ANNIVERSARY ADDRESS—1979

LIMITS AND LIMITATIONS*

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THE purpose of Defence Research is to keep the capability of the fighting forces at the highest level with the use of modern science and technology. This requires a cadre of well-informed and able scientists who are able to appreciate the value of the latest discoveries of science and new developments in technology to be of relevance to the defence effort and be in a position to translate these new developments to make it a viable tool for creating either new types of defence weapons or upgrade the existing ones to a higher quality. In a way it is fortunate that the laws of physics, chemistry and science in general set a limit to what is possible in this regard and one can, therefore, in principle be guided by these laws as to the limits of such possible developments. It is only after considering these limits, one can talk of the limitations of what is actually achievable as a result of financial, logistic and other constraints. In this lecture, I propose to bring to your attention a few of the scientific constraints which will restrict development of weapon system from more basic considerations. For this purpose, it is necessary to appreciate what a modern defence effiort requires. In spite of the risk of being very sketchy and naive, I shall state the following facts :

An army should have a tank having sufficient power to give it manoeuvrability in the relevant fighting conditions. It should have a sufficient number of modern effective armaments of the desired power which is a common requirement for any other fighting system such as warships, submarines, aircraft and mobile vehicles. The type of armaments would consist of guns and mortars of various categories and fire, power, torpedoes, missiles, etc., and most of them will have to be controlled by electronic devices. Since tank manoeuvres are a nocturnal operation, modern night vision using infrared to visible light converters is essential.

Our defence effort should include a strong navy especially because of the large coast line. A strong navy implies effective working groups in naval design, design of submarines, study of the problems of corrosion in sea water, detection of other naval aircraft in the vicinity and communication between vessels. The growing application of electronics to warfare calls for a strong group in naval electronics which I shall call navionics.

Modern warfare depends very much on the appropriate aircraft for specific combat operations; be it for an activity deep inside another country for supporting army manoeuvres or even for mere transport. Aircraft design involves a tremendous appreciation of aerodynamics and allied problems. It also implies the development of reliable engines, which I could say is the heart of an aircraft. The aircraft must have the necessary weapons which can be set into operation swiftly as the time involved in such operations is of the order of a fraction of a second. As aircraft has a large

*Presidential Address : Hyderabad, January 1979.

obsolescence rate, it must be supported by a strong R & D group which helps to improve constantly the existing design. It may advise even completely rejecting a previous design and the starting of a new one. Because of the high maintenance cost of an aircraft, simulation for training is a vital part of any air R & D activity. The development of pilotless aircraft as targets to test systems would also be part of such a programme.

No defence is possible without a highly sophisticated communication system, be it for the detection of enemy aircraft, for communication with other sea going vessels or aircraft for just plain communication required in army manoeuvres. Electronics has progressed enormously in the last few years and has changed the whole concept of communication. One of the important needs in warfare is the identification of an enemy or friend either in the air or on the ground and electronics has done much to solve this vital problem. The coming of satellites has added an entirely new dimension to defence communication, and surveillance.

Wars are unfortunately fought by human beings and as such the study of the limits of human endurance plays an important part in the work of Defence R & D. The psychological and physiological behaviour of personnel either deep in a submarine or high up in the air travelling at a speed much faster than sound requires a greater study especially in Indian conditions and sociological background.

There are several other problems in a defence effort such as the development of various materials, e.g., chemicals, plastics, etc., preservation of food, the behaviour of snow avalanches especially in the border areas and so on. The list given here is a small one selected from a very large number and I mention these in passing purely for the sake of giving you an idea of wide variety of disciplines involved.

Material Development

The greatest importance in any R & D effort in defence is the development of new materials particularly of metallurgical value. It is required as armour of a tank, as various components of a ship or structural material of the aircraft where it undergoes tremendous stresses and strains in flight. In all this, the search for new alloys will go on. This search is an exciting field, since in recent years great advances have been made in the understanding of solid state structure. We can even say that now a days alloys can be tailor-made to any particular requirement. However, the elastic and plastic behaviour of materials and alloys finally set a limit to this. The engineering behaviour of any materials appropriately described by a characteristic stress-strain relation and the corresponding stress-strain curve, which possesses many limiting points, each limiting point describing a different behaviour of the material. A typical stress-strain curve will appear as Fig. 1.

Here point P represents the limit of the linear behaviour of the material. Within this limit, if the load is withdrawn from the material, it recovers to its original shape.

Beyond P, the curve bends to another limiting point Y which represents the yield-point stress. At this stage the plastic flow sets in. Hereafter, any unloading and reloading will have different values for the yield limits. The upper limit of these yield points is denoted by U, the ultimate stress. The material cannot stand loading beyond this limit. Point B corresponds to the post effects of creep etc., where the fracture takes place.

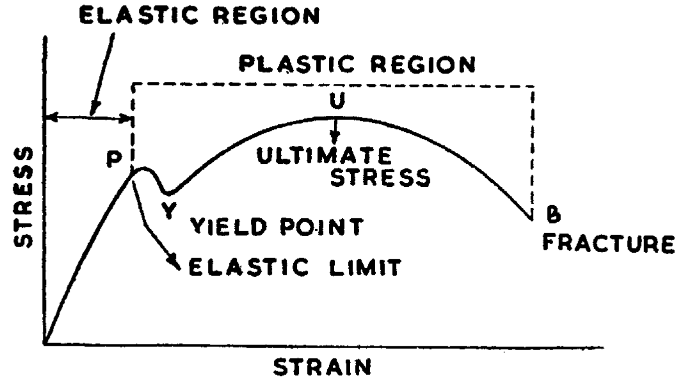

FIG. 1. A typical stress-strain curve.

As another example of the limit set to materials by purely physical considerations, we consider the case of fracture of an armour plate of a tank. It is known that fracture by spalling or scabbing takes place in an armour plate when a reflection of an induced compressional wave leads to intense tensile stresses.

In a simple model loading of a plate by an explosive pulse $p \exp(-\sigma t)$ over an area of a circle with radius a and plate thickness h, we obtain an approximation to the scab surface by finding the locus of the points at which the principal stress

$$S_1 = -\Sigma, \text{ the tensile limit.}$$

In an accurate evaluation this locus takes the form

$$(\Sigma / P) = 1 - \exp\left\{-\frac{2\sigma}{c_1}(h - z)\right\} - \text{edge wave contributions}$$

$$(c_1 = \text{velocity of compressional wave}),$$

where the last term will be a function of both the cylindrical coordinates r and z. The following figures show the relevant schematic results (Figs. 2, 3a, b & 4) :

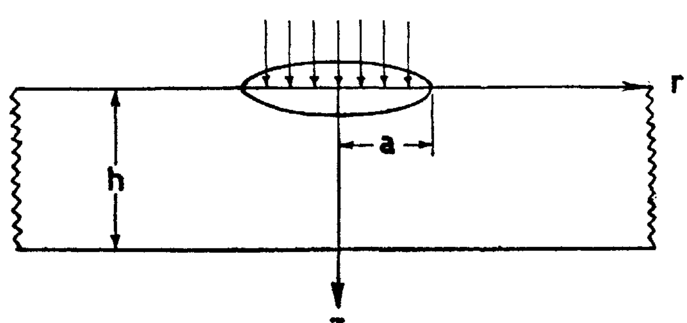

FIG. 2. Loading.

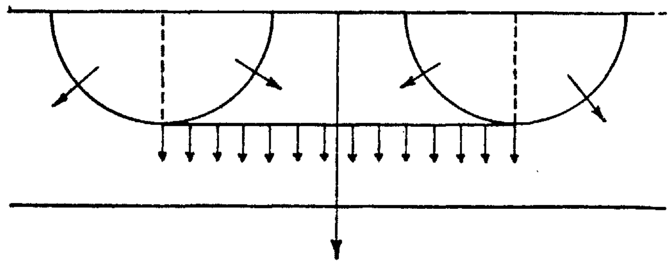

FIG. 3 (*a*). Progress of wavefronts before reflection.

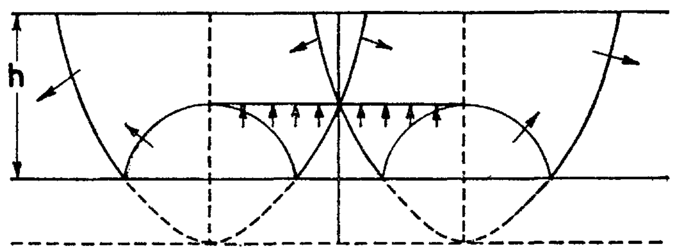

FIG. 3 (*b*). Progress of wavefronts after reflection.

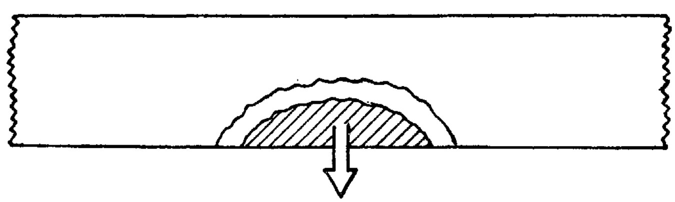

FIG. 4. A typical scab.

Calculations for a material and loading governed by

$P = 3\,\Sigma$, $a = 4$ inches, $h = 3$ inches, $\rho = 0.283/\text{lb/in}^3$,
$c_1 = 19500$ ft/sec, $c_2 = 10200$ ft/sec and $\Sigma = 56800$ psi

with σ so chosen that the maximum height of the scab is given to be say 0.75 inch which means that

$$-\frac{c_1}{2\sigma}\log\left(1-\frac{\Sigma}{P}\right) = 0.75.$$

We obtain for the primary scab the parameters :

Mass of scab = 3.5 lbs.

Velocity = 263 ft/sec.

These are reasonable figures compared with observation.

Armaments

In recent years, new developments in the field of armaments have been in the fields of rockets and missiles. I do not refer to the various developments in the more conventional armaments for lack of time. Now a days, practically all types of weapon carriers are equipped with rockets or missiles—be they guided or otherwise. The missile could be from surface-to-surface, surface-to-air, air-to-surface or air-to-air.

The five major components of any missile are airframe, propulsion system, guidance and control, warhead and power supply, each of which can be developed only within certain scientific limits and limitations. The scientific limits play an important role in the overall design of the missile system. Since the performance characteristics of the various components of the missile system are mutually interdependent, the limits and limitations of each component are further enhanced when they are developed into an integrated system. For example, the size of the guidance equipment affects the size of the airframe. Increased airframe size results is greater weight and drag, which in turn raises the thrust, weight and size of the propulsion unit and further increases the gross weight. But greater gross weight demands larger aerodynamic forces so that the required manoeuvrability may be maintained. Greater aerodynamic forces are obtained by increasing the size of the wings, thus further increasing the gross weight. This expanding process will continue until some compromise is achieved; but a satisfactory solution is not likely to be reached unless the limitations on the various characteristics of each pertinent component are studied separately and jointly.

Besides these scientific limits, the military requirement of the missile system also sets an upper and a lower limit on its design parameters. The upper and the lower limits are the 'desired level' and the 'minimum acceptable level' of performance. The desired level represents the best estimate of what the military planners believe is necessary to achieve unquestioned military superiority in a given area of interest whereas the minimum acceptable level represents a capability which military planners believe is still useful enough to justify the weapon system cost.

The military and the scientific requirements of a missile system set the limits on its various design parameters such as its effectiveness as a weapon, manoeuvrability, firing rate, reliability, missile size and weight, combustion characteristics of the propulsion system, cost, safety, etc. To illustrate on this point, I cite a few examples for the limits on the combustion characteristics of a solid propellant rocket.

There are some special combustion properties which sometimes impose major limitations on rocket design. Such characteristics as the combustion limit, pressure limit and temperature limits are considered below :

(*i*) *Combustion Limit :* If a number of rockets identical except for the exhaust nozzle throat diameter are fired, a graph such as the following can be plotted showing the chamber pressure as a function of the throat diameter. It is found, as might be expected, that the pressure decreases as the throat diameter increases. However, when a certain throat diameter is exceeded, the chamber pressure is found to be far below the pressure predicted from an extrapolation of the high pressure portion of the curve. The pressure corresponding to this critical diameter is called the combustion limit.

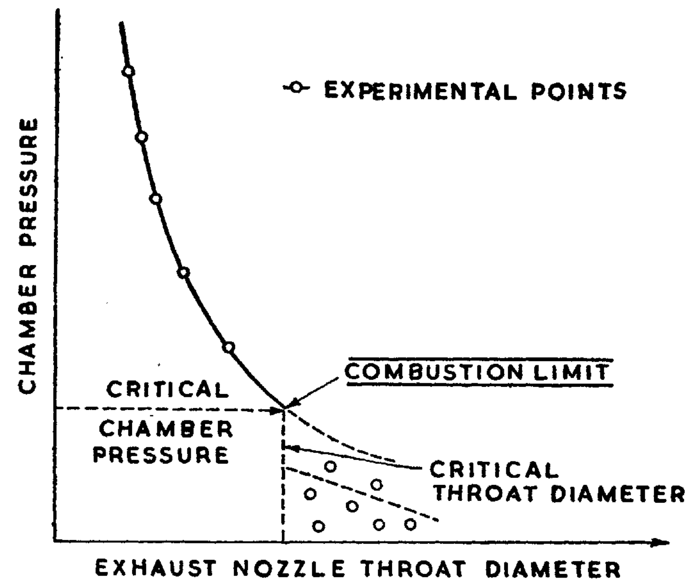

FIG. 5

Thus it appears that a given propellant cannot be used at an arbitrarily low pressure above the combustion limit if reproducible performance from unit to unit is to be obtained. When low overall rocket weight is desirable a high combustion limit is a serious disadvantage, since the weight of the walls of the combustion chamber is essentially proportional to its volume and to the design chamber pressure.

The combustion limit of some extruded double base propellants is about 500 lb/in^2; that of cast asphalt-potassium perchlorate propellants about 1000 lb/in^2. The composite propellants have a combustion limit not exceeding 100 lb/in^2. The combustion limit of the straight nitrocellulose propellants frequently used in guns exceeds 5000 lb/in^2. Therefore, N.C. propellants are not suitable for rockets.

(*ii*) *Pressure Limit :* Some propellants may safely be used only below a critical chamber pressure, this pressure being called the pressure limit. If the pressure limit is exceeded, the propellant burns in a violent and unpredictable manner. Brittle propellants with a granular structure are particularly subject to this effect. For most of the commonly used rocket propellants, the pressure limit exceeds 5000 lb/in^2 and therefore, does not constitute a problem in rocket unit design.

It is observed that, when the pressure in a rocket motor decreases below a certain critical value, the chamber pressure may fall suddenly to atmospheric and the charge ceases to burn. At times, however, the charge reignites after a delay lasting from a fraction of a second to many seconds and a new period of normal burning follows. This cycle may be repeated a number of times, leading to a series of explosions or 'chuffs.'

(*iii*) *Temperature Limits* : Special limitations on the temperature range within which a rocket may be used are sometimes introduced by a change of mechanical properties of the propellant with temperature. Certain types of propellants, those having thermoplastic fuels, may soften and deform sufficiently when stored at high temperature so that an abnormally large burning area is exposed. Upon ignition, the resulting high chamber pressure may cause failure of the unit. Some double-base propellants may soften sufficiently at high temperatures so that the large pressure gradient along the charge which is present in radial burning units, may cause the charge to break up, exposing a large burning area, leading to failure of the unit. At sufficiently low temperatures, some propellants may become so brittle that they shatter upon ignition of the charge. The large burning area exposed in a failure of this kind may lead to a violent explosion. Improvement of temperature limits is a continuing task in propellant development.

Besides these limits, there are various others which are required to be set for a stable burning of the propellant. These limits are due to erosive burning, resonant burning, etc. If these limits are not observed, the propellant burning either stops, thus causing a rocket failure or the rocket blows off. It is not possible to consider these topics here because of their specialized nature.

AIRCRAFT

The aircraft, considered as a rigid body flying through the airspace, moves along paths that are determined by the aircraft's inertia characteristics, the attraction from the earth's gravitational field, the propulsive forces generated by its power plant, and the aerodynamic forces and moments created on it because of the reaction between it and the air through which it moves. The forces and moments created on the aircraft are functions of the velocity of the aircraft, density of the air through which it flies, the geometry of the aircraft and finally the angle that the relative wind makes with the aircraft.

The paths along which the aircraft can fly in the airspace are limited by the aerodynamic characteristics of the aircraft, its propulsive system and the structural strength of the airframe. These limitations indicate the maximum performance and manoeuvrability of the aircraft. If the aircraft is to realize maximum utilities, it must be safely controllable by the pilot to these limits without exceeding his strength and without requiring acrobatic abilities on his part.

If the aircraft is to fly steadily along any arbitrary flight path within its aerodynamic or strength limitations, the forces acting on it must be in static equilibrium if the path is a straight one and in dynamic equilibrium if the flight path is curved or accelerated in any way. The four fundamental forces controlling the equilibrium of the aircraft are the weight, lift, drag and thrust.

For the given shape, size and velocity of the airplane and the given properties of surrounding air (density, viscosity, elasticity and turbulence), there is an upper limit on the lift and a lower limit on the drag. Similarly, for a given propulsive system and its efficiency there is an upper limit on the maximum thrust, that can be attained. The efficiency of the propulsive system, of course sets an upper limit on the thrust, produced per unit of fuel consumption. The limits on the lift, drag and thrust forces in turn set the limits on the speed, rate of climb, time to climb, range and take-off of the airplane. I shall now touch upon some of the limits which a designer comes across in the study of the dynamics of an aircraft.

For the level flight of an aircraft, the weight has to be balanced by the lift. The lift is dependent upon the velocity; therefore, there is a minimum speed that the aircraft must have before it can take-off. This minimum speed demands long runways. Since long runways cannot be provided for many missions particularly in defence, the problem has been tackled in two different ways. Firstly, helicopters were invented where the lift is provided by the propellar itself. But these propellars cannot provide too much power because of the aerodynamic limitations and hence the speed of a helicopter is limited. The other method for short runways led to the development of STOL (Short take-off and landing), VTOL (Vertical take-off and landing) and JATO (Jet assisted take-off) types of aircrafts.

When the aircraft manoeuvres, the centrifugal forces, so set up, put an extra load on the aircraft structure. For tighter turns, therefore, the aircraft structure has to be stronger. The strength of the structure of any particular aircraft, therefore, sets an upper limit for the manoeuvrability of the aircraft. Further, the tighter turns will put extra loads on the pilot also. Therefore, the physical capability of a pilot to withstand such loads sets an upper limit to the manoeuvrability of the aircraft and lead to the development of Anti *g* suits.

Aircraft engine depends upon the airsupply for its working. As we go higher, the air becomes rarer setting a ceiling hight to the proper functioning of any aircraft engine. Thus, there is a limit of height to which any aircraft can go. Besides this, since the fuel capacity of any aircraft is limited, the total distance which may be covered by the aircraft or the total number of flying hours without refuelling get restricted.

Communications

The two most important defence communication systems are a Radar and a Sonar which respectively use the radio waves and the sound waves as the means of communication. The ultimate limits on the communication speeds of radar and sonar are set by the speeds of radio waves, velocity of light and sound waves respectively. It is almost impossible to achieve these limits because of several other important constraints. In weapon system, a radar or a sonar works in combination with other system elements such as human operators, the carrying vehicle (ship, aircraft or missile) and its associated propulsion, navigation, armament, flight control, support and data processing systems. The limitations of these system components, in fact, determine the limits of achievable communication speeds.

The operational requirements and the technical feasibility of a communication system (radar or sonar) will set the limits on such specifications as its range, coverage angle, information accuracy, system reliability, information handling, transfer and display, etc.

An idea about some of the limits can be obtained from the case of radar system sampling frequencies (transmitted bandwidth, transmission periodicity and angular scanning frequency) which set limits on the resolution element size and the total unambiguous measurement interval of each coordinate—range, angles and velocities.

For example, the transmitted bandwidth, which determines the rate at which radar system can collect pieces of range information, sets a lower limit on the width of the range resolution element of the radar. The transmission periodicity, which is defined as the fundamental repetition frequency of the radar signal, puts upper limits on the unambiguous range interval, unambiguous relative velocity interval and the scanning frequency. The angular scanning freqency, which defines the minimum signal bandwidth puts a lower limit on the velocity resolution element.

One of the most formidable limitations to the usefulness of a radar is imposed by 'clutter'. Often a radar system sees too much, rather than too little; the picture is confused by unwanted echoes, or clutter. This can be made up of echoes from surrounding objects on the ground like hills, trees and buildings or echoes from the irregular surface of the sea or even of echoes from storm clouds. It is this limitation of radar which makes it difficult to track a low flying plane. Though this limitation is partially removed by doppler detection systems, the clutter problem is not eliminated completely. The reason is that the doppler system is effectively applicable only to moving targets, and then only when the unwanted echoes from surroundings do not fluctuate so rapidly as to defeat the pulse-to-pulse comparision which is an essential part of the scheme. Another limitation of the doppler system is set by target manoeuvres, which cause a shift in the doppler spectrum. This shift in doppler spectrum causes the signal to be greatly attenuated if the target doppler transits the filter band-pass range before the filter has time to build up. To avoid this situation one has to set a lower limit on the doppler filter bandwidth which turns out to be $2a^{1/2}/\lambda$ where a is the acceleration and λ the wave length.

Though radar is very effective in air and space communications, its utility as an underwater communication system is severely limited due to the fast absorption of radio waves in water. Because of this limitation of radar, the sonar is mostly used as an underwater communication system.

Human Endurance

I have referred to some of the limits and limitations of technical devices used in defence. Of great interest is the endurance limits of the human element, which depend upon his environment and the biological strain of adaptation to extreme conditions.

Table I

Endurance limits for extreme hot climate

Air temperature (°C) in relation to relative humidity and average human endurance (Normal work cloths, moderate activity, moderate air movement, men acclimatised)

Average endurance (Min)	Relative humidity (%)		
	20	50	100 (saturated)
300	48.5 °C	39.7 °C	32.2 °C
180	52.8	42.3	33.9
60	58.1	45.8	35.9
40	61.1	47.3	36.8
30	66.1	50.0	38.9

TABLE II

Endurance limits under extreme cold climate

(Tolerance time in min. of average Indian soldiers (light activity) in shade)

Clothing + air insulation (Clo units)	Air temperature °C		
	—40	—20	0
4.5 (Arctic clothing)	80	330	—
3.5 (Heavy winter clothing)	45	100	—
2.5 (Ordinary winter clothing)	28	43	174

Man's physical strength and mental activity are at their best only within certain limits of climatic conditions and strains. Beyond these limits, his efficiency lessens, while stresses and the possibility of disease increase.

The major elements of climatic environment which limit human comfort and endurance can be categorized as : air temperature, humidity, air movement and solar

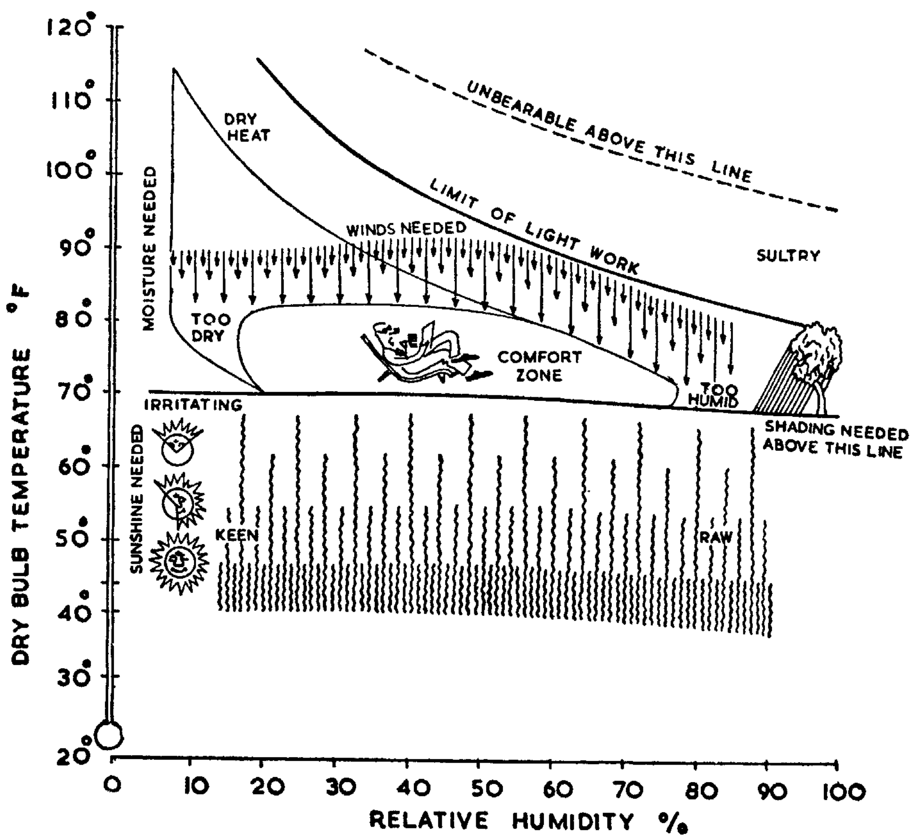

FIG. 6. Schematic bioclimatic index for moderate zone inhabitants.

radiation. The human endurance limits for extreme hot and cold climatic conditions are shown in Tables I and II respectively.

Endurance limits, of course, vary from individual to individual and also depend upon the degree of acclimatization. Schematically it is shown in Fig. 6.

Atmospheric pressure puts another severe limit on human endurance. Since atmospheric pressure varies with altitude, there are limits to the altitude at which exertion such as climbing can occur and there are limits to which a person may be safely carried without his exertion. As for example, slight anoxia symptoms may

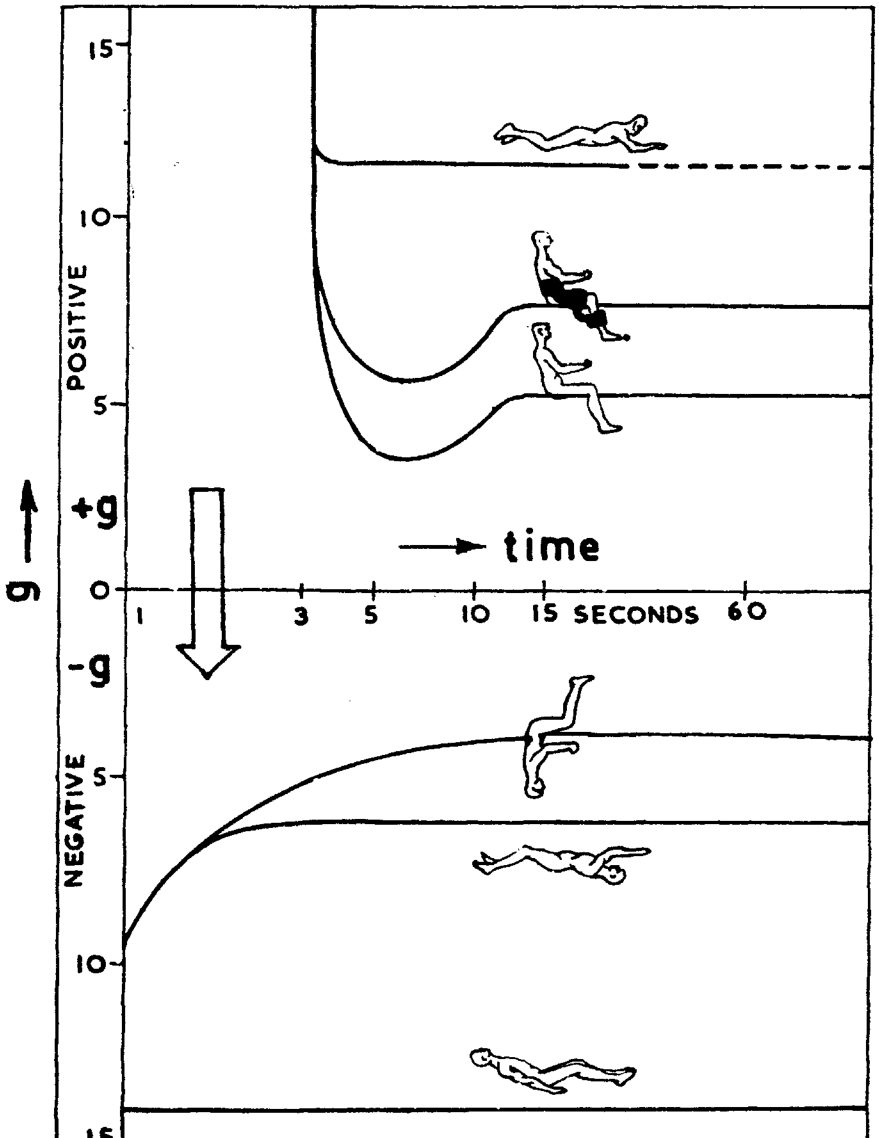

FIG. 7. Time-g tolerance for postures in negative and positive acceleration.

appear at about 8000 ft. The peril of oxygen lack first arises between 10,000 and 20,000 ft. The limit of consciousness while breathing pure oxygen is not known but is not far about 45,000 ft. Though the modern aircraft has pressurised cabins, the above limits become very important under the conditions of war where the aircraft may be damaged and decompressurised or the pilot has to eject himself from a falling aircraft.

High speeds as such, as encountered in supersonic aircraft, space vehicles, etc., do not pose any problem for human endurance, so long as the velocity remains constant. However pilot's endurance is very much limited when his aircraft is accelerating, decelerating, turning or manoeuvring. In such situations, he encounters acceleration stress which may affect his endurance even if it lasts for a second or so. These acceleration stresses are usually referred to as g-limits which may be positive or negative. The terms positive and negative g are used respectively to designate whether the force is acting from head to foot or from foot to head.

Apart from the sensation of increased weight, the earliest effect of positive acceleration are related to vision. A generalised veiling with apparent loss of contrast leads to a progressive impairment in the extent of the visual field. Higher accelerations above about 4 g produce further narrowing of the field until central vision is also lost, a state known as 'black out'. With further increase in the acceleration by 0.5 to 1 g, consciousness is also lost. The time-g endurance for postures in negative and positive acceleration are shown in Fig. 7.

I have dealt on a few problems of defence, looking at them from the point of view of physical, chemical and biological limits. For obvious reasons, I have not dealt with nuclear weapons as they form a class of ultimate weapons of destruction. Hans Bethe wrote on the problems of the use of anti-ballistic missiles in the *Scientific American* of 1968. I would refer you to this paper for more details.

Defence Science requires the help of all laboratories and industry in the country. For this collaborative effort to be effective, the problems have to be clearly identified. If considered from a point of view of basic limits, there is no question of secrecy or classification and our Raksha Mantri has often stated that a considerable part of defence is unnecessarily classified. With this attitude, it should be possible for more scientists and laboratories to volunteer to play a positive role in the indigenous design and development of defence equipment for the country. This would be a great contribution to the Nation and a more economic way of looking at the defence effort.