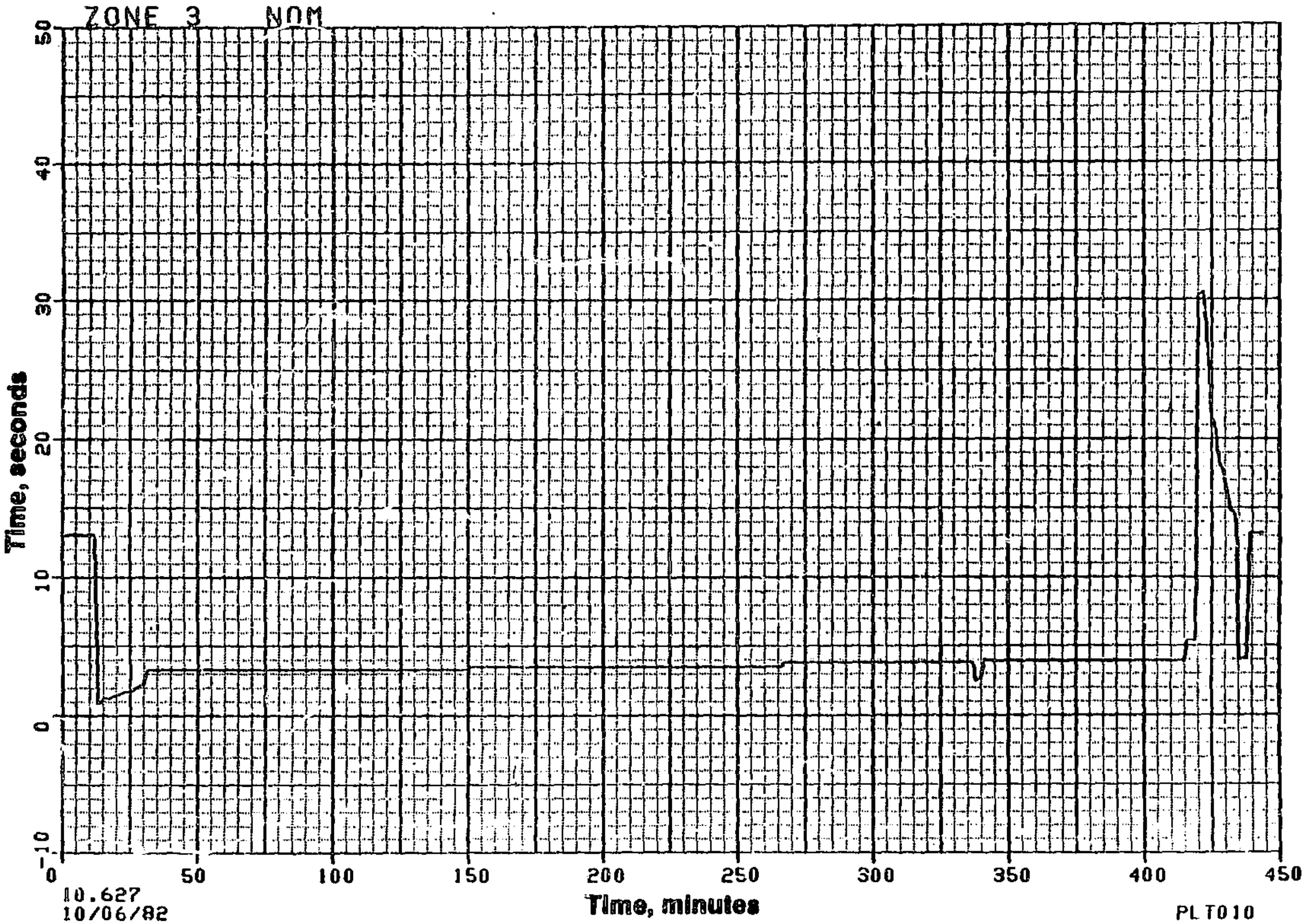


Figure 120a. Zone 3 Residence Time - Nominal Flight.

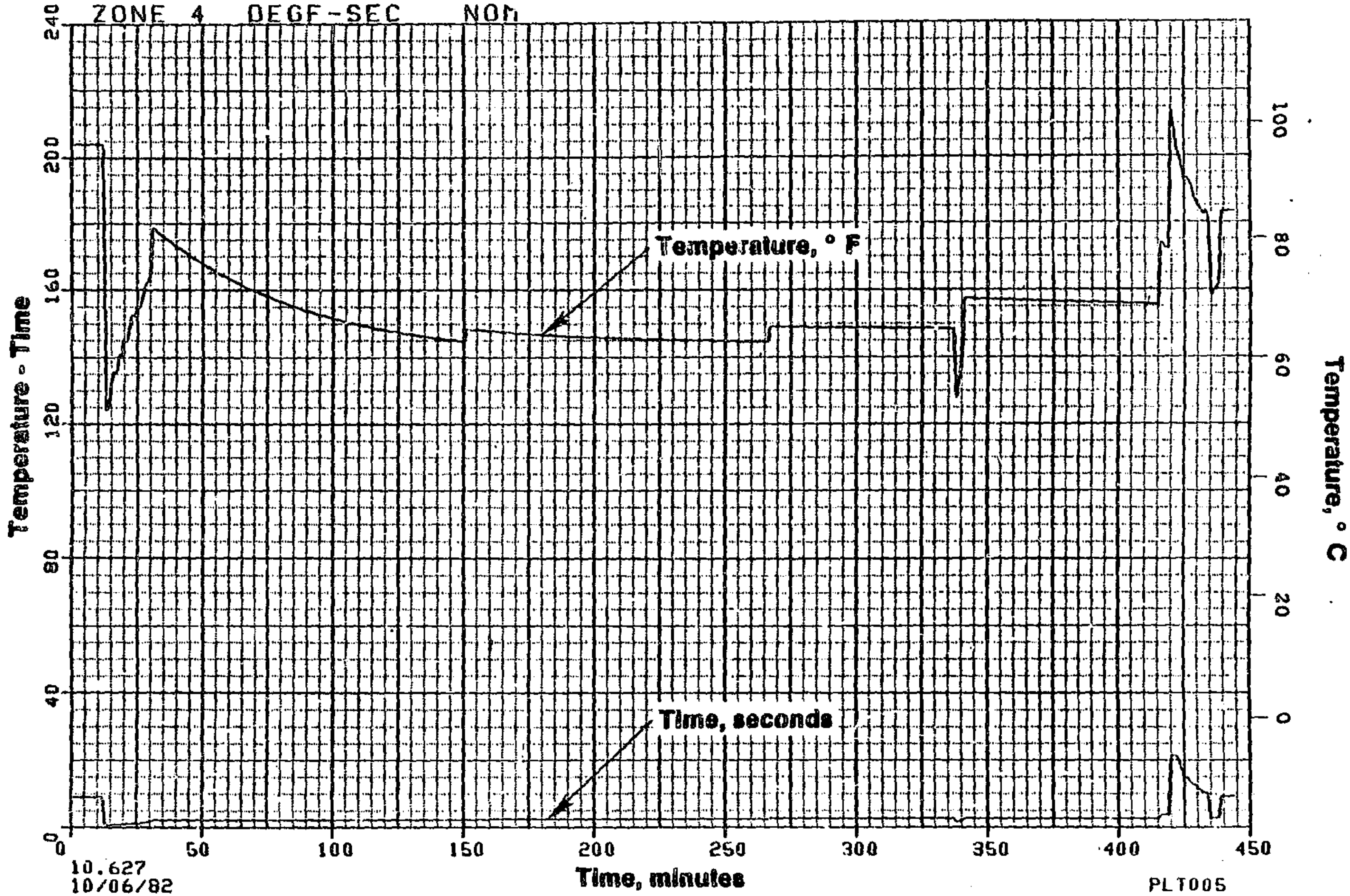


Figure 121. Zone 4 Residence Time and Temperature - Nominal Flight.

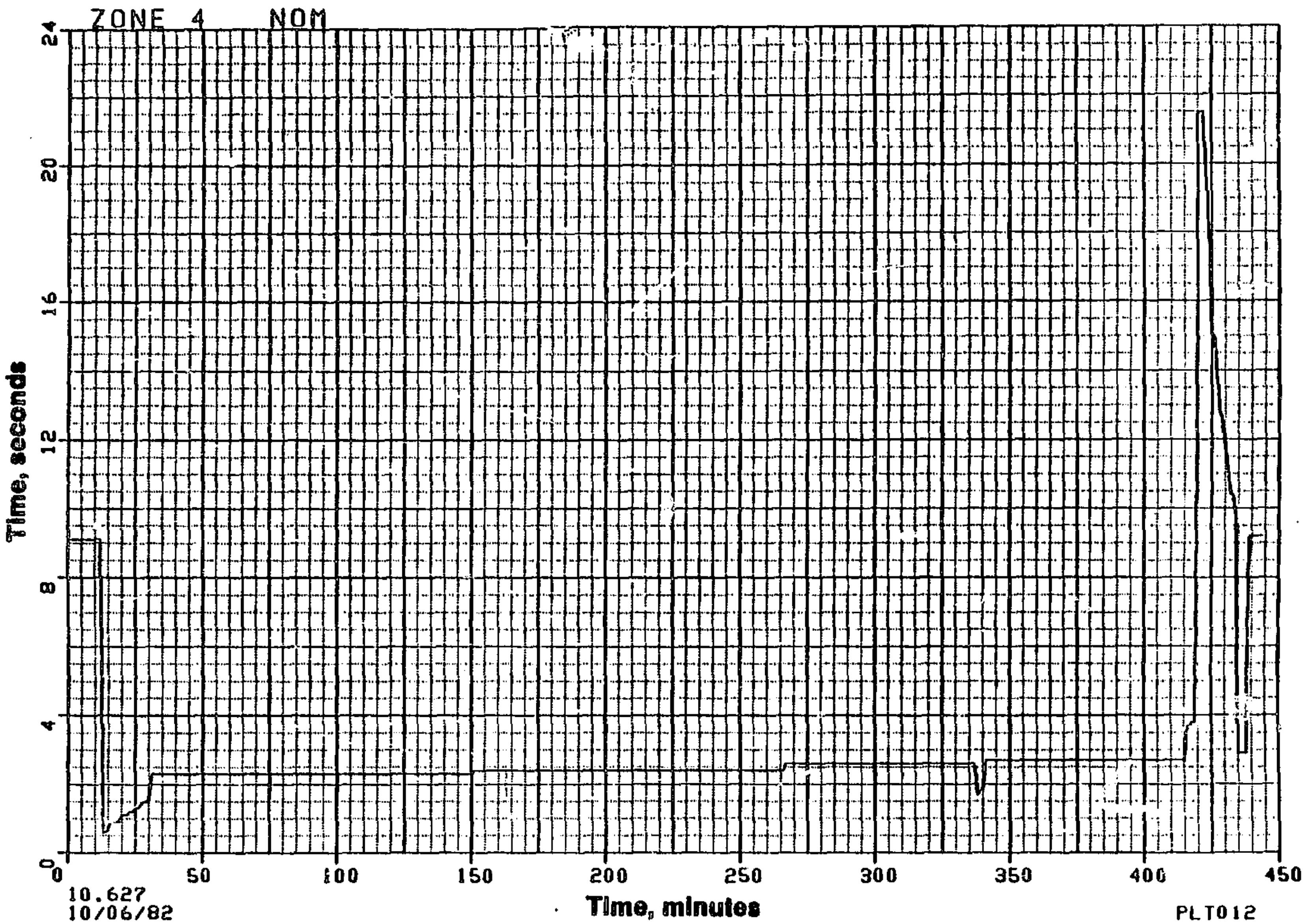


Figure 121a. Zone 4 Residence Time - Nominal Flight.

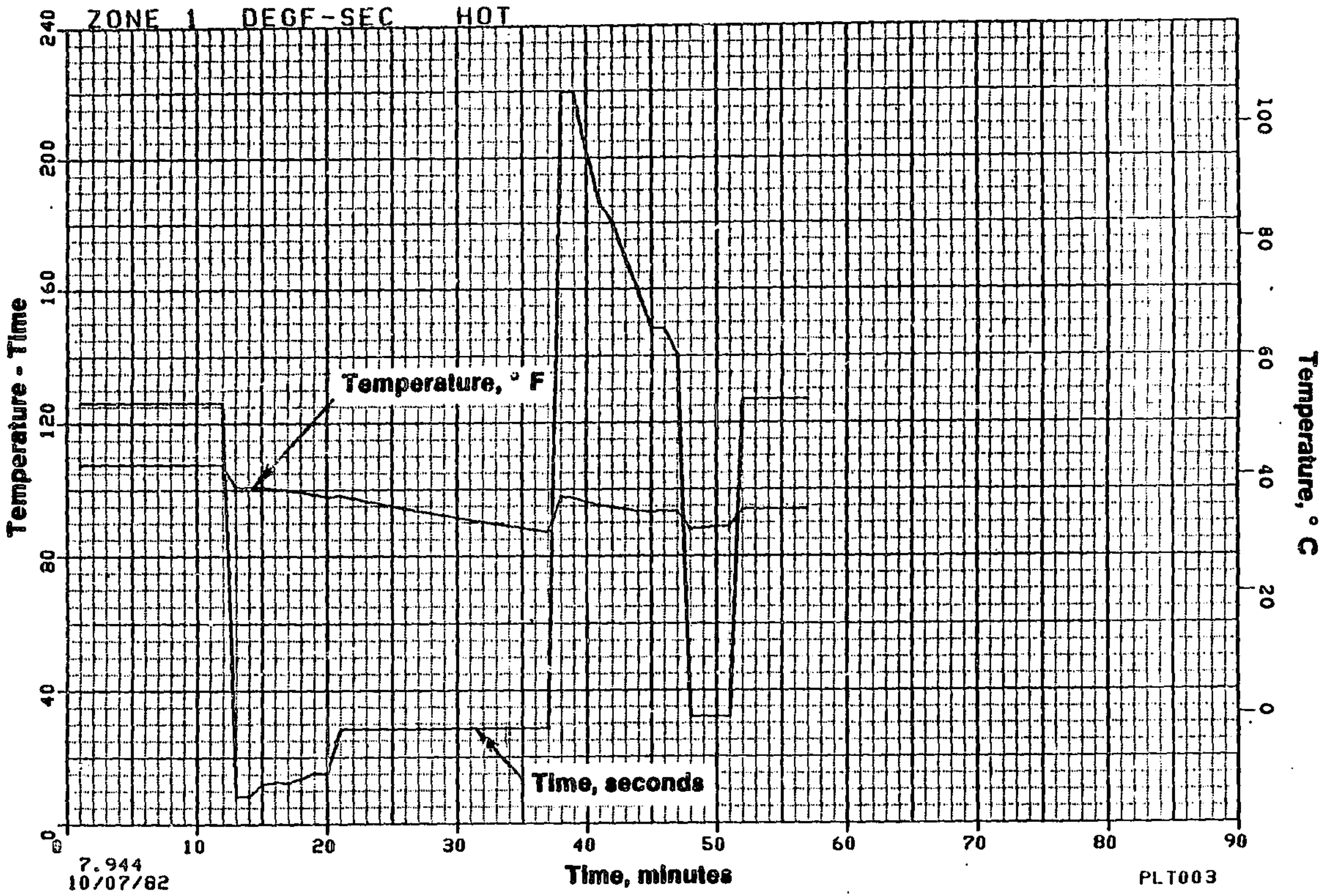


Figure 122. Zone 1 Residence Time and Temperature - Hot Flight.

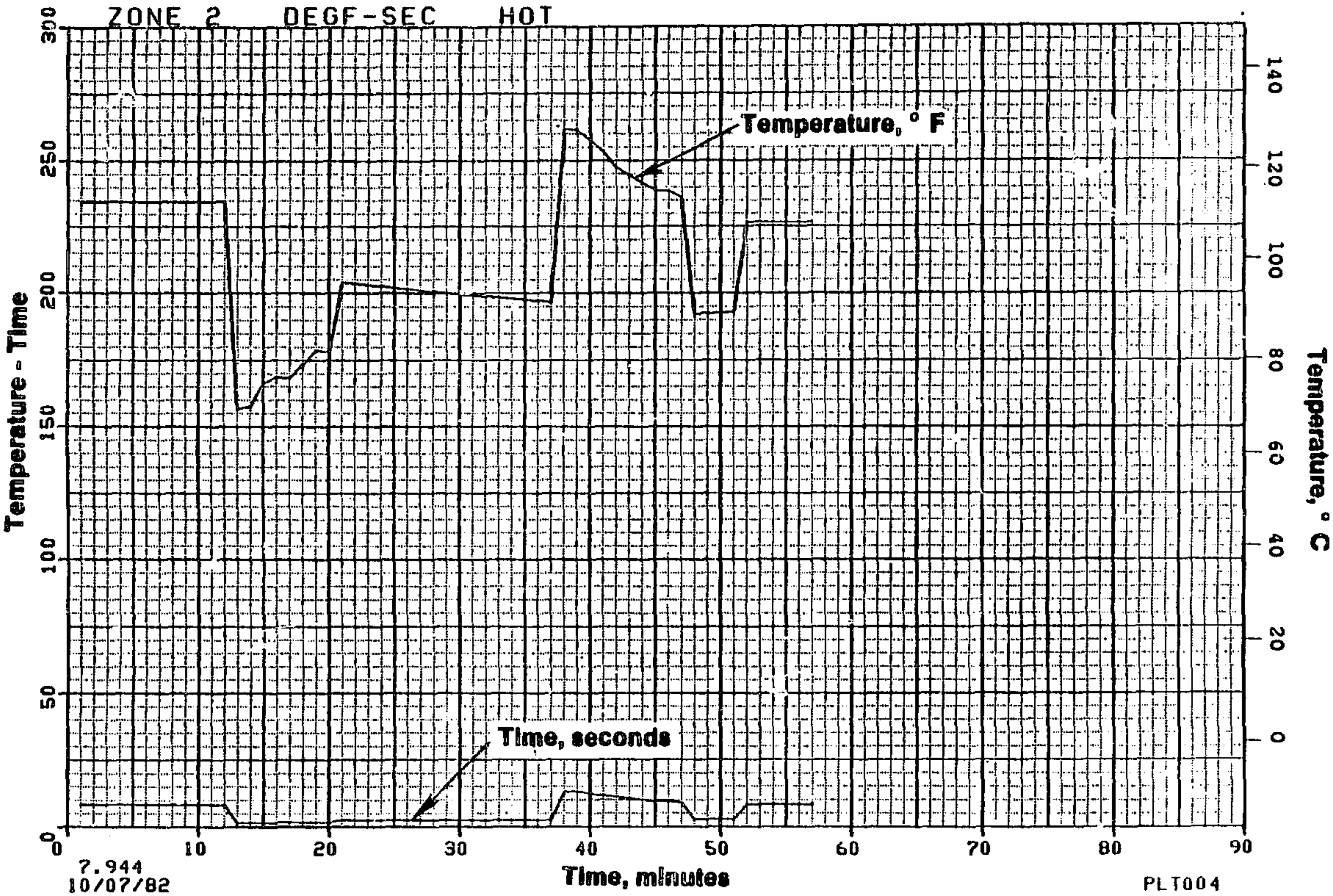


Figure 123. Zone 2 Residence Time and Temperature - Hot Flight.

Figure 123a. Zone 2 Residence Time - Hot Flight.

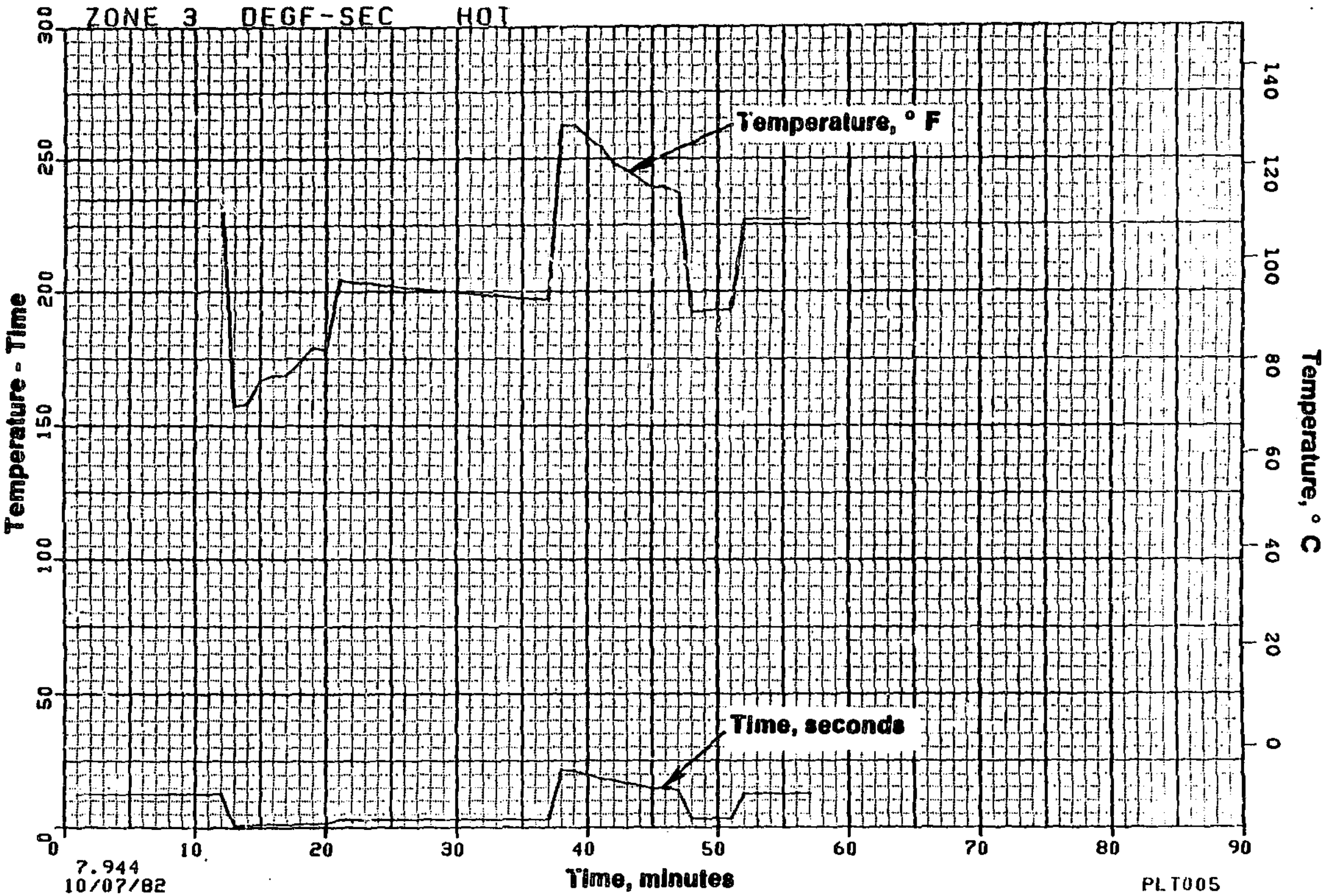


Figure 124. Zone 3 Residence Time and Temperature - Hot Flight.

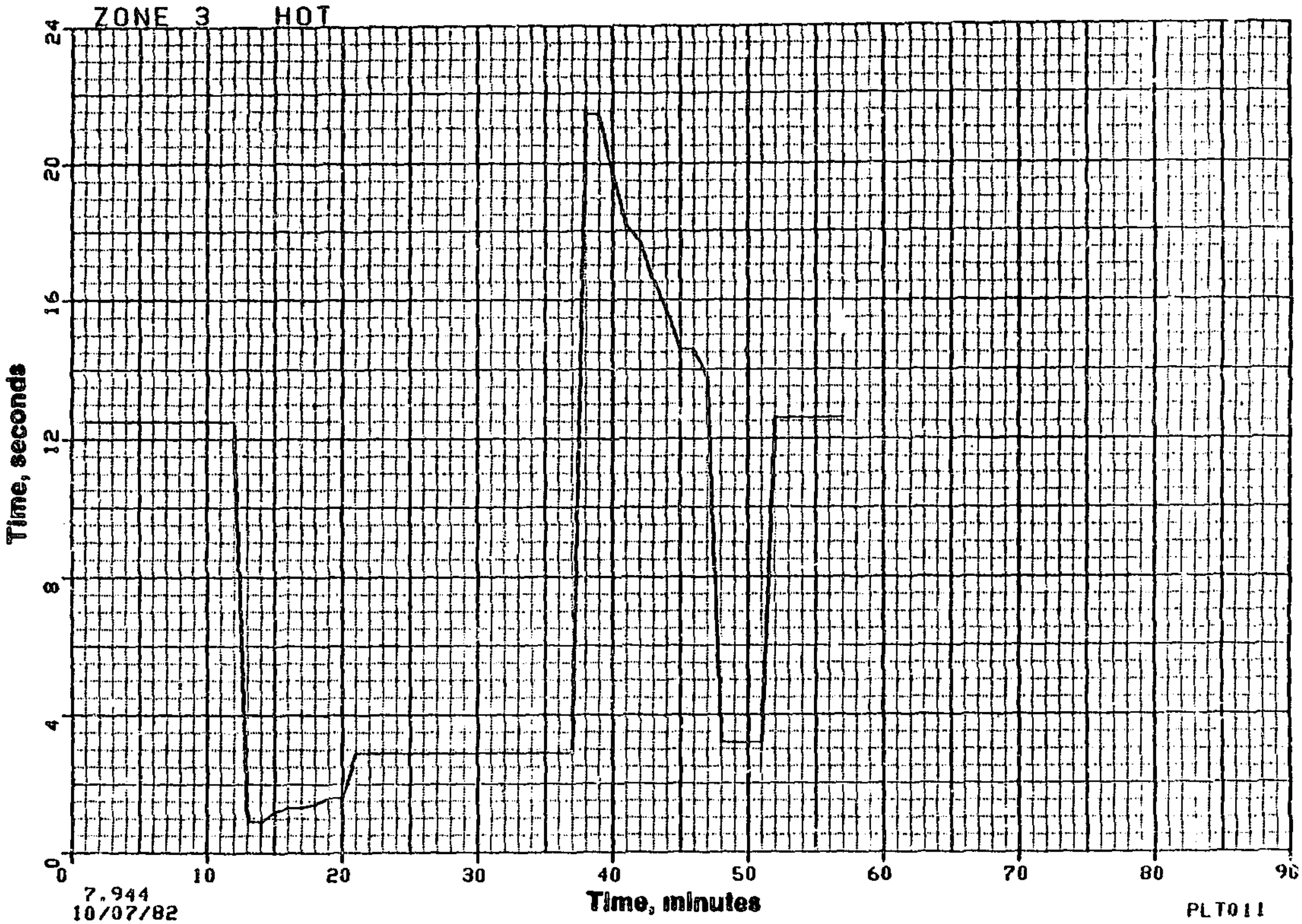


Figure 124a. Zone 3 Residence Time - Hot Flight.

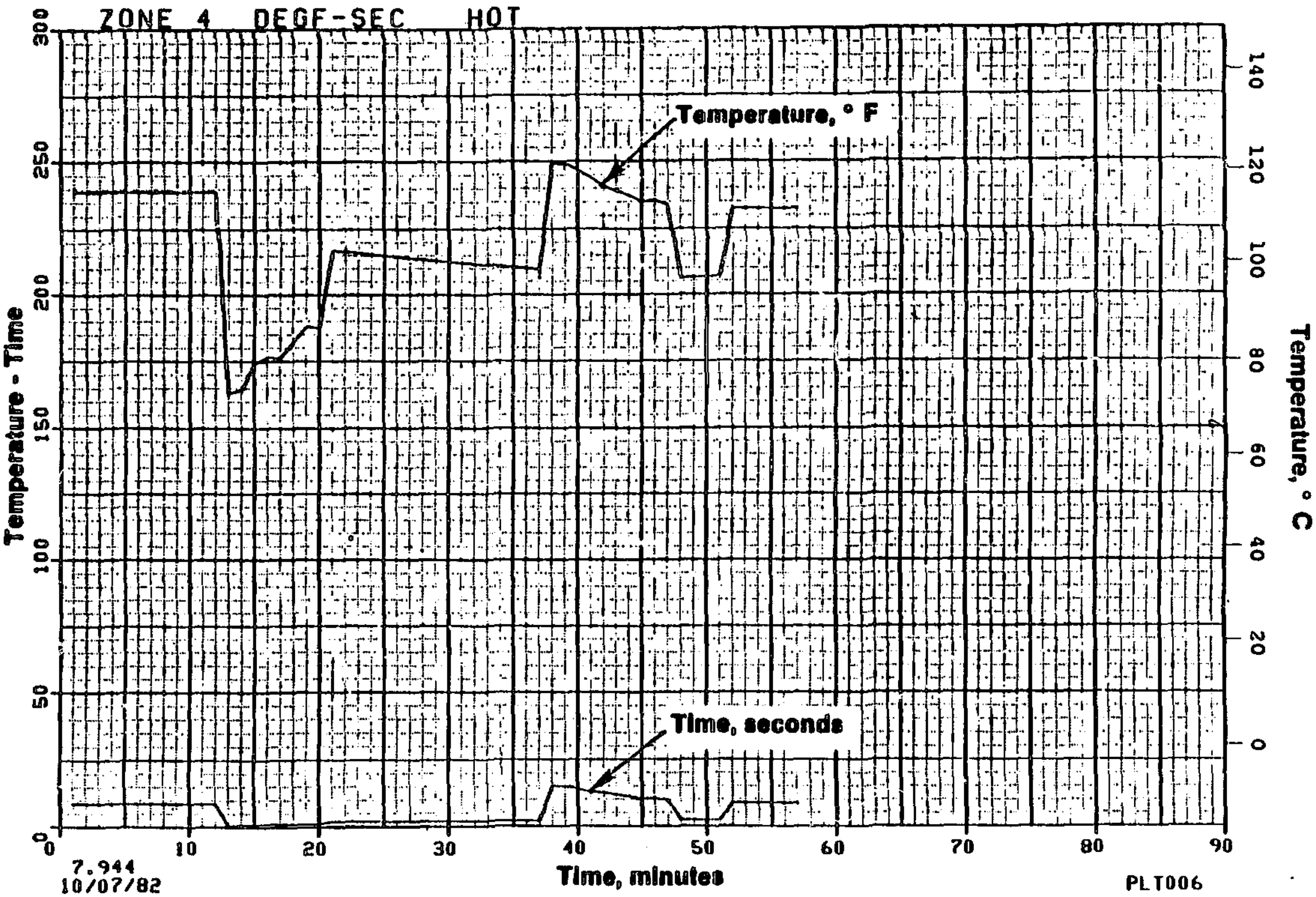


Figure 125. Zone 4 Residence Time and Temperature - Hot Flight.

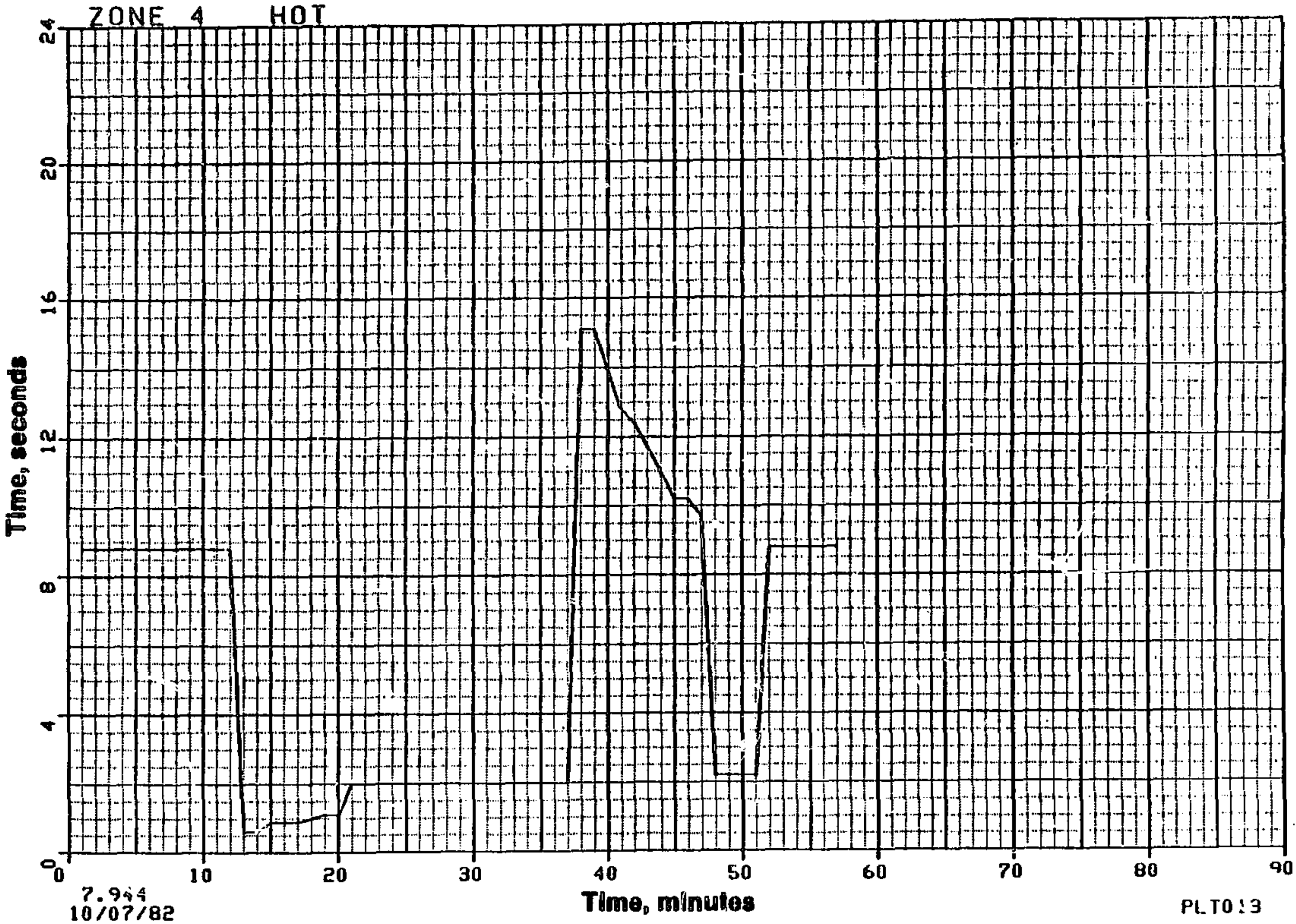


Figure 125a. Zone 4 Residence Time - Hot Flight.

- Fuel interruption time with a large slug of air or vapor in the engine feed line.

Extremely high fuel tank temperature could present problems such as engine or tank boost pump cavitation (excessive release of air or vapor from hot fuel at low pressure). In a tank heating system this would be most likely to occur with low tank reserves (low level of fuel heat sink). The results of the emergency flight scenario described in paragraph 6.2.5 are shown in Figures 126 through 137 and are tabulated as follows:

Advanced System	Flight Time (Min)	Main Tank Level kg (Pounds)	Outboard Tank Temp °C (° F)	Engine Inlet Temp °C (° F)
A	6	1383 (3050)	57.2 (135)	42.8 (109)
B	40	227 (500)	53.3 (128)	45.6 (114)
C	18	771 (1700)	77.8 (172)	50 (122)

At these times in the computer runs, it became impossible to maintain iterative continuity. No attempt was made to change the computer formulations. The message is clear, however.

1. All systems show fair tolerance to excessive tank heating under simulated emergency conditions.

2. In spite of this tolerance, provisions should be included with each system to permit tank heating thermal relief.

The system provisions previously shown in Figures 19 through 21 provide the necessary emergency capabilities. For System A, fuel recirculation can be routed back to the engine pump and the system will function the same as the Baseline. For System B, an air/oil cooler is provided and will adequately cool the tank recirculation fuel as desired. For System C, engine bleed air can be reduced or shut off while all the heat is transferred to engine fuel flow and none to the tank.

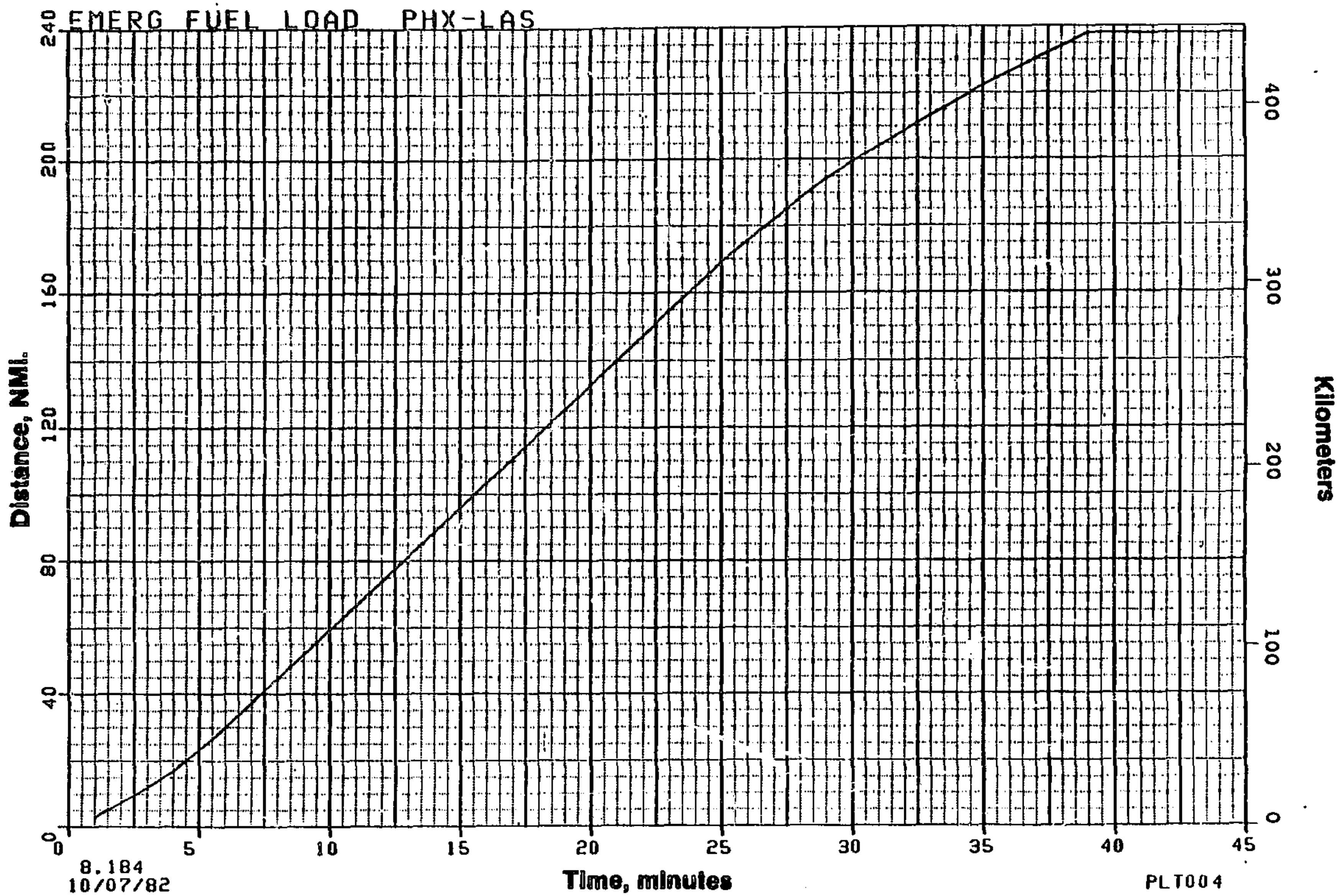


Figure 126. Baseline Emergency Flight - Distance.

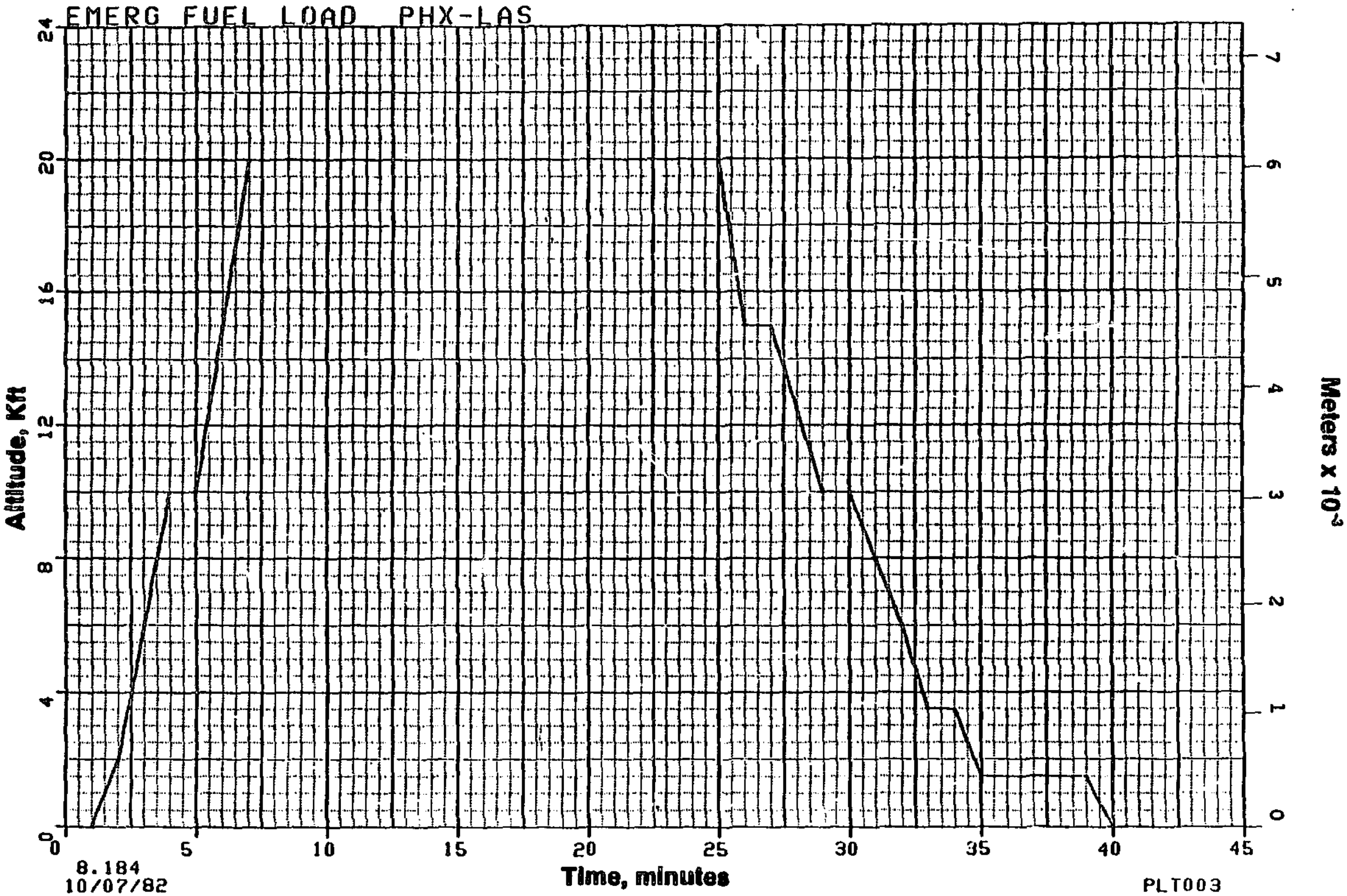


Figure 127. Baseline Emergency Flight - Altitude

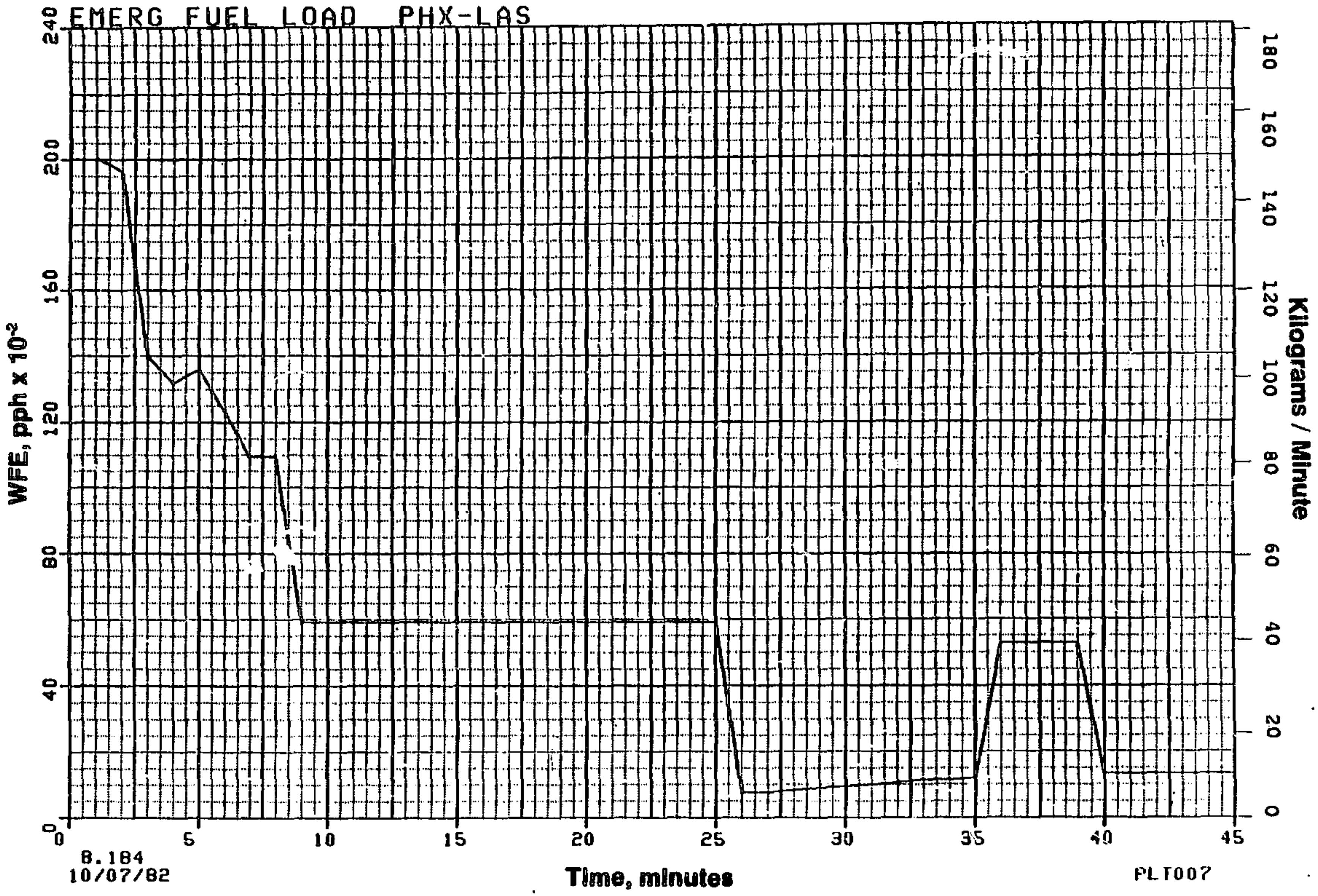


Figure 128. Baseline Emergency Flight - Engine Fuel Flow.

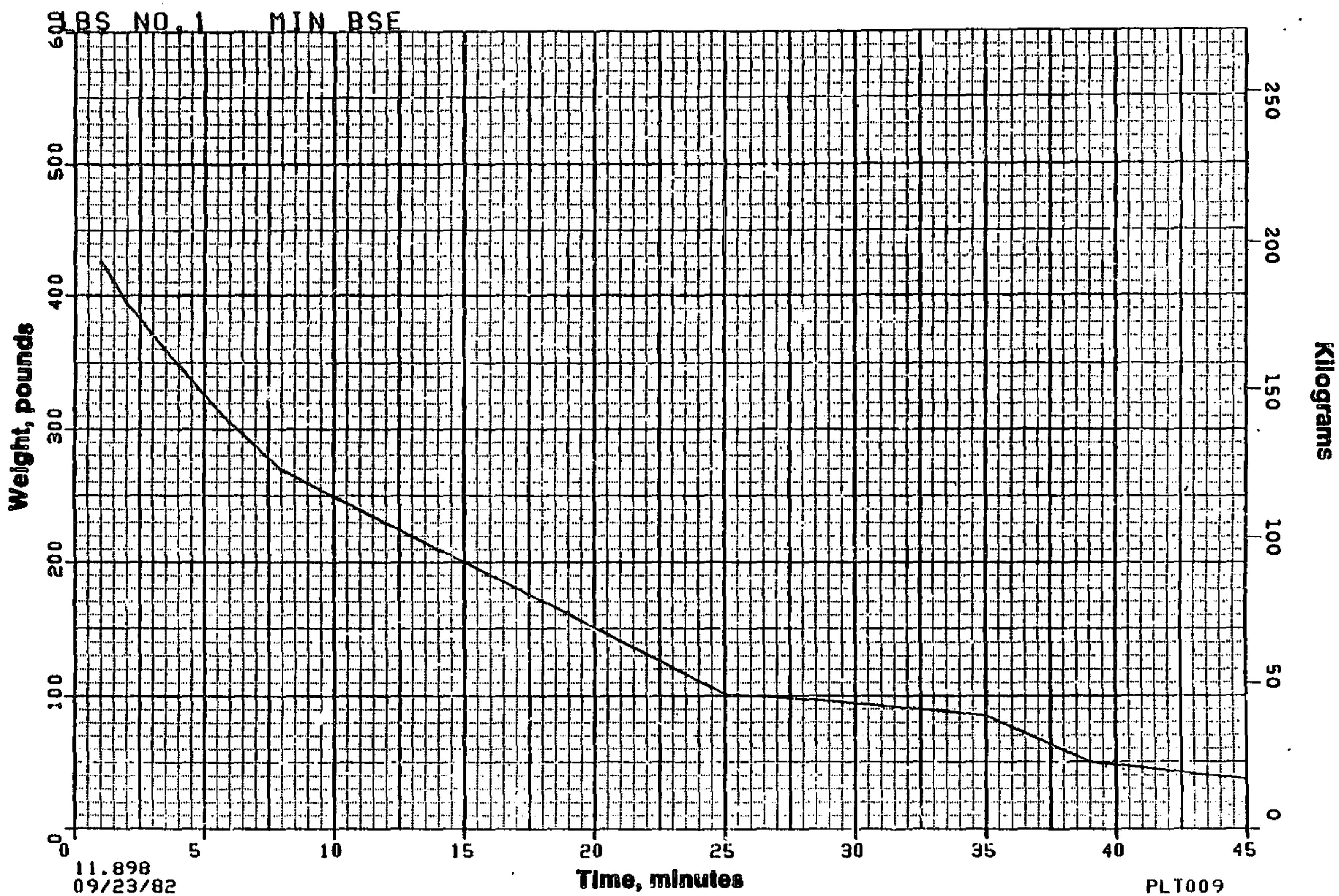


Figure 129. Baseline Emergency Flight - Main Fuel Tank Quantity.

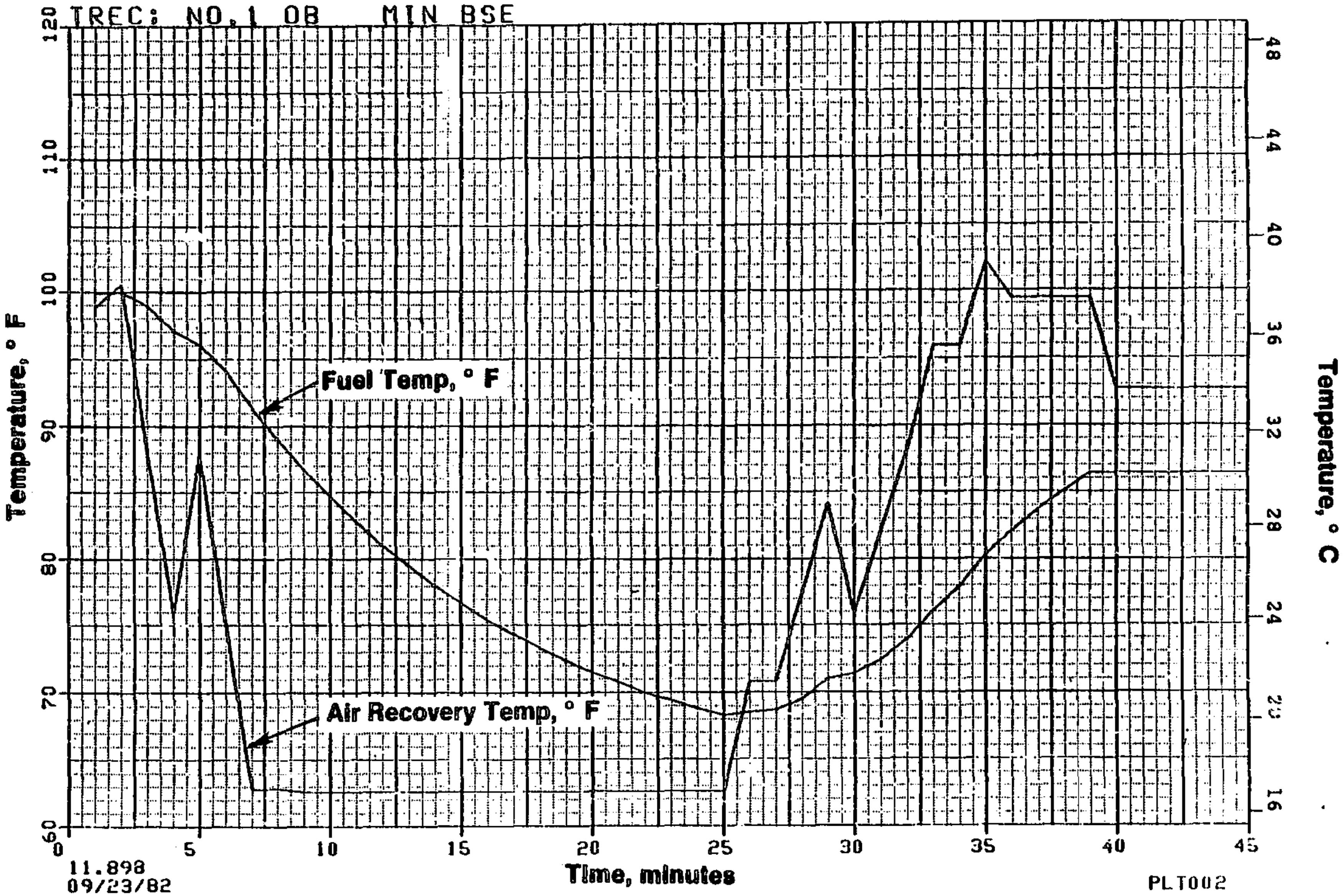


Figure 130. Baseline Emergency Flight - Outboard Tank Fuel Temperature.

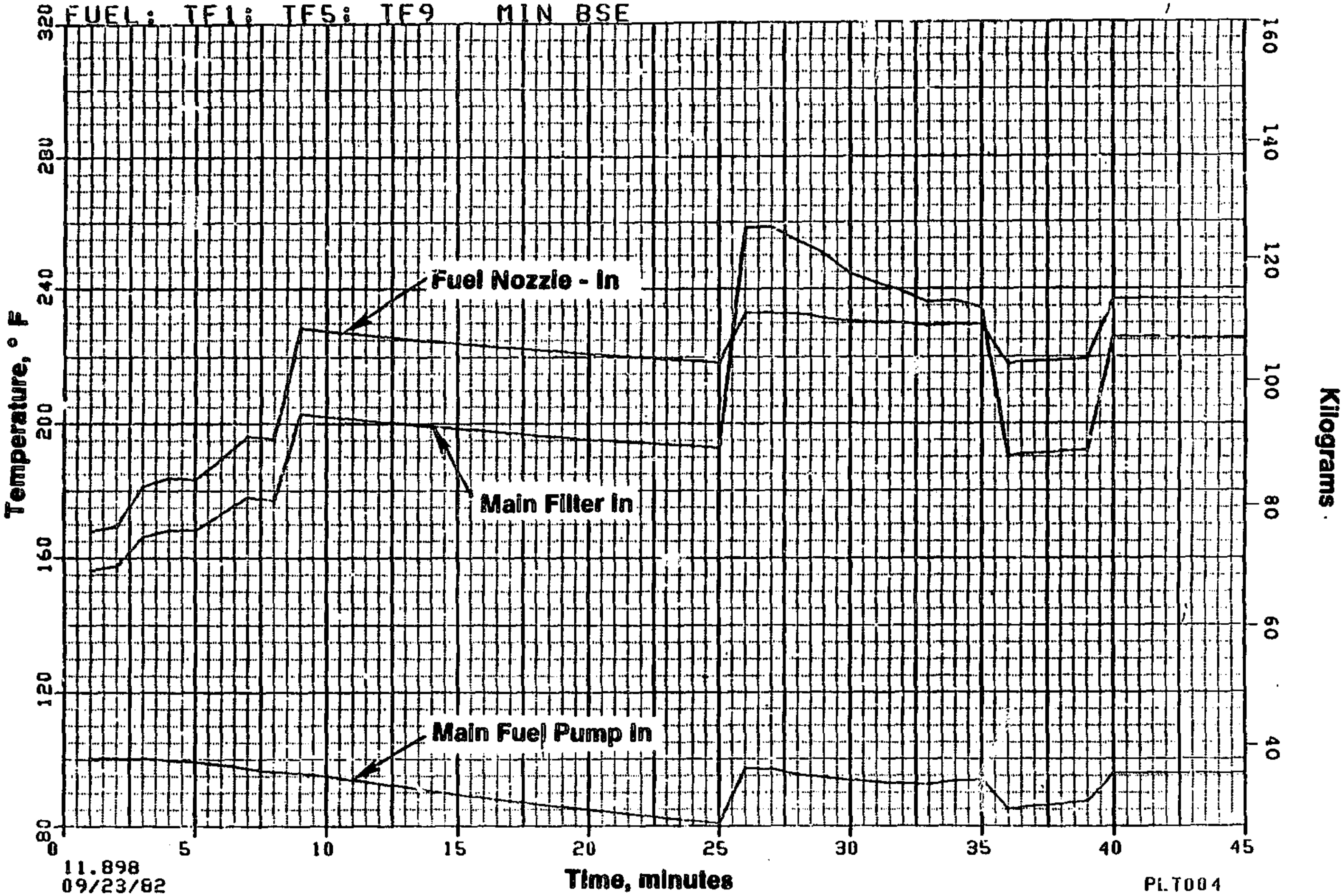


Figure 131. Baseline Emergency Flight - Engine Fuel Temperatures.

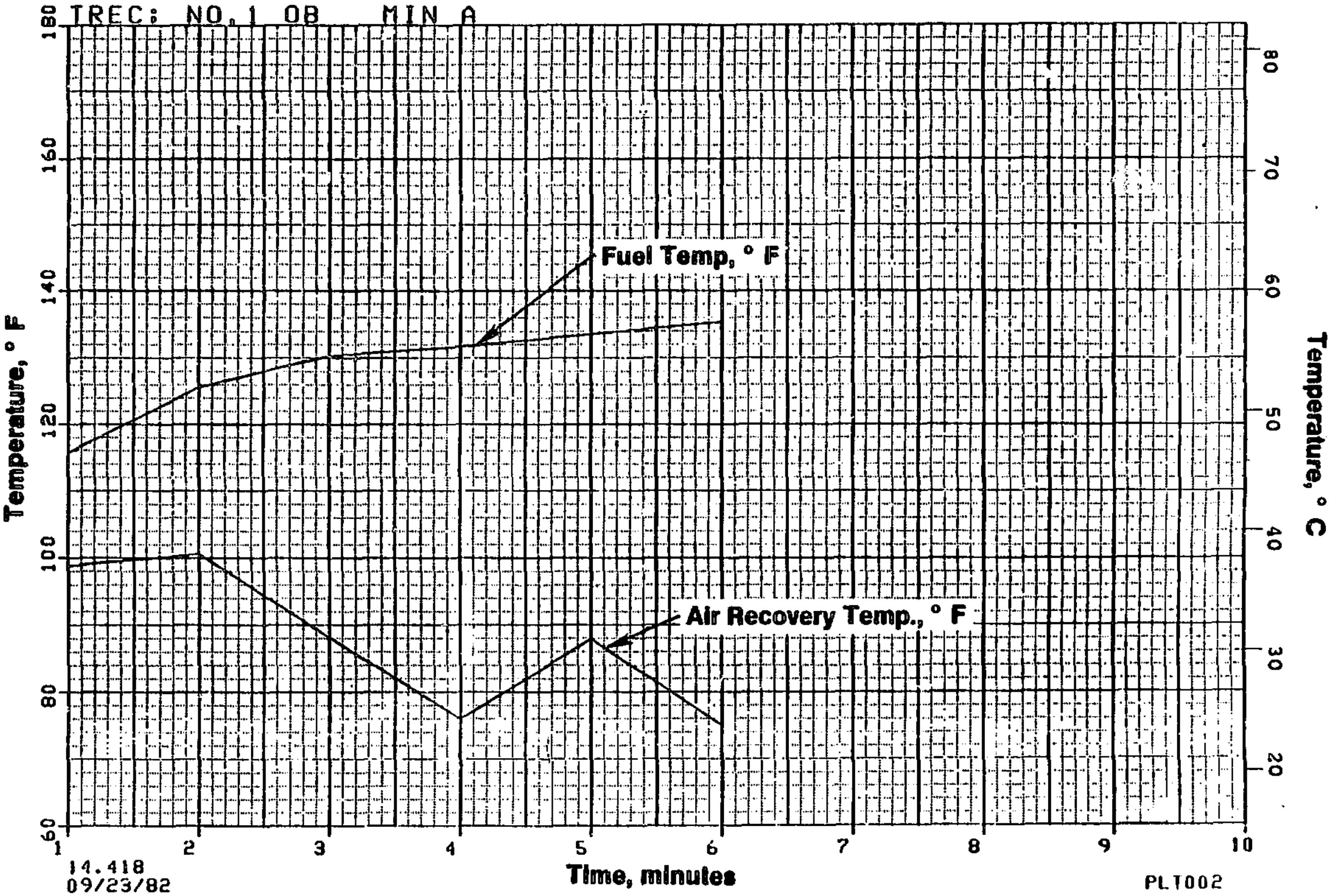


Figure 132. Emergency Flight System A - Outboard Tank Fuel Temperature.

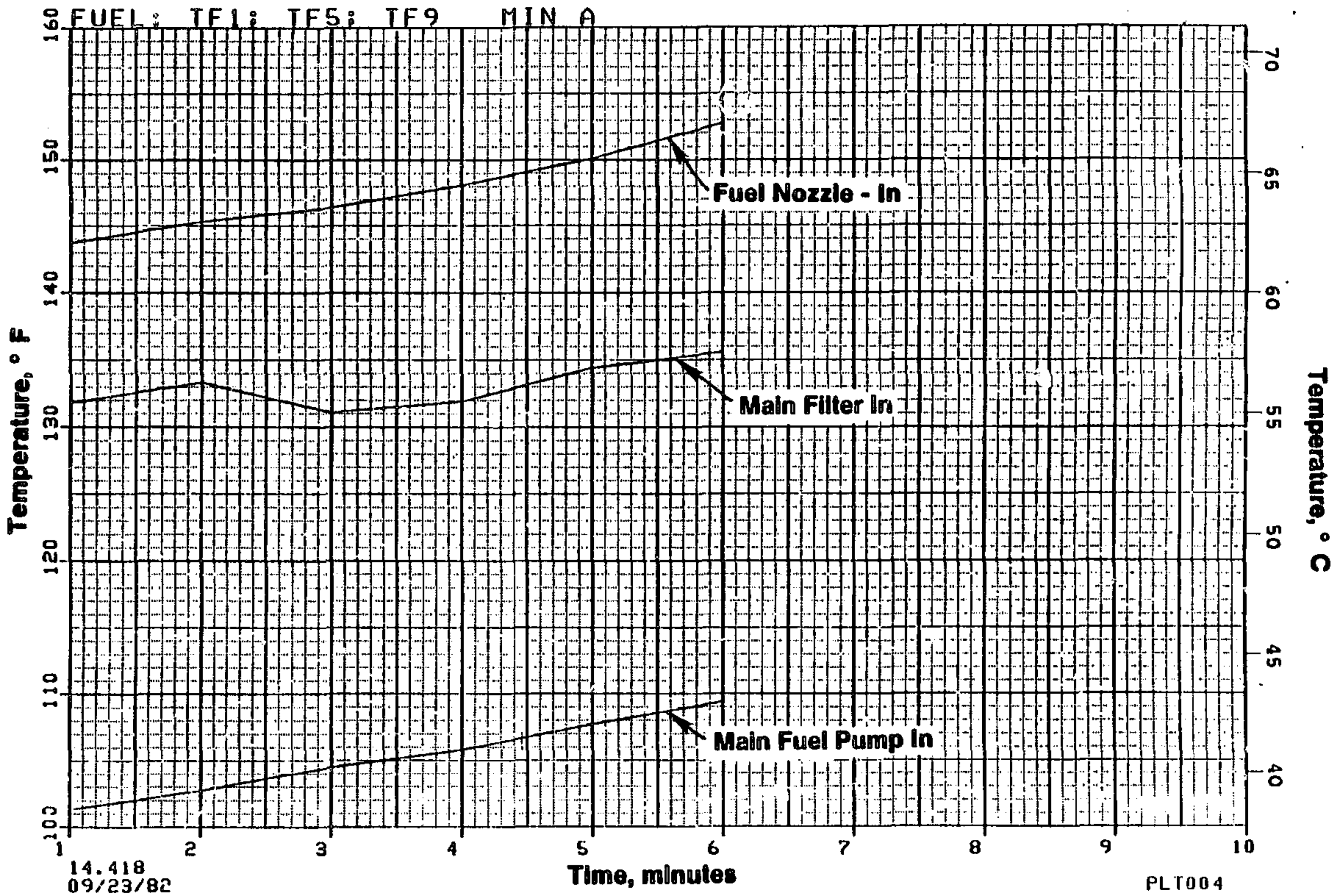


Figure 133. Emergency Flight System A - Engine Fuel Temperatures.

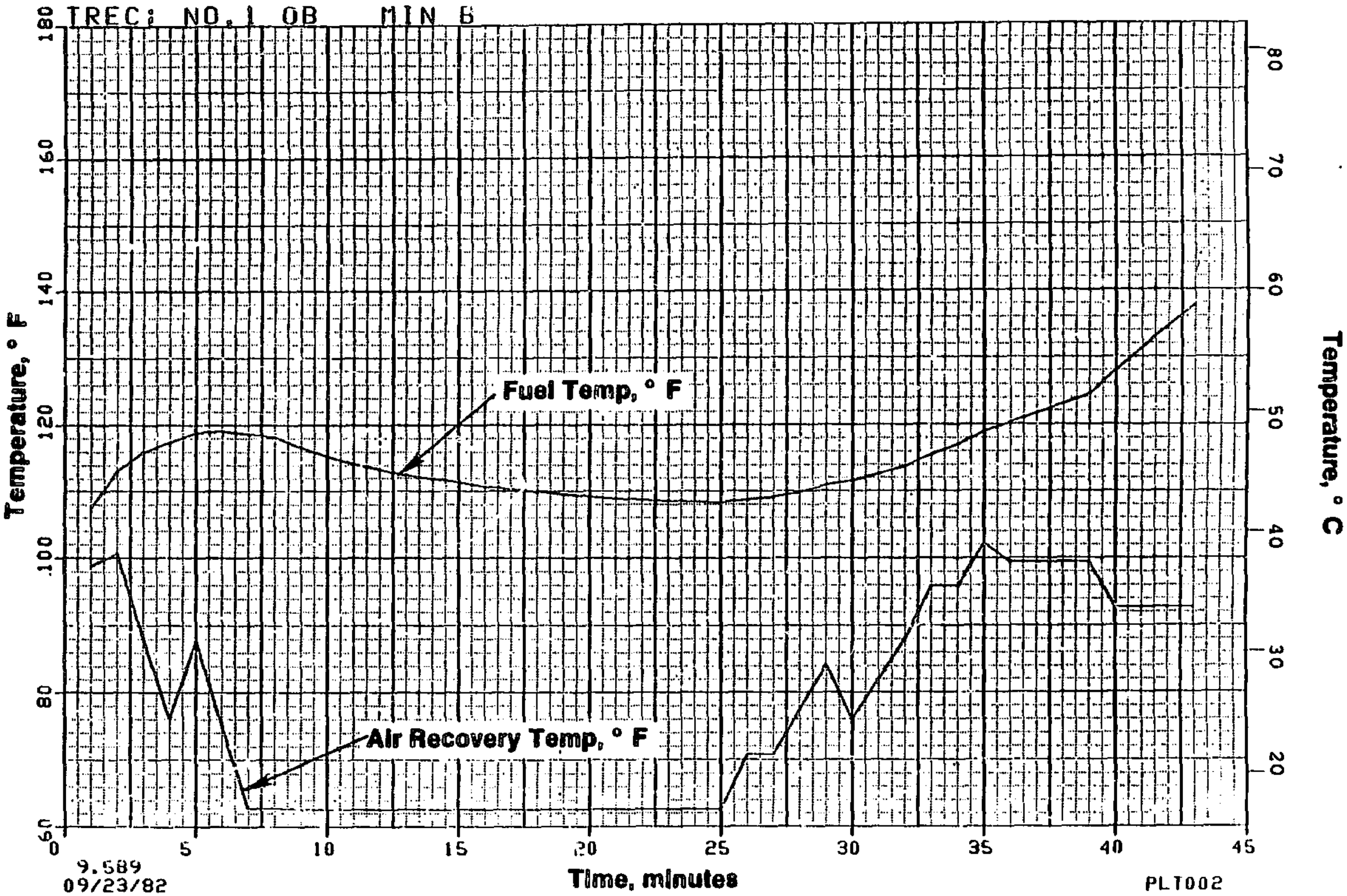


Figure 134. Emergency Flight System B - Outboard Tank Fuel Temperature.

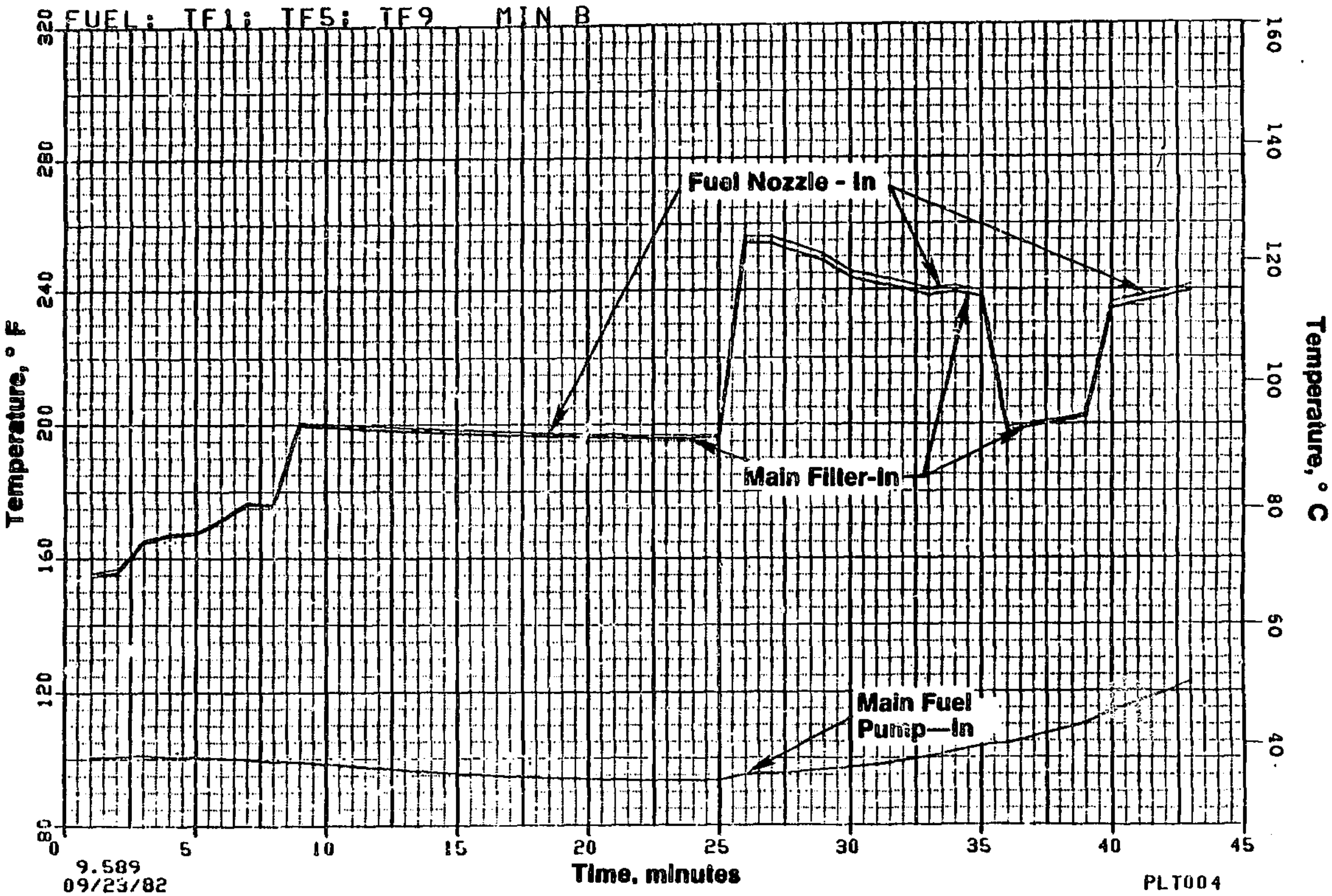


Figure 135. Emergency Flight System B - Engine Fuel Temperatures.

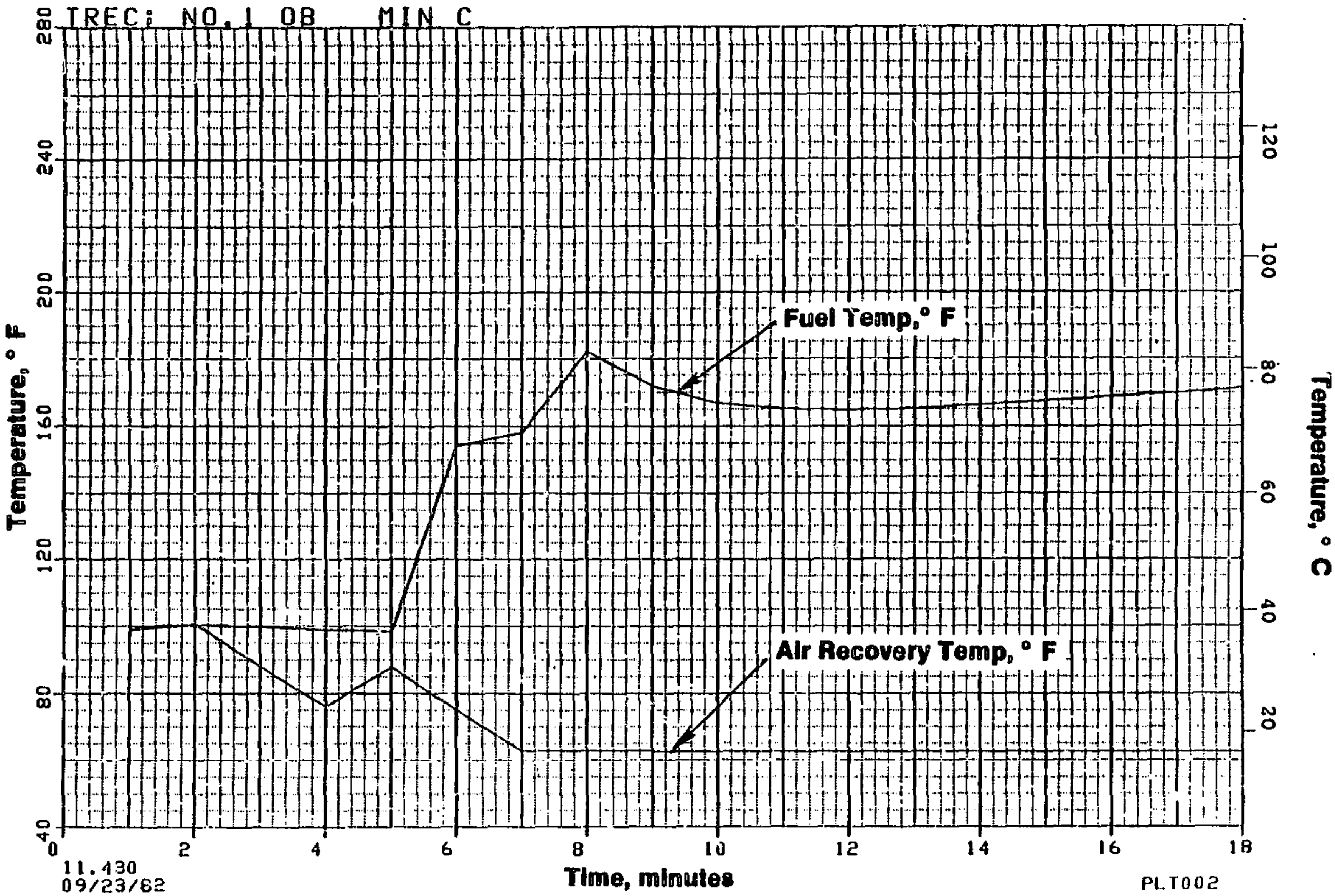


Figure 136. Emergency Flight System C - Outboard Tank Fuel Temperature.

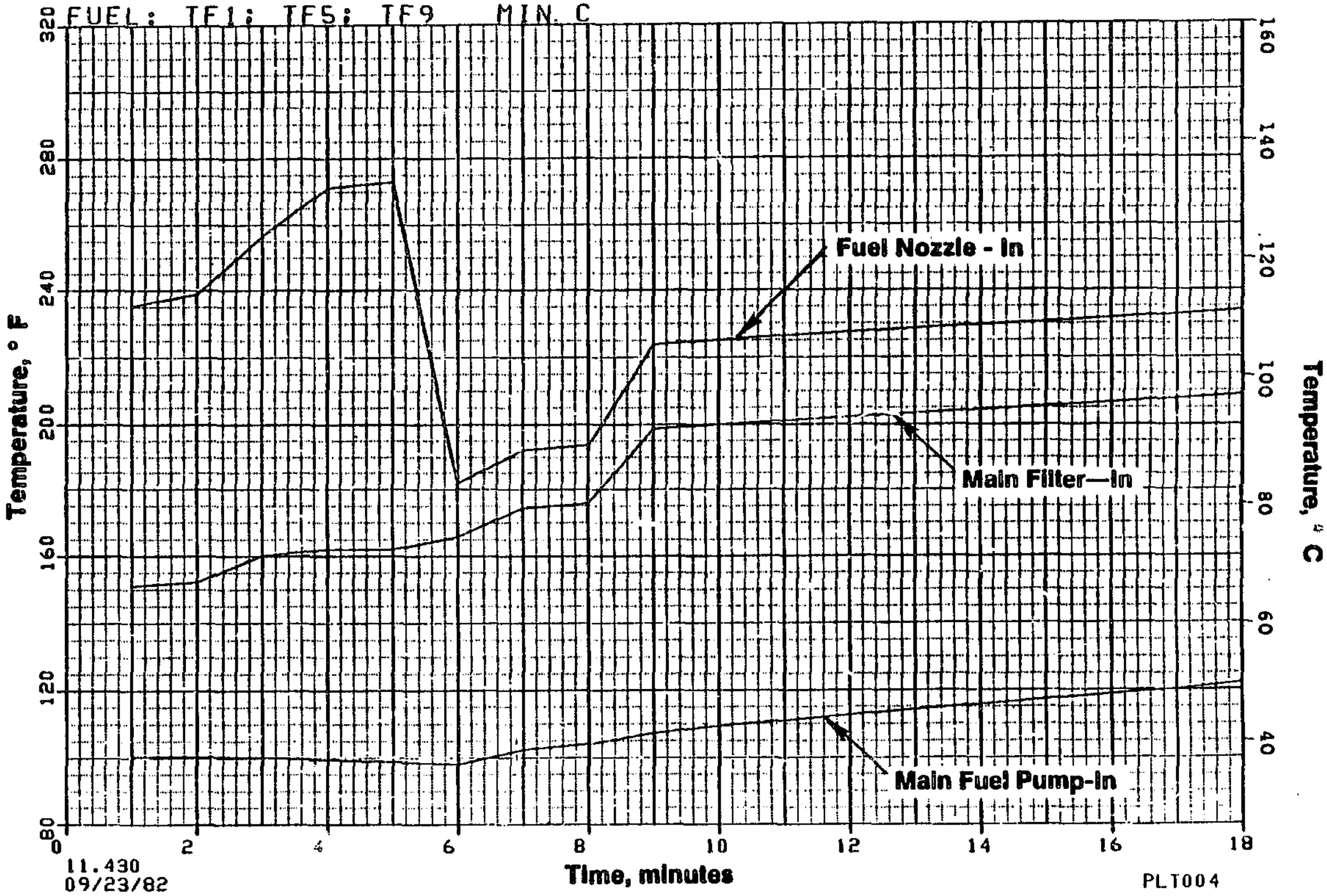


Figure 137. Emergency Flight System C - Engine Fuel Temperatures.

9.0 SYSTEM EFFECT ON FUEL CONSUMPTION

9.1 INTRODUCTION

Selection of an Advanced System for compatibility with broadened-property fuel cannot be realistically made without consideration of the impact on engine fuel consumption. Consequently, the flight simulation models included change in fuel consumption. Consequently, the flight simulation models included change in fuel consumption relative to the Baseline System. Fuel consumption would be affected by the following:

- Weight.
- Power extraction to drive the fuel pump.
- Fan bleed air extraction for ECS precooling.

For interpretation of the results which follow, a brief description of the terminology used is offered here.

$$\% \Delta sfc = \frac{\Delta sfc}{sfc}$$

where % Δsfc is the percent change in specific fuel consumption; Δsfc is the change in sfc associated with the particular parameter of concern (weight, HP,... etc.) and sfc is the specific fuel consumption for the engine.

$$\% \Delta \text{ Block Fuel} = \frac{\Delta \text{ Block Fuel (Lbs)}}{\text{Total Block Fuel (Lbs)}}$$

where %Δ Block Fuel is the percent change in block fuel; Δ Block Fuel is the change in fuel burned associated with the parameter of concern and Total Block Fuel is the total block fuel used for the nominal flight.

With respect to combustor fuel preheating, the energy available at the fuel nozzle per pound of block fuel was determined for all systems. The difference between the results for the baseline and the advanced systems was then divided by the heating value of the fuel to provide the %Δ Block Fuel.

9.2 RESULTS

Flight profile plots were made showing the above-mentioned effects for each system. The effect of system weight on specific fuel consumption (% Δsfc) is shown in Figures 138 and 139. System C weight of 185 pounds assumes a complete system without a fan air precooler. The Baseline and Advanced Systems A and B all weigh about 52.1 kg (115 pounds). These weight effects were calculated in the model by assuming a proportionality between engine component weight and aircraft fuel weight in terms of adjusted engine thrust. Change in engine power setting (fuel flow) for constant air speed and altitude was known from the initial engine flight profile computer runs. Likewise, change in fuel flow was known for aircraft altitude change. These same derivatives were used and multiplied by 1.25 to account for aircraft structural weight needed to carry the engine outboard on the wing. This approach is different than that customarily used and which does not account for the precise flight profile and is predicated on constant thrust rather than constant aircraft speed. Although the difference is minor considering the small effect of weight (for this study) on sfc, the study approach is believed to be more valid.

Fuel pump shaft power has a minor effect on sfc for a high fan bypass engine because of the large power associated with the low pressure turbine (which drives the fan). The high pressure turbine is directly affected by pump power since it drives the engine accessory gearbox. Figures 140 through 143 show pump power and its effect on sfc. Only System C using a centrifugal pump had measureable influence on sfc.

ECS bleed flow was scheduled for nominal DC-10-30 conditions during the nominal flight. The compressor bleed schedule is shown in Figure 144. Corresponding sfc penalty for fan air precooling is shown in Figure 145.

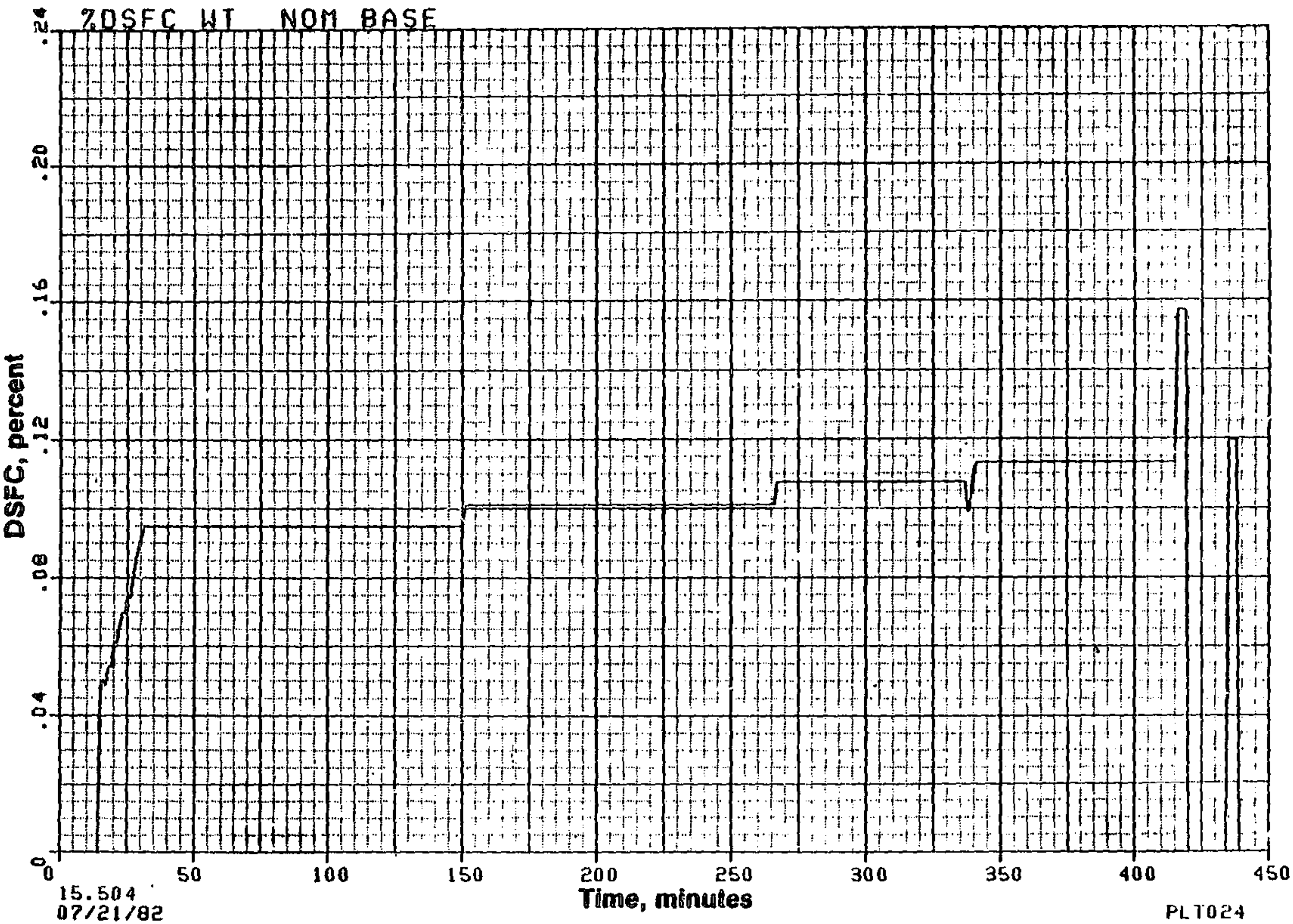


Figure 138. Nominal Flight %ΔSFC for 115 lb. (512 N)
Weight Baseline, Systems A and B

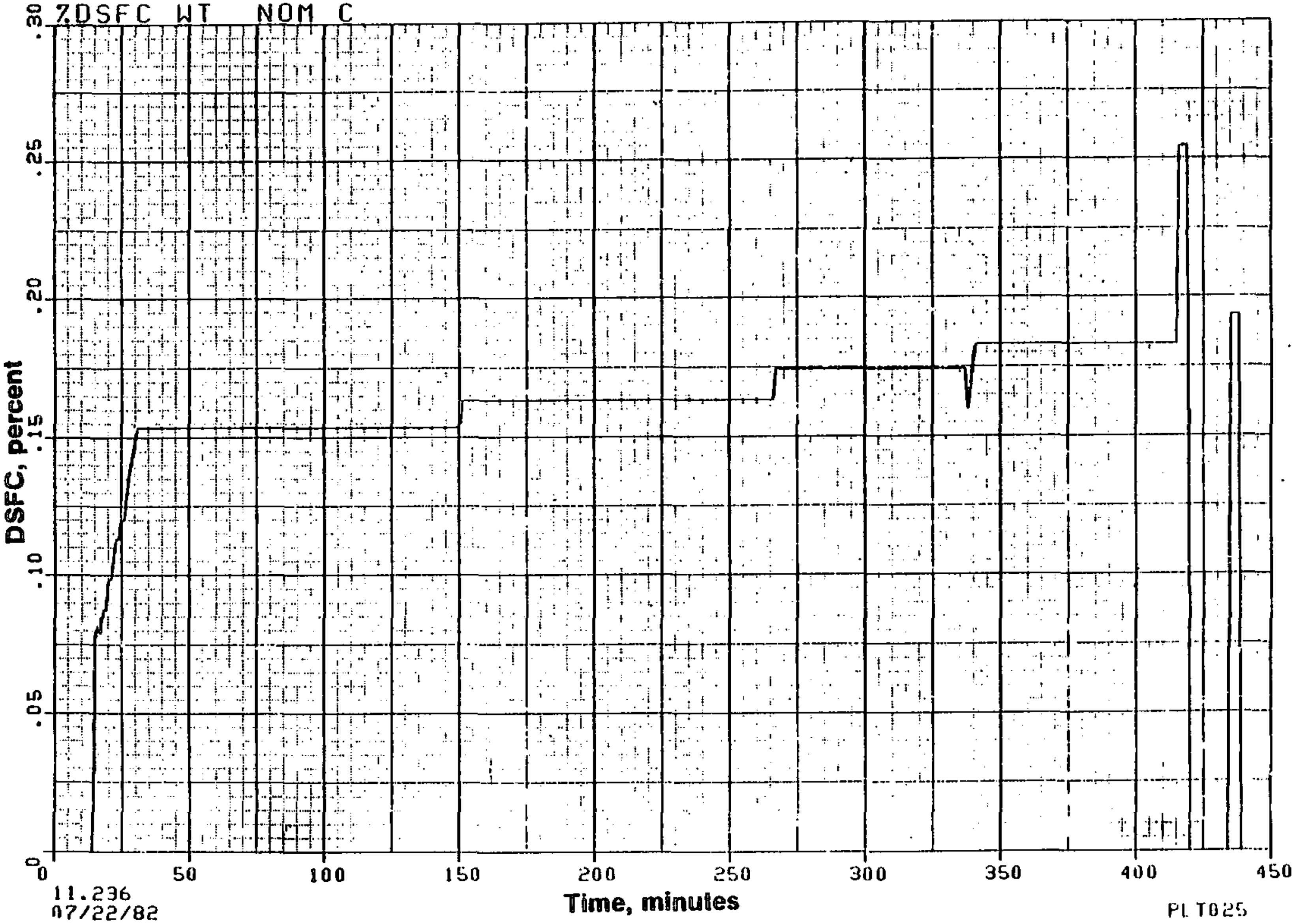


Figure 139. System C - Nominal Flight %ΔSFC for 185 lb (823 N) Weight.

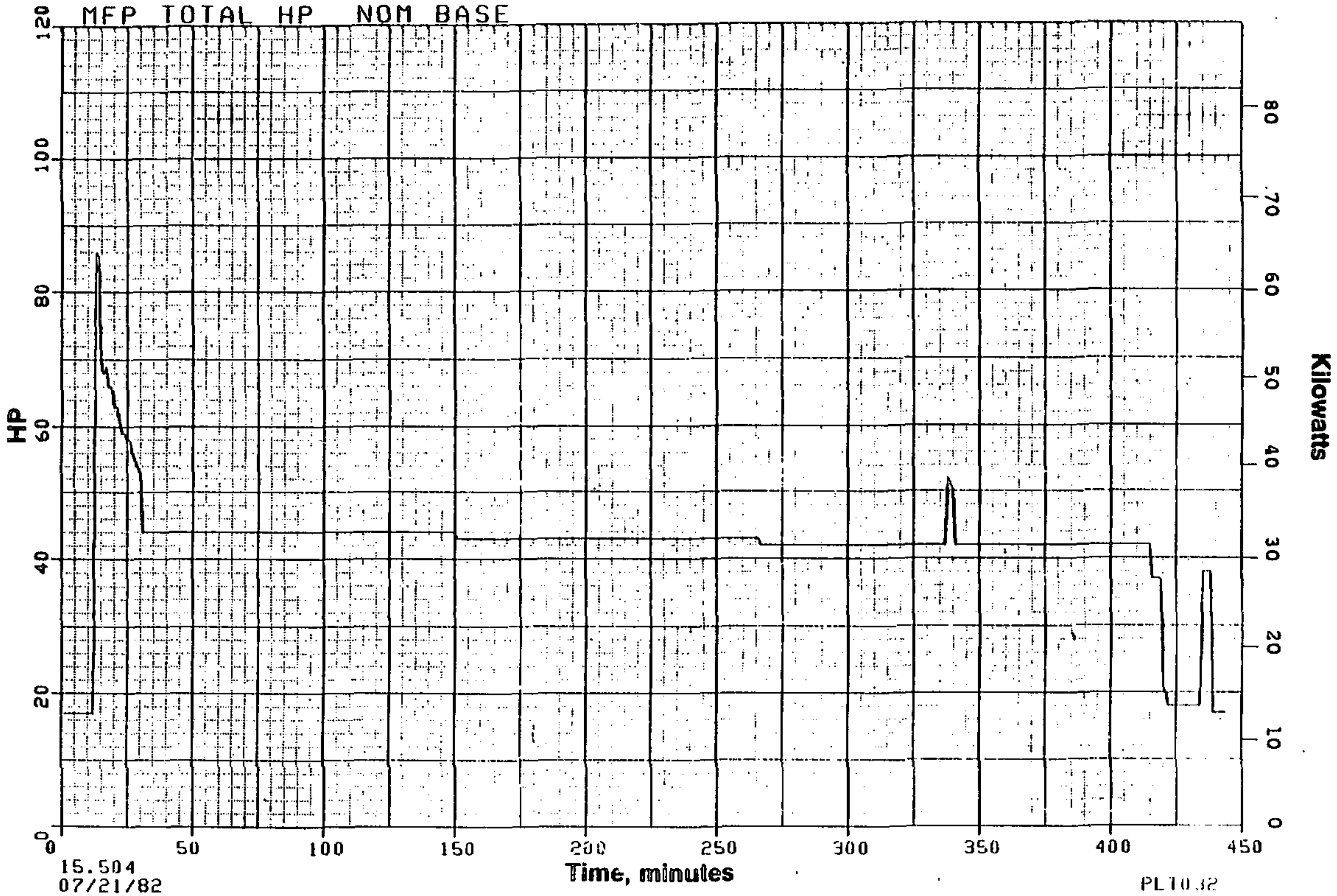


Figure 140. Baseline - Nominal Flight Fuel Pump Input Horsepower.

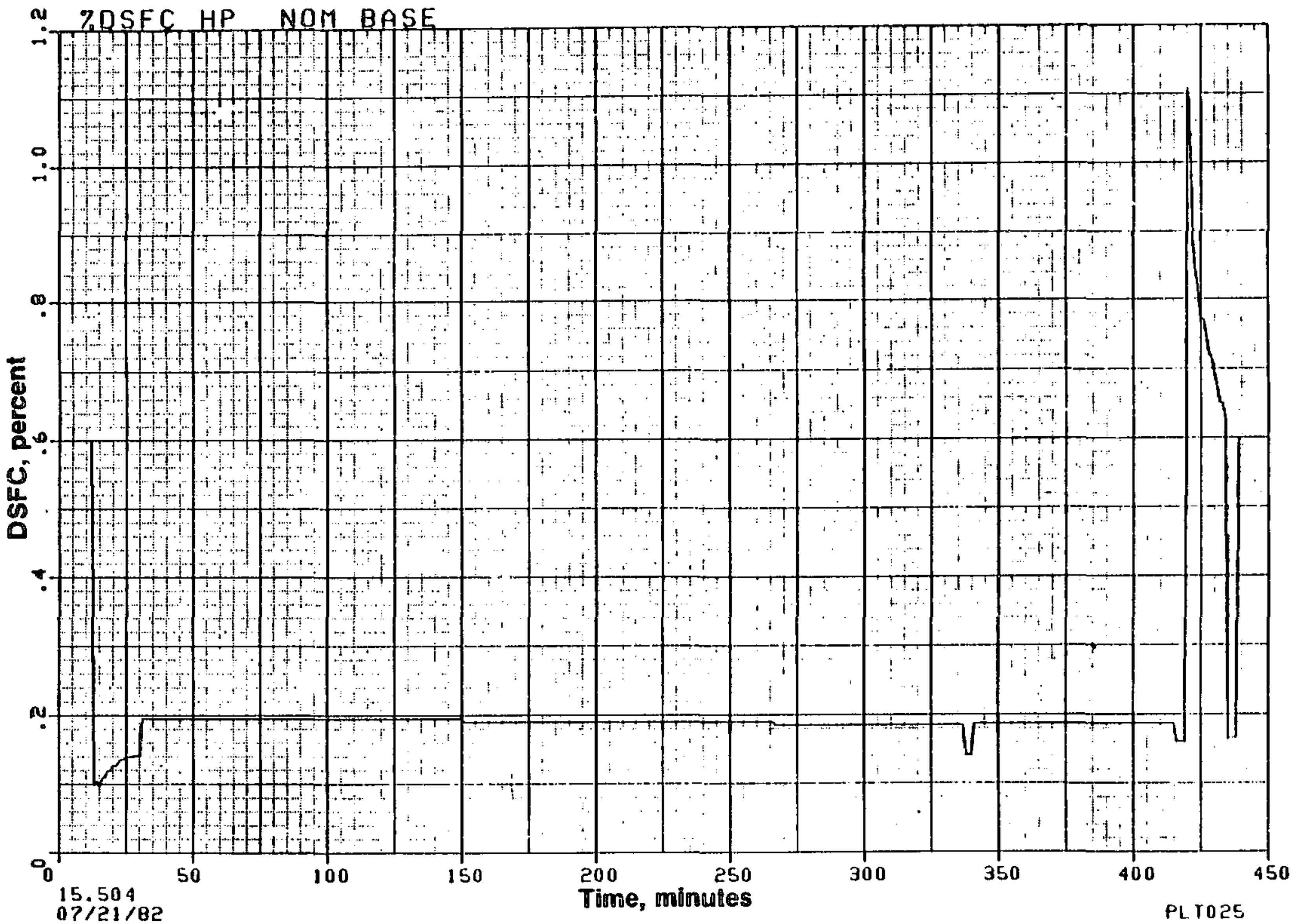


Figure 141. Baseline - Nominal Flight %ΔSFC for Fuel Pump HP.

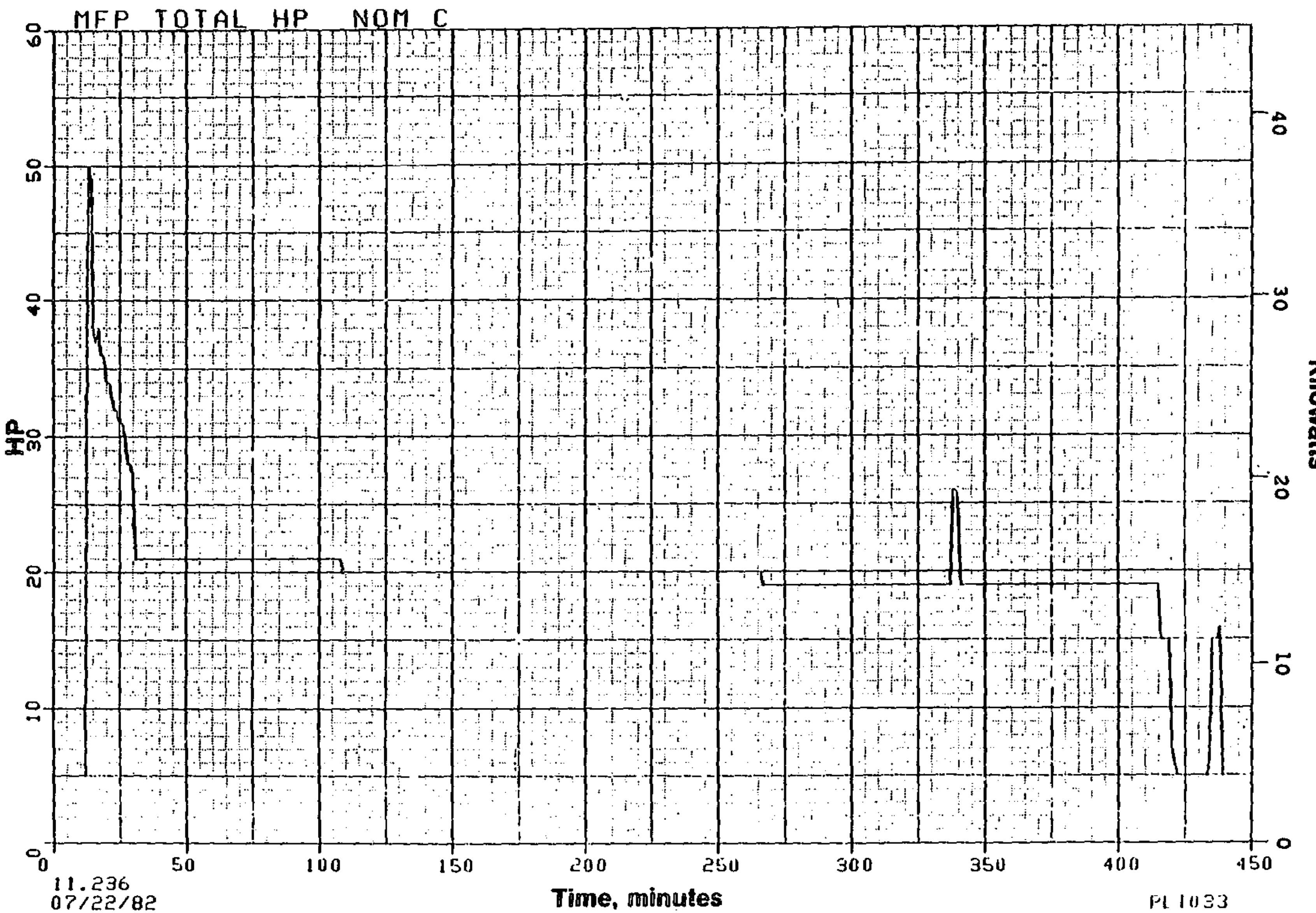


Figure 142. System C - Nominal Flight Fuel Pump Input Horsepower.

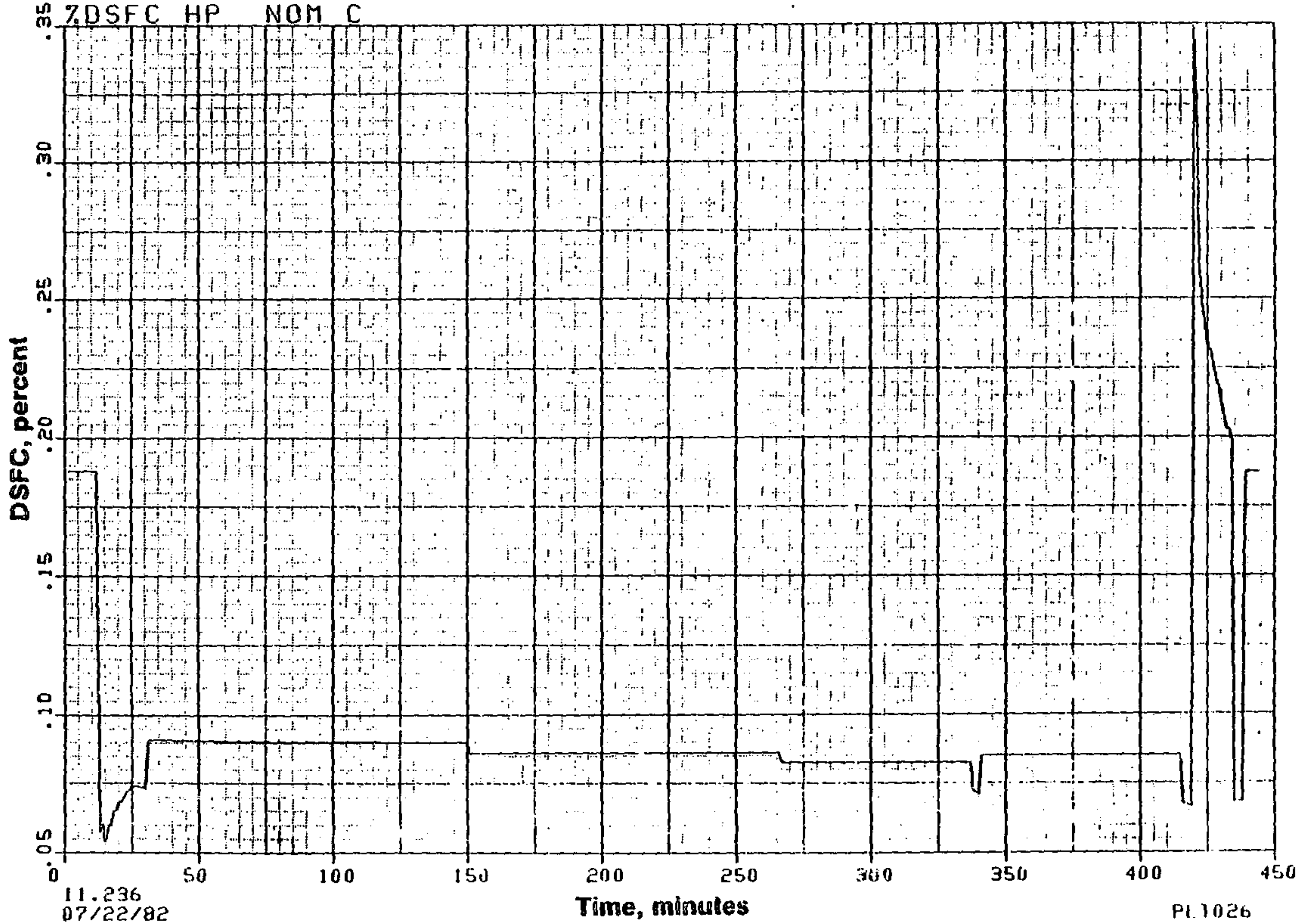


Figure 143. System C - Nominal Flight %ΔSFC for Fuel Pump HP.

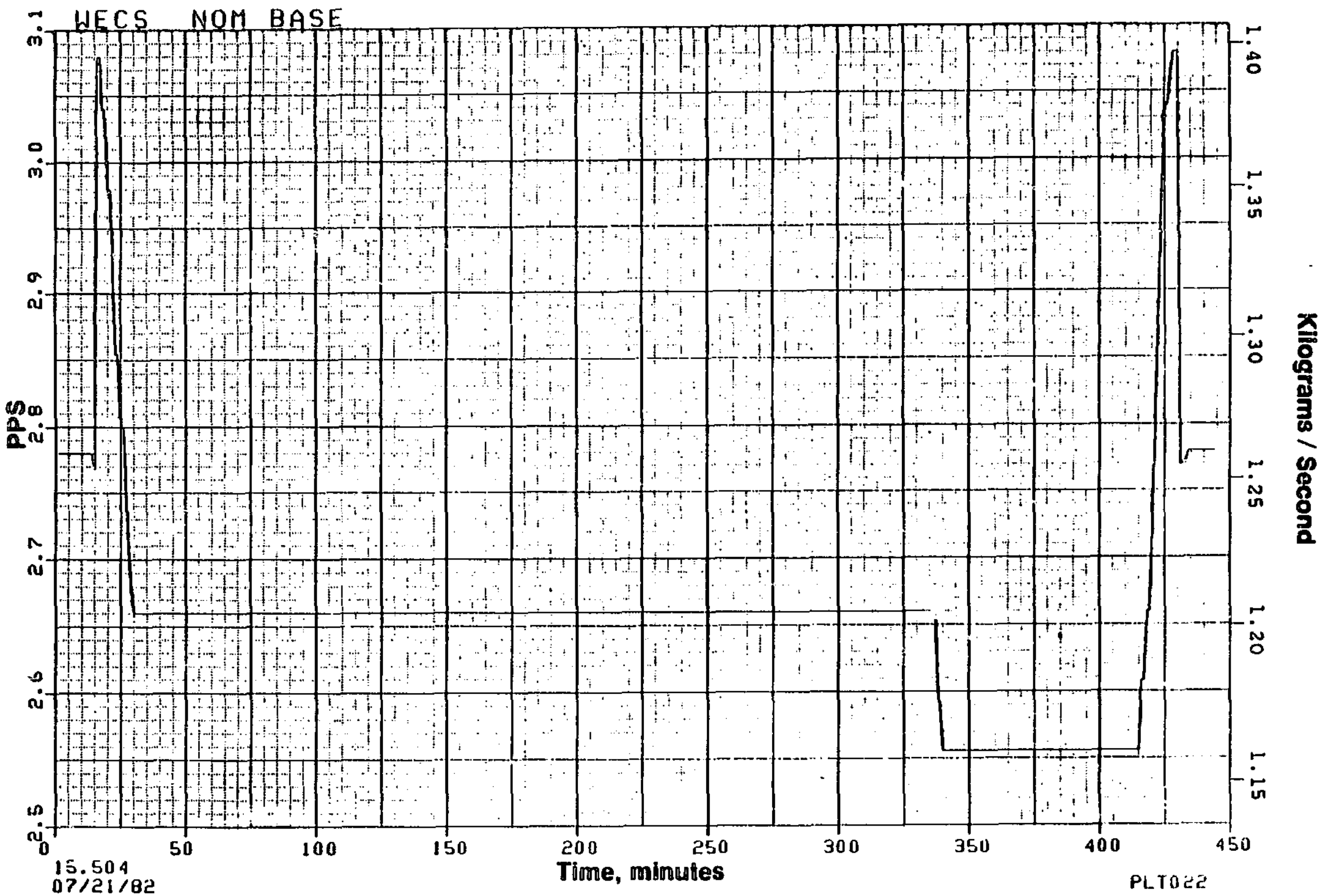


Figure 144. Nominal Flight ECS Bleed Air Flow.

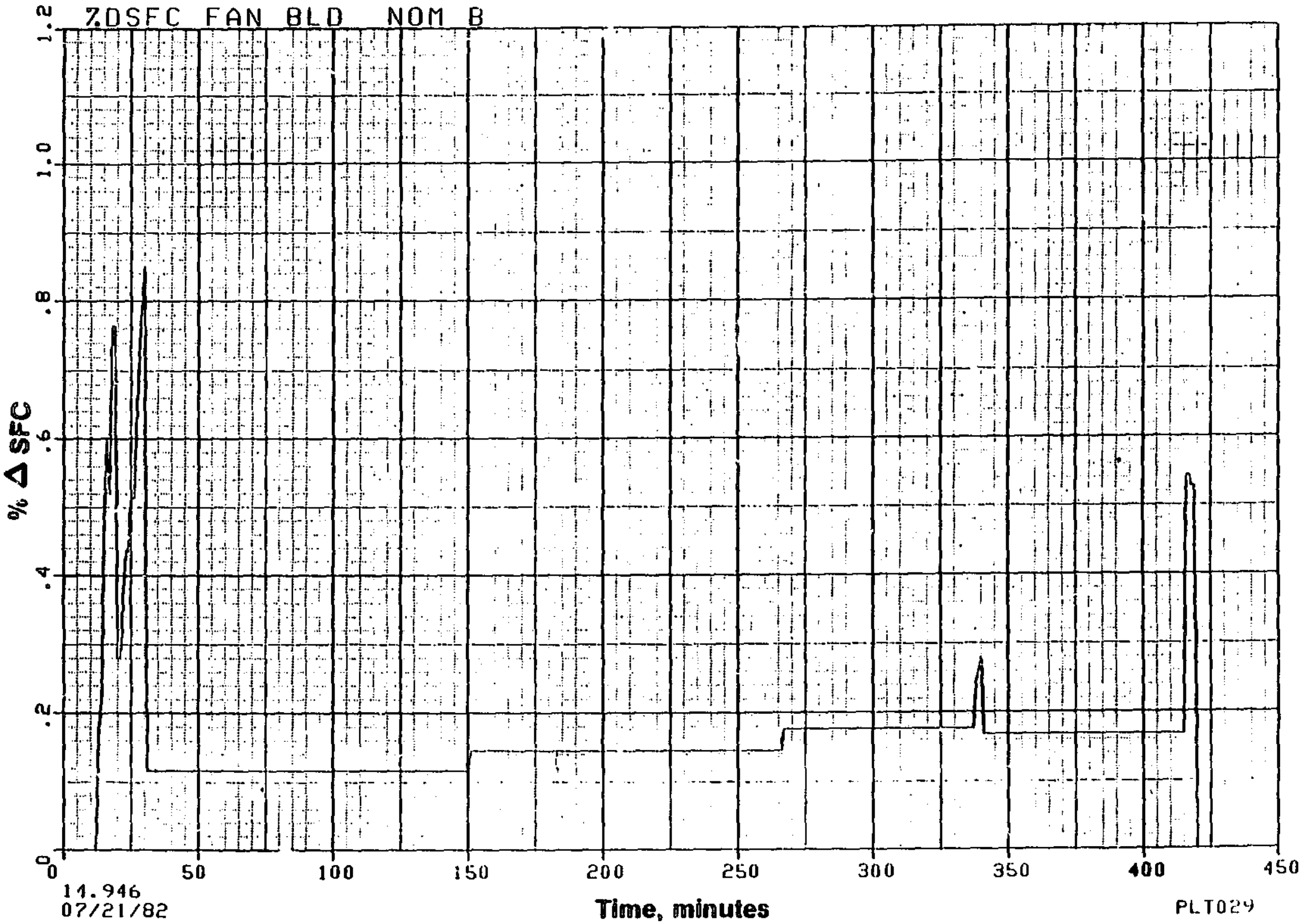


Figure 145. Nominal Flight %ΔSFC for ECS Preccoler Fan Bleed Baseline, Systems A and B.

Although sfc is a popular measure of comparison, it is usually applied only to cruise conditions. A more meaningful result is the absolute change in fuel flow (pounds per minute). Figures 146 through 149 summarize the fuel consumption results of all systems. Using these one-minute-interval results the computer model accumulated the total flight fuel change (block-to-block). These results are shown in Tables 17, 18 and 19. These tabulated results show how the fuel burn increase or decrease is accomplished. Table 17 is the direct effect of pump shaft power, fan bleed (precooler), and system weight. Table 18 is for the effect of fuel heating. These results show the flight-average BTU/lb of thermal energy imparted to engine metered fuel by the system. The increase in thermal energy such as for System C results in a decrease in fuel consumption. Table 19 shows the net fuel consumption effect of each system. The values listed in the right-hand column are the most meaningful in terms of the system merit relative to fuel consumption. Note that only Advanced System C offers an improvement (-0.342 percent block fuel consumption) over the Baseline System.

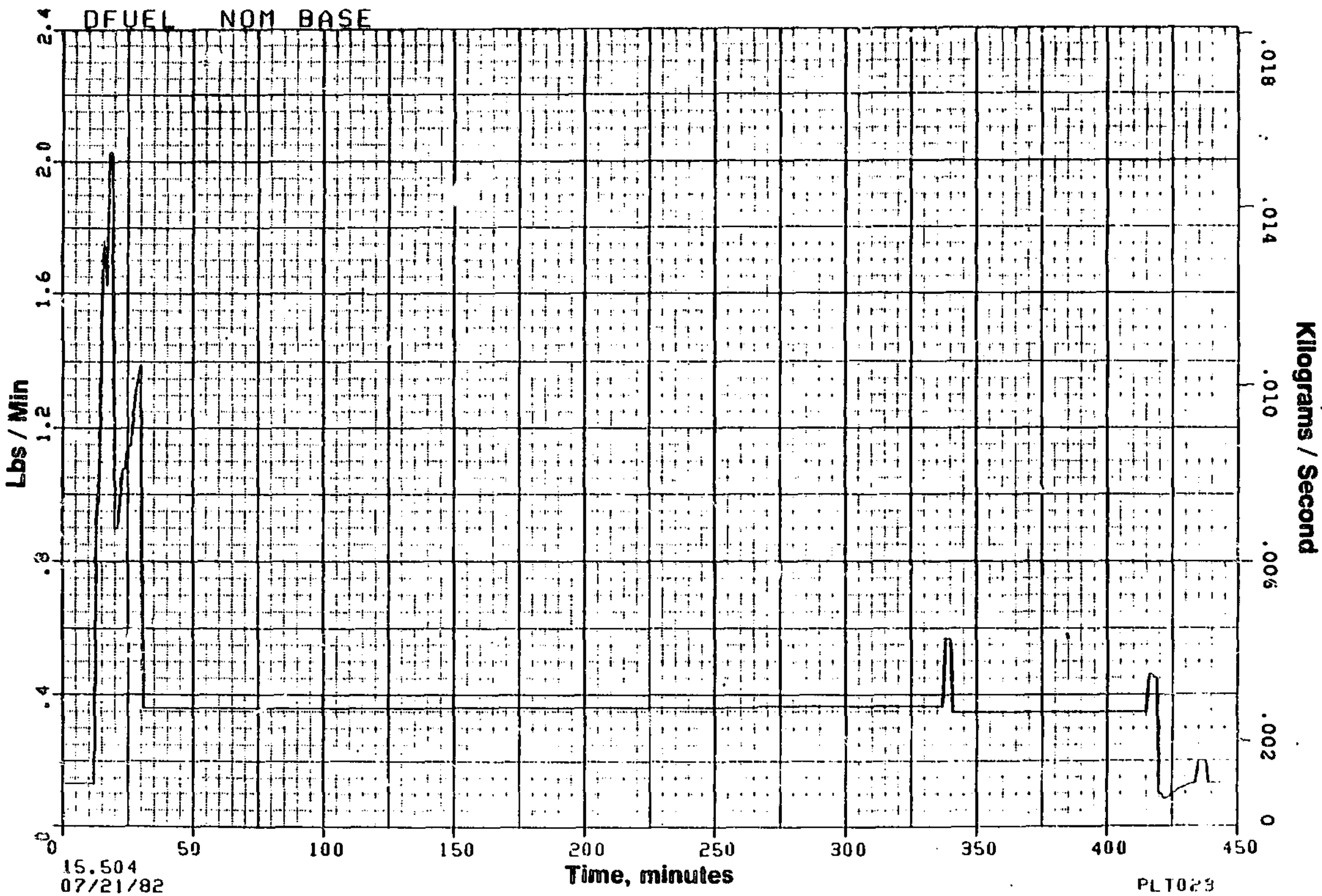


Figure 146. Baseline - Nominal Flight ΔFuel Burn for ECS Fan Bleed, Fuel Pump HP, 115 lb (512 N) Weight.

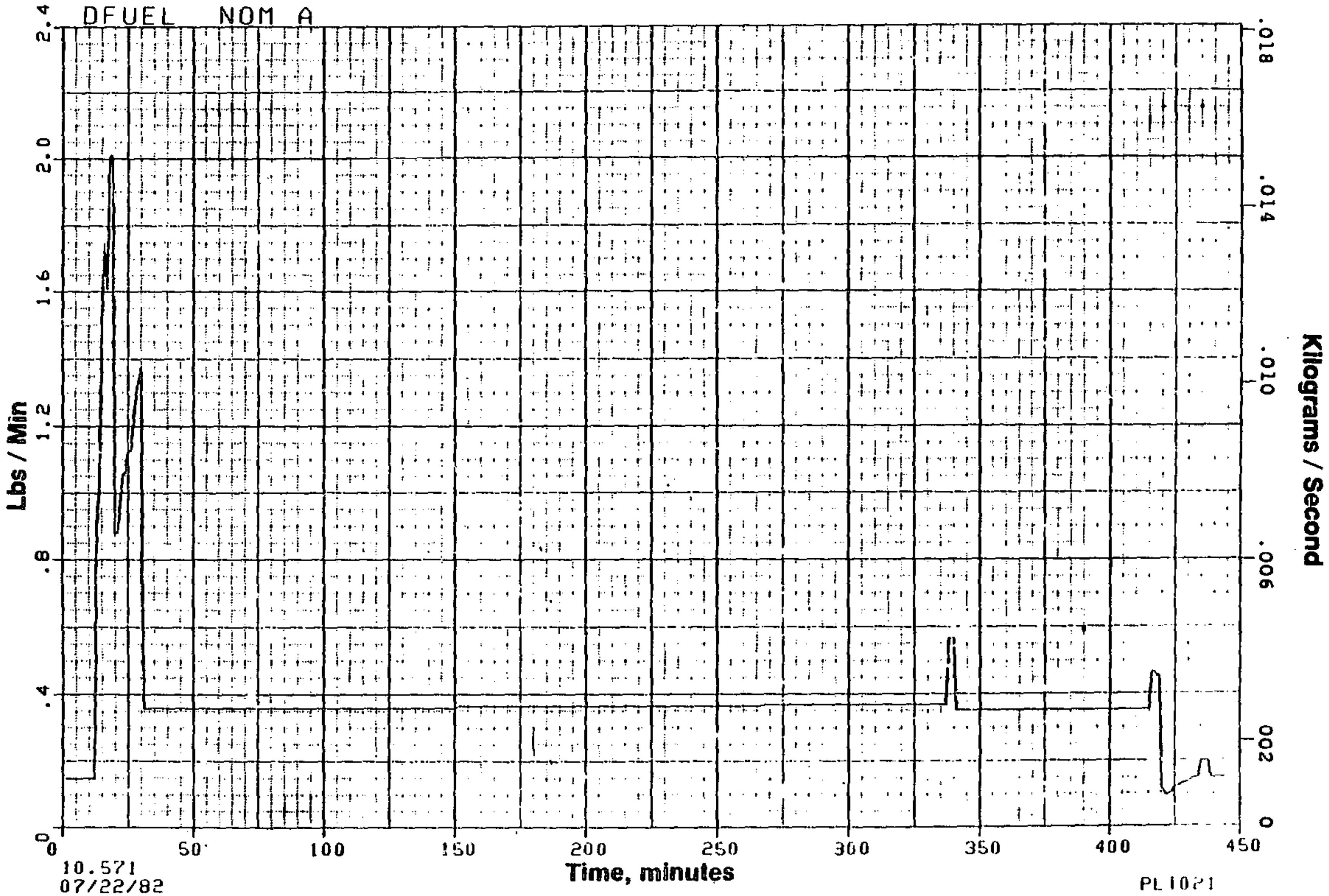


Figure 147. System A - Nominal Flight ΔFuel Burn for ECS Fan Bleed,
Fuel Pump HP, 115 Lb. (512 N) Weight.

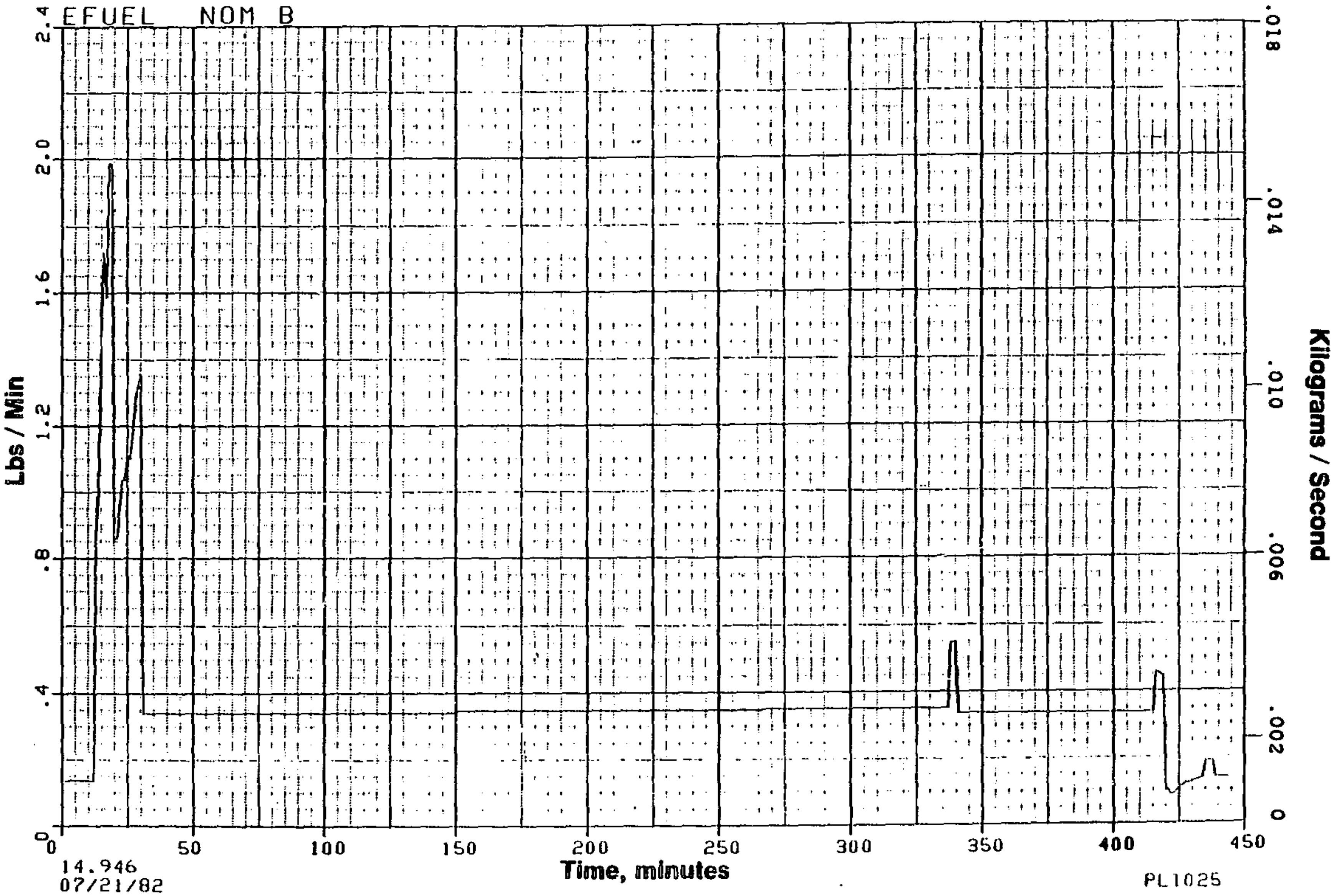


Figure 148. System B - Nominal Flight ΔFuel Burn for ECS Fan Bleed, Fuel Pump HP, 115 Lb. (512 N) Weight.

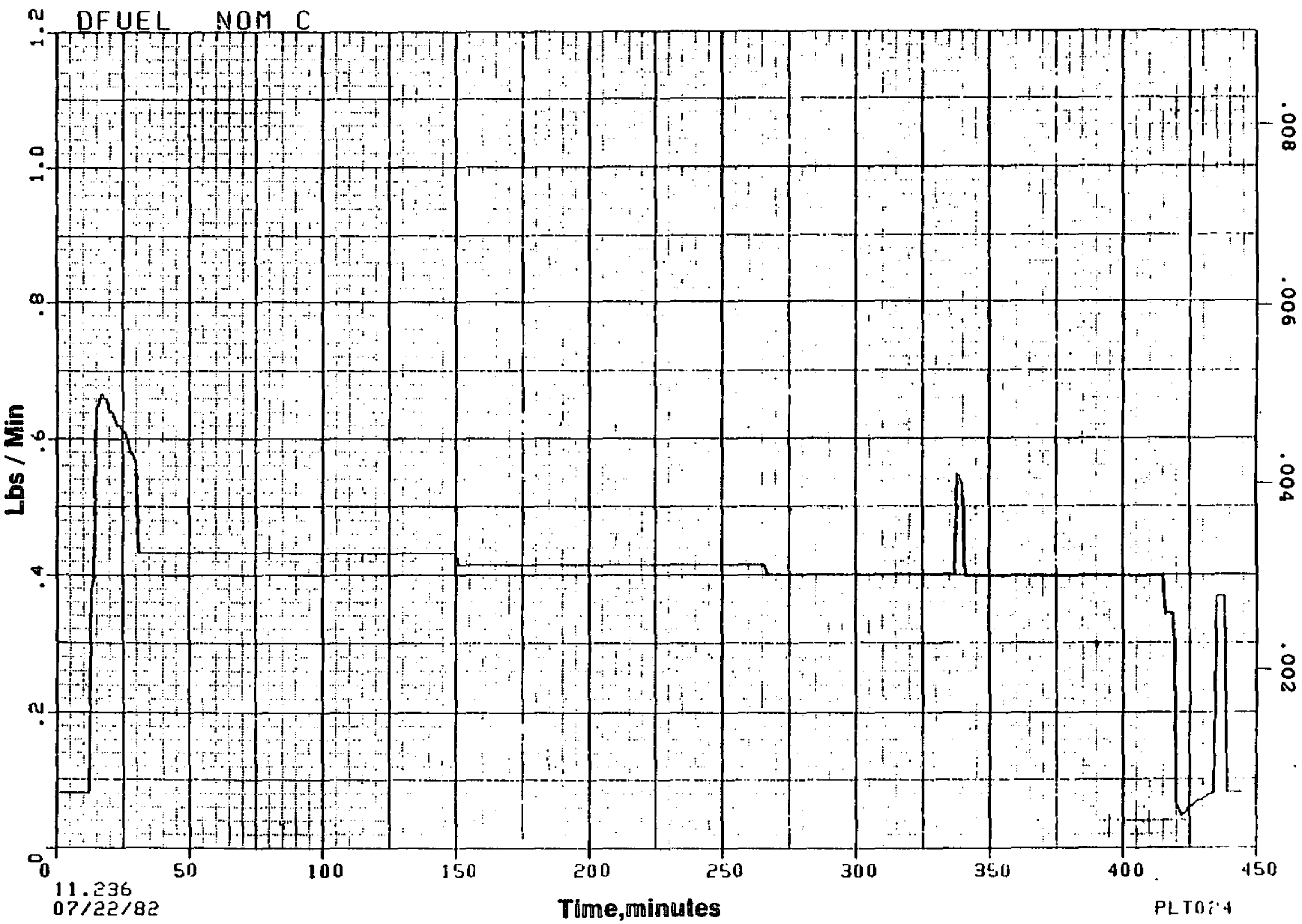


Figure 149. System C - Nominal Flight Fuel Burn for Fuel Pump HP, 185 Lb. (823 N) Weight.

TABLE 17. NOMINAL FLIGHT %Δ BLOCK FUEL FOR PUMP POWER, FAN BLEED, AND WEIGHT (LOSS) PER ENGINE.

	Block Pounds (kg)	ΔBlock Pounds (kg)	% Δ Block Fuel
Baseline	169 (77)	Ref	Ref
System A	170 (77)	+1 (+0.5)	+0.003
System B	162 (73)	-7 (-3)	-0.019
System C	88 (40)	-81 (-37)	-0.222

Flight Block Fuel = 36,420 Pounds (16520kg) per Engine

TABLE 18. NOMINAL FLIGHT %Δ BLOCK FUEL FOR COMBUSTOR FUEL PREHEATING (GAIN) PER ENGINE.

	Btu/Lb (kJ / Kg)	Δ Btu/Lb (ΔkJ / kg)	%Block Fuel
Baseline	229* (533)	Ref	Ref
System A	187 (435)	-42 (-98)	+0.228
System B	212 (493)	-17 (-40)	+0.092
System C	251 (584)	+22 (+51)	-0.120

*Based on Enthalpy = 0 at 0° R (0° K)

Flight Block Fuel = 36,420 Pounds (16520 kg) per Engine

TABLE 19. NOMINAL FLIGHT %Δ BLOCK FUEL NET INCLUDING LOSS AND FUEL HEATING GAIN PER ENGINE.

	%ΔBlock Fuel Loss	%ΔBlock Fuel Gain	%ΔBlock Fuel Net
Baseline	Ref	Ref	Ref
System A	+0.228	+0.003	+0.231
System B	+0.092	-0.019	+0.073
System C	-0.120	-0.222	-0.342

Flight Block Fuel = 36,420 Pounds (16520 kg) per Engine

10.0 ECONOMIC ANALYSIS

10.1 INTRODUCTION

A computer program was formulated to evaluate the investment incentive to the airline for each Advanced System. The basic objective is involved with managerial decision making. Business investments have two distinguishing characteristics: First, they often involve depreciable assets, and the return (saving to company) which the assets provide must be sufficient to recoup the original investment itself as well as to provide a satisfactory yield on the investment. Second, investments are generally long term in nature, necessitating recognition of the time-value of money. Present Value and Rate of Return on Investment are the two generally accepted methods for determining the incentive for an investment.

Present Value is simply a measure of the total savings anticipated over the life of the investment at the time the investment is made. This value (savings) less the investment cost is the net investment incentive or, in other words, the anticipated profit before taxes. Rate of Return (ROR) indicates the anticipated annual percentage profit on the investment which would normally be 10 percent on cash-savings. Both methods were considered in the analysis.

In this case where savings are negative, the Present Value method still provides an indication for economic decision making - the more positive (least negative) Present Value is chosen. ROR, however, has no meaning in this case.

The treatment of tax credits and depreciation was as follows:

An initial tax credit of seven percent (7%) of the investment cost was taken at the end of the base year of the economic analysis, the year the investment is made. Since corporate tax on U.S. income is approximately 50%, this tax depreciation allowance is equivalent to a credit of 50% of each year's depreciation. The double-declining balance depreciation method was used for the first two years and the sum-of-the-year's-digits method for the remaining years until the tenth year from purchase. This provided the largest present value of tax savings early in the life of the asset.

The economic analysis is a key basis for comparison of the results of this Advanced Fuel System study. Fuel property change, if it were to occur, may be gradual. Consequently, as it turns out, each of the Advanced Systems A, B and C offers a solution to the fundamental issue of broadened-property fuel. Although performance results do vary for each system, the degree of property change could permit use of any of the Advanced Systems. The results can therefore be treated on an economic basis because all systems are acceptable for airline use within their respective limits of fuel properties. With appropriate design feature such as a means for fuel cooling with low reserve, each system is viewed to be acceptable from the standpoint of safety and airline operational considerations.

The DC-10-30 was chosen for the study because it is a long-range aircraft likely to be influenced by the fuel freezing point issue. Also, the DC-10 fuel system with its wing tip tanks is of sufficient modern design to yield a broad solution from the aircraft design standpoint. In the economic study, departure from the DC-10-30 definition was, however, necessary. It was necessary to assume the more general case of a wide-body long-range aircraft expected to have a fleet life of 15 years. This presents then an airline management decision to purchase such an aircraft (with an Advanced System) so as to achieve broadened-property fuel compatibility over the anticipated 15-year aircraft use time.

Thus, it was assumed that Advanced Systems would be applicable to new aircraft and engines and subsequently have a service life of 15 years. As shown in Table 20, the economic influences used for the study included initial equipment cost, maintenance cost, and fuel consumption. These factors for each system were determined using cold, hot and nominal flight results combined with individual engineering assessments.

TABLE 20. ECONOMIC INFLUENCES.

	Baseline	System A	System B	System C
Maintenance				
• Fuel Nozzle Coking Only				
• Unscheduled Removals (Events/M—Hrs.)				
Jet-A	50	1	15	13
Future Fuel	140	1	41	37
Fuel Burn				
• Δ% Block Fuel	*	+0.231	+0.073	−0.342
Equipment Cost				
• At Airline Cost Level for 3-Engine Aircraft	*	−$1260	−$2760	$167,610
• For New Aircraft				

* Baseline is Reference

Initial equipment costs were estimated from actual (baseline) component production costs wherever possible. These costs were used for Baseline System components and comparable Advanced System components. The basis for all other equipment costs is: present production costs for similar parts, previous studies of advanced components, and experience resources of the General Electric Company and its vendors. The resulting costs in 1982 dollars are shown in Table 21.

Maintenance costs were based solely on engine fuel nozzle coking rates. These removal rates, as shown in Table 22, were estimated based on relative life estimates for each of the fuel systems for operation on the baseline and study limit fuels. Relative life was estimated using a correlation for TF-39 flow divider valve failure as a function of fuel temperature and fuel breakpoint temperature (See Reference 7). Failure was defined as a 10% increase in valve hysteresis. The TF-39 data correlation was used because of the engines for which data were available, the TF-39 is most similar in scale and design to the CF6-80. Relative life estimates and corresponding unscheduled removal rates are presented in Table 22.

The correlation equation for fuel nozzle life is of the form

$$\text{Life} \propto K_f \exp \frac{(C1 + C2\, T_{BP} - T_F}{10}$$

where:

T_{BP} = Fuel breakpoint temperature, K

T_F = Fuel temperature at valve, K

K_f = Constant to account for valve force level

C1, C2 = Correlation constants equal to 229.9K and 0.407, respectively, for the TF-39

The minimum fuel breakpoint temperature from the program fuel property specification limits (Table 2) was used for each fuel. Maximum fuel inlet

TABLE 21. SYSTEM COST TO AIRLINE PER ENGINE.

COMPONENT	SYSTEM	COST	TOTAL
Main Engine Control	Baseline	54,050.	
Main Fuel Pump	Baseline	11,200.	
Fuel Manifold	Baseline	6,570.	
Fuel Feeder Tubes	Baseline	8,120.	
Fuel Nozzles		40,780.	
			$120,720.
Main Engine Control	A	54,050.	
Low Lubricity Main Fuel Pump	A	11,430.	
Fuel Manifold	A	9,160.	
Fuel Feeder Tubes	A	8,120.	
Fuel Nozzles	A	34,040.	
Manual Switch & Wiring	A	500.	
Plumbing, Clamps, Etc.	A	3,000.	
			$120,300.
Main Engine Control	B	54,050.	
Low Lubricity Main Fuel Pump	B	11,430.	
Fuel Mainfold	B	9,160.	
Fuel Feeder Tubes	B	8,120.	
Fuel Nozzles	B	34,040.	
Plumbing, Clamps, Etc.	B	3,000.	
			$119,800.
Main Engine Control	C	54,050.	
Fuel Control Mod Kit	C	14,690.	
Boost Pump	C	4,320.	
Centrifugal Pump	C	12,530.	
Gearbox Adapter	C	5,180.	
400 Hz Electrically Driven Start Pump	C	2,590.	
Electrical Relay & Control	C	860.	
Fuel Distributor	C	12,270.	
Feeder Tubes	C	23,840.	
Fuel Nozzles	C	28,860.	
Adv. Waste Heat Recovery System			
Air/Water HX	C	7,500.	
Tank Fuel/Water HX	C	2,250.	
No. 1 HX Control Valve	C	3,000.	
Engine Fuel/Water HX	C	2,250.	
No. 2 HX Control Valve	C	3,000.	
Water Pumps & Electrical	C	6,000.	
Accumulator	C	1,500.	
Temp & Press Sensors	C	500.	

TABLE 21. SYSTEM COST TO AIRLINE PER ENGINE (CONCLUDED).

COMPONENT	SYSTEM	COST	TOTAL
Water Loop Plumbing	C	3,000.	
Fuel Tank Return Plumbing	C	6,250.	
Electrical Controls & Readouts	C	7,500.	
Water/Dowfrost® Mixture	C	900.	
			$202,840.

TABLE 22. LIFE ESTIMATES

System	Fuel	K_f - Value Force Constant	Fuel Breakpoint K (° F)	Fuel Temperature K (° F)	Relative Life	Removals per 10^6 hr
Baseline	Baseline	1	518 (473)	388 (238)	1.0	51
	Study Limit	1	493 (428)		0.36	140
A	Baseline	1	518 (473)	323 (122)	644	1
	Study Limit	1	493 (428)		236	1
B	Baseline	1	518 (473)	376 (216)	3.45	15
	Study Limit	1	493 (428)		1.26	41
C	Baseline	5	518 (473)	391 (243)	3.87	13
	Study Limit	5	493 (428)		1.41	37

temperatures calculated for the nominal flight (Table 15) were used as T_F for all of the advanced systems, where the valves were mounted on the fuel manifold. For the baseline system, where the valves were mounted in the nozzle, an additional 17K (30°F) fuel temperature increase was assumed to account for fuel heating in the nozzle. The constant K_f was taken to be 1.0 for the baseline and concepts A and B, which have one valve per nozzle. For concept C, which uses a single valve to feed all 30 of the fuel nozzles, a larger valve was assumed. When fuel valve piston area is increased, spring force must be increased proportionally to obtain the same flow characteristics. However, the perimeter of the piston, where contact with the wall and fuel residue on the wall provides the resistance force that causes valve hysteresis, is proportional to the square root of the piston area. For System C, it was estimated that the piston area (and spring force) would be increased by a factor of 25, while the wetted perimeter of the piston (and resistance force) would be increased by a factor of 5. Therefore, the ratio of spring force to resistance force would also be increased by a factor of 5, thereby decreasing the likelihood of hysteresis. This effect was reflected in the relative life correlation by setting $K_f = 5$ for System C.

The unscheduled removal rate was taken to be inversely proportional to relative life. Removals were then adjusted to obtain a level of 51 unscheduled removals per million hours for the baseline system on baseline fuel which is the estimated value for the CF6-80A engine.

It should be noted that the above estimates involve extrapolation of data obtained in accelerated fuel nozzle fouling tests. Because of this extrapolation and required assumptions on fuel heating in the nozzle mounted valve and the effect of valve force levels, there is considerable uncertainty in the unscheduled removal estimates given in Table 22.

Fuel consumption differences are for the nominal flight and include all factors such as weight, engine air bleed and fuel heating (to engine combustor).

All calculations were based on constant 1982 dollars. Results were calculated for Jet-A and a future broad property fuel at a cost of $1.06 per gallon.

The argument can be made that Jet-A fuel properties derived from alternate crudes or future heavy petroleum crudes may increase the cost of the airline fuel. These cost increases relative to present Jet-A would result from increases in refinery process costs and/or increases in market costs (competitive demand for kerosene fuels). These cost differentials cannot be determined from this Advanced Fuel System study. However, two opposite points of view to this question were addressed. These are, what it would cost the airline to modify the aircraft to achieve present day (Jet-A) compatibility with various future broadened-property fuels and what fuel cost reduction would be required to justify the Advanced System.

Fundamentally, the economic study shows:

1. The airline economic advantage or disadvantage for use of System A, B, or C based on the assumption that Jet-A fuel is always available and no property change or fuel-economic changes take place over the next ten years.

2. The airline economic break-even point for use of System A, B, or C assuming a fuel differential cost advantage for using broadened-property fuel. In other words, a lower cost for broadened-property fuel such that the particular Systems A, B or C yields the same present-day economy to the airline after choosing the system. For this result the Present Value of each system, which is an economic statement of the anticipated savings of the system over 15 years, could equal the present (immediate) cash outlay for the system. The airline who chooses the lowest initial cost system and retains fuel property compatibility over 15 years might be assumed to have made the best choice. However, a different system offering other advantages such as better sfc may, in fact, be the best choice since

Present Value may be higher relative to the initial cost investment. Ultimately, the decision rests on the validity of the economic analysis and confidence in the fuel price; i.e., property change and fuel cost differential.

10.2 RESULTS

Advanced System airline cost differentials calculated for new aircraft and engines are shown in Table 21. The airline differential purchase cost is the difference between the cost of the Advanced System of interest and the Baseline System. These costs were derived from the airline costs shown in Table 20. It should be noted that the airline purchase cost of System C is modified to reflect the reduction in cost associated with deletion of the equipment no longer needed (based on the assumption that this is a new aircraft). The reduction in cost is $26,250 and corresponds to the deletion of the air precooler, cold air ducts and control valve, electrical controls and readouts. The differential maintenance costs (Table 23 and Table 24) show the increase in fuel nozzle maintenance required when Jet-A and the study fuel are used in the different systems. Differential percent block fuel consists of block fuel burn effects for pump power, fan bleed, system weight, and combustor fuel preheating for each system (relative to the Baseline System).

This information was entered in the economic computer model. The results for each engine are shown in the computer printouts of Figures 150 through 156. Figure 152 includes alphabetical labels on each item as reference for the brief description that follows:

Item	Description
A	Years of aircraft service life.
B	Airline expected rate of return in percent, based on constant dollars.

TABLE 23. ECONOMIC TRADEOFFS - FUTURE FUEL.

	System A	System B	System C
Increased Initial Investment	- 1,260	- 2,760	167,610
Annual Increased DOC			
• Maintenance	-47,640	-4,140	- 2,280
• Fuel (1.06/Gal)	25,596	8,088	-37,896
Net Increased DOC	-22,044	3,948	-40,176
Present 1982 Value (15 Years — 10% ROR)	167,148	-31,182	375,372
Net 1982 Investment Incentive	$\boxed{168,408}$	$\boxed{-28,422}$	$\boxed{207,762}$
Recovery of Investment			
• Number of Years			3
• Investment % ROR			31.8

Values at Airline Cost and 1982 Dollars for 3-Engines

TABLE 24. ECONOMIC TRADEOFFS - JET-A FUEL.

	System A	System B	System C
Increased Initial Investment	- 1,260	- 2,760	167,610
Annual Increased DOC			
• Maintenance	-16,800	-12,390	-11,910
• Fuel (1.06/Gal)	25,596	8,088	-37,896
Net Increased DOC	8,796	4,302	-49,806
Present 1982 Value (15 Years — 10% ROR)	-67,422	31,566	448,617
Net 1982 Investment Incentive	$\boxed{-66,162}$	$\boxed{34,326}$	$\boxed{281,007}$
Recovery of Investment			
• Number of Years			3
• Investment % ROR			38.4

Values at Airline Cost and 1982 Dollars for 3-Engines

ECONOMIC FACTORS FOR SYSTEM A

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	-420.	JET A

<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS: FUEL PRICE $/GAL	FUEL FACTORS: INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-5600.	1.06	8532.	2932.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	-420.				-420.
1		-29.	-42.	2932.	-2730.
2		0.	-34.	2932.	-2451.
3		0.	-30.	2932.	-2225.
4		0.	-26.	2932.	-2020.
5		0.	-22.	2932.	-1834.
6		0.	-19.	2932.	-1665.
7		0.	-15.	2932.	-1512.
8		0.	-11.	2932.	-1373.
9		0.	-7.	2932.	-1247.
10		0.	-4.	2932.	-1132.
11		0.	0.	2932.	-1028.
12		0.	0.	2932.	-934.
13		0.	0.	2932.	-849.
14		0.	0.	2932.	-772.
15		0.	0.	2932.	-702.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE:	-22474.
NET 1982 INVESTMENT INCENTIVE:	-22054.

Figure 150. System A Economic Factors Per Engine - Jet A.

ECONOMIC FACTORS FOR SYSTEM B

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	-920.	JET A

<<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS: FUEL PRICE $/GAL	FUEL FACTORS: INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-4130.	1.06	2696.	-1434.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	-920.				-920.
1		-64.	-92.	-1434.	1161.
2		0.	-74.	-1434.	1124.
3		0.	-65.	-1434.	1028.
4		0.	-57.	-1434.	940.
5		0.	-49.	-1434.	860.
6		0.	-41.	-1434.	786.
7		0.	-33.	-1434.	719.
8		0.	-25.	-1434.	657.
9		0.	-16.	-1434.	601.
10		0.	-8.	-1434.	550.
11		0.	0.	-1434.	503.
12		0.	0.	-1434.	457.
13		0.	0.	-1434.	415.
14		0.	0.	-1434.	378.
15		0.	0.	-1434.	343.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE:	10522.
NET 1982 INVESTMENT INCENTIVE:	11442.

Figure 151. System B Economic Factors Per Engine - Jet A.

ECONOMIC FACTORS FOR SYSTEM C

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

A AIRCRAFT LIFE YRS	B CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	C INCREASED INITIAL INVESTMENT D$	D ANTICIPATED FUEL TYPE
15	10.0	55870.	JET A

<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>

E INCR. MAINTENANCE COST D$	F FUEL FACTORS FUEL PRICE $/GAL	G INCR. FUEL BILL D$	H INCR. TOTAL DOC D$
-3970.	1.06	-12632.	-16602.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
	C	I	J	H	K
BASE	55870.				55870.
1		3911.	5587.	-16602.	23727.
2		0.	4470.	-16602.	17414.
3		0.	3973.	-16602.	15458.
4		0.	3476.	-16602.	13713.
5		0.	2980.	-16602.	12158.
6		0.	2483.	-16602.	10773.
7		0.	1986.	-16602.	9539.
8		0.	1490.	-16602.	8440.
9		0.	993.	-16602.	7462.
10		0.	497.	-16602.	6592.
11		0.	0.	-16602.	5819.
12		0.	0.	-16602.	5290.
13		0.	0.	-16602.	4809.
14		0.	0.	-16602.	4372.
15		0.	0.	-16602.	3974.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE: 149539. L

NET 1982 INVESTMENT INCENTIVE: 93669. M

RECOVERY OF INVESTMENT

YEAR	OUTSTANDING INVESTMENT DURING YEAR	NET CASH IN-FLOW	RETURN ON INVESTMENT	RECOVERED INVESTMENT DURING YEAR	UNRECOVERED INVESTMENT END OF YEAR
	N	O	P	Q	R
1	55870.	26099.	5587.	20512.	35358.
2	35358.	21071.	3536.	17535.	17822.
3	17822.	20574.	1782.	18792.	0.

YEAR INVESTMENT RECOVERED= 3 S

TIME-ADJUSTED-RATE-OF-RETURN-METHOD

CONSTANT-DOLLAR RATE OF RETURN= 38.4% T

Figure 152. System C Economic Factors Per Engine - Jet A.

ECONOMIC FACTORS FOR SYSTEM A

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	-420.	STUDY

<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS FUEL PRICE $/GAL	FUEL FACTORS INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-15880.	1.06	8532.	-7348.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	-420.				-420.
1		-29.	-42.	-7348.	6615.
2		0.	-34.	-7348.	6045.
3		0.	-30.	-7348.	5498.
4		0.	-26.	-7348.	5001.
5		0.	-22.	-7348.	4549.
6		0.	-19.	-7348.	4137.
7		0.	-15.	-7348.	3763.
8		0.	-11.	-7348.	3423.
9		0.	-7.	-7348.	3113.
10		0.	-4.	-7348.	2832.
11		0.	0.	-7348.	2575.
12		0.	0.	-7348.	2341.
13		0.	0.	-7348.	2129.
14		0.	0.	-7348.	1935.
15		0.	0.	-7348.	1759.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE:	55716.
NET 1982 INVESTMENT INCENTIVE:	56136.

Figure 153. System A Economic Factors Per Engine - Study Fuel.

ECONOMIC FACTORS FOR SYSTEM B

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	-920.	STUDY

<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS: FUEL PRICE $/GAL	FUEL FACTORS: INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-1380.	1.06	2696.	1316.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	-920.				-920.
1		-64.	-92.	1316.	-1339.
2		0.	-74.	1316.	-1149.
3		0.	-65.	1316.	-1038.
4		0.	-57.	1316.	-938.
5		0.	-49.	1316.	-848.
6		0.	-41.	1316.	-766.
7		0.	-33.	1316.	-692.
8		0.	-25.	1316.	-625.
9		0.	-16.	1316.	-565.
10		0.	-8.	1316.	-511.
11		0.	0.	1316.	-461.
12		0.	0.	1316.	-419.
13		0.	0.	1316.	-381.
14		0.	0.	1316.	-347.
15		0.	0.	1316.	-315.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE:	-10394.
NET 1982 INVESTMENT INCENTIVE:	-9474.

Figure 154. System B Economic Factors Per Engine - Study Fuel.

ECONOMIC FACTORS FOR SYSTEM C

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	55870.	STUDY

<<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS: FUEL PRICE $/GAL	FUEL FACTORS: INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-760.	1.06	-12632.	-13392.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	55870.				55870.
1		3911.	5587.	-13392.	20809.
2		0.	4470.	-13392.	14761.
3		0.	3973.	-13392.	13046.
4		0.	3476.	-13392.	11521.
5		0.	2980.	-13392.	10165.
6		0.	2483.	-13392.	8961.
7		0.	1986.	-13392.	7891.
8		0.	1490.	-13392.	6942.
9		0.	993.	-13392.	6101.
10		0.	497.	-13392.	5354.
11		0.	0.	-13392.	4694.
12		0.	0.	-13392.	4267.
13		0.	0.	-13392.	3879.
14		0.	0.	-13392.	3526.
15		0.	0.	-13392.	3206.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW
OVER TOTAL AIRCRAFT LIFE: 125124.

NET 1982 INVESTMENT INCENTIVE: 69254.

RECOVERY OF INVESTMENT

YEAR	OUTSTANDING INVESTMENT DURING YEAR	NET CASH IN-FLOW	RETURN ON INVESTMENT	RECOVERED INVESTMENT DURING YEAR	UNRECOVERED INVESTMENT END OF YEAR
1	55870.	22889.	5587.	17302.	38568.
2	38568.	17861.	3857.	14004.	24563.
3	24563.	17364.	2456.	14908.	9655.
4	9655.	16868.	966.	15902.	0.

YEAR INVESTMENT RECOVERED= 4

TIME-ADJUSTED-RATE-OF-RETURN-METHOD

CONSTANT-DOLLAR RATE OF RETURN= 31.8%

Figure 155. System C Economic Factors Per Engine - Study Fuel.

ECONOMIC FACTORS FOR SYSTEM B

NOTES: (1) ALL DOLLARS=1982 DOLLARS
(2) AT AIRLINE COST LEVEL FOR NEW AIRCRAFT AND ENGINES
(3) ALL COMPARISONS RELATIVE TO BASELINE SYSTEM

AIRCRAFT LIFE YRS	CONSTANT DOLLAR MIN ATTRACTIVE RATE OF RETURN %	INCREASED INITIAL INVESTMENT D$	ANTICIPATED FUEL TYPE
15	10.0	-920.	STUDY

<<<<<<<<<<<<<<<<ANNUAL DIRECT OPERATING COST INCREASES>>>>>>>>>>>>>>>>

INCR. MAINTENANCE COST D$	FUEL FACTORS: FUEL PRICE $/GAL	FUEL FACTORS: INCR. FUEL BILL D$	INCR. TOTAL DOC D$
-1380.	0.97	1451.	71.

PRESENT-VALUE-METHOD

YEAR	INITIAL INVESTMENT INCREASE	INITIAL TAX CREDIT INCREASE	TAX DEP ALLOWANCE INCREASE	SYSTEM DOC INCREASE	PRESENT VALUE INCREASE
BASE	-920.				-920.
1		-64.	-92.	71.	-206.
2		0.	-74.	71.	-119.
3		0.	-65.	71.	-102.
4		0.	-57.	71.	-87.
5		0.	-49.	71.	-74.
6		0.	-41.	71.	-63.
7		0.	-33.	71.	-53.
8		0.	-25.	71.	-44.
9		0.	-16.	71.	-37.
10		0.	-8.	71.	-30.
11		0.	0.	71.	-25.
12		0.	0.	71.	-23.
13		0.	0.	71.	-20.
14		0.	0.	71.	-19.
15		0.	0.	71.	-17.

FOR 15 YEAR LIFE

PRESENT 1982 VALUE OF INVESTMENT CASH FLOW OVER TOTAL AIRCRAFT LIFE:	-920.
NET 1982 INVESTMENT INCENTIVE:	-0.

Figure 156. System B Economic Factors Per Engine - Study Fuel. Fuel Cost for Zero Investment Incentive.

C Increase in required airline investment cost relative to Baseline (for Advanced System).

D Anticipated fuel type (for aircraft service life).

E Increase in maintenance cost portion of direct operating costs (DOC) relative to Baseline.

F Fuel cost per gallon (held constant over study period).

G Increase in fuel bill portion of direct operating costs relative to Baseline. Calculated from annual delta fuel burn multiplied by fuel cost.

H Increase in system direct operating costs (DOC) relative to Baseline. Algebraic sum of maintenance and fuel bill increase in cost.

I The initial tax credit taken in the first year at seven (7) percent of the increase in initial airline investment.

J Annual tax depreciation allowance -- Double-Declining-Balance-Method is used for first two years; Sum-of-the-Years-Digits Method used from third to tenth year -- based on 50 percent of initial investment increase relative to baseline because corporate taxes are approximately 50 percent.

K Annual value (in 1982 dollars) of the net cash flows (savings) promised by the system at the min attractive rate of return (B above) -- based on initial investment increase relative to Baseline.

L Present 1982 dollar value of investment cash flows over the 15-year aircraft life -- the sum of the annual values (K).

M The net value in 1982 dollars provided by the system -- L minus C -- indicates dollars promised by system over and above the initial investment cost increase relative to the Baseline.

N Outstanding investment during the year based on the initial investment increase relative to the Baseline.

O Annual net cash in-flow -- sum of tax credit I, tax depreciation allowance J, and system direct operating costs H for year -- this in-flow is made up of the two following parts:

P Part one of the annual net cash in-flow (O) -- represents the interest return at 10 percent on the investment -- decreases each year because the amount of the unrecovered investment decreases each year.

Q Part two of the annual net cash in-flow (O) -- represents the amount of the investment recovered during the year -- O minus P.

R The unrecovered investment at the end of the year -- N minus Q.

S Year during which the investment is recovered (unrecovered investment goes to zero).

T The Time-Adjusted Rate of Return -- if, instead of purchasing the fuel system, the dollars of the initial investment relative to the Baseline are invested, then this is the discount rate which provides the same annual cash in-flows as those the system promises.

Comparison of Figures 150 through 152 provides an indication of the system's relative value when operating with Jet-A fuel at $1.06 per gallon, a 10 percent rate of return, 15-year service life, and constant 1982 dollars. For System A (Figure 150), the present value is (-)$22,474 indicating a cost increase (to the airline) over the 15-year period. This cost increase is a result of the annual differential cash outflow effected by the increase in engine fuel consumption. This cost is listed under the heading "Incr. Fuel Bill." The Net 1982 Investment Incentive is (-)$22,054. In contrast, System B (Figure 151) shows a savings to the airline of $10,522 over the 15-year period. Here, the annual fuel cost (cash outflow) is more than offset by the maintenance cost savings; and results show a positive net cash flow (negative increase) and a Net 1982 Investment Incentive of $11,442. Under similar conditions, System C (Figure 152) presents the best choice. The Present Value of the cash flows is $149,539, and the Net 1982 Investment Incentive is $93,669 even though this system is the only system that presents an initial investment <u>cost</u> ($55,870) relative to the Baseline System. The annual fuel savings provide the means of obtaining a favorable annual cash in-flow which, when summed with the maintenance cost differential, initial tax credit, and tax depreciation allowance, provide a favorable position relative to the other systems. System C provides recovery of the differential initial investment during the third year. The Time-Adjusted-Rate of Return Analysis indicates a 38.4 percent rate of return is required to match the annual cash flows inherent in this system (compared with 10 percent in constant dollars desired for airline investments).

Figures 153 through 155 show the various system results for the same conditions as above, except the <u>study fuel</u> is used at $1.06 per gallon. System A (Figure 153) now provides a positive Present Value of $55,716 and a positive Net 1982 Investment Incentive of $56,136 because of the good maintenance cost differential. Conversely, System B (Figure 154) now has both a negative Present Value (-$10,394) and Net 1982 Investment Incentive (-$9,474) resulting from additional maintenance needs when the study fuel is used. In other words, the maintenance savings (the maintenance costs are still less than the baseline) are insufficient to offset the fuel cost relative to the Baseline System. System C (Figure 155) again is the preferred system with a $125,124 Present Value, $69,254 Net 1982 Investment Incentive, recovery of the differential investment in the fourth year, and a Time-Adjusted-Rate of Return of 31.8 percent.

Figure 156 lists the results of incrementing the study fuel price to find the fuel price that is required to bring the Net 1982 Investment Incentive to zero for System B. This then is the fuel price for which the system generates cash flows over the 15-year life that, when Present Valued, equal the differential initial investment. The fuel price is found to be $0.57 per gallon -- not a likely cost expectation. This system, therefore, is not a feasible economic choice. This same analysis was not necessary for either System A or System C since they have already shown a favorable advantage compared to the Baseline System operating on the study fuel.

The economic results for the aircraft system (three engines) generally show significant dollar influence as the result of maintenance and fuel consumption (See Table 23 and 24). In the case of System A, a $168,000 profitability is projected for airline operation on future fuel. This comes about largely because of lower fuel supply temperature to the nozzles. For System C, block fuel savings of 0.342 percent offsets the higher initial investment of $167,000 and goes on to yield a $207,000 to $281,000 profitability. A problem one may have with these results is their dependency on the accuracy of the overall study. However, these results do suggest that future fuel compatability can be achieved without economic penalty so long as early planning and anticipation is made by the aircraft/engine manufacturer.

11.0 CONCLUSIONS

Computer model representation of the DC-10-30 aircraft and CF6-80X engine resulted in simulated flight results affecting the aircraft and engine fuel systems. Flight simulations included nominal, cold, hot and emergency (low fuel reserve) conditions. These flight simulation results coupled with an analysis of equipment and operational cost factors yielded cost incentive comparisons. Collectively these results provided a comparison between a baseline (conventional) fuel system and three advanced fuel systems operating on broadened-property fuel. The most significant conclusions to be drawn from this study are as follows:

1. Using a combination of statistical weather data and DC-10-30 route structure computer analysis, the coldest (one-day-per-year) cruise ambient temperature was found to be -70° C (-94° F). For this long flight from Helsinki to Seattle, tank bulk fuel temperature reached -42° C (-44° F) [within 1.1° C (2° F) of wing boundary layer recovery temperature] during the first third of the flight (178 minutes after gate departure). These results suggest that from a practical airline operational standpoint, recovery temperature may be used as a guide for the prediction of the onset of fuel freezing in the tanks. Using computer techniques similar to those employed in this study, it may be possible in the future for an airline to predict fuel tank temperature for a particular flight. In this case, selection of fuel type could be more selective and afford a more economical match between fuel properties and aircraft design capability.

2. With advanced systems employing means for tank heating, the coldest bulk fuel temperature was:

(a)	Using engine lube heat	-33.9° C	(-29° F)
(b)	Using generator lube heat	-41.7° C	(-43° F)
(c)	Using ECS bleed air precooling heat	-32.2° C	(-26° F)

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Each of these systems, therefore, provides improvement in aircraft tanks freezing protection. Each would permit airline operation with a broadened-property fuel.

3. Use of engine lubrication system heat as a means for tank fuel freezing protection should be carefully considered from the standpoint of engine oil temperature. Simple means for direct heat transfer can result in oil temperatures lower than those desired for proper oil distribution in the engine. This same cold oil problem may occur with generators or other lubrication systems.

4. Conflict may exist between heat sources used for engine fuel icing protection (such as engine lube oil heat) and means for tank heating. The study did not conclude that these heat sources would exist as a logical consequence of future aircraft/engine systems design. Tank heating capability will have to be planned well in advance of its implementation.

5. Low lubricity fuel problems, if they occur, can probably be solved by proper choice of fuel pump materials. Centrifugal pumps would not be subject to low lubricity influence. The study did not reveal any difficulties associated with pump selection.

6. Several advanced design concepts are available to improve combustor fuel nozzle and divider valve tolerance to lower fuel thermal stability. The study fuel with a thermal breakpoint 43° F less than Jet-A could be accommodated without increase in component removal rate. In the broadest sense, it may be concluded that proper and deliberate attention to the total fuel system (including pump selection) would afford adequate compatibility with lower thermal stability fuels.

7. Economic results were as expected in that sfc is the driving factor. The most complex and initially most expensive advanced

system using ECS bleed air was the most attractive from the airline life-cycle-cost standpoint. This was the only system yielding a reduction in fuel consumption. This conclusion does, however, depend on the assumption that engine bleed and air-to-air precooling continues in future aircraft/engine designs.

8. Of all the broadened fuel property issues addressed by this study, tank heating for fuel freezing protection is the most formidable problem. The study showed, however, that excessive fuel tank temperature even with low (emergency) fuel reserves could be avoided. Consequently, the major issue (heating a cold tank) appears to be the driving factor.

9. It is expected that the performance and economic techniques developed as a result of this study will provide significant benefits in future consideration of aircraft/engine system design. The complexities of fuel property interaction with aircraft/engine systems does not afford simplistic consideration.

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