HYPERSONIC AIRCRAFT CONCEPTUAL DESIGN METHODOLOGY*

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Abstract

In the development of an aircraft great importance resides in the early phase of its design (conceptual design). In this phase computer programs are commonly used in order to synthesize the most important design requirements in a preliminary configuration. These programs generally contain performances relationships, weight estimation relationships and mathematical models for aerodynamics and propulsion: all these connections are managed by means of parametrical analysis and/or optimization algorithms in order to reach a level of design useful to point out difference among configurations.
Compared with the conventional aircraft field, a conceptual design computer program for the hypersonic planes presents some peculiarities: it has to take into account several kind of performances, different weight estimation relationships, a greater complexity in modelling the aerodynamic phenomena and the propulsion, etc...
Such a computer program has been developed at our Department: it is intended in performing preliminary studies of feasibility, evaluation of technical hypotheses, comparison of alternative configurations.
The characteristics of this methodology and some different applications will be outlined in the following paper.

Introduction

In the aeronautical field the computerized methodologies for the conceptual design have great importance; in fact it is well known that the choices made in the preliminary phases of the design heavily affect the success of the future aircraft. Furthermore a simple and versatile calculation program for the aircraft conceptual design easily allows to do evaluations of capability and analysis of feasibility, whoever conceived the various hypotheses of the system.
From this point of view, we think that the University could also have the interest in developing this kind of software.
At Turin Polytechnic, under the guide of Prof. G. Gabrielli(1)(2), an activity was planned in order to work out some researches inherent to the conceptual design of an aircraft; this activity also continued during the years(3)(4)(5), and now, we are trying to extend the methodology from the field of conventional aircraft to the latter and widely interesting one of the hypersonic aircraft.
In the following we will delineate the main characteristics of a simple methodology for the conceptual design of spaceplanes carried out at the Aerospace Department (DIASP) of Turin Polytechnic.

Generality about the Conceptual Design Methodology

The aim of the above–mentioned methodology is achieved if this creates schemes with a level of definition so detailed that it makes them comparable, though they are not yet feasible. Figure 1 clearly shows the inputs to the methodology, the constraints, coming from the current technological level, and above all the design requirements. In Figure 1 we can also observe that the programs for the conceptual design essentially are based on:

- equations of the flight mechanics which join the desired performances (Requirements) with the main technical characteristics of the aircraft (unknown);
- weight estimation relationships (usually derived from statistical analysis) in which the weight (unknown) of the various subsystems forming the whole aircraft is related to the aforesaid main technical characteristics of the upcoming aircraft;

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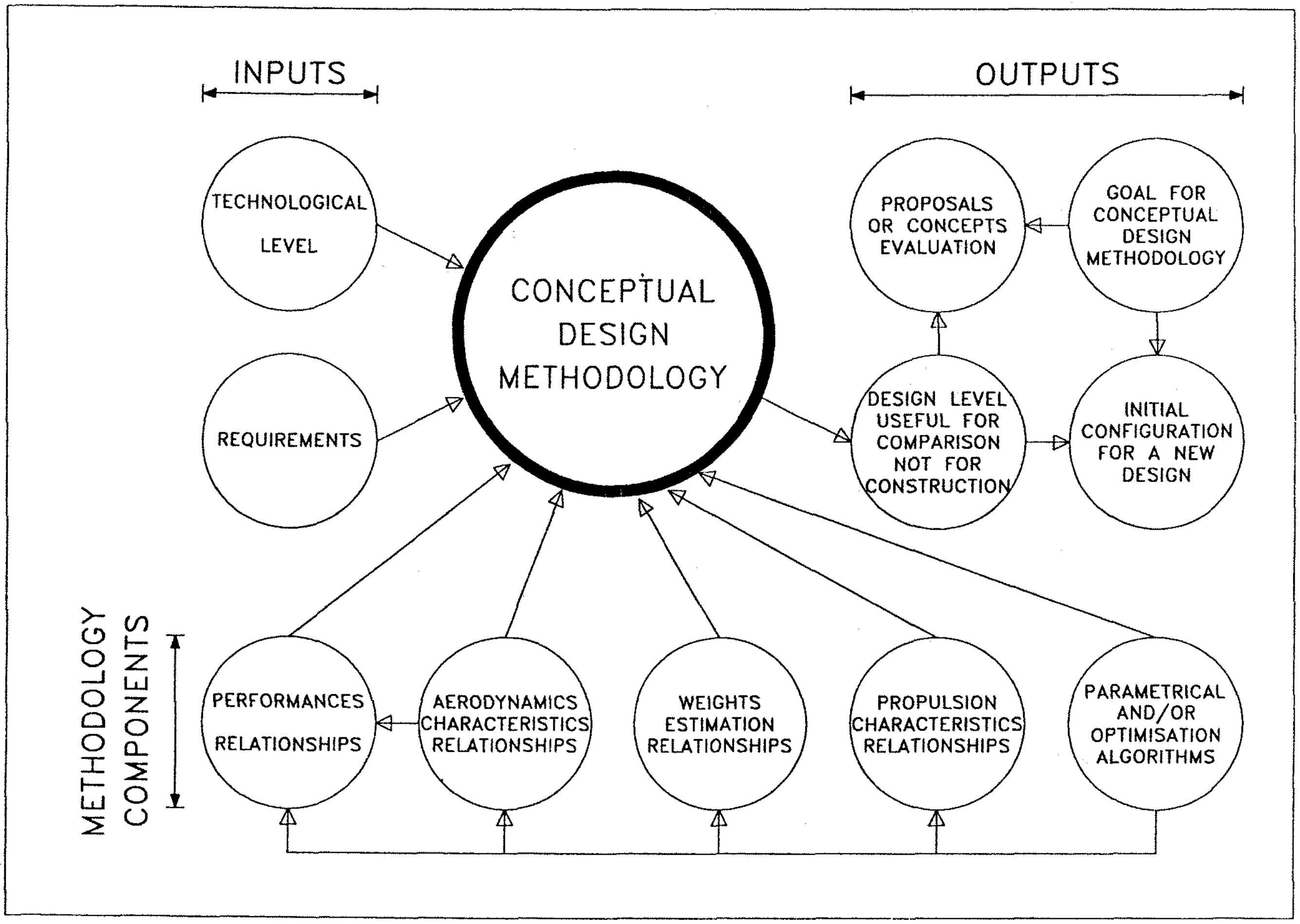

Figure 1

- equations for the aircraft aerodynamic characteristics estimation (included in the performance estimation relationships) in correlation with the geometrical characteristics of the aircraft, usually by an empirical way;
- equations representing the performances of the propulsion system and its specific fuel consumption in function of the Requirements.

The management of all these equations is carried out by algoritms of optimization and/or methods of parametric analysis in order to obtain the solution (sometimes more than one) of the "design theme", that is the definition of the main technical aircraft characteristics, able to meet the design requirements.
In Figure 2 the development of our conceptual design methodology is schematically showed. The Designer, considering the requirements to meet, can hypothesize several architecture of the aircraft (Single Stage To Orbit or Two Stage To Orbit, aerodynamical shape, power plant layout,..); the architectures, the design requirements and the attempt values for some technical characteristics represent the input data to the program of calculus: according to these inputs the program generates the aircraft shape complying with the requirements, its aerodynamic characteristics, its performances, the weights of the aircraft subsystems, and finally the manufacturer empty weight and the maximum take-off weight.
Purpose of the subsequent paragraph is a more detailed explanation of our conceptual design methodology.

Computer Program

The flow-chart on Figure 3 schematically shows the organization of the conceptual design methodology: it begins by demanding some pieces of information about the mission profile which could be a standard mission, recorded on a data file, or it could be defined by the Operator; in this case he introduces the mission through a series of points and settles the three coordinates: time t (passed after the take-off), altitude z and Mach number M, for each of these points. Moreover, it is possible, for the Operator, to go on a

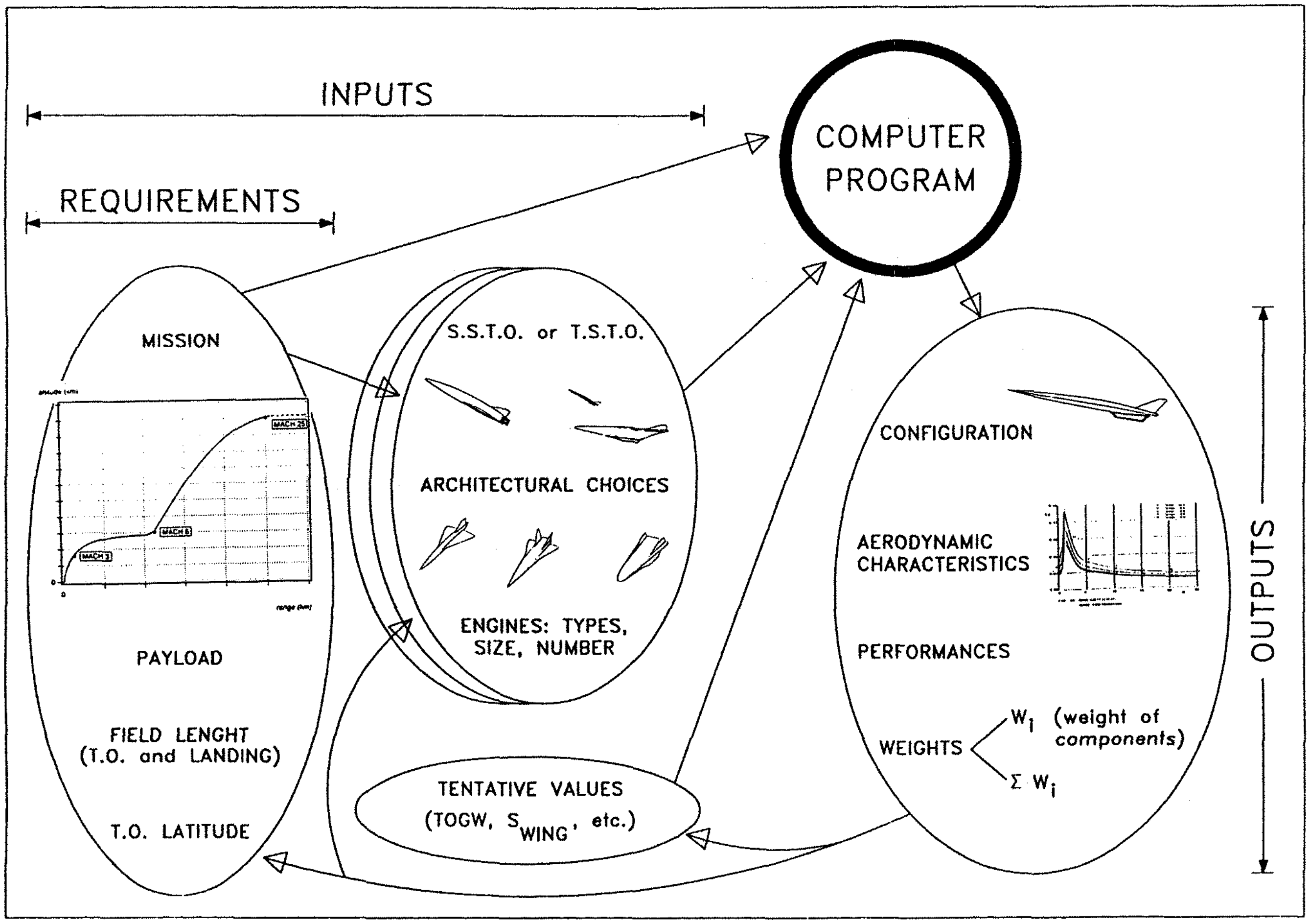

Figure 2

rough optimization of the mission in order to avoid extreme accelerations a; if we are in the case of an orbital mission, the program shows the flight profile to the Operator and verifies the respect of the typical "flight corridor": it espresses the acceptable range of altitudes versus the Mach number.

The Figure 4 shows an example of this graphical tool by which the program allows to modify, totally or partially, the mission profile.

The following step of the program is the definition of a *preliminary attempt geometry* (Figure 5): it presents the following two different ways to proceed;

1. it is possible to insert several detailed geometrical data if we want to study an already defined aircraft,
2. it is possible to assign few basic geometrical values; they consist of:
    - the indication of the main aerodynamical shape (wing body, lifting body or blended body),
    - the number and the type of tail unit and control surfaces,
    - an attempt value for the wing area.

From this step the program carries out a complete definition of the aircraft geometry; it makes use of *empirical/statistical relationships and checks that*, at the maximum speed, the whole aircraft is contained inside the Mach cone.

Now the program goes along to the definition of the propulsion system; it is possible to choose turbojet, ramjet, scramjet and rocket propulsion or many combinations of them.

Figure 6 shows that, at the insertion of the number and kind of engines, the program completes the aircraft architecture and hypothesizes some solutions of the propulsion system layout: it normally installs the rockets *inside the fuselage and the airbreathing* engines in such a way to comply with a request of their air intakes and nozzles.

We point out that a connection between the frontal area of the air intakes and the engine thrust exists as well as between the frontal area of turbojets and of ramjets when the two types of engine are joined in a combined cycle engine. At this point the aircraft geometry, even though at an attempt level, is entirely defined.

Now the program proceeds in the evaluation of the aerodynamic characteristics, particularly of the $C_{Do} = C_{Do}(M)$ and of $C_L = C_L(M, \alpha)$ (Figure 7). The bases of this evaluation are the classical low Mach relationships (Data Sheets, Roskam method[6], etc..) and some of their estrapolations, at high Mach number, including values obtained by computational fluid-dynamics or by the experiments[7],[8] of an aircraft with configuration similar to the wing body, blended body or lifting body.

The definition of the geometrical, aerodynamical, weight and propulsion data, even though at an attempt level, allows to do some performance verifications.

1. The first verification is on the take-off, obviously if the aircraft is a first stage or a SSTO. This step verifies if the calculated balanced field length BFL is shorter than a specified take-off runaway S_{to}: if the condition isn't satisfied the program lets the Operator to increase the available thrust of the working engines during the take-off phase.

2. The second verification is on the feasibility of the mission profile defined by the Operator. The program can proceed on the evaluation of the necessary fuel weight (included the liquid oxigen in the case of the rockets utilization) on the basis of the flight mechanics equations and of the engines specific fuel consumption SFC (Figure 8). In every phase of the mission the program calculates the necessary thrust (this value allows evaluation of the fuel consumption) and compares it with the available thrust: when the last one results insufficient or extremely higher (even if at an only point of the mission) the Operator provides with a modification of the choices on the propulsion system or on the mission profile and then the program repeats the calculations (obiouvsly only if necessary) from the beginning. At every mission phase a check on the attitude value α is also performed: if it exceeds the maximum the Operator has to modify the mission profile and or the wing area S; then the whole procedure restarts.

It is possible, now, to proceed toward the weight evaluation of the subsystems forming

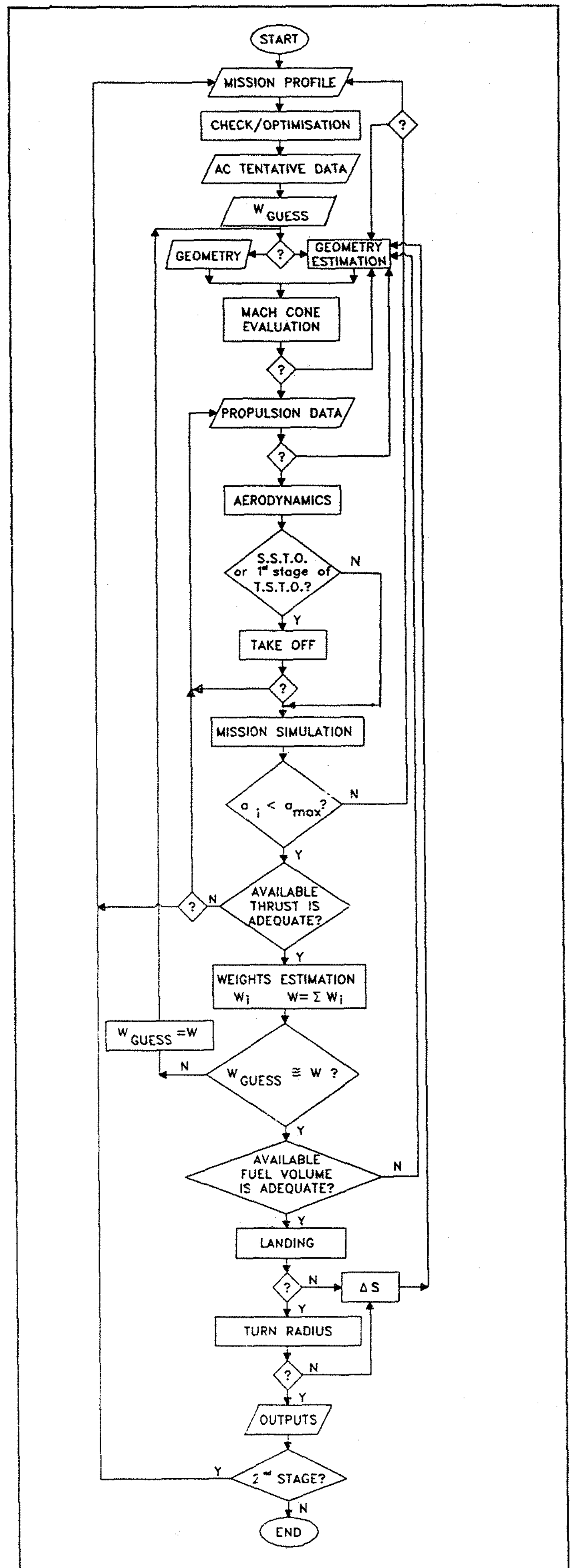

Figure 3

the whole aircraft. Like Figure 9 shows, we have got ready a set of Weight Estimation Relationships ($WER's$) collected from several sources[(9),(10),(11)]; these equations have needed some small calibration and some of them are obtained by an original elaboration. In order to check the consistency of the $WER's$ we have tried to apply them to some hypersonic aircraft of which we know the weight list. The $WER's$ depend on maximum take-off weight W and on empty weight W_e of the aircraft; so as we can see in Figure 3, the fuel weight, necessary for the mission, also depends on W so the program has to iterate on the value of W till to reach the convergence, since the W is fixed at the beginning by an attempt value.

3. The third verification is about the block fuel: if the internal volume is not enough to receive the fuel necessary for the mission, the program allows the Operator to increase the aircraft dimensions and then the entire procedure begins again.

4. The last two verifications are on the landing runaway length L and on the minimum radius r of turn during the approach phase; when these conditions are not satisfied the program allows the Operator to increase the wing area S, restarting the entire procedure (of course without the not necessary steps which, for simplcity do not appear in the Figure 3 flow-chart).

When all the above-mentioned verifications (Figure 10) are satisfied we can consider the aircraft synthesis finished, of course for a given aerodynamic shape and a given propulsion configuration chosen by the Operator at the beginning. If the analysis is applied to a second stage vehicle, weights and characteristics defined by the program represent the input to the conceptual design of the first stage, which will be carried on it.

Applications

In order to validate the above presented computer program, we have tested it performing some applications: many of them were related to studies of hypersonic planes described in technical literature. For example in Figures 11, 12, 13, and 14 some results are reported; in particular Figures 11 and 12 concern a TSTO and Figures 13 and 14 two SSTO with different power plant. The results agree the available data

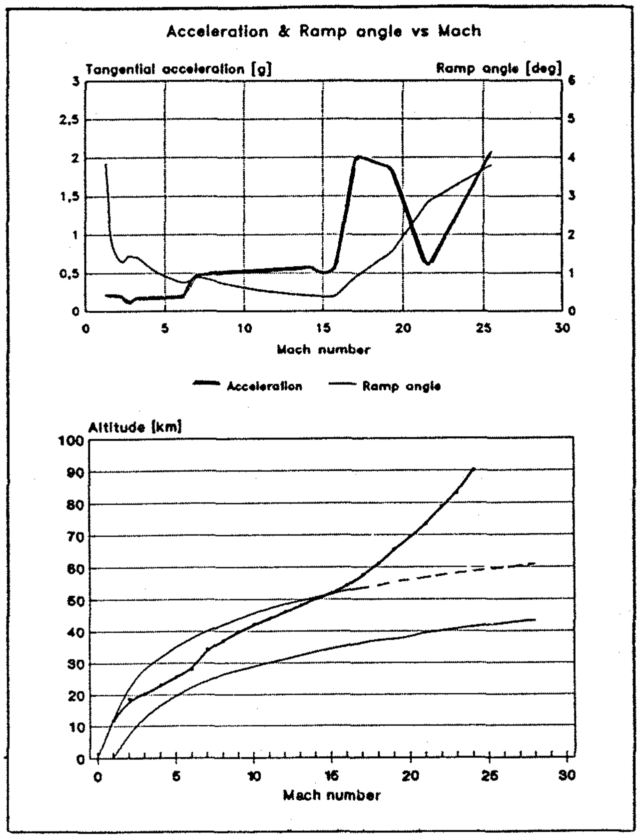

Figure 4

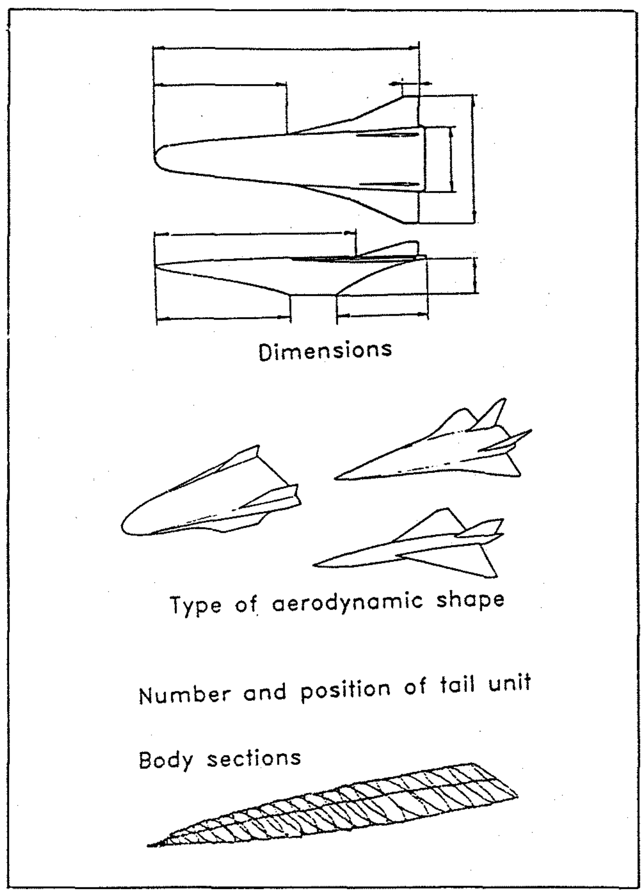

Figure 5

regarding studies performed by Industries. These results, and many other here not reported because of shortness reasons, allow us to think we have reached our target.

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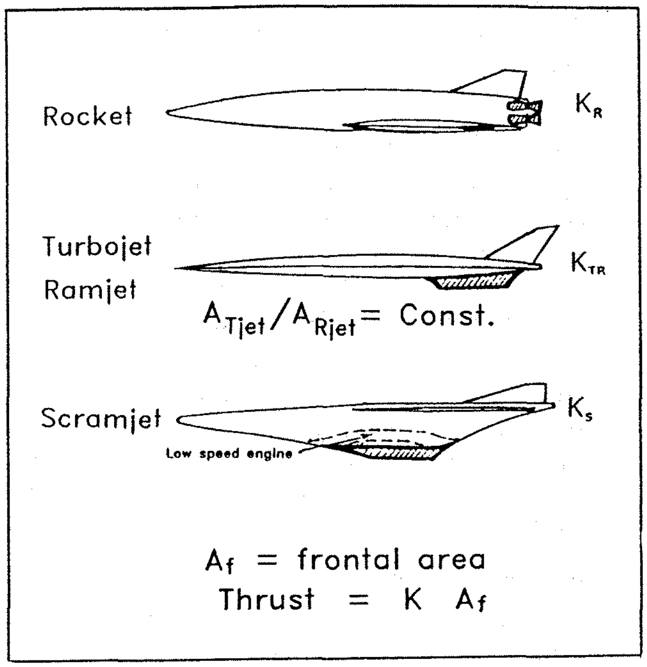

Figure 6

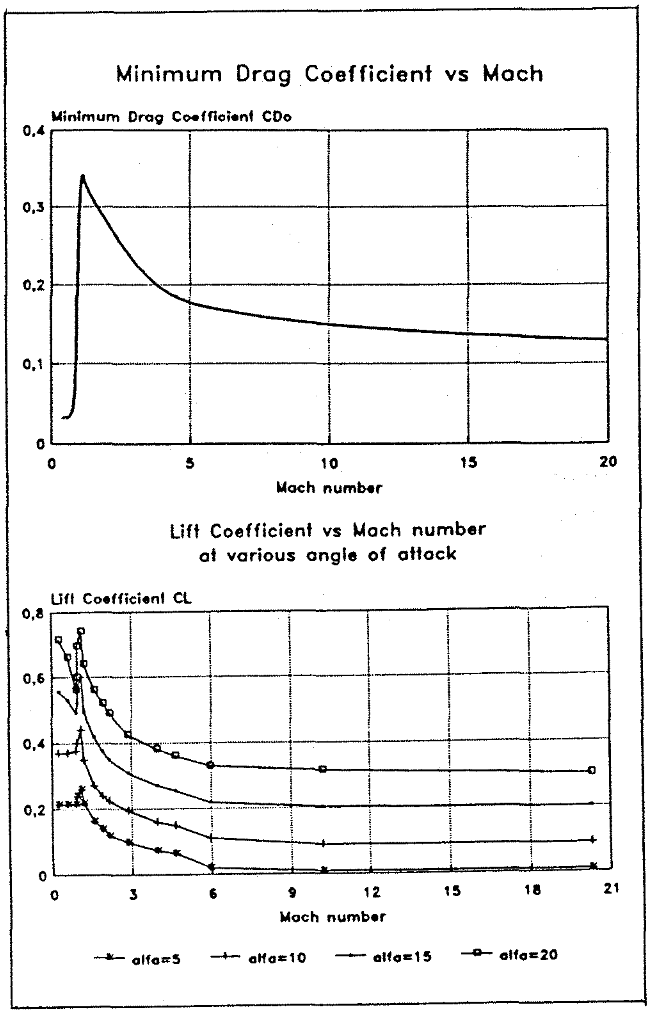

Figure 7

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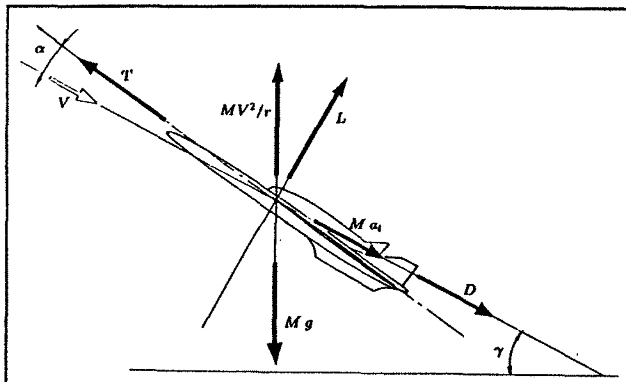


T = thrust
α = incidence angle
γ = ramp angle
M = aircraft mass
$r = r_e + z$ = earth radius + flight altitude
$g = \mu/r^2$ = gravitational acceleration; $\mu = 3.98984.10^{14}[m^3/s^2]$
V = aircraft speed
D = drag
L = lift
a_t = tangential acceleration

Figure 8

Component	Weight estimation relationships dependence
Wing	$W_w = W_w (N_z, W_l, f, S_b, S_{wexp}, T_r, L_w, L_b)$
Tail unit	$W_t = W_t (S_{vt})$
Body	$W_f = W_f (W_{dg}, N_z, L_f)$
Fuel tank	$W_{ft} = W_{ft} (V_{ox}, V_{lh})$
Landing gear	$W_g = W_g (W_l)$
Surface controls	$W_{sc} = W_{sc} (S_{sc})$
Thermal protection	$W_{tps} = W_{tps} (S_{wexp}, S_{vt})$
Hydraulics	$W_h = W_h (S_w, S_{vt})$
Electrical	$W_{el} = W_{el} (S_{bwet})$
Electronics	$W_{av} = W_{av} (S_{bwet})$
Air conditioning	$W_{ac} = W_{ac} (S_{bwet})$
Engines	From available data

Parameters	Definition
N_z	Product of the ultimate load factor of safety and the wing limit load produced by a 2.5 g subsonic maneuver
W_l	Weight of the vehicle at landing
f	Wing/body load distribution factor
S_b	Body planform area
S_{wexp}	Exposed wing planform area
T_r	Exposed wing root chord maximum thickness
L_w	Exposed total structural wing span
L_b	Body width at wing-body juncture
S_{vt}	Vertical tail planform area
W_{dg}	Aircraft flight design gross weight = WTOW - .4 WFUEL WTOW = take-off max weight, WFUEL = max fuel weight
L_f	Body length
V_{ox}	Volume of the main oxidizer tank
V_{lh}	Volume of the main fuel tank
W_l	Weight of vehicle at landing
S_{sc}	Exposed control surfaces planform area
S_w	Wing area
S_{bwet}	Wetted area of body structure

Figure 9

Verifications		Actions
Type	Comparison	
Take off	BFL > Required take-off runaway	+ ΔThrust
Mission feasibility	Available thrust < Necessary thrust	Mission and/or Geometry modifying ± ΔThrust
	Incidence angle > Maximum incidence	Mission and/or Geometry modifying
Fuel volume	Available tank volume < Necessary fuel volume	Geometry modifying
Landing	Landing lenght > Required landing lenght	+ ΔS
Turn radius	Turn radius > Required turn radius	+ ΔS

Figure 10

AIRCRAFT IDENTIFICATION NAME: **SANGER type**

Is the aircraft a Single Stage (1) or a Two Stage (2) ? **2**
Mach of separation between first and second stage ? **6.5**

FIRST STAGE DATA INPUT
Maximum take-off weight (attempt value N) ? **2569000**
Wing area (attempt value m^2) ? **950**

Select one of these aircraft configurations:
 1- Lifting body
 2- Wing body
 3- Blended wing body
3

How many propulsive phases are forecast ? **2**

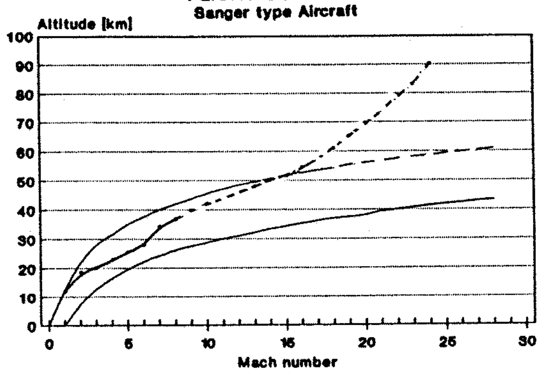
Mach number at the end of the first phase ? **2.5**
Kind of propulsion working during the first phase ? **TURBOJET**

Mach number at the end of the second phase ? **6.5**
Kind of propulsion working during the second phase ? **RAMJET**

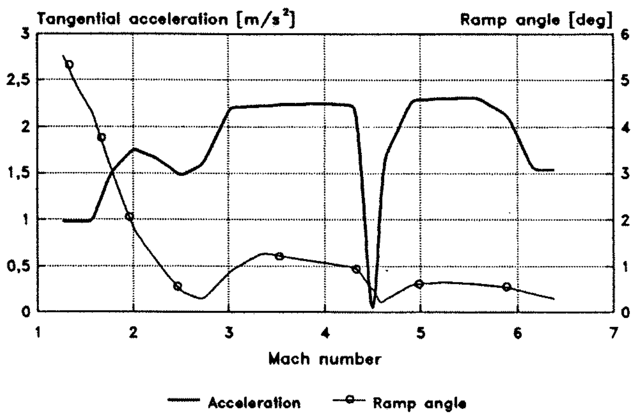
Maximum thrust of the turbojet engine (N) ? **383440**
Number of turboramjet engines ? **6**

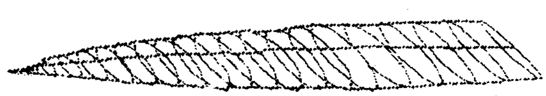
Body wing location: low (1) or mid (2) ? **2**
Is there the horizontal tail (Y/N) ? **N**
Is the vertical tail canard (1) or normal (2) ? **2**
Vertical tail location: wingtip (1) on the body (2) ? **1**
Vertical tail single (1) or double (2) ? **2**

FLIGHT CORRIDOR
Sanger type Aircraft

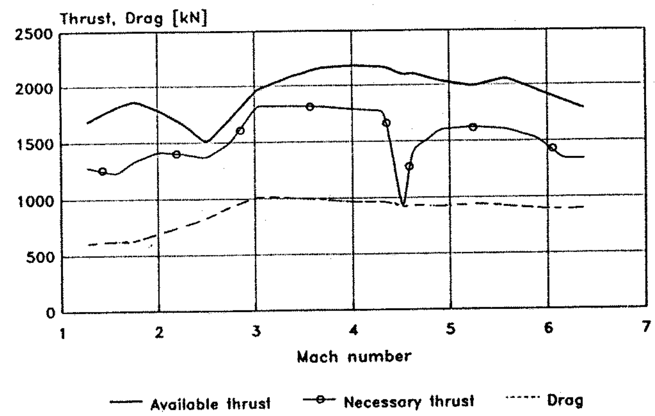


SANGER TYPE MISSION
Acceleration & Ramp angle vs Mach





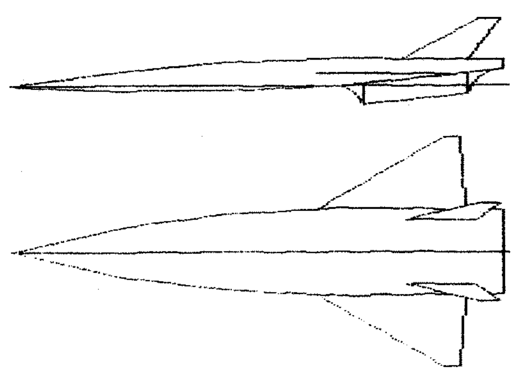
SANGER TYPE MISSION
Thrust & Drag vs Mach



FIRST STAGE

AIRCRAFT COMPONENTS WEIGHT LIST

Wing	= 270810 N
Tail unit	= 33716 N
Body	= 361612 N
Tank	= 6157 N
Thermal protection system	= 116839 N
Landing gear	= 84851 N
Surface controls	= 12255 N
Hydraulic system	= 17189 N
Elecrical system	= 23814 N
Avionics	= 19471 N
Environment conditioning system	= 15299 N
AiRFRAME WEIGHT	= 789164 N
GENERAL SYSTEMS WEIGHT	= 172879 N
EMPTY WEIGHT (without engines)	= 962043 N
Engines	= 305799 N
EMPTY WEIGHT	= 1267842 N
FUEL WEIGHT	= 1047016 N
PAYLOAD (Second stage)	= 906249 N
TOTAL WEIGHT	**= 3221107 N**



OUTPUT DATA

AIRCRAFT IDENTIFICATION NAME: FIRST STAGE SANGER type

Wing leading edge sweep-back = 60.8 deg
Wing area = 1011 m^2
Airfoil thickness at wing/body junction = 1.74 m
Maximum body width = 17.0 m
Body length = 90.0 m

Body internal volume = 2451 m^3
Wing internal volume = 74.0 m^3
Liquid hydrogen volume = 1525 m^3
Field balanced length = 1105 m
Landing length = 1311 m
Turn radius = 934 m

Figure 11: *First Stage of a TSTO*

AIRCRAFT IDENTIFICATION NAME: **SANGER type**

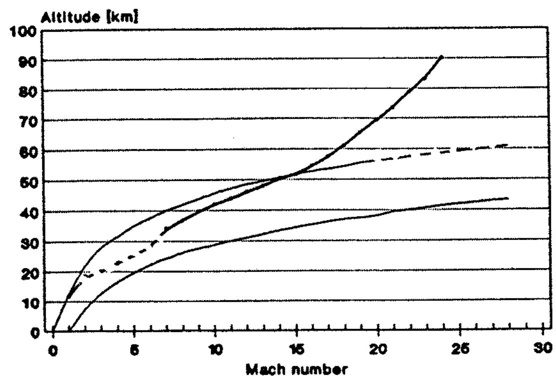
SECOND STAGE DATA INPUT

Maximum separation weight (attempt value in N) ? **853200**
Wing area (attempt value in m^2) ? **160**

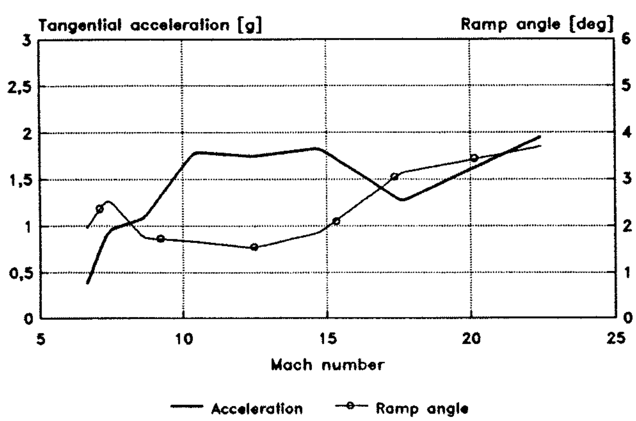
Select one of these rockets for installation: **3**
1- RD-0120 ....: 1962 kN of thrust
2- Vulcain ....: 1120 kN
3- Interim HoToL ....: 883 kN
4- Flat AVIO ....: 600 kN
5- Other
3
Number of rocket ? **2**

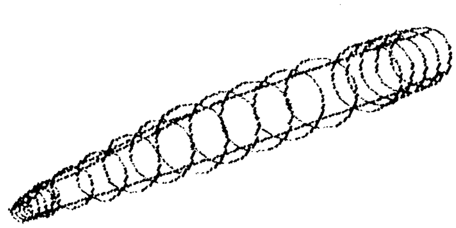
Body wing location: low (1), mid (2) or high (3) ? **2**
Vertical tail location wingtip (1) on the body (2) ? **1**
Payload (expressed in N) ? **69000**

FLIGHT CORRIDOR
Sanger type Aircraft

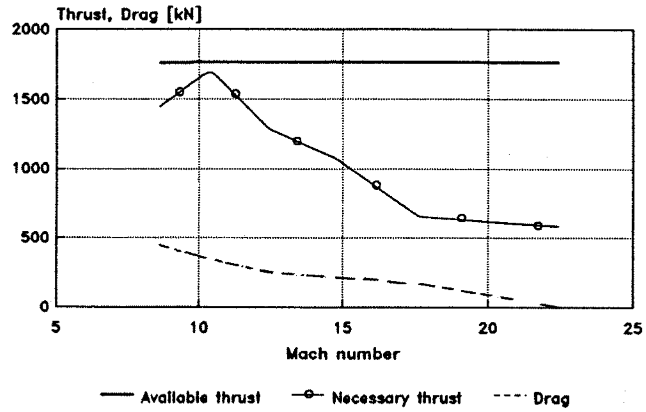


SANGER TYPE MISSION SECOND STAGE
Acceleration & Ramp angle vs Mach





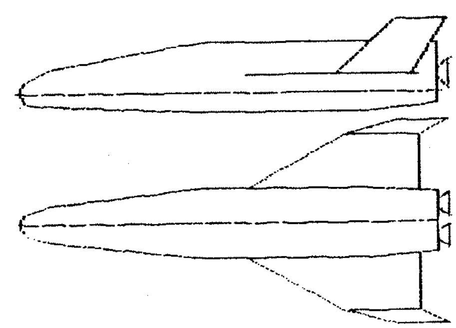
SANGER TYPE MISSION SECOND STAGE
Thrust & Drag vs Mach



SECOND STAGE

AIRCRAFT COMPONENTS WEIGHT LIST

Wing	= 30429 N
Tail unit	= 8361 N
Body	= 47773 N
Tank	= 10487 N
Thermal protection system	= 23704 N
Landing gear	= 5592 N
Surface controls	= 5033 N
Hydraulic system	= 3607 N
Elecrical system	= 12230 N
Avionics	= 10542 N
Environment conditioning system	= 5531 N
AIRFRAME WEIGHT	= 120754 N
GENERAL SYSTEMS WEIGHT	= 42535 N
EMPTY WEIGHT (without engines)	= 163289 N
Engines	= 20495 N
EMPTY WEIGHT	= 183784 N
FUEL WEIGHT	= 653465 N
PAYLOAD	= 69000 N
TOTAL WEIGHT	**= 906249 N**



OUTPUT DATA

AIRCRAFT IDENTIFICATION NAME: SECOND STAGE SANGER type

Wing leading edge sweep-back = 61.1 deg
Wing area = 149 m^2
Airfoil thickness at wing/body junction = 0.69 m
Maximum body width = 5.2 m
Body length = 31.0 m

Body internal volume = 420 m^3
Wing internal volume = 7.0 m^3
Liquid oxigen volume 47.7 m^3
Liquid hydrogen volume = 129.5 m^3
Landing length = 1535 m
Turn radius = 1762 m

Figure 12: *Second Stage of a TSTO*

AIRCRAFT IDENTIFICATION NAME: **STS-2000 type**

Is the aircraft a Single Stage (1) or a Two Stage (2) ? **1**
Maximum take-off weight (attempt value N) ? **3320000**
Wing area (attempt value m^2) ? **700**

Select one of these aircraft configuration:
1- Lifting body
2- Wing body
3- Blended wing body
3

How many propulsive phases are forecast ? **3**

Mach number at the end of the first phase ? **2.6**
Kind of propulsion working during the first phase ? **TURBOJET**

Mach number at the end of the second phase ? **6.6**
Kind of propulsion working during the second phase ? **RAMJET**

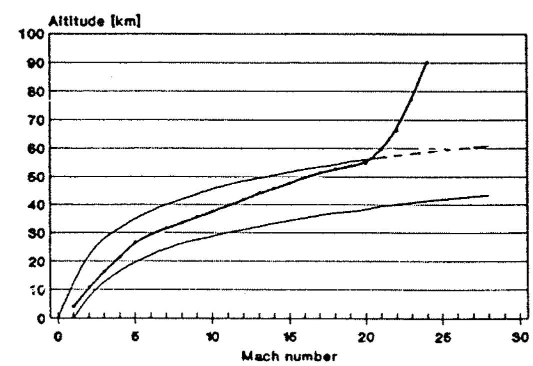
Mach number at the end of the third phase ? **24**
Kind of propulsion working during the third phase ? **ROCKET**

Maximum thrust of the turbojet engine (N) ? **490000**
Number of turboramjet engines ? **4**

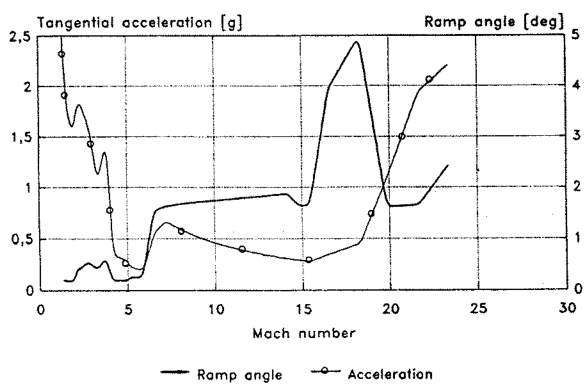
Select one of these rocket installed:
1- RD-0120 ....: 1962 kN of thrust
2- Vulcain ....: 1120 kN
3- Interim HoToL ....: 883 kN
4- Fiat AVIO ....: 600 kN
5- Other
3
Number of rocket ? **4**

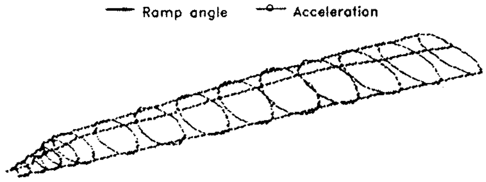
Body wing location: low (1) or mid (2) ? **2**
Is there the horizontal tail (Y/N) ? **N**
Is the vertical tail canard (1) or normal (2) ? **2**
Vertical tail location: wingtip (1) on the body (2) ? **1**
Payload (in Newton) ? **69000**

FLIGHT CORRIDOR
STS-2000 type Aircraft

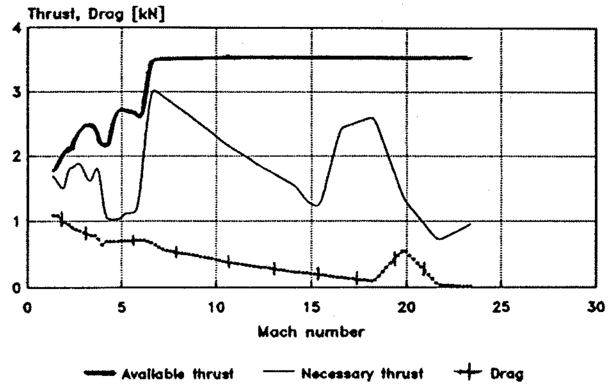


STS–2000 TYPE MISSION
Acceleration & Ramp angle vs Mach



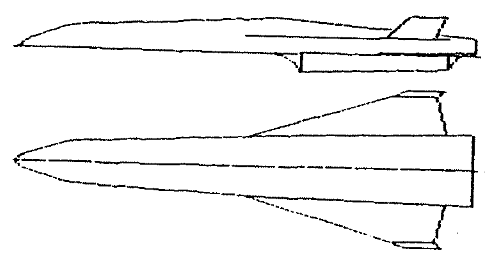


STS–2000 TYPE MISSION
Thrust & Drag vs Mach



AIRCRAFT COMPONENTS WEIGHT LIST

Wing	= 79858 N
Tail unit	= 10243 N
Body	= 182242 N
Tank	= 45078 N
Thermal protection system	= 60996 N
Landing gear	= 18819 N
Surface controls	= 7291 N
Hydraulic system	= 11405 N
Elecrical system	= 17847 N
Avionics	= 14872 N
Environment conditioning system	= 11153 N
AIRFRAME WEIGHT	= 378417 N
GENERAL SYSTEMS WEIGHT	= 81387 N
EMPTY WEIGHT (without engines)	= 459804 N
Engines	= 301689 N
EMPTY WEIGHT	= 761493 N
FUEL WEIGHT	= 2755669 N
PAYLOAD	= 68649 N
TOTAL WEIGHT	**= 3585811 N**



OUTPUT DATA

AIRCRAFT IDENTIFICATION NAME: STS-2000 type

Wing leading edge sweep-back = 73.5 deg
Wing area = 656 m^2
Airfoil thickness at wing/body junction = 1.98 m
Maximum body width = 11.3 m
Body lenght = 73 m

Body internal volume = 1150 m^3
Wing internal volume = 49.6 m^3
Liquid oxigen volume = 180 m^3
Liquid hydrogen volume = 1070 m^3
Payload volume = 50 m^3
Field balanced length = 1340 m
Landing length = 1186 m
Turn radius = 1585 m

Figure 13: *Turbo-Ram-Rocket SSTO*

AIRCRAFT IDENTIFICATION NAME: **SSTO Rocket-Ram-Rocket**

Is the aircraft a Single Stage (1) or a Two Stage (2) ? **1**
Maximum take-off weight (attempt value N) ? **6629000**
Wing area (attempt value m^2) ? **420**

Select one of these aircraft configurations:
1- Lifting body
2- Wing body
3- Blended wing body
2

How many propulsive phases are forecast ? **3**

Mach number at the end of the first phase ? **2.5**
Kind of propulsion working during the first phase ? **ROCKET**

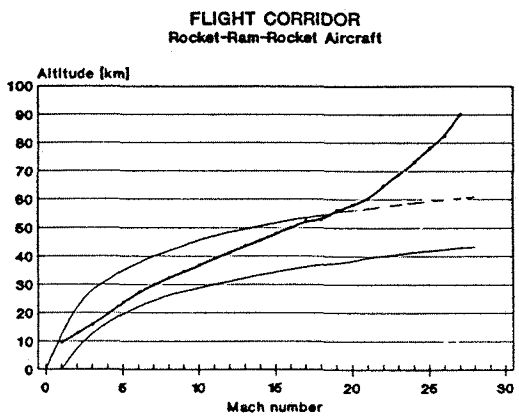
Mach number at the end of the second phase ? **6.5**
Kind of propulsion working during the second phase ? **RAMJET**

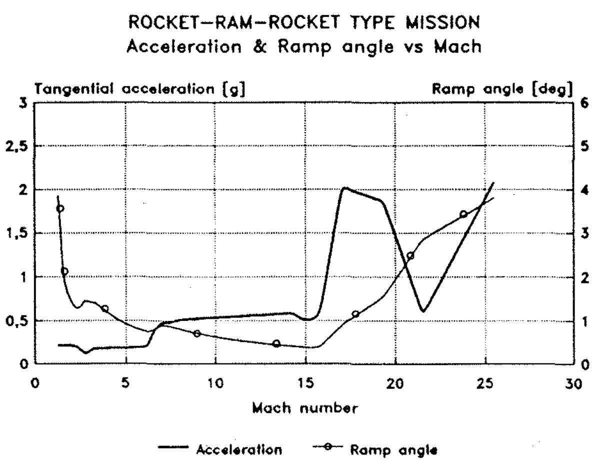
Mach number at the end of the third phase ? **26.8**
Kind of propulsion working during the third phase ? **ROCKET**

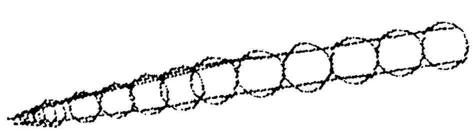
Cross section of ramjet intake (m^2) ? **2**
Number of ramjet engines ? **4**

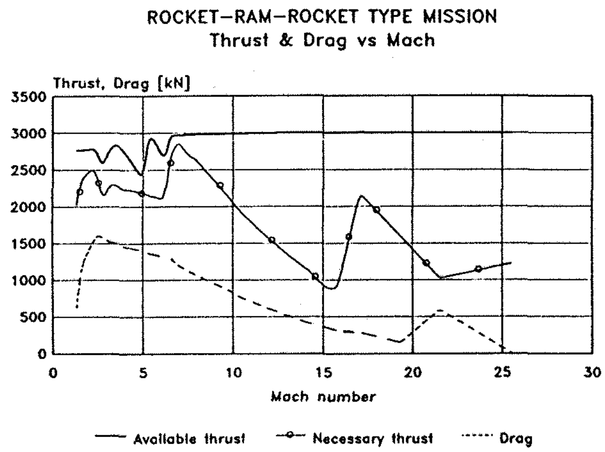
Select one of these rockets for installation:
1- RD-0120 ....: 1962 kN of thrust
2- Vulcain ....: 1120 kN
3- Interim HoToL ....: 883 kN
4- Flat AVIO ....: 600 kN
5- Other
3
Number of rockets ? **6**

Body wing location: low (1), mid (2) or high (3) ? **2**
Is there the horizontal tail (Y/N) ? **N**
Is the vertical tail canard (1) or normal (2) ? **1**
Vertical tail location wingtip (1) on the body (2) ? **1**
Payload (in Newton) ? **69000**



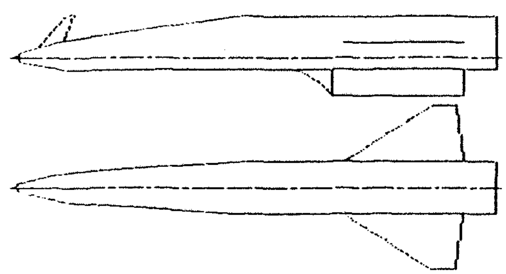






AIRCRAFT COMPONENTS WEIGHT LIST

Wing	= 78077 N
Tail unit	= 2599 N
Body	= 256880 N
Tank	= 67837 N
Thermal protection system	= 47697 N
Landing gear	= 12640 N
Surface controls	= 6575 N
Hydraulic system	= 7233 N
Elecrical system	= 19196 N
Avionics	= 15912 N
Environment conditioning system	= 12187 N
AIRFRAME WEIGHT	= 453090 N
GENERAL SYSTEMS WEIGHT	= 73743 N
EMPTY WEIGHT (without engines)	= 526833 N
Engines	= 73642 N
EMPTY WEIGHT	= 600475 N
FUEL WEIGHT	= 5403533 N
PAYLOAD	= 69000 N
TOTAL WEIGHT	**= 6072657 N**



OUTPUT DATA

AIRCRAFT IDENTIFICATION NAME: SSTO Rocket-Ram-Rocket

Wing leading edge sweep-back = 57.7 deg
Wing area = 408 m^2
Airfoil thickness at wing/body junction = 1.08 m
Maximum body width = 8.40 m
Body length = 77.6 m

Body internal volume = 1271 m^3
Wing internal volume = 27.0 m^3
Liquid oxigen volume = 373 m^3
Liquid hydrogen volume = 1011 m^3
Field balanced length = 3580 m
Landing length = 1580 m
Turn radius = 4315 m

Figure 14: *Rocket-Ram-Rocket SSTO*