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The Economic Effects of Meteorological Forecasting Standards for Supersonic Civil Transports

by

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THE ECONOMIC EFFECTS OF METEOROLOGICAL FORECASTING STANDARDS FOR SUPERSONIC CIVIL TRANSPORTS

by
A. L. Courtney

SUMMARY

As an aid to discussions on the future provision of meteorological forecasting services for civil transport operations, an approximate assessment is made of the effects of changes in the accuracy with which en-route and take-off winds and temperatures can be forecast. The results are given in terms of the annual value calculated over the world total of long-range civil operations, first for a current subsonic fleet equivalent to about 350 Boeing 707's and then for a possible supersonic fleet equivalent to about 4.00 Concords, such as might be in operation in 1980-1985.

It is found that in current long-range subsonic operations the accurate forecasting of en-route winds is the most important item. In future supersonic operations, however, the most important item is likely to be the accurate fore-casting of en-route temperature, wind being of comparatively minor importance. Accuracy in forecasting the airfield temperature for take-off is also likely to be important for supersonic transports.

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* Replaces R.A.E. Technical Report 66297 - A.R.C. 28747

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1 INTRODUCTION

Recent discussions on the requirements for meteorological forecasting for supersonic transports have underlined the need for some form of economic yardstick against which possible improvements or shortcomings in forecasting accuracy may be judged. This Report attempts to provide such a yardstick, using characteristics similar to those of Concord for the supersonic aircraft and cross-referencing against an aircraft such as the Boeing 707 in order to illustrate changes in emphasis or values compared with the existing subsonic situation. Since the object is only to give a broad indication of relative sensitivities, fairly rough assumptions have been made, and the results should therefore not be used for other purposes such as aircraft performance assessments.

It should be noted that the economic evaluation given here is concerned only with the effects of errors in forecasting mean winds and temperatures over complete flights. There are of course other aspects of meteorology, including for instance the ability to forecast or detect extremes of wind and temperature, thunderstorm activity, high-altitude turbulence, hail, icing etc., which are not dealt with here but which have an important bearing on flight planning and safety and are obviously of considerable value.

2 GENERAL PHILOSOPHY

2.1 En-route winds and temperatures

Pre-flight forecasts of en-route winds and temperatures affect the amount of fuel which the operator loads in order to achieve a desired overall frequency of arrival at destination with enough fuel remaining to execute a last-minute diversion should this prove necessary. Because of differences between the forecast en-route conditions and those actually experienced on each flight, the fuel remaining at destination will of course vary from flight to flight. The fuel remaining also varies from other causes, e.g. variability of aircraft and engine performance, ATC track variations, navigational errors, variation of cruise speed, holding time above destination etc. The statistical combination of these variabilities yields a relationship between what has been termed the "sector" fuel reserve (that part of the total which is needed for en-route contingencies plus destination hold) and the "destination regularity", i.e. the proportion of occasions, typically around 99%, on which an aircraft can be expected to arrive at destination without having eaten into the other part of its fuel reserve, the "terminal" or "diversion" reserve. Typical curves of the sector fuel reserve* versus destination regularity (or more strictly, the percentage of arrivals at destination with more than a given amount of fuel) are shown in Fig.1 for a Mach 2 SST and far a subsonic jet on the London-New York route. The effect of en-route forecasting errors is to increase the sector reserve fuel that needs to be carried in order to achieve the desired destination regularity. The size of the increase has to be determined statistically by combining the various chances of encountering different levels of en-route contingencies, with and without the variability due to meteorological forecasting errors, and then taking the difference in total sector reserve at equal regularity. It may be noted in passing that this process considerably reduces the effect of any given variability compared with what might be expected from looking, for instance, simply at the "1 in 10^n" forecast error. This is because, in the absence of bins, forecast errors are as likely to be favourable as unfavourable, and it is important to keep this in mind. The statistical process takes account of <u>all</u> the chances of meteorological errors, favourable and unfavourable, in combination with all the other contingencies. Simply to look at the unfavourable half of one distribution on its own, deducing that there is a "1 in 1000 chance of requiring perhaps 5000 lb more fuel", can give a completely misleading impression of the importance of this contingency.

In addition to the effect on reserve fuel, a further factor which could conceivably affect the issue is that on some sectors, at some seasons of the year, the payload on a proportion of flights might be restricted by the aircraft performance capabilities relative to the sector distance and the field length available. Operators deal with this problem by writing their aircraft performance requirements in terms of the payload to be carried on all but, e.g., 15% of flights during each season, i.e. in terms of the "85% day", and basing their bookings on this. Current long-range subsonic jets are virtually limit-free on most sectors so far as passenger payload is concerned (since on most flights they carry freight as well, which serves as a "buffer"), so at present the problem hardly arises. Supersonic aircraft, at any rate in the first generation, are likely to be more critical, and on some proportion of the 15% of flights not covered by the performance and operating specification the payload booked will exceed that which can be carried under normal flight-planning rules. On such occasions an adverse error in meteorological forecasting could in principle result in passengers having to be off-loaded. Equally, of course, a favourable error could lend to additional

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*At take-off, i.e. including the fuel required to carry it to the point at which it is used.

passengers being loaded from the wait-list , if there happened. to be one for that flight. The nett effect, however, <u>if</u> off-loading of booked payload were practised in commercial operations, would be a loss of revenue on critical flights, and this penalty would be *additional to* that due to the increase of fuel reserve on all flights discussed above.

The effects of forecast errors or other adverse contingencies are sometimes expressed in these terms, giving a somewhat dramatic answer. In commercial practice, however, it seems likely that on SST's, as on current aircraft, the off-loading of booked payload due to adverse meteorological forecasts just before take-off will be a very rare occurrence and should not be taken into account in assessing the economic effects of forecasting accuracy. The operators' working rule is likely to be that if payload has been booked and presents itself, it will be 'carried. The means available to allow the payload to be carried is of course to modify the flight plan if the forecast happens to be adverse on the day. Instead of planning direct to New York, for instance, the flight would be planned to Boston, or even Gander in an extreme case. On most such flights the fuel state on approaching Boston will be such as to allow the aircraft to be re-cleared in safety to New York, but on a proportion of them, when the adverse forecast materialises or is exceeded, and the other en-route contingencies including forecast holding time at New York also combine in an adverse direction, the pilot will have to land at Boston to refuel. In affect, relative <u>*to* its real destination</u> (New York) the aircraft is despatched with reduced fuel reserves and has a potentially reduced destination regularity (while of course maintaining adequate safety reserves at all points en-route). The effect of winds and temperatures more adverse than the level used for booking purposes thus shows itself in practice as a contribution to reduced destination regularity on these critical flights, rather than as a revenue loss due to off-loading of booked payload. It is important to note that this loss of regularity would of course occur even if forecasts were perfect; it is due not to errors in forecasting but simply to the fact that the actual winds and temperatures are sometimes more adverse than the booking level. On this operational approach the effect of wind and temperature <u>errors,</u> on either critical or non-critical flights, is also a loss of destination regularity rather than a loss of payload. The additional reserve fuel needed *to* make up this loss of regularity is of course simply the increase already discussed above. Thus, on the assumption that payload is not off-loaded, no additional allowance needs to be made for the effects of the forecasting errors on critical flights.

2.2 Take-off winds and temperatures

On most flights, with take-off not critical, wind and temperature on the airfield do not affect fuel or payload. On a proportion of occasions, however, airfield conditions (high temperature or variable wind along the runway) will limit the allowable take-off weight to a value less than that needed for carrying the booked payload, the block fuel for the forecast en-route conditions, and the standard fuel reserve. On these occasions, as in para.2.1 above, it will usually be the fuel load rather than the payload which will be reduced (e.g. by adopting re-clearance procedures), giving a reduction in destination regularity on these critical flights. Also as in para 2.1, such a reduction would occur even if take-off conditions could be forecast without any errors, arising simply from the fact that airfield winds and temperatures arc sometimes more adverse than the 85% condition typically used for planning purposes. Compared with this minimum reduction in regularity assuming perfect forecasting, the effect of errors in forecasting the take-off conditions is to introduce an additional variability in the fuel loaded, and therefore an additional variability in the fuel available at destination, leading to a further reduction in destination regularity on critical flights. This is not one of the variabilities allowed for in the curves in Fig.1, and a separate allowance is therefore needed for take-off forecasting errors on the critical flights in question. An obvious way of dealing with this effect is to increase the standard fuel reserve on all flights so that the loss in regularity due to take-off forecasting errors on critical flights is balanced by an increase on the majority of flights. This approach will be followed below.

The main difficulty is in putting a number to the proportion of flights affected by take-off restrictions. If payload booking is based on 85% conditions the proportion is clearly less than 15%. It would be exactly 15% if <u>every</u> high-temperature take-off occurred in conjunction with a full passenger load; in practice, however, load factors will be distributed about a value such as 70%, or perhaps 80% bearing in mind that critical conditions occur mainly in Summer when traffic is heavy. For illustrative purposes, the arbitrary assumption will be made that one-third of the take-offs beyond the 85% scheduling condition, amounting therefore to 5% of total flights, occur in conjunction with a 100% load factor so that the fuel is affected by the error in forecasting. On the other 95% of flights the combination of sector distance,

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*A steady wind along the runway will presumably be turned to advantage by taking-off in the appropriate direction.

en-route conditions, airfield conditions and load factor is assumed to be such that the forecast take-off conditions, and therefore errors in the forecasts, do not affect the total fuel carried.

3 CALCULATION PROCEDURE

The first step is of course to determine the exchange rates between the sector fuel required and the en-route wind and temperature, and between the permissible take-off weight (i.e. loadable fuel) and the airfield temperature and effective wind. This is done, fairly roughly, for a Mach 2 SST similar to Concord, and for a typical subsonic jet, on the London-New York sector.

Given these exchange rates, the standard deviations of errors in forecasting can be directly converted into standard deviations (σ) of the excess or defect of fuel required or available at take-off relative to a correct forecast.

Assuming that the forecasting errors are normally distributed and uncorrelated, these standard deviations of fuel are then combined with the other en-route contingencies noted in pars 2.1 (including destination hold time). Fig.1 shows the statistical sum of those other conditions versus the frequency with which aircraft arrive at destination without having consumed more than this amount of additional fuel (for convenience this is referred to as "destination regularity", although in operational practice this term includes also aircraft which fail to arrive for reasons other than fuel shortage - e.g. airport closure - which are not included in Fig.1).

The basic curves of Fig.1 are markedly non-Gaussian because they include large skew terms, e.g. for destination hold, en-route ATC restrictions etc. The simple process, for Gaussian distributions only, of adding the variances (σ^2) for the forecasting errors to the basic variance of Fig.? to obtain a new total variance, and then reading off at, say the 98% frequency or "2σ" level, therefore gives incorrect results. Instead, the combination process has to be done by direct numerical computation. The result obtained, at about the 98%-99% frequency level, is that for each additional Gaussian distribution with standard deviation σ_i (lb of fuel at take-off), the fuel at take-off must be increased, for equal destination regularity, by

$$\underline{\Delta F_i = 0.0002\,\sigma_i^2 \text{ lb}} \quad .$$

Hence, if errors in the forecast cruise temperature corresponded to a standard deviation of 1000 lb fuel at take-off, for instance, then the increase in fuel for the same regularity would be 200 lb. The cushioning effect of the combination process is thus apparent, as also is the danger in making arbitrary "spot-point" quotations: an S.D. of 1000 lb implies, and might be quoted as, a 1 in 1000 chance of needing as much as 3000 lb of extra fuel; in the event, it turns itself into an increase in fuel of only 200 lb on all flights, with everything else equal.

4 EXCHANGE RATES

The basic exchange rates which have been assumed between wind and temperature and take-off weight for a London-New York flight are as follows:-

Table 1

Basic exchange rates between take-off fuel, wind and temperature

	Change in T.O. fuel (lb)	
	Subsonic	Bach 2 SST
En-route:-		
1 knot mean cruise wind $^{(1)}$	250	100
1°C mean cruise temperature $^{(1)}$	100$^{(3)}$	400-800$^{(2)}$
1 knot climb and descent wind	40	30
1°C climb and descent temperature	-$^{(3)}$	100-200$^{(2)}$
	Change in allowable T.O. weight	
Take-off:-		
1 knot take-off wind	700$^{(4)}$	500$^{(4)}$
1°C take-off temperature	1300	1400

Notes:-

(1) The cruise sensitivities relate to route mean winds and temperatures. A conversion will be necessary, depending on the number of measuring stations along the route and the degree of correlation between them, before the final answers can be expressed in terms of single-point measuring accuracy.

(2) The sensitivity of the SST to en-route temperature depends on the detailed intake and nozzle design, and a range of possible values is therefore used.

(3) For the subsonic aircraft the effect of temperature on climb and descent performance is small; the number quoted for cruise in fact covers the whole of the flight.

(4) The exchange rates for take-off wind already include allowance for the factors applied operationally whereby the advantage of a headwind is decreased and the penalty of a tailwind is increased, i.e. they are the real operational exchange rates against the meteorological office basic forecasts. The numbers used correspond to the more usual headwind case.

5 EFFECTS ON TAKE-OFF FUEL REQUIRED

5.1 En-route wind and temperature errors

The effects of errors in en-route wind and temperature forecasting, using the above exchange rates, are shown in Fig.2. The increases in reserve fuel at take-off, for a given destination regularity, are plotted against the standard deviation of errors in forecasting the route mean winds and temperatures assuming all the variabilities are uncorrelated. Thus, if forecasting accuracy were such as to give an S.D. of 10 knots for the route mean wind error in cruise, the reserve fuel penalty would be 200 lb for the SST and 1000 lb for the subsonic aircraft. The results follow a square law, i.e. if the inaccuracy is doubled (S.D. = 20 knots) the fuel penalty is quadrupled, to 800 lb for the SST and 4000 lb for the subsonic aircraft.

As would be expected, the subsonic aircraft is sensitive to cruise wind and insensitive to temperature, whereas the SST is sensitive to cruise temperature and relatively insensitive to wind. Neither aircraft is sensitive - so far as reserve fuel is concerned - to climb and descent conditions, since only a small proportion of the total fuel is affected. For the SST, however, this statement is subject to some reservation, since in deriving the exchange rates it has been assumed that the aircraft varies its transition procedure to suit higher ambient temperatures. Depending on just how critical the transition phase is, this could mean:

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*London-New York

(a) A reduced angle of climb, maintaining the same Mach number/height relationship, with consequent prolongation of the acceleration phase in time and distance, and/or

(b) A modified Mach number/height relationship at higher temperatures, a given Mach number being achieved at a lower height.

Both these have ramifications on Air Traffic Control problems and sonic bang levels, especially when transition occurs over land. In the present calculations assumption (a) has been used, with fixed engine thrust rating, since this is the only condition for which results are readily available. In practice, however, depending on the severity of the ATC/bang problem, it may be that the transition thrust will be varied with ambient temperature, e.g. by varying the amount or duration of reheat and/or varying the engine rpm, so as to ensure that $M = 1.3$, for instance, is always attained at a certain distance regardless of temperature. The effect of such a technique on the variation of fuel used with temperature has not yet been calculated; compared with the exchange rate used here it could go either way, since on the one hand the engine lb/hr would be increased at high temperatures, while on the other hand the time spent in the inefficient climb and transition phase would be decreased compared with the present assumptions. What is certain is that unless some such procedure can be developed to cope with temperature variations (and, for that matter, with weight variations and piloting variations) considerable flexibility will be needed in ATC handling during the climb and acceleration. These questions require further joint study by the various interests concerned.

Returning to the en-route fuel penalties, Fig.2 indicates the levels of forecasting accuracy that are expected or have been assumed for performance assessment purposes, in order to give some idea of relative scale along the abscissae. For the subsonic aircraft on the North Atlantic, for instance, the M.O.A. Fuel Reserves Working Party, based on work by Durst[1,2] used an S.D. of 12 knots for errors in forecast of route mean wind, and an S.D. of $4\frac{1}{2}$°C for errors in forecast of route mean temperature. For the SST, the Working Party based itself on an equivalent headwind error to represent both wind and temperature errors, since on the North Atlantic there is apparently some correlation between wind and temperature variations at SST altitudes, particularly in Winter. This is inappropriate here, since we wish to consider wind and temperature effects separately. For winds, we use International Geophysical Year data supplied by Mathematics Department, R.A.E. which, with a forecasting factor* of about 0.7 as used by the Reserves W.P., would indicate an S.D. of about 6 knots for errors in route mean forecasts at Concord altitudes on the North Atlantic. For temperature, we use the U.S. Weather Bureau j-year data[3] for 1957-1962 at 80 mb, which on the same basis gives an S.D. of rather less than $1\frac{1}{2}^{\circ}$C for errors in route mean forecasts on the North Atlantic.

Looking at these points on Fig.2, it can be seen that at the assumed levels of forecasting accuracy the Mach 2 SST gets away quite lightly, needing an additional reserve fuel of only 200-400 lb to cover both wind and temperature errors, whereas the subsonic jet needs about 1600 lb, nearly all for wind errors. However, at the higher sensitivity to temperature the SST temperature penalty increases quite sharply, and if the S.D. were 3°C instead of $1\frac{1}{2}^{\circ}$C the reserve fuel penalty would be 1200 lb instead of 300 lb. This point is noted because of suggestions which have been made that an S.D. of only about $1\frac{1}{2}^{\circ}$C for temperature errors is unrealistically low. It may be that such suggestions are based on interpretations of single-point readings rather than overall route means. On the North Atlantic at any rate, the extensive U.S. Weather Bureau data show that although the mean temperature of course varies with time (season) and the single-point measurements vary along the route, nevertheless the rms average, over the year, of the monthly standard deviation of daily route mean temperatures is only about 2°C at Concord altitudes. That is, if <u>no</u> forecasting was undertaken, but flights were instead planned simply on the average route temperature for any particular month, the errors would amount only to an S.D. of 2°C over the year as a whole (more in Winter, less in Summer). We are assuming only about 30% improvement on this for daily forecasting.

It is possible that the North Atlantic is a particularly stable area so far as short-term temperature variability at SST altitudes is concerned, in which case, for world-wide applicability, we should shift our illustrative datum point to the right in Fig.2. The figures given in Ref.4 could perhaps be interpreted in this way. Ref.4 quotes the frequency of occurrence of different route mean temperatures round complete circles of latitude, and at 50°N the standard deviation derived from the quoted frequencies and temperatures is more than twice that for the North Atlantic. This may be due to the fact that widely differing areas of the world are being covered, giving a large point-to-point variation around the complete circle of latitude. This, combined with

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*Factor applied to the monthly S.D. of measured daily values in order to obtain the assumed S.D. of' errors in forecasting.

the possibility that the world-wide readings were not synchronised (the North Atlantic readings were all at 12.00 G.M.T.) would tend to increase the overall variability. In particular areas, e.g. Central Russia, North Pacific, North America, the route mean variability at any given time about the monthly average might be no greater than that found for the North Atlantic. This requires further study: for the time being we simply note that the illustrative points shown in Fig.2 apply strictly to the North Atlantic route only, and that on this route the penalty for the assumed errors in both wind and temperature forecasts at Mach 2 SST altitudes is relatively small compared with that already existing for subsonic aircraft. An attempt will be made in para 6 to turn the curves of Fig.2 into £ per knot or per degree improvement in forecasting accuracy, although it is clear in advance that the answers (proportional to the slopes in Fig.2) will depend markedly on where one thinks one is to begin with.

5.2 Take-off wind and temperature errors

As noted in para 2.2, take-off wind and temperature errors are dealt with here by increasing the fuel reserve on the majority of flights so as to give an improvement in regularity sufficient to offset tho loss on the small proportion of flights which are critical at take-off. The results are given in Fig.3, but since the procedure is less straightforward than for the en-route case it is perhaps worthwhile illustrating the derivation of one of the points in Fig.3.

SST: Effect of an S.D. of 3°C in errors of forecast airfield temperature

S.D. of take-off fuel variation (1400 lb/°C, para 4):	4200 lb
Therefore increase in reserve fuel for the same regularity (0.00028, para 3):	3530 lb
Decrease in regularity on the flights affected due to non-provision of this extra reserve (Fig.1):	2.4%
Assumed proportion of flights affected (para 2.2):	5%
Therefore contribution to overall loss of regularity:	0.12%
Therefore increase in reserve fuel on all flights to recoup this loss (i.e. from 98.8% to 98.92% in Fig.1):	390 lb

The results in Fig.3 show that up to a certain level of inaccuracy (~5 knots S.D. in wind and 2-3°C in temperature) the penalties are fairly small, but beyond this level they increase quite sharply. This is due partly to the operation of the square law noted earlier, but there is an additional effect from the non-linearity of the curves in Fig.1, since we are offsetting losses in regularity on critical flights by improvement on other flights. The answer is also dependent on the assumption (para 2.2) that 5% of take-offs - i.e. one-third of the 15% not covered by planning for the 85% condition - are critical on weight and field-length. For current subsonic jets, which are comparatively limit-free, this assumption (made originally to cover SST's) is probably pessimistic, i.e. the true effect is probably less than that given in Fig.3. For SST's the assumption is little more than a guess, and the true answer must await experience from actual SST operations. It will depend on just how critical SST's turn out to be in relation to the field lengths available at the time, and also of course on the load factors achieved - the higher the mean load factor the greater the proportion of critical take-offs and the greater the need for accuracy in forecasting take-off conditions.

Information on the degree of accuracy achieved in take-off forecasts is somewhat scanty but the points indicated in Fig.3 are thought to represent a reasonable approximation to current standards, i.e. standard deviations of about 4 knots in wind and 2°C in temperature. These figures, like the rest of Fig.3, cf course refer to errors relative to forecasts made at the time of flight planning (fuel loading). The points shown happen to lie on the flat part of the curves in Fig.3, but if the errors were significantly higher than assumed high penalties would be incurred, particularly as regards take-off wind on the SST.

6 ECONOMIC ASSESSMENT

For assessing the overall economic effect of different levels of accuracy in meteorological forecasting, the most direct and appropriate method is to calculate the increase in operating costs that would be caused by notionally redesigning the aircraft so as to be able to accommodate the increased fuel reserve without relaxation in any performance or operational characteristic, i.e. maintaining the same overall regularity (already assumed), the same average load factor, the same take-off and landing and of course cruise performance, the same payload capacity, the same structural integrity etc. To assume that the aircraft is "stretched" in any of these respects in order to accommodate the extra fuel is simply to hide some of the real cost against deteriorations in performance, airworthiness, regularity, ease of scheduling and operation, and passenger service and goodwill, all of which cost money to provide and should therefore be costed if altered.

In Figs.2 and 3 the weight penalties shown are simply the increases in fuel weight for an unmodified design, i.e. allowing take-off and landing performance, strength etc. to deteriorate. To avoid such deterioration it is necessary to increase the structural strength, wing area, engine size etc., thereby increasing the weight still further. It is this final "snowballed" weight increase which we need for costing purposes, since the aircraft direct operating cost is quite closely proportional to the final all-up weight for a given payload.. For a Mach 2 SST such as Concord it is found that the factor by which the (take-off) weight penalties in Figs.2 and 3 must be increased in order to obtain the final all-up weight for the same performance etc. is about 2.0. For a subsonic jet such as the Boeing 707 the factor is about 1.4. The effect of, say, 1000 lb of extra fuel in Figs.2 and 3 can therefore be assessed as follows:-

	SST	Subsonic
Increase in fuel in Figs.2 and 3	1000 lb	1000 lb
Increase in A.U.W. for same performance	2000 lb	1400 lb
Datum A.U.W.	-340 000 lb	-315 000 lb
Therefore % increase in D.O.C. (=% increase in A.U.W.)	0.59%	0.45%

The next step is to turn these D.O.C. Increments into total costs per annum. It will be assumed here that the main interest lies in getting an indication of possible changes in emphasis and values in future SST operations compared with the existing subsonic situation on which present ideas are based. We will therefore use current statistics for long-range subsonic traffic and a forward estimate for SST's.

Current subsonic long-range traffic amounts to about 60 × 10^9 passenger-miles per annum, equivalent to about 350 Boeing 707's. At an average direct operating cost of about $2\frac{1}{4}$d per passenger-mile the world-wide total of direct operating costs for current subsonic traffic is therefore about £560m per annum. Thus, 1000 lb in Figs.2 and 3, which we have seen is equivalent to 0.45% D.O.C., is worth about £2.5m per annum spread over the current world total of long-range subsonic operations.

Estimates of future supersonic traffic vary considerably. Allowing for continued traffic growth, however, and assuming that SST's are successful, it will be assumed that in about 15-20 yews time there will be the equivalent*

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*i.e. including possible American SST's.

of 400 Concords in service, corresponding to about 120 × 10^9 passenger-miles per annum. Assuming a D.O.C. of $2\frac{3}{4}$d per passenger-mile at currant money values, this corresponds to a world-wide total for supersonic transports of about £1400m per annum. On this basis 1000 lb in Figs.2 and 3, worth 0.59% D.O.C., corresponds to a total of <u>£8.1m per annum</u> spread over a possible world total of SST operations in 15-20 years time. A large part of the difference between this figure and the previous figure of £2.5m per annum for subsonic aircraft is of course due to the fact that we are here assessing <u>future</u> supersonic operations against a datum of existing subsonic operations, with a factor of two between the respective traffic volumes.

These costs per 1000 lb of fuel can now be combined with slopes taken from Figs.2 and 3 to give the value per knot or per degree change in standard deviation of forecasting errors. As noted earlier, we meet at this point the difficulty of deciding whereabouts on Figs.2 and 3 to measure the slopes, since the curves are non-linear. In the table below the slopes have been measured in the neighbourhood of the typical values which are thought to have been or are expected to be achieved. The slopes used are quoted, and if it is wished to use different values the answers can be scaled up or down with reference to Figs.2 and 3.

<u>Table 2</u>

<u>Effects of 1 knot or 1°C change in the standard deviations of wind and temperature forecasting errors</u>

	Slope assumed	Annual value per knot or per degree C
<u>Current long-range subsonic operations:-</u>		
1 knot S.D. in route mean wind	230 lb/knot	£0.58m
1°C S.D. in route mean temperature	30 lb/°C	£0.08m
1 knot S.D. in take-off wind	60 lb/knot	£0.15m
1°C S.D. in take-off temperature	100 lb/°C	£0.25m
<u>Future supersonic transport operations:-</u>		
1 knot S.D. in route mean wind	30 lb/knot	£0.24m
1°C S.D. in route mean temperature	130-430 lb/°C	£1.05m-£3.48m
1 knot S.D. in take-off wind	30 lb/knot	£0.24m
1°C S.D. in take-off temperature	150 lb/°C	£1.21m

Apart from en-route wind, the economic effects of 1 knot or 1°C change in the standard deviation of forecasting errors are all higher for the assumed future SST operations than for existing long-range subsonic operations. As noted above, this is partly due to the assumed increase in traffic. However, in the case of en-route temperature there is also a large increase in sensitivity, with the result that the value of 1°C change in S.D. will be very much higher in future supersonic operations than it is in current subsonic operations. Accurate forecasting of take-off temperature will also be appreciably more important than at present.

Since changes of 1 knot or 1°C, in the table above, represent quite different proportionate changes relative to datum as between different conditions and as between subsonic and supersonic operations, it is useful to re-cast the results to show instead the effects of equal percentage changes in accuracy for each condition. This is done in Table 3 below, using for illustration a change of 25% compared with the datum accuracy assumed.

Table 3

Effects of 25% changes in the standard deviations of wind and temperature forecasting errors relative to the assumed datum values

	Assumed datum	Annual value per 25% change in S.D.
Current long-range subsonic operations:-		
25% S.D. in route mean wind	12 knots	£1.74m
25% S.D. in route mean temperature	4½°C	£0.09m
25% S.D. in take-off wind	4 knots	£0.15m
25% S.D. in take-off temperature	2°C	£0.12m
Future supersonic transport operations:-		
25% S.D. in route mean wind	6 knots	£0.36m
25% S.D. in route mean temperature	1½°C	£0.39m-£1.30m
25% S.D. in take-off wind	4 knots	£0.24m
25% S.D. in take-off temperature	2°C	£0.60m

Thus, in terms of equal percentage changes in accuracy compared with what has been achieved or is expected to be achieved, the only item of real importance in current subsonic operations is en-route wind, where it is worth paying as much as £1.74m per year to effect a 25% improvement. With the datum values used here, nothing on supersonic transports is as important as wind on the subsonics so far as a given percentage change in accuracy is concerned.

However, the other items are significantly more important than on subsonics. Whereas in current subsonic operations the conclusion would be that any additional effort available should be applied mainly to improving the accuracy of forecasting en-route winds, in future supersonic operations it would seem that effort should be spread between en-route temperature and take-off temperature. The importance of take-off temperature on SST's is worth noting, since in preliminary discussions the emphasis has usually been laid on en-route temperature. As discussed earlier, however, it must be noted that some doubts have been raised on the validity of the datum assumption of $1\frac{1}{2}^{\circ}$C S.D. for route mean temperature errors, based on North Atlantic data. If this were 50% higher, for instance, the value per degree change in S.D. (Table 2) would be about 40% higher, i.e. £1.47m-£4.89m per annum, and the value per 25% change (Table 3) would be over twice as great, i.e. £0.82m-£2.74m per annum, depending in each case on the sensitivity of the engine/intake/nozzle system to ambient temperature.

The wide spread of answers for en-route temperature effects is unfortunate but unavoidable at the present state of knowledge. To reduce it, effort must be applied on the one hand to improving our knowledge of what the standard of world-wide route mean forecasting accuracy is likely to be at SST operating altitudes, i.e. whether the assumption of $1\frac{1}{2}^{\circ}$C S.D. based on North Atlantic data is representative or not, and on the other hand to defining with more certainty the sensitivity of SST engine/intake/nozzle systems to ambient temperature. So far as the latter aspect is concerned the only figures currently available in this country are for Concord with the pre-production intake and nozzle system. BAC/Sud hope to be able to improve on this for later (Stage I) aircraft; the lower sensitivities quoted correspond to this hope and the higher sensitivities to the currently-designed system. In 6-12 months we should have a better idea of the extent to which the hoped-for improvement will be achieved on Stage I Concords. On American SST's we have no knowledge of the temperature sensitivity, and since this is highly dependent on the general philosophy and detailed matching of engine, intake and nozzle, any attempt to estimate it aithout a proper knowledge of the system proposed could be considerably in error.

Despite the uncertainty about; the precise numbers, it is clear that accurate en-route temperature forecasting will be much more important in future supersonic operations than it has been in subsonic operations, and if the standard deviation of errors is appreciably greater than the assumed value ($1\frac{1}{2}^{\circ}$C route mean) high economic penalties will be Incurred.

It should perhaps be noted once again that the comparative results for supersonic and subsonic operations in Tables 2 and 3 are directly affected by the assumptions made concerning relative traffic volumes, and. that the above figures all refer to assumed future supersonic operations, represented by the equivalent of 400 Concords in 15-20 years time, compared with existing long-range subsonic operations equivalent to about 350 Boeing 707's. One might instead be Interested in the comparison of future supersonic operations with future subsonic operations, in order to decide between competing demands on limited future facilities. In this case, in order to bear the correct relativity to the quoted supersonic figures, the subsonic figures must be scaled up to allow for future subsonic traffic growth. On the assumptions made here, based on a 60% penetration of the long-haul market by SST's in 1980-1985, the scaling factor on the existing subsonic figures in Tables 2 and 3 would be about 1.5. If the market penetration of SST's were smaller than assumed here, the supersonic figures would need to be scald down compared with those given above, while the subsonic figures would be increased still further. Thus:-

Relative supersonic/subsonic share of future traffic	Scaling factors on the results of Tables 2 and 3 for future subsonic and supersonic operations	
	Supersonic	Subsonic
60% SST/40% subsonic (as here)	1.0	1.5
50% SST/50% subsonic	0.83	1.88
40% SST/60% subsonic	0.67	2.25

The effect of such changes is of course to increase the relative importance of accurate en-route wind forecasting for subsonic aircraft compared with the importance of accurate temperature forecasting for supersonic aircraft.

7 CONCLUSIONS

(i) The effects of errors in meteorological forecasting can be expressed in terms of the extra reserve fuel needed to achieve a given operational regularity, and hence in terms of tho additional operating cost caused by designing the aircraft so as to be able to carry this higher reserve fuel without degradation of any other performance, operational or passenger-service characteristic. It is important when attempting to cost meteorological errors or the influence of any other variability that the effects should be properly combined with all other contingencies on a statistical basis, otherwise exaggerated results will be obtained.

(ii) On current long-range subsonic jets, by far the most important meteorological factor is the error in forecasting the route mean wind, currently assessed as a standard deviation of 12 knots. A 25% change in this standard, i.e. ±3 knots, is estimated to be worth £1.74m per year over the current world-wide total of subsonic long-range operations.

(iii) On SST's the most sensitive en-route variable is temperature. Looking to a world-wide supersonic transport fleet equivalent in productivity to 400 Concords in 15-20 years time, it is calculated that 1°C change in the standard deviation of error in the route mean temperature will be worth £1.1m to £4.9m per year, depending on the absolute level of accuracy achieved and on the sensitivity of the engine/intake/nozzle system to temperature. North Atlantic statistics suggest a standard deviation of route mean forecast error of only 1½°C. A 25% change in this standard would be worth £0.39m to £1.30m per year, but if the datum error were 50% higher than assumed (i.e. 2¼°C instead of 1½°C), then a 25% change would be worth £0.82m to £2.74m per year.

(iv) Accurate forecasting of airfield temperature for take-off will be more important for supersonic transports than for current aircraft. Assuming a standard deviation in forecasting error of 2°C, a 25% improvement in accuracy is estimated to be worth about £0.6m per year.

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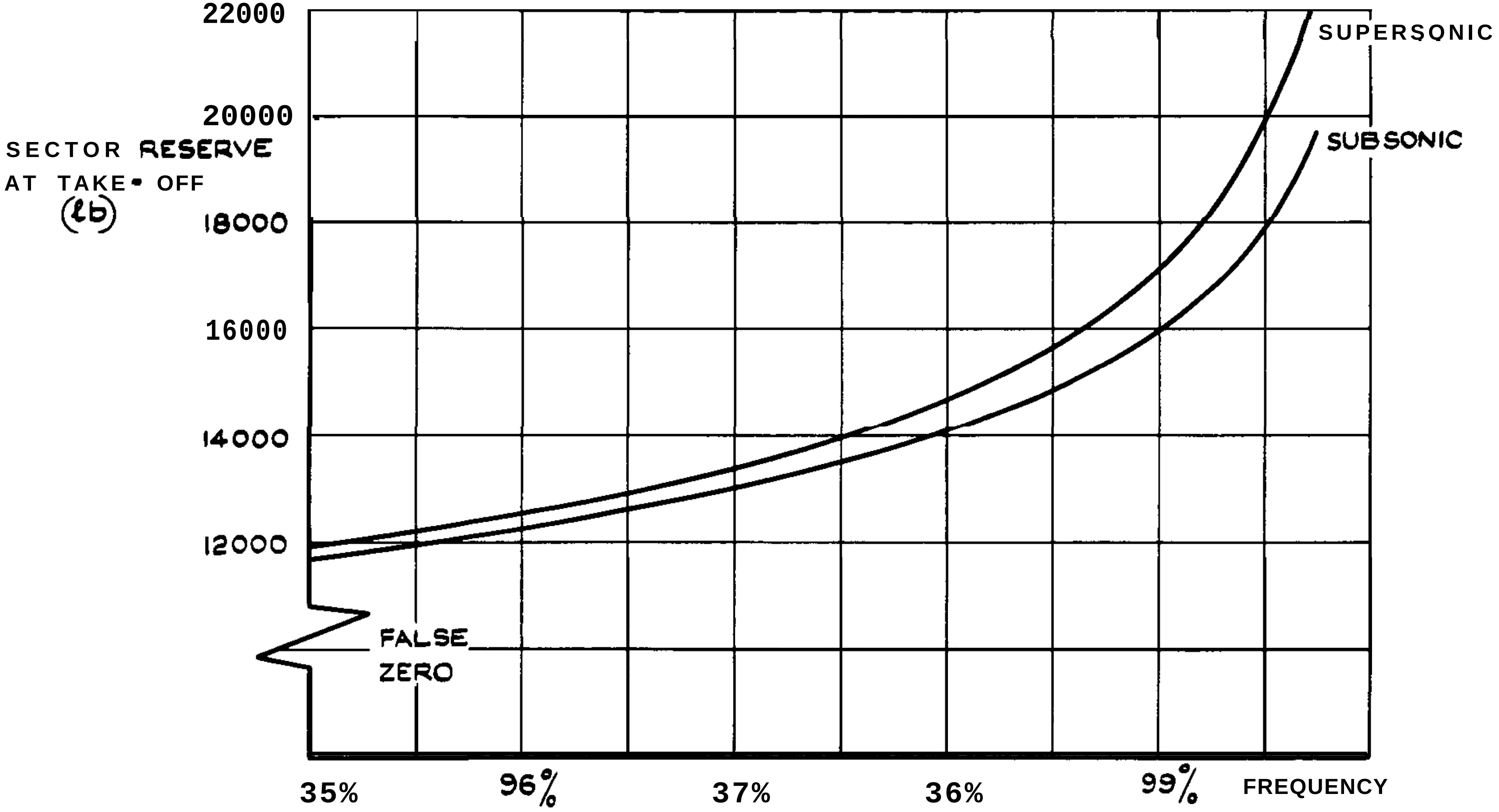

FIG. I SECTOR RESERVE (EN-ROUTE CONTINGENCIES PLUS DESTINATION HOLD)FOR MACH 2 SST AND SUBSONIC JET, LONDON-NEW YORK.

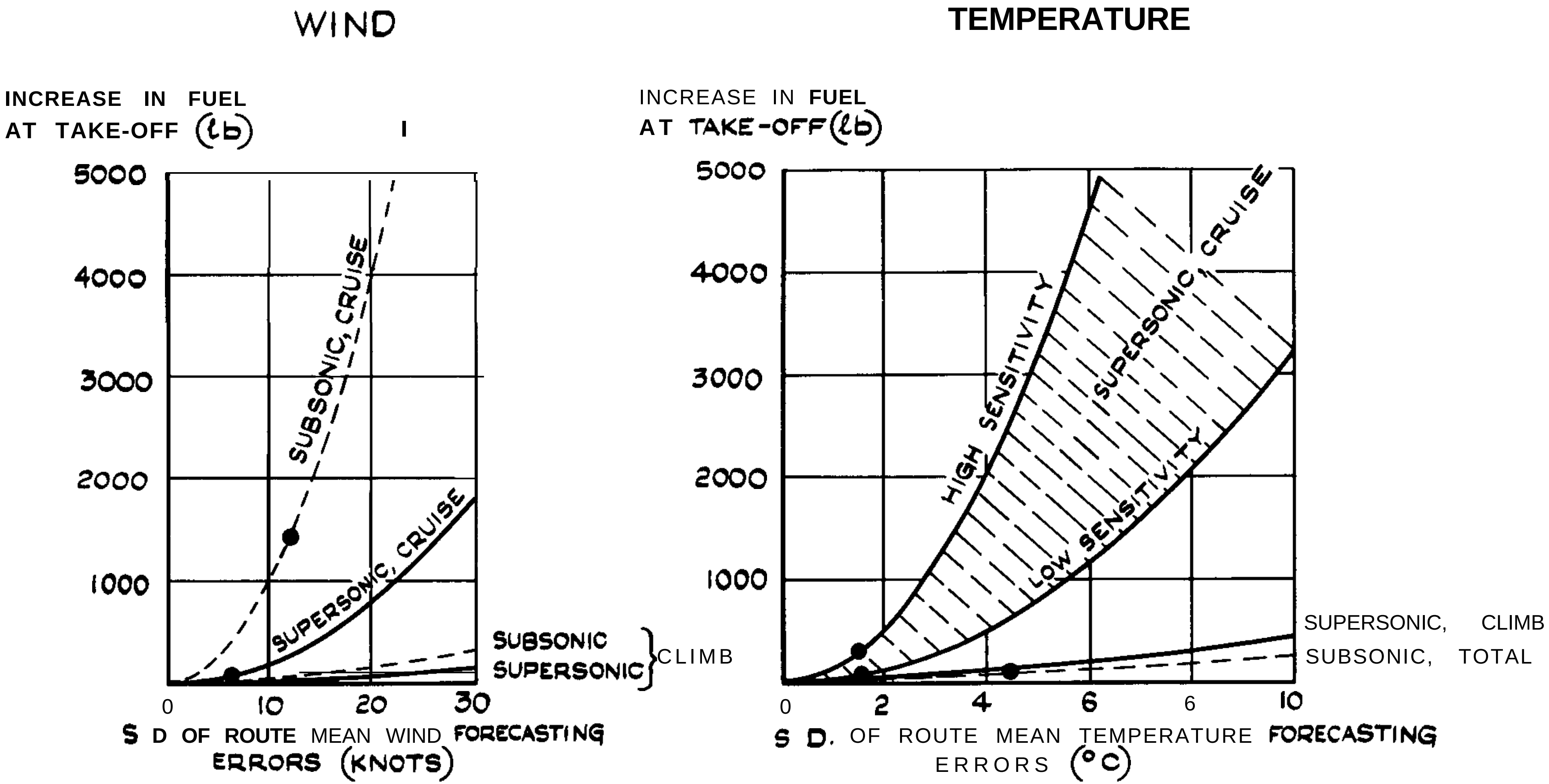

FIG. 2 EFFECTS OF ERRORS IN FORECASTING EN-ROUTE WINDS AND TEMPERATURES, LONDON-NEW YORK ROUTE.

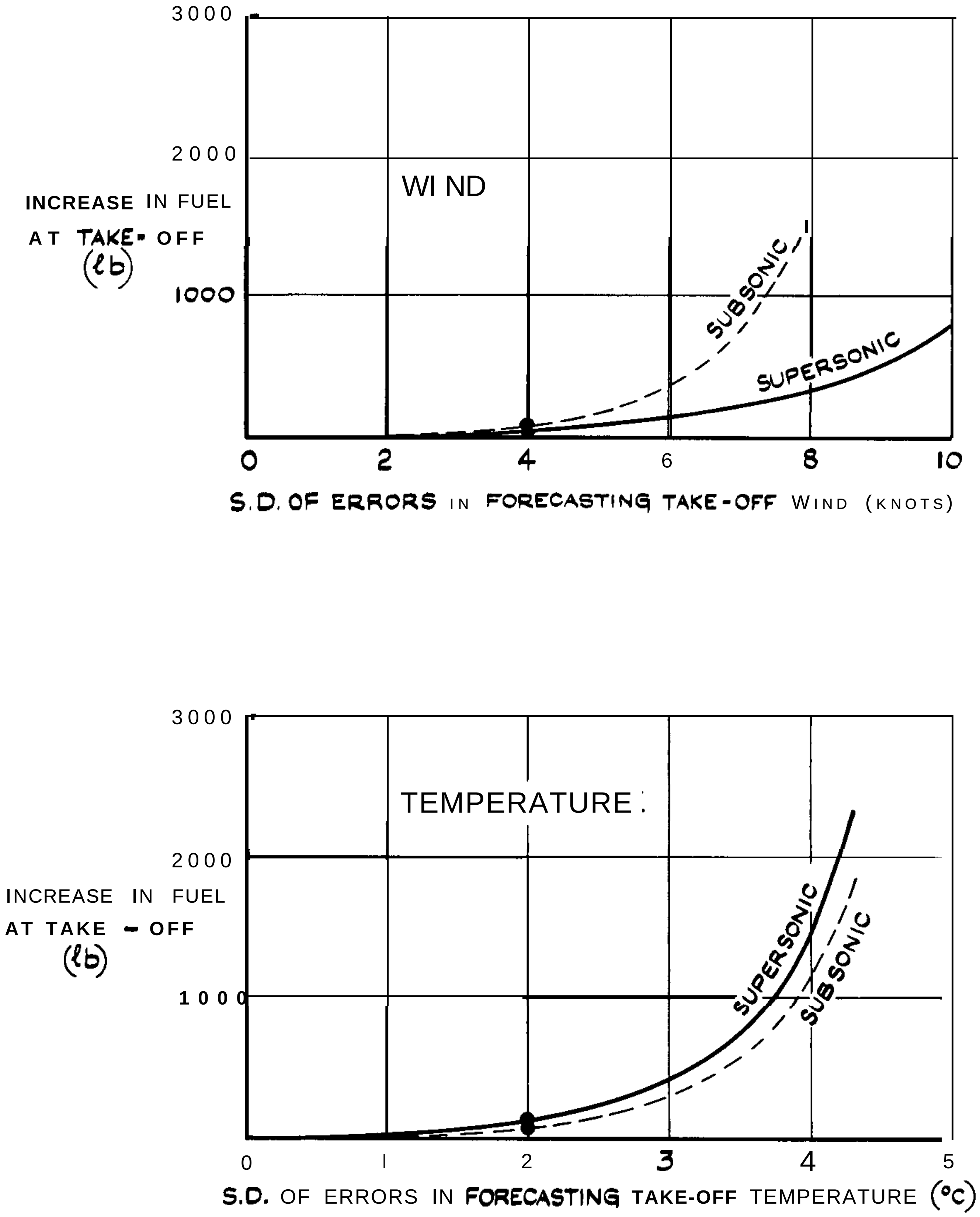

FIG. 3 EFFECTS OF ERRORS IN FORECASTING TAKE-OFF WINDS AND TEMPERATURES.

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THE ECONOMIC EFFECTS OF METEOROLOGICAL FORECASTING STANDARDS FOR SUPERSONIC CIVIL TRANSPORTS

As an aid to discussions on the future provision of meteorological forecasting services for civil transport operations, an approximate assessment is made of the effects of changes in the accuracy with which en-route and take-off winds and temperatures can be forecast. The results are given in terms of the annual value calculated over the world total of long-range civil operations, first for a current subsonic fleet equivalent to about 350 Boeing 707's and then for a possible supersonic fleet equivalent to about 400 Concords, such as might be in operation in 1980-1985.

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