MODULE III

ENGINE PERFORMANCE

Design Point Performance

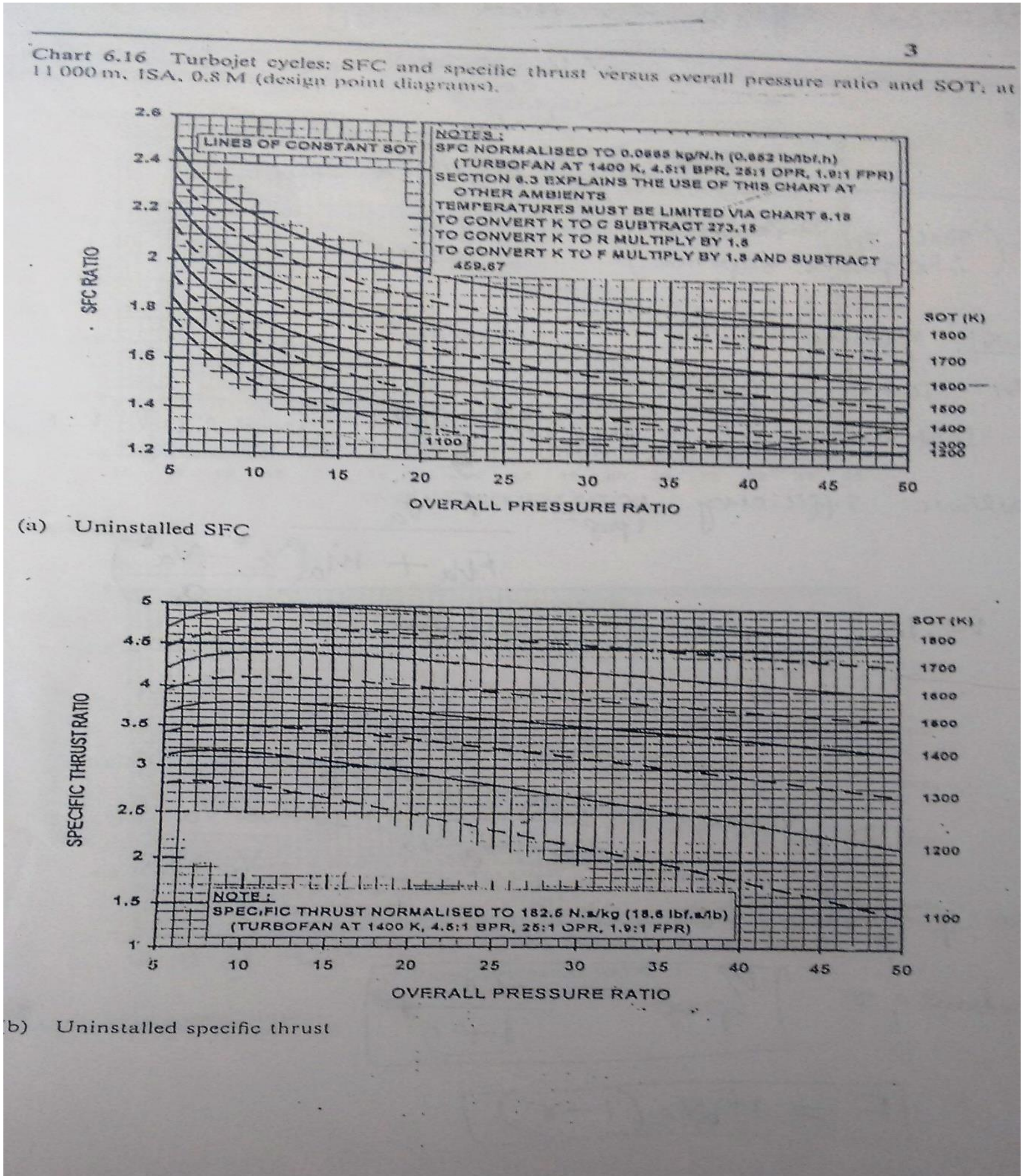
- The operating conditions where engine will spend most time has been traditionally chosen as engine design point.
- The engine geometry is fixed by the design point calculations, the performance at other key operating conditions (off-design) can be evaluated.

Design Point Performance Parameters

- **Output power or net thrust**
- **Exhaust gas power** – for turboshaft engine core this is the output power that would be produced by a power turbine of 100% efficiency.
- **Specific thrust or power** – This is the amount of output power or thrust per unit of mass flow entering the engine. It provides a good first order indication of engine weight, frontal area and volume.
- **Specific fuel consumption** – This is the fuel burnt per unit time per unit of output power or thrust.
- **Thermal efficiency** – This is the output divide by the rate of fuel energy input, usually expressed as percentage.
- **Exhaust temperature** – For military aircraft applications low exhaust gas temperature is important to reduce the infrared signature presented to heat seeking missiles.
- **Exhaust mass flow** – Indication of heat available in gas turbine exhaust.
- **Propulsive efficiency** – Useful propulsive power produced by the engine divided by rate of KE addition to the air.

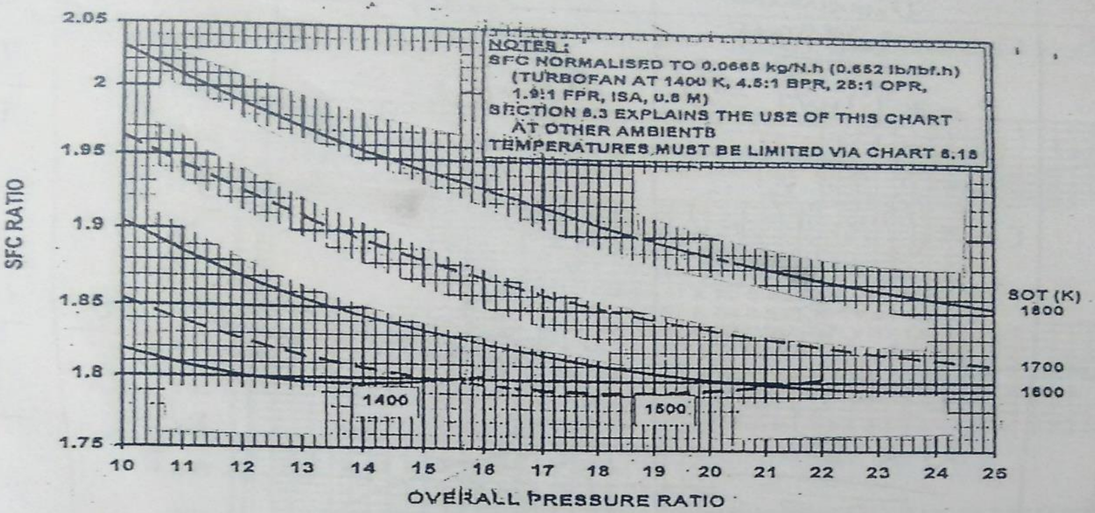
Design Point Diagram:

- This is obtained by plotting engine performance parameters versus the cycle parameters.
- The design point charts may be applied to any altitude, if the referred form of specific power or thrust, SFC, etc., are used.
- Referred groups are directly proportional to Quasi-dimensionless group and hence interchangeable in usage.
- The difference is the substitution of theta and delta for engine or component inlet pressure and temperature.
- **Quasi-dimensionless group:** These have specific gas constant, gamma and the engine diameter is eliminated.
- **Dimensionless group:** These group contain all variables affecting engine or component performance including engine linear scale and fluid properties.

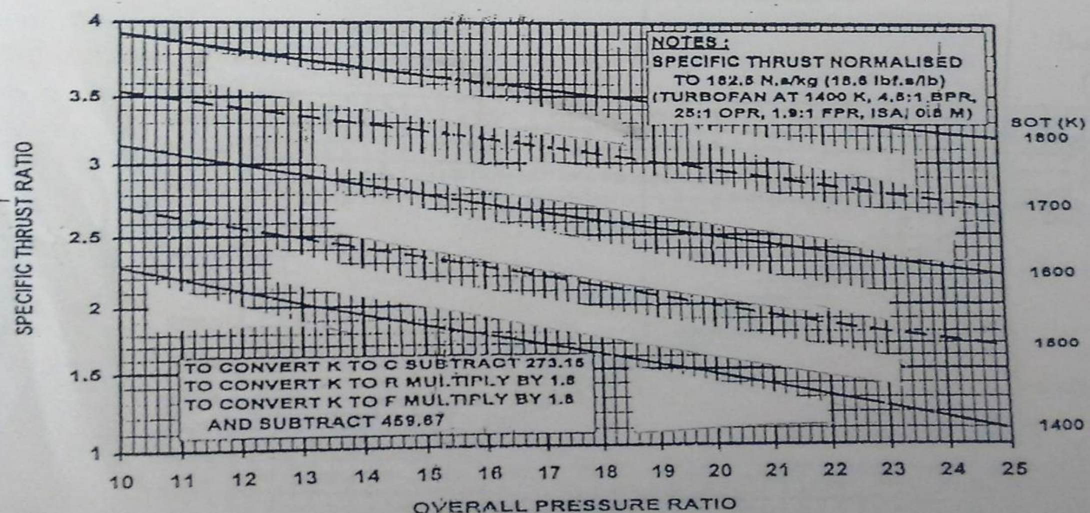


- SFC increases with SOT increase, but specific thrust improves.
- For a given pressure ratio, increasing Mach number from 0.8 to 2.2 increases compressor delivery temperature.
- At supersonic speeds there is similar trend, except that at the lowest SOT level SFC raises again at the higher pressure ratio, due to reducing SFC
- SFC improves with pressure ratio

Chart 6.17 Turbojet cycles: SFC and specific thrust versus overall pressure ratio and SOT, at 11 000 m, ISA, 2.2 M (design point diagrams).

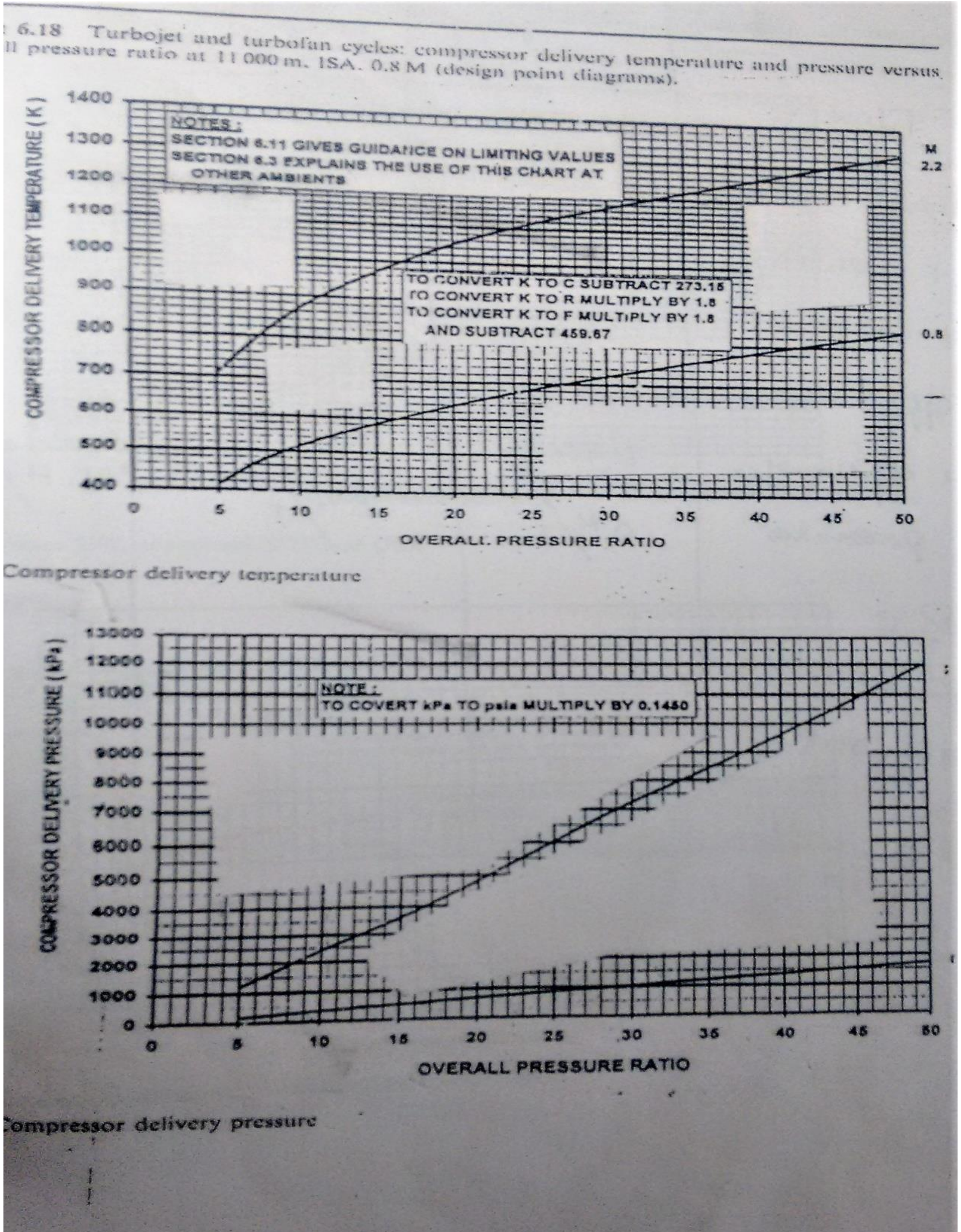


(a) Uninstalled SFC



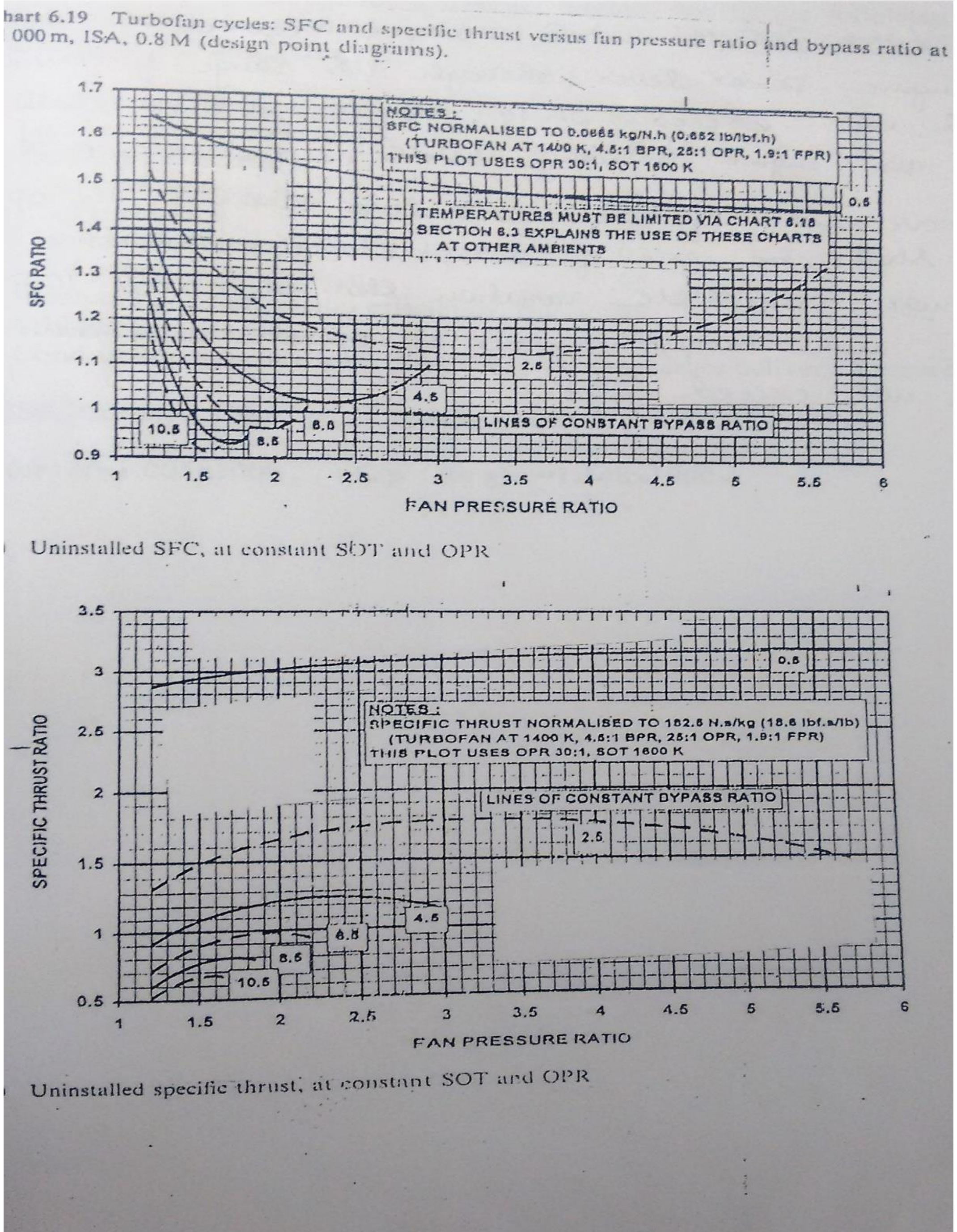
(b) Uninstalled specific thrust

Turbojets design point performances.



Compressor delivery pressure and temperature versus pressure ratio

Graph shows drop in compressor delivery pressure and temperature



Turbofan Design Point Performance:

- Graph shows that for each combination of bypass ratio, overall pressure ratio and SOT there is a optimum fan pressure ratio, giving both maximum specific thrust and minimum SFC.
- Optimum specific thrust and SFC occur at the same fan pressure ratio since for a fixed core engine combustion mass flow is fixed, as are combustion entry and exit temperature, fuel flow must therefore be fixed.

Continue…,

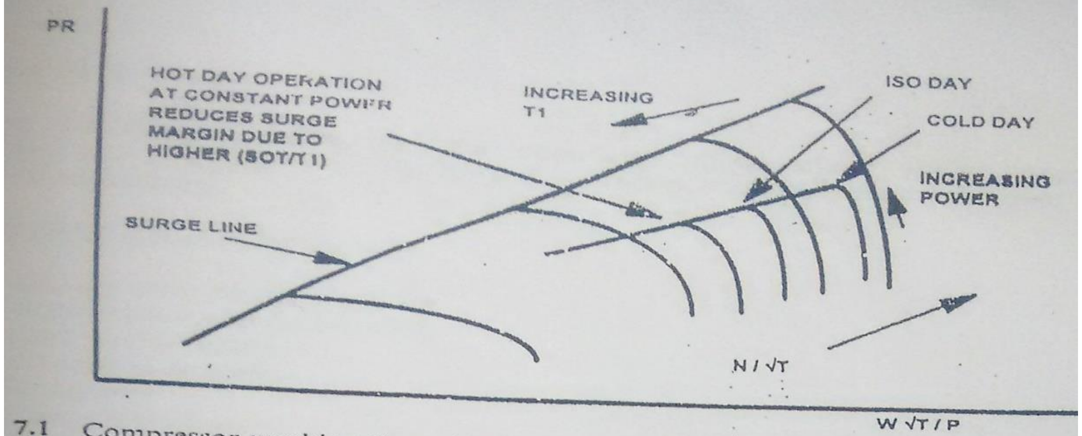
- At the optimum fan pressure ratio the overall energy conversion to thrust is maximized.
- Increasing bypass ratio at fixed SOT and overall pressure ratio reduces the optimum fan pressure ratio sharply.
- This is due to reduced core nozzle pressure ratio and hence jet velocity, resulting from an increased LP turbine power requirement to compress the bypass stream.

Off-Design Performance

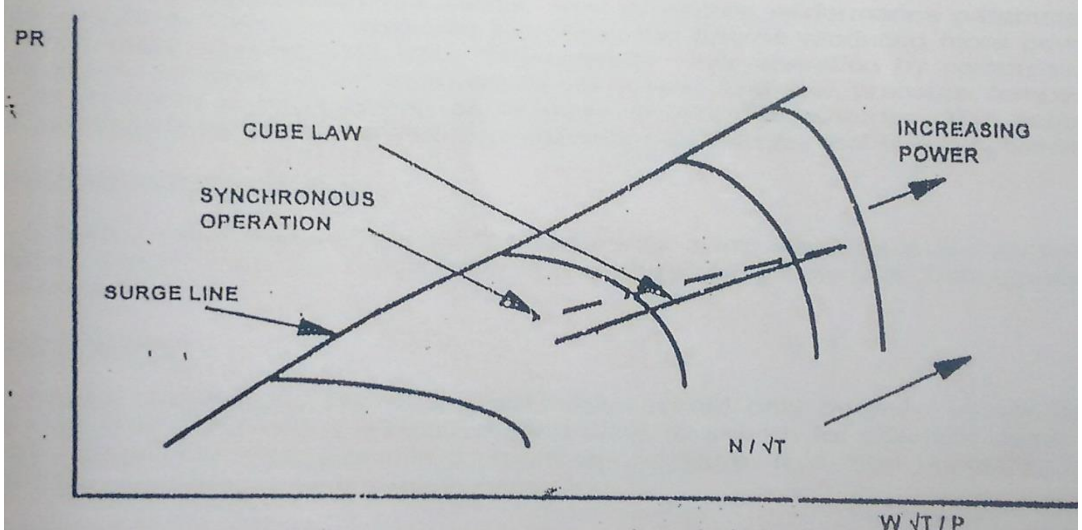
- Steady state performance of a fixed engine design as the operational conditions are changed.
- This addresses the other key operating points as well as all corners of the operational envelope.
- As the power or thrust level is varied, the referred parameter groups allow a unique running line or families of running lines which are independent of ambient conditions.

Turboshaft single spool:

- In turbo shaft engine turbine drives both, the engine compressor and the output load. Referred performance chart is shown in below graph.
- Referred compressor delivery pressure and temperature increase significantly as day temperature is reduced and the referred speed increases.
- For a given day temperature as fuel flow, hence SOT and output power, are increased the compressor operating point moves up the constant referred speed line.
- Equally if the day temperature increases, referred speed falls. If the engine is flat rated then on hot days, surge margin will reduce, as referred SOT must increase.



7.1 Compressor working line, single spool turboshaft or turboprop.



.2 Compressor working line, single spool gas generator with free power turbi

Compressor working line for single spool turboshaft or turboprop Engine.

Compressor working line for single spool gas generator and free power turbine.

Turboshaft or Turboprop, Single spool gas generator & free power turbine:

- In this configuration the engine compressor is driven by one turbine, and the second turbine drives the output load.
- Referred performance is shown in the above graph. It shows that the compressor referred speed changes with power level.
- The power turbine speed law sets the part load trend; the reductions in capacity and efficiency produced by synchronous operation reduced surge margin at low power.

Off-design operation of the single-shaft gas turbine:

- Select a speed line on the compressor characteristics and choose any point on this line, the values of $m\sqrt{T01}/P01$, $P02/p01$, $N\sqrt{T01}$ are then determined.

- The corresponding point on the turbine characteristic is obtained from consideration of compatibility of rotational speed and flow.

- Having matched the compressor & turbine characteristics, it is necessary to ascertain whether the work output corresponding to the selected operating point is compatible with that required by the driven load, this requires the knowledge of variation of power with speed, which depends on the manner in which the power is absorbed.

Transient Performance

- Transient performance deals with the operating regime where the engine performance are changing wrt time.
- Engine operation during transient manoeuvre is often referred to as handling.

➢ Transient Performance Maneuvers:

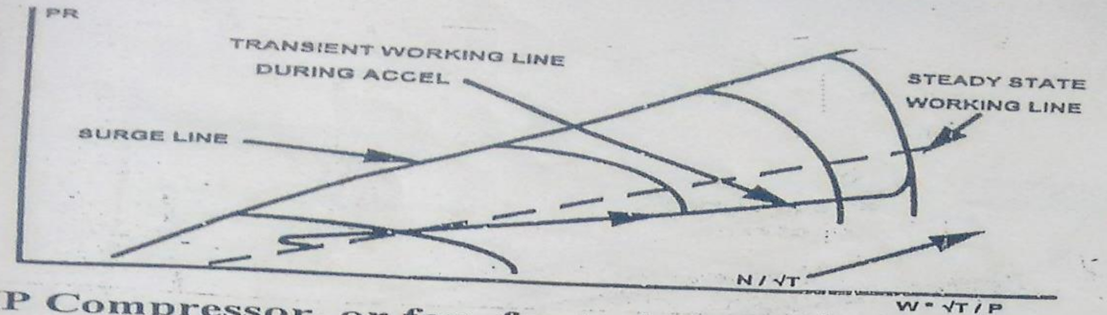
- ❖ Slam acceleration and deceleration
- ❖ Slow acceleration and deceleration
- ❖ Cold start – acceleration
- ❖ The hot reslam or bodie
- ❖ Shaft breakage
- ❖ Emergency shutdown
- ❖ Drop Load
- ❖ Bird or Water ingestion

1. Slam acceleration and deceleration:

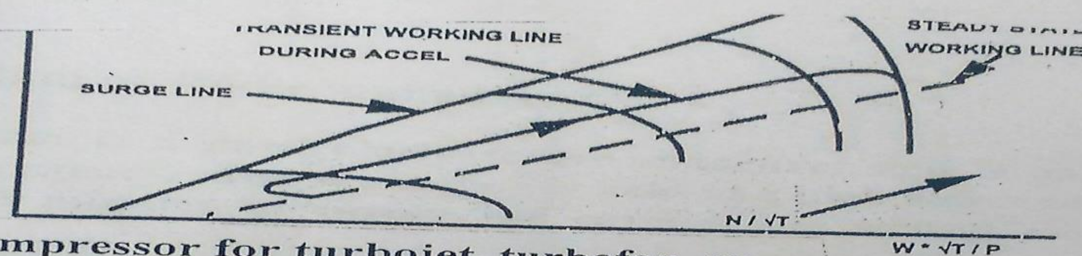
Below figure shows typical response versus time of engine performance parameters to a slam or step increase.

Owing to additional fuel flow, the turbine produced more power than required compressor working lines differ from steady state operation by compressor.

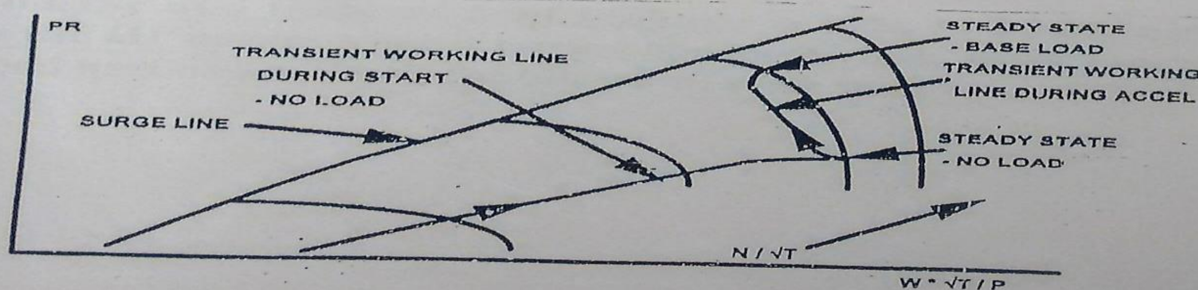
The unbalanced power produces spool acceleration. Air power, fuel flow, pressure, temperatures etc., and hence thrust or shaft power, all increases as spool accelerates. This acceleration continues until the steady state condition corresponding to the new fuel flow is achieved.



LP or IP Compressor, or fan, for turbojet, turbofan or free power turbine turboshaft/turboprop-two or three spools



H P Compressor for turbojet, turbofan or free power turbine – one, two or three spool



Single spool turboshaft or turboprop with load driven directly from the gas generator

Transient working lines during acceleration maneuver

2. Slow acceleration and deceleration:

Whenever longer engine response times than those for slam manoeuvres are acceptable to the application, the PLA &hence fuel flow are changed at slow rates. This greatly eases the operability concerns.

3. Cold start acceleration:

Except in military applications the cold acceleration would only be used in service in an emergency, but it is used during development testing to search for potential surge margin shortfalls. The engine is soak down to ambient temperature. It is then started to idle and immediately slam accelerated to maximum rating.

The cold start- acceleration is particularly severe in that it maximizes the difference in thermal growth of the disc and blades relative to casing.

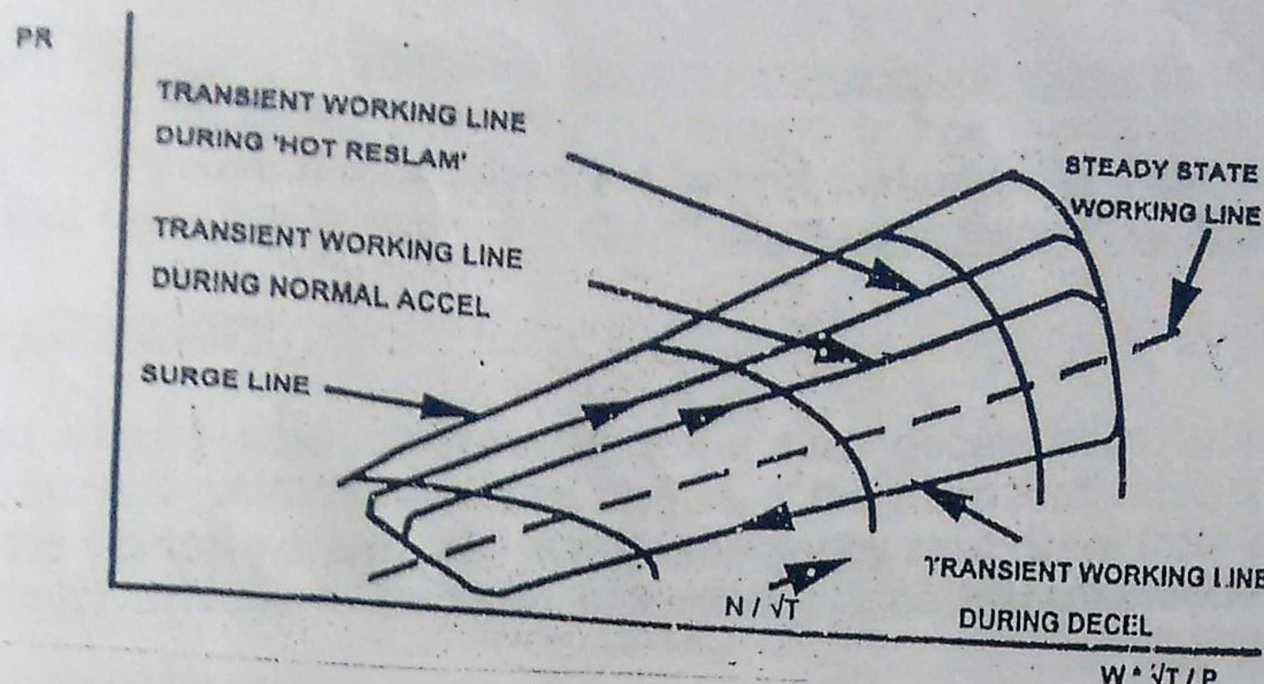
During acceleration, the thermal growth of compressor or turbine disc is slower than the pressure and thermal growth of casing, causing blade tip clearances to be temporarily increased. Higher tip clearances significantly degrade compressor surge lines.

4. The hot reslam or Bodie Maneuver:

The hot reslam is a particularly sever maneuver and is only used during an emergency. First the engine is held at a high power condition for at least 5 minutes to ensure the carcass has soaked to its hot condition.

A slam deceleration to around idle is followed immediately by a reslam back to high power, allowing no time for carcass to thermally soak at the low speed.

In the combustor and turbines heat soakage is akin to additional fuel flow and in the HP compressor it lowers the surge line, as it changes the referred speed and hence flow capabilities of rear stages.



HP Compressor transient working line

e hot reslam or Bodie maneuver

e hot reslam is a particularly severe maneuver and is on

5. <u>Shaft breakage:</u>

In rear event of engine shaft failure, rapid over speed will follow as the power of the turbine is decoupled from its driven compressor, leaving a low inertia and a very large power to accelerate it. To prevent over speed the control system must instantaneously close the main fuel valve and open bleed valve. If a shaft fails, no disc burst should occur.

6. <u>Emergency shutdown:</u>

A standard engine shutdown comprises a slow deceleration to idle, a short stabilization for around 5 minutes and then closure of the main fuel valve causing engine run down. However the control system may signal emergency shutdown from any operating condition if safety is involved. Here the main fuel valve closes instantaneously and bleed valve may open.

This is a severe maneuver with respect to LP compressor surge margin. Even during an emergency surge is unacceptable.

7. <u>Drop Load:</u>

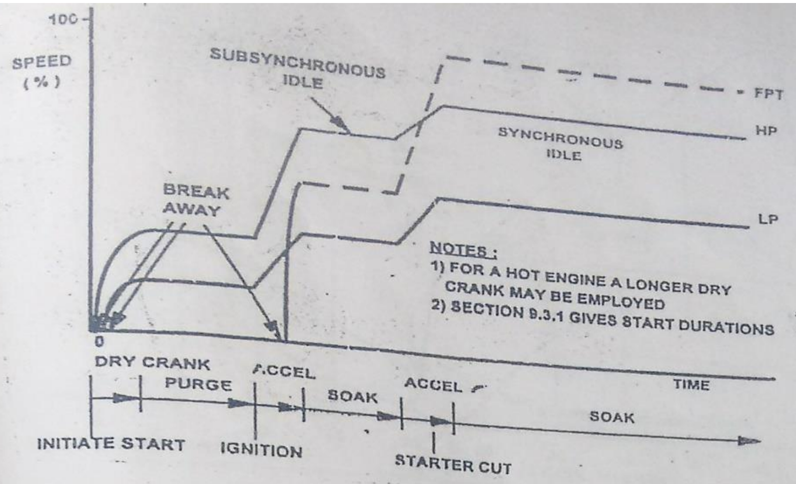
A sudden drop of electrical load may occur due to electrical failure. Fuel must be pulled of more rapidly to avoid overspread, and engine must be decelerated to idle to be available for reloading. Hence the drop load is challenge for the combustor stability.

8. <u>Bird or Water Ingestion:</u>

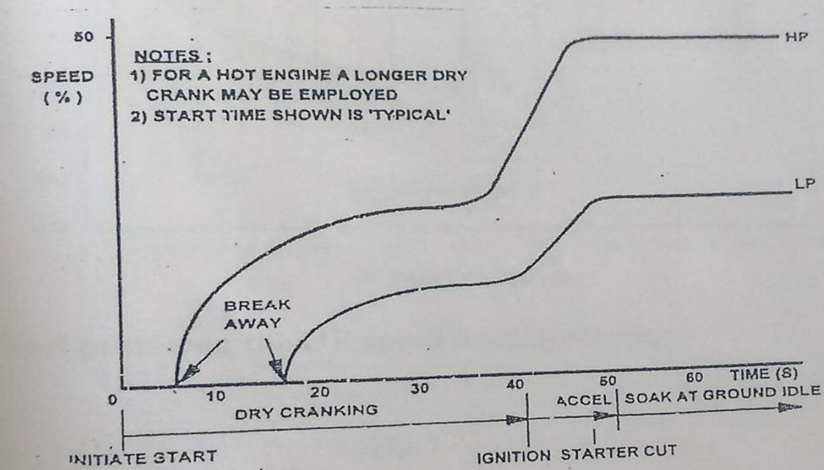
As stipulated in airworthiness a requirements, engines are required to ingest a number of birds or a given amount of water/ice, and function safely both during this event and afterwards.

Starting: The fundamental starting process involves

- Dry Cranking: The engine Hp shaft is rotated by the starter with no fuel being metered to the combustor.
- Purging: This ensures that there is no fuel from previous operations or failed start attempts in the engine gas or exhaust that may ignite and cause damage.
- Light off: Fuel is metered into the combustor, and the igniters are energized. This causes ignition locally within the combustor, and then light around of all the burners.
- Acceleration to idle: This is achieved via a steady increase of flow, and continuing starter assistance.



Two spool gas generator plus free power turbine

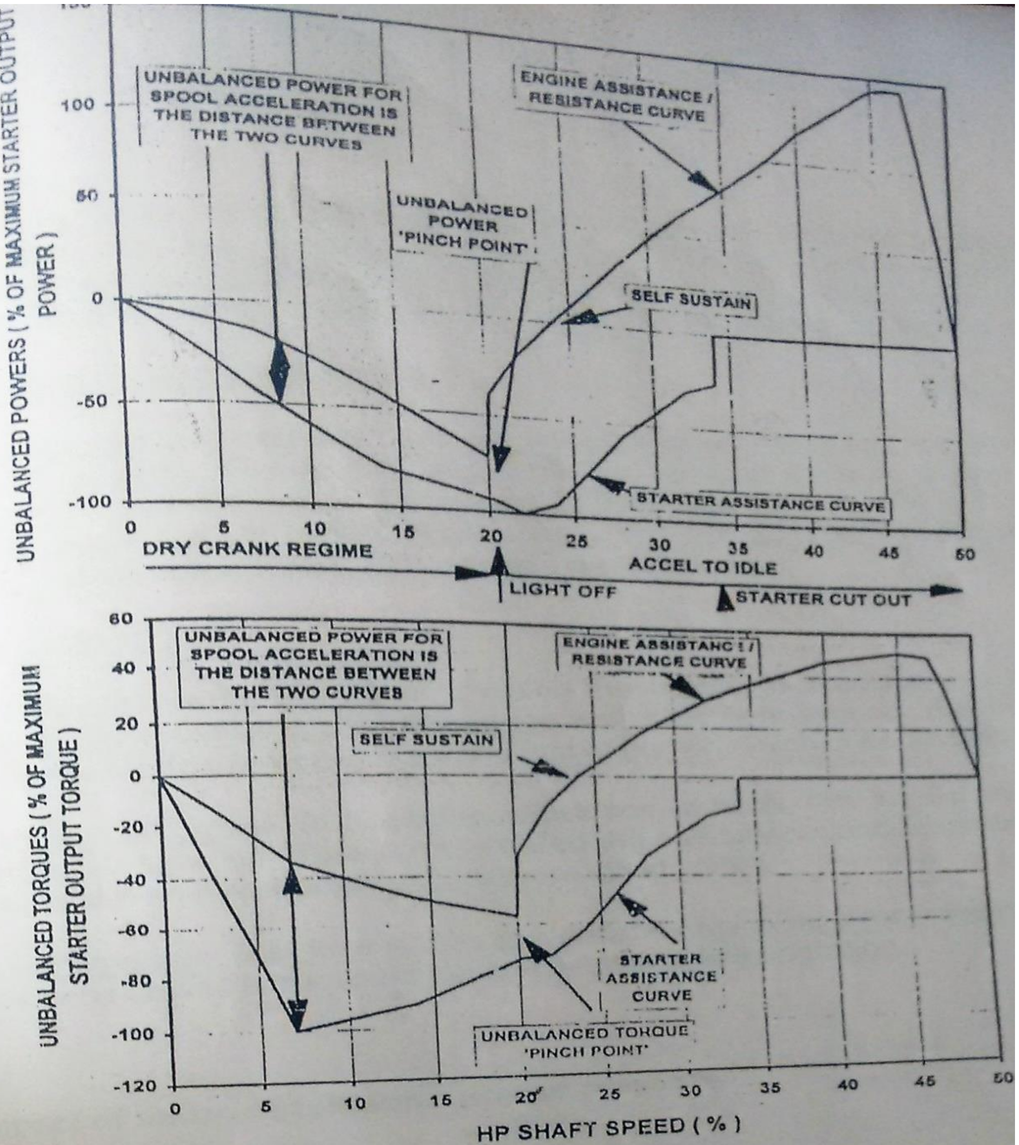


Two spool turbojet or turbofan

Key engine start phases and speed versus time

Thermal soakage: Engines are often held at idle to allow the carcass to thermally soak to the new temperature to preserve cycle life.

Above figure shows rotational speeds versus time for both a free power turbine turboshaft engine and turbofan during a start.



Torque and power on the HP spool during starting

Fig. 9.2

- Figure shows the torque and power balance on the HP spool. The two curves shown are referred to as the engine resistance/assistance and starter assistance.

- Engine assistance or resistance is the net engine unbalanced torque or power output during the start, negative value being resistance and positive value being assistance.

- By standard convention the starter motor torque or power is shown as a negative value even though it is assistance. The net unbalanced assistance torque or power is represented by vertical distance the two curves

Dry Cranking:

- The purpose of dry cranking is to develop sufficient pressure and mass flow in the combustor to permit light off. At start initiation the starter is energized and applies torque to the HP spool.
- To minimize the shock torque loads, torque is applied gradually, for example via slow opening of air valves for a turbine starter. The HP spool then rotates and accelerates due to excess starter assistance power.
- The airflow induced by HP compressor causes the LP spool and if applicable, eventually the free power turbine to break away from the stiction of the oil at the bearing.

PURGING:

- Purging is required for all starts with gas fuel, and may be used for liquid fuels following a failed engine start or emergency shutdown. During the process the combustor has been lit before the HP spool has accelerated to appoint where engine net resistance equals the starter assistance.

Light off-ignition and light around:

- Here the igniters are activated and a constant light off flat of fuel is metered to the combustor by control system. Figure shows that on light off there is a step reduction in engine resistance. However, starter assistance is still required to continue HP spool acceleration.
- Turbine output power is still usually less than the sum of the compressor input power bearing and windage loses, and auxiliary requirements.

Acceleration to Idle

- Fuel flow is steadily increased, causing the engine to accelerated to idle. The starter motor continue to provide crank assistance well after light around.
- As the speed increases the engine assistance eventually dwarfs that of starter, which cuts out before idle.
- As shown in graph, the engine resistance crosses the x axis and becomes assistance shortly after light off. This point is called the self sustain and theoretically if the starter motor were cut the engine could operate there steady state.
- On reaching idle, fuel flow is cut back and the engine assistance/resistance becomes zero, no unbalance power is required for steady state is idle operation.

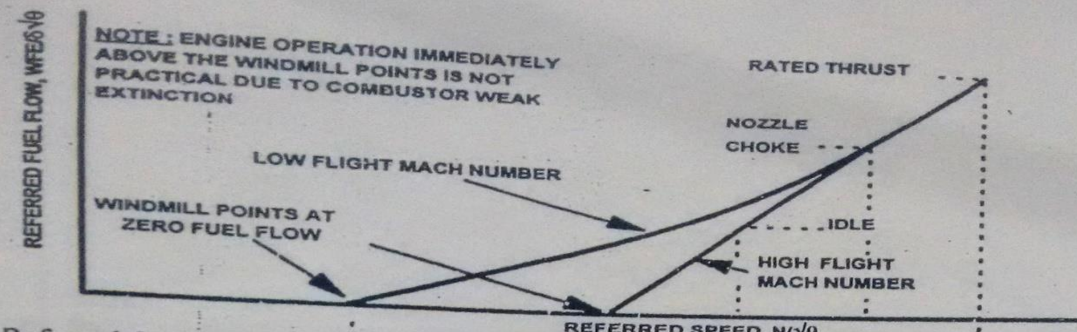
Windmilling

- Windmilling occurs when air flowing through an unlit engine causes spool rotation.
- Direction of rotation is same as that for normal operation.
- Free windmilling is where all the engine spools are free to rotate. Locked rotor windmilling is where the HP spool is mechanically prevented from rotation.

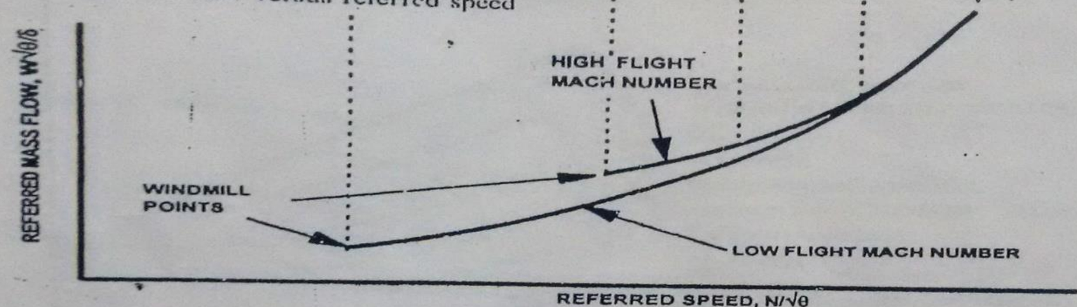
- A knowledge of key performance parameters during windmiling is essential for following reasons:
  - Ensure relight
  - Understand bearing lubrication requirements
  - Knowledge of drag during windmilling

Turbojet Windmiling

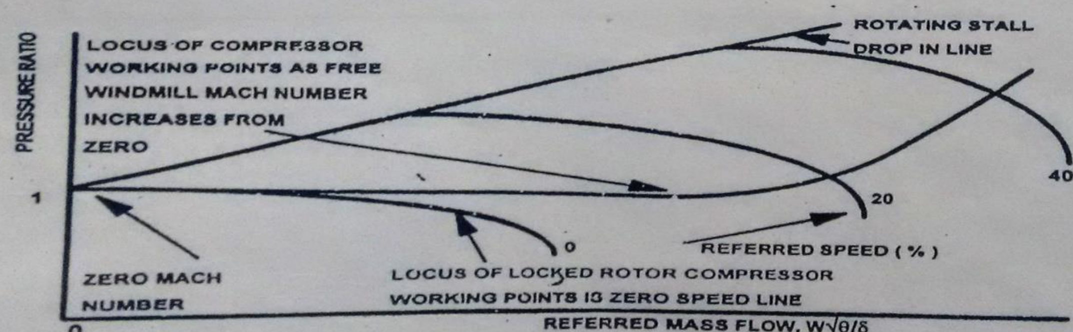
- Below figure shows windmill regime. Referred fuel flow and mass flow are shown versus referred speed for high and low Mach numbers.
- Mass flow increases with higher Mach number.
- Figure also shows locus of operating points for free and locked rotor windmilling on the low speed compressor map.



(a) Referred fuel flow versus referred speed



(b) Referred mass flow versus referred speed

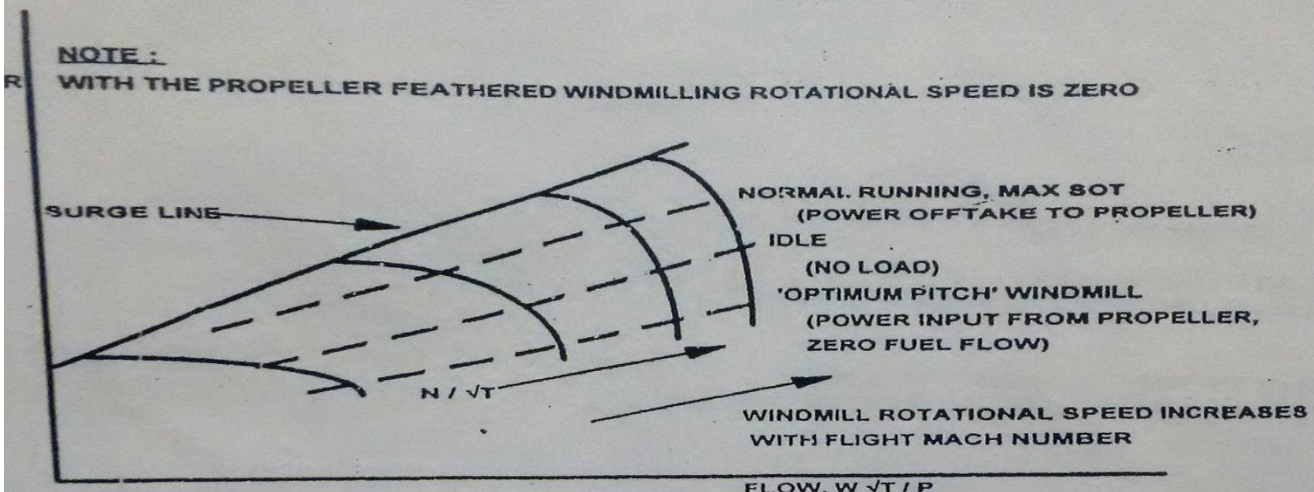


(c) Compressor working points

Fig. 10.1 Turbojet windmilling: referred parameter group relationships.

Turbo prop Windmilling

- The dominant parameter determining the turboprop windmilling behaviour is the propeller pitch.
- Figure shows the compressor working line is lower than no load line.
- The drag is predominantly created by the propeller. At high speeds the drag of the propeller approach that of the engine thrust in normal operations.
- In actual flight situation such a drag makes it impractical to operate with the propeller in position.
- Hence the engines are fitted with reverse torque switch in the gear box, with that the propeller is brought to feather condition, where the propeller blades are parallel to air flow condition.



).2 Single spool turboprop windmilling: compressor working lines.

Engine Performance monitoring

- In the recent years, a method of monitoring the gas turbine engines day to day condition has been adopted by many operators.
- Aerodynamic performance is measured by:
  - EPR
  - Rpm
  - Fuel flow
  - EGT
  - Throttle position
- Mechanical performance is measured by:
  - Vibration amplitude
  - Oil consumption (includes periodic spectrometric oil analysis)

- Cockpit instrumentation readings are taken once a day or every flight. The data is then processed to compared with normal data established by manufacturer. Trend in operating parameters are ten observed.
- Engine performance monitoring is proving to be very effective method of providing early warning information of ongoing or impending failures, thus reducing unscheduled delays and more serious failures.

Trend Analysis: A case study

- Compressor contamination: Contamination of compressor may occur due to operation near salt water, the use of impure water for water injection, an oil leak in forward part of the engine that may cause fine dust to adhere to blades, or contamination from ingestion during reversing.
- Often the effects of compressor contamination can be eliminated by water washing.
- Contamination of compressor blades changes their aerodynamic shape, roughens their surface and reduces the airflow area.
- Reduced airflow area in turn reduces compressor efficiency and airflow capacity.
- When compressor lose efficiency, more power and higher rotor speeds are required to achieve the desired compression ratio and hence EPR.
- The additional power is obtained by pushing the throttle forward increasing fuel flow and increasing the inlet temperature.