EVALUATION OF 2 POSSIBLE FURTHER DEVELOPMENTS OF THE UK IN-FLIGHT RADIATION WARNING METER FOR SSTS

I J Wilson and R C Eustace
Radiation Measurement Section
UKAEA/AWRE Aldermaston, UK of GB

Various radiation measurements have been made to investigate 2 possible further developments of the present hybrid ionisation and neutron detection system of the Dose-Equivalent Ratemeter commissioned for the SST Concorde, namely

(i) A reduction of the mass of the moderator from that of the Anderson-Braun neutron-remmeter assembly, and

(ii) the inclusion of a response to the nucleon flux responsible for the tissue-star component of the total dose-equivalent rate by means of a high atomic number material as a nucleon-neutron converter within the moderator.

Radiation situations at SST cruising altitudes (~20 km) due to solar proton flares were simulated approximately both in the stratosphere and on the ground. Actual stratospheric situations due to galactic cosmic radiation with a limited range of Quality Factor values (2-4) were encountered during slow ascents by balloons to 36 km from Aire-sur-Adour (France). Synthetic situations obtained from high and low energy accelerator radiations were used to obtain radiation distributions having a larger range of Quality Factor values ($1\frac{1}{2}$-9) than experienced in the stratosphere. The measurements made in these simulations related to the Directly Ionising, Neutron and Tissue-Star components of Dose-Equivalent Rate.

The stratospheric and high energy accelerator experiments taken together with results from both radioactive and machine neutron sources indicated 2 conclusions. Firstly that, due to the restricted range of neutron spectra encountered in the stratosphere, a significant and welcome reduction of the mass of the moderator by 4 kgm could be made, provided the moderator is clad with cadmium or some other slow neutron absorber. Secondly, that to achieve a tissue-star response with a lead insert would result in a nett increase in moderator-assembly weight of $5\frac{1}{2}$ kgm. Hence the lead insert proposal was abandoned, while the potential moderator reduction is being exploited.

A reduced moderator geometry compatible with the existing electronics package was derived; its oversensitivity with respect to the Anderson-Braun neutron remmeter was determined for a number of fast neutron energies. Two different methods of correcting the oversensitivity - a slow neutron absorber within the moderator and a reduced sensitivity boron trifluoride counter - were tested. As a result, a new - reduced weight - version of the In-Flight Radiation Warning Meter for the SSTs can now be designed in detail.

Reasons for the Experiments

The balloon-borne experiments at Aire-sur-Adour in the autumn of 1969 were a recent phase in the continuing British programme of stratospheric radiation research and development for the Concorde - described by Wilson (Ref.1). At ground level, we are unknowingly enjoying the benefits of a radiation shield provided by the atmosphere, which is equivalent to a 1 metre (~1 yard) thickness of lead. But the cosmic radiation shield for a Concorde flying at a height of ~17 km (~11 miles) is equivalent to only about 8 centimetres (3 inches) of lead!

The background cosmic radiation - mostly protons of 10000 MeV (million electron volts), produces a stratospheric dose-equivalent-rate which differs with latitude and varies with the 11 year solar activity cycle. The maximum dose-equivalent-rate was measured in 1964 at Fort Churchill, Canada, during the International Quiet Sun Year, and reported by Fuller and Clarke (Ref. 2).

Maximum Cosmic Radiation Dose-Equivalent-Rates at Concorde Cruise Altitudes (these will only be met on polar and northerly transatlantic flights)

Ionisation (Chambers and Geiger Counters)	1.1 milli-rem/hr
Neutron (Instruments and Activation)	0.6 milli-rem/hr
Tissue Star (Nuclear Emulsions + Microscope)	0.5 milli-rem/hr
Total	2.2 milli-rem/hr

Maximum Cosmic Radiation Dose-Equivalent/flight	= 5 milli-rem, Passengers
Maximum Cosmic Radiation Dose-Equivalent/Year	= ~1.0 rem, Crew
(Maximum Permissible Dose-Equivalent/Year	= 5 rem Radiation Worker)

The International Commission on Radiological Protection has stated that there is 'No need for personal dosemeters where the annual dose-equivalent is not greater than 3/10 maximum permissible, provided the radiation environment is monitored'.

The global (i.e world-wide) average dose-equivalent-rate due to cosmic radiation at Concorde cruising altitude will be about 1 milli-rem/hr (probably less) which is unlikely to present any operational problems!

However, Solar Proton Flares do pose a problem - Buley (Ref. 3), see Figs 1 and 2. It is estimated that on about 1 occasion per year, averaged over a solar activity cycle of 10-12 years solar outbursts of high energy protons (1000 MeV) will cause dose-equivalent rates greater than 100 milli-rem/hr in the Concorde cruising altitude band at northerly latitudes. Thus, only one northerly flight in several thousand such flights will be affected. On these very few occasions the Concorde will make a normal, controlled descent to increase the atmospheric shielding. As the atmospheric tenth-value attenuation layer for solar flare protons is about 40-50 gm/cm^2, a descent to an altitude of about 14-15 km (45000 - 50000 ft), which is well above the subsonic flight levels, should suffice to reduce the dose-equivalent-rate to less than 100 milli-rem/hr. (Solar proton flares are expected to have no effect on the operations of supersonic passenger aircraft at tropical or equatorial latitudes.)

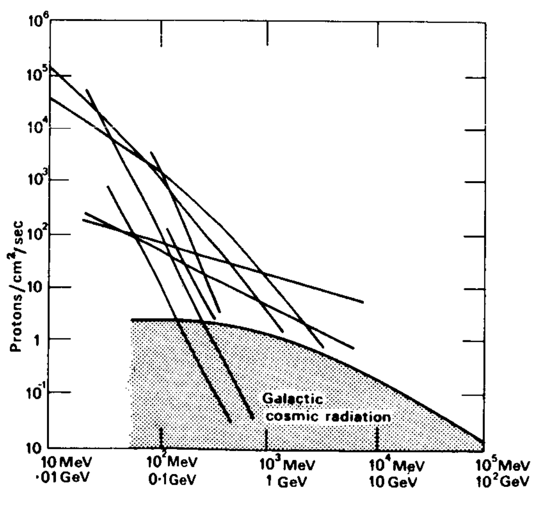

FIGURE 1. ASSORTED INTEGRAL ENERGY SPECTRA OF SOLAR FLARE PROTON AND COSMIC RADIATIONS.

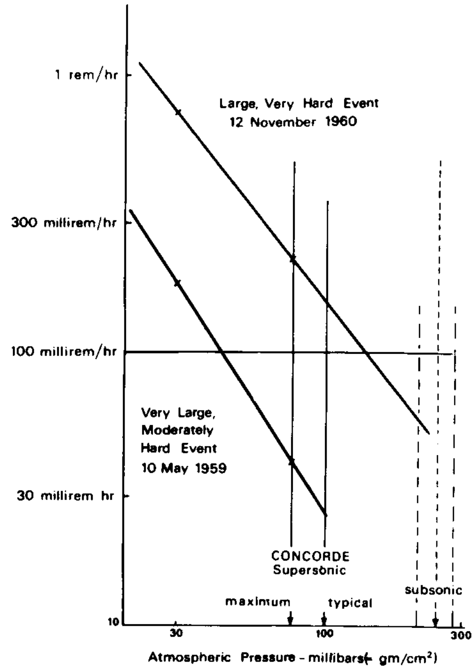

FIGURE 2. ESTIMATED SOLAR PROTON FLARE DOSE-EQUIVALENT RATES IN THE STRATOSPHERE.

Neither ground nor satellite systems can give radiation warnings sufficiently reliable or exact to be useful for the flight management of supersonic airliners. Thus, an In-Flight Radiation Warning Meter was specified for Concorde: it has been described by Benbow (Ref. 4). The present instrument is a hybrid device based on the Fort Churchill results, plus information on Solar Proton Flares in the last 2 solar cycles:-

(Direct Ionisation	(Low LET -- Low QF)
(Geiger Counters	
(Neutrons	(Medium LET -- Medium QF) likely to contribute the major component of dose-equivalent during a solar proton flare.
(Anderson-Braun moderator plus Boron Trifluoride Tube	although a smaller moderator was thought to be adequate for the restricted range of stratospheric neutron spectra.
(Tissue-Stars	(High LET -- High QF)
(Instrumental Scaling Factor	an indirect measurement of this component was thought to be possible by the use of a high atomic number material - such as lead - within the moderator.

[LET = Linear Energy Transfer, QF = Quality Factor]

The electronic package of the instrument utilizes silicon microcircuits and devices with components tested to military environmental requirements, and uses 9 to 11 watts from the aircraft 115v 400 Hz power supply. The Geiger counter (ionization) and boron trifluoride tube (neutron) pulses are brought together to drive a single ratemeter which gives a 4 decade logarithmic indication of total dose-equivalent-rate at a display unit separate from the electronic package but linked by a multi-signal cable. For simplicity of readout by SST aircrew personnel of 'the radiation level', the meter scale is marked in 20 equispaced divisions. The 4 decades are indicated by coloured quadrants - the first and second (0.1-10 mrem/hr) being coloured green to indicate safe ambient ranges, the third (10-100 mrem/hr) being orange for an alert range, and the fourth (100 mrem/hr - 1 rem/hr) being red for the action range. There are orange and red signal lamps corresponding to the orange and red dose-equivalent rate ranges: also, there is an audio signal when the dose-equivalent-rate exceeds the threshold of the red (action) range, 100 mrem/hr. Dose-equivalent integration is performed by a register in which each digit represents 1 mrem: this register will continue to function without loss up to a dose-equivalent-rate in excess of 10 rem/hr. While the weight of the electronics package plus display unit is only $3\frac{1}{2}$ kgm/8 lb, the weight of the Anderson-Braun moderator assembly is $8\frac{1}{2}$ kgm/18 lb: hence the interest in a smaller moderator.

The very reason for the Warning Meter, the unpredictability of the infrequent large solar proton flares, makes the validation of smaller and modified moderator assemblies during an actual solar proton flare virtually impossible prior to regular Concorde flights. Simulation with high energy accelerators is usually difficult and limited: normally the radiation is delivered in short intense pulses, the particle beams are of restricted cross-sectional area, and the common shielding material concrete is not equivalent to air because it contains both elements with higher atomic masses than air, and hydrogen (which moderates neutrons). The alternative is to make use of the various situations due to cosmic radi tion to be found at different stratospheric altitudes. Some simulation of the range of solar proton flare situations within the Concorde cruising altitude band 16-19 kms (10-12 miles), is available with cosmic radiation at progressively higher altitudes.

Actual Stratospheric Exposure

French colleagues provided balloon flights to heights of 36 km (22 miles) (where the air pressure is only $\frac{1}{27}$ of that at ground level) from their excellent balloon launching site at Aire-sur-Adour in the south of France. Unlike nearly all other balloon experiments which need a quick ascent and a long float, a slow ascent and a short float was required. The primary aim was not to measure the stratospheric radiation environments, but to use the various radiation situations for the comparison of instruments with different moderator assemblies - one standard Anderson-Braun moderator assembly and 3 modifications obtained by-

I Removing the inner parts of an Anderson-Braun moderator to produce a hollow moderator having a reduced moderator wall thickness

II Cladding such a hollow moderator with cadmium to remove the resulting enhanced slow neutron response

III Including a lead insert within such a cadmium-clad hollow moderator to give an indirect 'tissue-star' response -see Fig.3 for the principle.

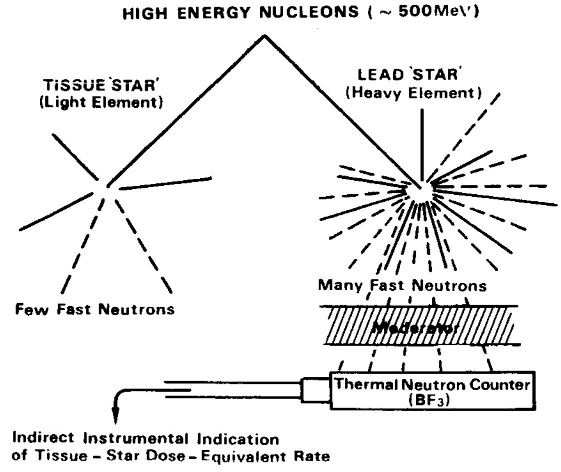

FIGURE 3. INDIRECT TISSUE-STAR RESPONSE

In the actual experimental assembly the lead was incorporated within the polythene outer moderator (the inner moderator etc. having been removed) as a sleeve around the boron trifluoride tube. The fast neutrons from the disintegrations of lead nuclei by high energy nucleons (protons, neutrons) were moderated by the polythene and reflected back through the lead to the boron trifluoride tube.

The secondary aim of the balloon experiments was to obtain an independent demonstration of the range of radiation situations encountered in the stratosphere. Recombination ionisation chambers, described by Wilson (Ref 5), were flown in an attempt to obtain some measure of the variation with altitude of the stratospheric quality factor at the place and time of the balloon flight. On the basis of nuclear emulsion and similar data obtained from polar balloon flights during the Quiet Sun period, as reported by Davison (Ref. 6), the stratospheric quality factor had been estimated as varying from 2 to $4\frac{1}{2}$ between 20 and 36 km, respectively - see Fig. 4. The maximum quality factor value encountered at Aire-sur-Adour would have been somewhat less. In the event it was not possible to derive any information relating to the variation with altitude of the stratospheric quality factor from the ionisation chamber results. (However, the neutron count rate and ratio profiles themselves qualitatively demonstrate the range of stratospheric radiation situations.)

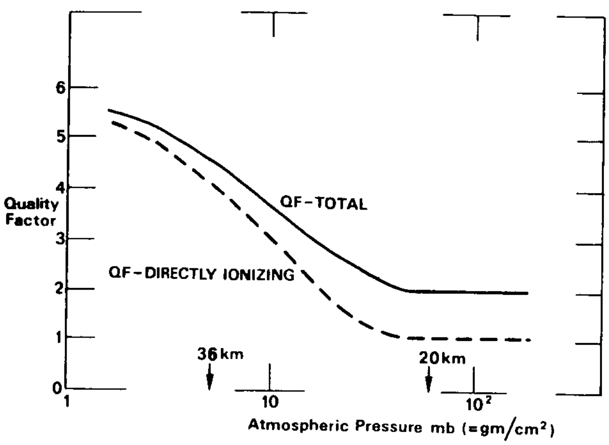

FIGURE 4. ESTIMATED STRATOSPHERIC QUALITY FACTORS.

The technical details of the counting equipment have been described by Benbow (Ref. 7).

The way that the count-rate from the Geiger counters varied with altitude was very nearly the same as the variation of the current output of ionisation chambers also flown from Aire at the same time - see Fig. 5. This provides yet another demonstration of the validity of using a compact and simple Geiger counter system for the ionisation channel of the Concorde In-Flight Radiation Warning Meter in place of a more bulky and more involved ionisation chamber system.

The results from the neutron counters were also as had been expected - see Fig. 6. The hollow moderator needed cadmium cladding to remove the enhanced response due to the slow neutrons from the other moderators in the balloon flight package - see curves I and II. (In a Concorde there will be some 110 tons of moderator - about 100 tons of fuel and about 10 tons of passenger and crew). Nevertheless the count-rate from the cadmium-clad reduced moderator was greater than that from the standard Anderson-Braun moderator (due to its internal partial neutron absorber) - see curves AB and II. The presence of an insert of lead within a cadmium-clad moderator caused an enhanced response due to the copious secondary neutron production - see curves II and III of Fig. 6.

Two important conclusions became apparent from comparison of the curves of Fig 6. The first conclusion comes from considering the ratio of the response of the cadmium-clad hollow moderator with that of the Anderson-Braun - see Fig. 7 (the results of the two flights, shown by circles and crosses respectively, are in agreement). The important feature here is that over the whole altitude range, the ratio of the count-rates from these two moderator assemblies was essentially constant. The stratospheric value of this ratio was confirmed by similar values obtained with 4 different laboratory radiation sources: at Aldermaston both radioactive (α-Be) and machine (D-D and D-T)

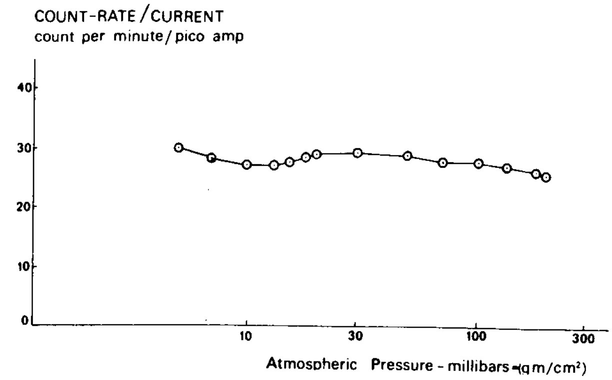

FIGURE 5. IONIZATION (Comparison of Geiger Counters with Ionization Chambers)

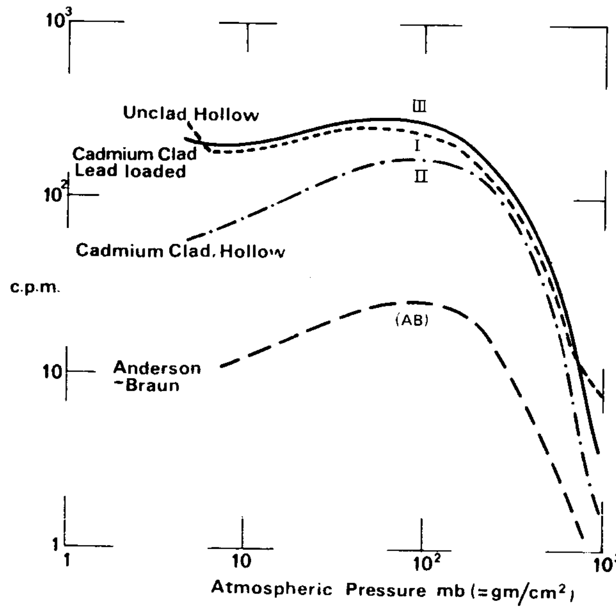

FIGURE 6. STRATOSPHERIC NEUTRON COUNT-RATES.

neutron sources, - and at the Rutherford High Energy Laboratory, scattered protons etc, transmitted through graphite were used to give some simulation of the stratospheric situation.

The first conclusion is that a reduction in the moderator for the In-Flight Meter could be made provided that it is clad in cadmium or some other slow neutron absorber. Aircraft operators and constructors seek equipments that perform their tasks reliably over a wide range of conditions with the minimum of weight - not an easy combination, as will shortly be illustrated. As the moderator accounts for the majority of the weight of the present instrument, the possibility of reducing the moderator weight by about half, to some 4 kilograms, is most welcome.

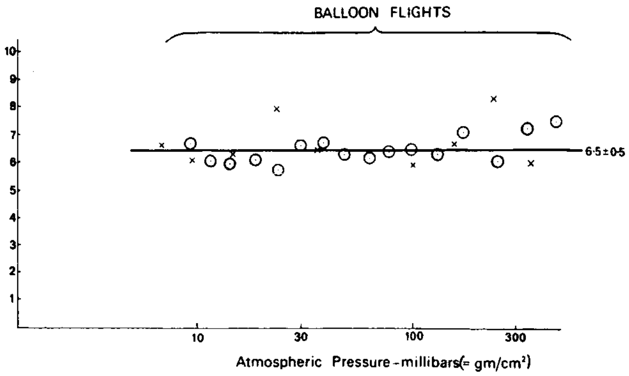

FIGURE 7. NEUTRON COUNTING RATIO: HOLLOW MODERATOR (Cadmium clad) /ANDERSON-BRAUN

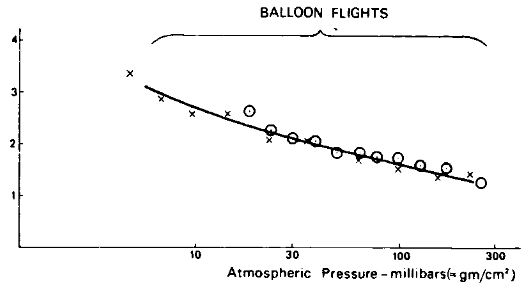

FIGURE 8. TISSUE-STAR COUNTING RATIO: LEAD INSERT/HOLLOW MODERATOR (both Cadmium clad)

The second conclusion comes from considering the ratio of the response of the cadmium-clad moderator loaded with $7\frac{1}{2}$ kilograms of lead to that of the hollow cadmium-clad moderator, the 'Lead Effect' - see Fig. 8 (the results of the two flights, shown by circles and crosses respectively, are in agreement). In this case the important feature is the steady increase of the effect with reduction of overlying air-mass (pressure) i.e with increasing altitude. The stratospheric values of this ratio are well in excess of those obtained with the 4 neutron sources used to simulate stratospheric neutrons: this indicates that the stratospheric 'Lead Effect' is not due to a modified response to neutrons external to the moderator. It is a genuine effect due to neutrons being produced within the moderator by the disintegration of lead nuclei as a result of high energy particle (nucleons etc) bombardment. This was confirmed by subsequent accelerator experiments (described later) some of which gave 'Lead Effects' greater than that experienced in the stratospheric balloon flights (see Fig. 9). In respect of the NIMROD-graphite simulation, it should be remembered that the majority of galactic cosmic radiation protons have energies in excess of those scattered through 90° from a 7 GeV proton beam: thus the difference between the balloon and NIMROD results.

High energy particles also cause the disintegration of light nuclei such as C, N and O and are thus the cause of 'tissue-stars'. The 'tissue-star' component of the total dose-equivalent-rate due to cosmic radiation at Concorde cruising altitude has been estimated from the Fort Churchill results as being equal to 80% of the neutron dose-equivalent-rate. To achieve an 80% enhancement of the neutron count-rate for cosmic radiation at an altitude of about 20 km, a lead insert of 6 kilograms would be needed. (Theoretical reasons indicate that 5 kilograms of uranium should do the same job, and also deal with some of the excess neutron sensitivity of the reduced moderator.)

The consequence of these conclusions is that either the In-Flight Radiation Warning Meter could be made lighter but without a 'tissue-star' response (as at present), or a 'tissue-star' response could be incorporated together with a reduction in the moderator mass to give an instrument of somewhat greater weight than at present: this is the sort of dilemma that developers of aircraft instruments often encounter. As the existing instrument already met the requirements for an In-Flight Radiation Warning Meter, only developments giving a significant weight reduction were of practical interest. Hence, although the balloon experiments showed that a 'tissue-star' response could be obtained by a simple reliable means, such a development is ruled out on the grounds of excessive weight.

Simulated Stratospheric Exposure and Other High Energy Accelerator Experiments

The set of moderators used in the balloon flights were also exposed in a number of environments found around the NIMROD (7 GeV proton) and NINA (5 GeV electron) accelerators in order to obtain experience in a range of high energy radiation situations differing from the graphite simulation of the stratosphere. To facilitate comparisons, details and results of all 12 experiments are tabulated together - see Fig. 9. The 'cadmium ratio' is the ratio of the count-rate response of the cadmium-clad hollow moderator to that of the unclad hollow moderator: this was normally less than one, indicating the presence of slow neutrons. The 'hollow ratio' is the ratio of the count-rate response of the cadmium-clad hollow moderator to that of the Anderson-Braun moderator: in situations comparable to the stratosphere, the value of this ratio lay within the restricted range 5-7. The 'lead ratio' is the ratio of the count-rate response of the cadmium-clad moderator containing the $7\frac{1}{2}$ kgm of lead to that of the cadmium-clad hollow moderator: the values of this ratio varied from 0.8 to 8. For experiment one, the balloon flights, the extremes of the ranges of values already indicated in Figs. 6, 7 and 8 are summarised.

Experiment	Radiation Source	Shielding	Overall Average Quality Factor	'Cadmium Ratio'	'Hollow Ratio'	'Lead Ratio'
1	Galactic Cosmic	5-500 gm/cm^2 Air	$(4\frac{1}{2}-2)$ a)	0.15-0.65 b)	6.5 ± 0.5 b)	3-1.5 b)
2	D-D	None	(9)	0.92	5.9	0.80
3	Am-Be	None	7.4	1.00	6.4	0.79
4	D-T	None	7.8	0.98	5.8	0.90
5	D-D	None	(9)	0.90	4.6	0.83
6	Am-Be	None	7.4	1.00	5.0	0.78
7	D-T	None	7.8	0.92	4.5	0.98
8	NINA, 2.5 GeV electrons	Thick concrete + iron	3.8	-	6.6	-
	NIMROD, 7 GeV protons					
9	Unanalysed 90° scatter	$\frac{1}{2}$ m graphite	3.3	0.54	5.4	0.93
10	Unanalysed 90° scatter	2 m concrete	4.8	-	5.1	1.1
11	1.0 GeV π^+ (and 0.5 GeV p)	0.3 m concrete	1.6	1.08 c)	3.9	4.0 (4.3) c)
12	1.0 GeV π^+ (and 0.5 GeV p)	None	2.3	-	4.3	7.4 (8.0) c)

a) Fort Churchill, Canada - Quiet Sun

b) Aire-sur-Adour, France - Active Sun

c) See comments in text regarding the anomalous aspects of experiments 11 and 12.

FIGURE 9. SUMMARY OF EXPERIMENTAL DETAILS AND RESULTS.

Experiments 2-7 inclusive were the simulations done at Aldermaston: in 2, 3 and 4 the cylindrical moderators, in their balloon flight configuration were irradiated normally with respect to their flat top surfaces - an irradiation situation similar to that experienced in the stratosphere. The 'hollow ratio' values of experiments 2-4 indicate that the Am-Be neutron spectrum can be used to represent the stratospheric neutron spectrum in simulation tests with moderators. In experiments 5, 6 and 7 the cylindrical moderators were irradiated normally with respect to their curved side surfaces, one moderator at a time. As the cadmium ratios for experiments 2-4 approximate to one, neutron scatter between the moderators in the flight configuration can be eliminated as a factor in the comparison of the results of 2-4 with those of 5-7: this is confirmed by the fact that the 'hollow ratio' values from experiments 5, 6 and 7 are all a constant 78% of the corresponding values from experiments 2, 3 and 4 respectively. Thus compared with the Anderson-Braun moderator, the cadmium-clad hollow moderator has an angular response which differs from isotropic by $\pm$ 12%. Although the 'lead ratios' for experiments 2-7 are all less than one, there is some indication of neutron enhancement with the D-T irradiations (experiments 4 and 7). Experiment 8 utilised a location behind one of the beamstops of the 5 GeV electron synchrotron, NINA, at the Daresbury Nuclear Physics Laboratory. At the Rutherford High Energy Laboratory, a graphite wall was erected for experiment 9 in a shield-tunnel facility at right angles to one of the external beams from the 7 GeV proton synchrotron NIMROD, at a distance of about 15 meters from the scattering target. The dimensions of the wall were about $1\frac{1}{2}$m x $1\frac{1}{2}$m x $\frac{1}{2}$m thick, providing a 'beam' of about $1m^2$ cross-sectional area. As the atomic number and mass of carbon are comparable with, but less than those of nitrogen and oxygen, it was considered that the graphite wall (~100 gm/cm^2) would approximate to the Concorde's maximum cruise altitude (~80 gm/cm^2). Experiment 10 was above the concrete top shielding of a different proton beam over another scattering target. In experiments 11 and 12 a pion beam was used: the anomalous 'cadmium ratio' obtained from 11 indicated that the cadmium generated neutrons instead of absorbing them and hence the 'lead ratios' for experiments 11 and 12 have been adjusted. As there was every indication that all neutrons detected during experiments 11 and 12 were produced within the moderator-assemblies (i.e no external neutron flux) these experiments must be regarded as unrepresentative.

The Quality Factor values for the stratosphere were derived from Ref. 6. The Quality Factor values for experiments 3/6, 4/7, 8, 9, 10, 11 and 12 were derived from measurements made with the AWRE portable LET spectrometer by B Day - see Ref. 8: the Quality Factor value for experiments 2/5 was interpolated from other measurements by B Day. Estimated values of Quality Factor are bracketed in Fig. 9.

The experimental results indicate that:

(a) An Am-Be neutron source can be used to represent the stratospheric neutron spectrum for the purpose of moderator tests.

(b) The cadmium-clad, hollow (i.e reduced wall thickness) moderator is a valid replacement for the Anderson-Braun remmeter in the context of the restricted range of stratospheric neutron spectra; but its sensitivity is considerably enhanced (see Figs 7 and 9).

(c) From the 'Lead Ratios', the relative stratospheric incidence of tissue-stars for a solar proton flare will be less than that for cosmic radiation, and hence for the purpose of the Concorde In-Flight Radiation Warning Meter an instrumental scaling factor will be adequate to deal with the approximately 20% tissue-star component of stratospheric dose-equivalent-rate during a solar proton flare.

The Reduced Moderator

Preliminary tests with a moderator of 17 cm/6.7" diameter having the same wall thickness as the previous hollow moderator (but without the internal cavity) and having the same length 24.5 cm/9.7", demonstrated that as expected it had the same relative neutron energy response as the hollow moderator and was a little less sensitive, but still significantly more sensitive than the Anderson-Braun assembly. However, computed sensitivities of moderators of different sizes as functions of neutron energy such as reported by Stevenson (Ref. 9) indicate that significant further reduction in moderator size should be possible before the minimum moderator adequate for the stratospheric environment would be obtained. Reduction of moderator size would also remove some of the over-sensitivity referred to above. The remaining over-sensitivity can easily be removed by including sufficient cadmium (or compound of lithium or boron) with the enriched boron trifluoride proportional counter within the moderator. A simple calculation indicated that the substitution of natural boron trifluoride in place of the usual counter filling of enriched boron trifluoride would remove nearly all of the over-sensitivity.

In the development of the reduced moderator version of the In-Flight Radiation Warning Meter some instrumental considerations had to be borne in mind. The electronics package had been

(a) Designed and built within a 15 cm/6" diameter case in the confident theoretical expectation that a moderator of about this diameter (and length) would be demonstrated as adequate for the stratospheric radiation environment

and

(b) Built and tested to general aircraft and particular SST specifications: hence the reduced moderator development should provide the same count-rate sensitivity with the same electronic operating conditions as the Anderson-Braun assembly in order to avoid expensive re-design, re-building and re-testing of the electronic circuitry.

In addition to the 2 general conditions (a) and (b) indicated above, the replacement moderator also had to be compatible with both the aircraft makers' requirements of overall instrumental dimensions, and the need to maintain a certain minimum neutron path length to the internal boron trifluoride tube through the moderator in all directions. These considerations resulted in a reduced moderator of dimensions, 15 cm/6" diameter and $20\frac{1}{2}$ cm/$8\frac{1}{4}$" length, which when clad with cadmium weighs $4\frac{1}{2}$ kgm/10 lb (ie comparable with the electronic package.)

The sensitivity of this reduced moderator was compared with that of an Anderson-Braun assembly for a number of fast neutron energies in the range ~0.1-15 MeV by normal irradiation of the curved surfaces of the moderators. As expected, the sensitivity ratio varied slightly with neutron energy and, for the neutron energies of most significance in the stratosphere, had a value of $3\frac{1}{2}$-4, see Fig 10. The deviation of the angular response of the reduced moderator from isotropy is typically $9\frac{1}{2}$% but with an extreme value of -20% corresponding to the case where neutron irradiation is of the flat moderator face through which the boron trifluoride counter tube is inserted.

Cadmium sleeves (20 milli-inch thick) with different degrees of perforation were mounted in turn upon the boron trifluoride counter tube and the resulting count-rate sensitivity of the reduced moderator was determined as a percentage of that for the unsleeved situation. Both whole counter tube sleeves and active length only sleeves were investigated: the results are given in Figure 11.

Source of Neutrons	Count Rate Ratio of Response of Reduced Moderator to that of an Anderson-Braun Assembly			
	Unmodified	5 cm/2" Fe	10 cm/4" Fe	15 cm/6" Fe (or Polythene)
D-D	4.1	4.7	5.7	6.3
Am-Be	3.5	-	-	3.8 Polythene
D-T	3.2	4.6	5.2	5.7

FIGURE 10. COMPARISON OF CADMIUM-CLAD REDUCED MODERATOR WITH AN ANDERSON-BRAUN ASSEMBLY FOR NEUTRONS ~ 0.1–15MeV

% Area		% Sensitivity	
Cadmium	Perforation	Whole BF_3 Tube Sleeve	Active Length Only Sleeve
0	100	100	100
10	90	-	81
20	80	54	64
30	70	41	53
40	60	31	42
50	50	25	34
60	40	20	26
70	30	14	19
80	20	10	12
90	10	6	5
100	0	2	2

FIGURE 11. EFFECT ON SENSITIVITY OF PERFORATED CADMIUM SLEEVE AROUND BORON TRIFLUORIDE COUNTER TUBE

The sensitivity of the reduced moderator with a natural isotopic mixture boron trifluoride proportional counter tube of the same dimensions and filling pressure as the usual enriched counter tubes was determined as 31% of that of the reduced moderator with an enriched tube. In respect of both pulse amplitude and resolution the natural isotopic mixture counter tube compared favourably with the enriched isotopic mixture counter tubes.

A theoretical estimate was made of the cadmium thickness necessary around an enriched boron trifluoride counter tube to achieve the required sensitivity fraction of 25-29% (i.e 1/4 - 1/3½). As the cadmium slow neutron absorption cross-section does not follow the usual inverse neutron velocity relation, an effective absorption cross-section was obtained for an assumed Maxwellian slow neutron energy distribution of temperature about 300°Kelvin (absolute). The transmission of slow neutrons, assumed to be isotropically incident on a cadmium-plated boron trifluoride counter tube, was obtained using a tabulation of the second exponential integral $-E_2(x)$, where x = the slow neutron mean free path. Cadmium thicknesses of 44 micrometers/1.7 milli-inches (25% transmission) and 38 micrometers/1.5 milli-inches (29% transmission) were indicated for the enriched isotopic mixture boron trifluoride counter tube.

A simulation of cadmium plating was obtained using indium foils as sleeves over the whole boron trifluoride counter tube. It had been theoretically estimated from consideration of the effective 300°K slow neutron absorption cross-sections, atomic mass numbers and densities that 21 milli-inches of indium would be equivalent to 1 milli-inch of cadmium. Using this equivalence factor, the indium simulation experiment indicated cadmium thicknesses of 38 micrometers/1.5 milli-inches (25% transmission) and 30 micrometers/1.2 milli-inches (29% transmission) for the enriched isotopic mixture boron trifluoride counter-tube - see Fig. 12.

Indium Sleeving Over Whole BF3 Counter Tube

Thickness (milli-inch)	0	5	10	15	20	25	30
% Count Rate	100	62	47.5	39	32.5	28.3	25

NB 1 milli-inch cadmium equivalent to 21 milli-inch indium

Cadmium Plating

Tube	Nominal Cadmium thickness (milli-inch)	% Count Rate		% Count Rate	
		With Cd on Stock	Without Cd on Stock	With Cd on Stock	Without Cd on Stock
Enriched	0	-	100		
Enriched	1.0	48	51.8		
Enriched	1.3	35.5	37.3		
Enriched	1.5	21.0	22.7		
Natural	0	-	30.8	-	100
Natural	0.1	24.6	26.8	79.8	86.9
Natural	0.2	22.4	24.4	72.5	79.1

FIGURE 12. EFFECT OF INDIUM SLEEVING AND CADMIUM PLATING ON BORON TRIFLUORIDE COUNTER TUBE SENSITIVITY

Guided by the results of theory and experiment, both the enriched and the natural isotopic mixture boron trifluoride counter tubes were plated with appropriate thicknesses of cadmium: the sensitivity fraction results are given in Fig. 12. It should be noted that (a) so as not to risk the reliability of the boron trifluoride counter tubes their mounting-stocks were not immersed in the plating solution, and (b) the cadmium plating thicknesses are only nominal, being equated with the measured cadmium thicknesses on flat test plates in the same solution for the same time and at the same current density. As the mounting-stocks of the counter tubes are also inserted within the moderator, the cadmium-plated tubes were tested for sensitivity both with and without a cadmium sleeve over their unplated stocks. The cadmium-plating experiment, in reasonably good agreement with theory and the indium simulation, indicated that a sensitivity fraction in the range 25-29% could be met by either:

a cadmium thickness of about 35 micrometers/1.4 milli-inches over an enriched isotopic mixture filling boron trifluoride counter tube
or
a cadmium thickness of about $1\frac{1}{2}$ micrometers/0.05 milli-inches over a natural isotopic mixture filling boron trifluoride counter tube.

As the natural isotopic filling boron trifluoride counter tube has no disadvantages and requires only a very slight adjustment of its sensitivity (the required cadmium thickness corresponds to about a tenth of the usual 'flashing' of cadmium employed as a protective finish) and may be acceptable without sensitivity adjustment, it appears to be a commendably simple solution to the reduced moderator over-sensitivity problem. This solution can be restated as a prediction - that the indication of stratospheric dose-equivalent-rate obtained from a cadmium-clad reduced moderator plus natural isotopic filling boron trifluoride counter tube (perhaps with a 1-2 micrometer finishing of cadmium) should be essentially the same as that from the earlier, Anderson-Braun version of the In-Flight Radiation Warning Meter (see Figs. 13 and 14 which are to the same scale): this prediction should be verified by flight testing.

SUMMARY AND COMMENT

In the course of the work described in this paper the fact that Geiger counters can give an adequate indication of the dose-equivalent-rate of the directly ionizing component of stratospheric radiation was demonstrated yet again. Although providing the In-Flight Radiation Warning Meter with a tissue-star response was shown to be technically possible, this development was not pursued because the weight increase that would have resulted was not considered justified for a ~20% component of dose-equivalent rate (an instrumental scaling factor will continue to be used for the stratospheric tissue-star dose-equivalent-rate). It has now been demonstrated that an adequate indication of the stratospheric neutron dose-equivalent-rate can be obtained from a simple moderator-detector comination of significantly less weight than the Anderson-Braun neutron remmeter but with the same count-rate sensitivity: a new reduced-weight version of the Concorde In-Flight Radiation Warning Meter can now be engineered (see Fig. 14).

The topics of this paper are but part of the British programme of work dealing with the radiological protection of supersonic passenger aircraft: this will be reviewed by Fuller and Day in a paper to be presented later this year at a CERN International Congress - see Ref. 10.

ACKNOWLEDGEMENTS

The work described in this paper was done under contracts for the Ministries of Technology and Aviation Supply, and for the British Aircraft Corporation by members of the AWRE Radiation Measurement Section with the technical support of the AWRE Nuclear Instrumentation Section. The balloon flights at the 'Centre de Lancement de Ballons', Aire-sur-Adour, were arranged by Dr R Kaiser of the 'Centre des Recherches Nucleaires' (CRN) in collaboration with Dr Miro and Dr Deltour of the 'Centre d'Enseignement et de Recherches de Medecine Aeronautique' (CERMA). The experiments around NIMROD and NINA were made possible by radiation protection staff of the Science Research Council at the Rutherford High Energy and Daresbury Nuclear Physics Laboratories respectively.

FIGURE 13. SST IN-FLIGHT RADIATION WARNING METER: ANDERSON-BRAUN VERSION

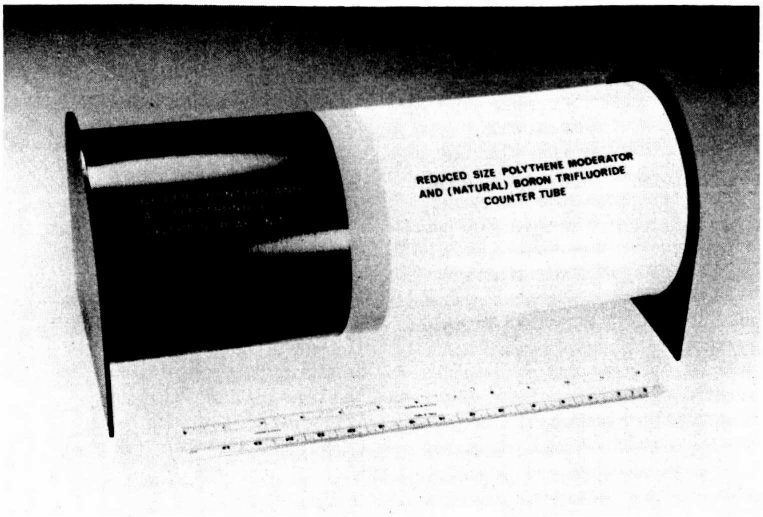

FIGURE 14. SST IN-FLIGHT RADIATION WARNING METER:

MODEL OF PROPOSED NEW REDUCED MODERATOR VERSION

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