Evaluation of the Hazard From Exposure to Electron Irradiation Simulating That in the Synchronous Orbit

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The electron spectrum predicted for the synchronous orbit has been simulated to determine the effects that might occur to astroscientists exposed to such irradiation while on a prolonged space station mission in that region. Miniature pigs were exposed to monoenergetic and spectral-fractionated irradiations with 0.5 to 2.1 MeV electrons. Clinical and pathological alterations observed in biopsies were correlated with depth-dose pattern and length of post-irradiation period up to one year. With monoenergetic electrons, the lowest dose causing a recognizable lesion was 1450 rad and with increasing dose lesions appeared earlier and were more severe. At the highest dose given, 2650 rad, ulceration extending into the dermis was present by twenty-one days and required about four months for complete healing. Spectral-fractionated irradiations, in which the total dose range was essentially comparable to that of the monoenergetic series, resulted in very minimal outer dermis edema at 1790 rad and at no dose employed did necrosis of epidermis or ulceration into dermis occur.

Apart from the possibility of a solar flare, nominally only low energy electrons constitute a possible radiation hazard for astronauts and scientists spending long periods of time lightly shielded on a space station in the region of the outer belt or in the synchronous orbit. In the course of determining the maximum permissible dose for such individuals the effects of monoenergetic, spectral-fractionated, and protracted irradiations with 0.5 to 2.1 MeV electrons are being investigated in miniature pigs. Clinical and pathological alterations in the skin are being correlated with depth-dose pattern, size of area exposed, and length of post-irradiation periods. The latter have been arbitrarily divided into (a) immediate, up to thirty days, (b) intermediate, thirty to one hundred and eighty days, (c) interval, six months to three years, and (d) long-term, three to ten years. From a practical point of view it is necessary to know whether any immediate undesirable responses such as blistering, oozing, or erythema may develop, which could impair the efficiency of the astroscientists. It is also important to determine whether long-term effects such as widespread dermatofibrosis or a malignant neoplasm may arise.

Dosimetry Methods

The methodology employed has been described previously (1) so that essentially only the general procedures are herein noted. A Dynamitron was the source of electrons. A Faraday cup was used to set the intensity levels for each irradiation and to check the stability of the Dynamitron. An extrapolation ion chamber, designed for this program, was used to determine the surface dose under the same irradiation conditions as in the animal irradiations. For these irradiations the miniature pigs were covered by space suit shielding equivalent to 2.0 mm of tissue. A mockup of the pig's body simulated the tissue surrounding the ionization chamber during correlation measurements. Thermoluminescent dosimeters were used to establish the correlation of the fields measured outside the space suit to the dose measured by the extrapolation chamber placed under the space suit. During the skin irradiations a matrix of TLD's was attached to the surface of the space suit shielding to monitor the variation in radiation level over the pig's skin. A 1 cc tissue-equivalent ionization chamber was used in a constant fixed geometry to monitor the relative beam intensity during the periods of irradiation.

Spectra Simulation

The time average electron integral flux at the equatorial synchronous altitude is indicated in the following equation:

$$\Psi(> E) = 5.2 \times 10^{7} \cdot e^{-5E} \frac{\text{electrons}}{\text{cm}^2\,\text{sec}} (*)$$

Where

E = electron energy in MeV

$(> E)$ = Flux of electrons with energy greater than E

This spectrum is plotted in Figure 1

*James I. Vette, Models of the Trapped Radiation Environment. Vol. III: Electrons at Synchronous Altitudes, Aerospace Corp., El Sequndo, Calif. NASA-SP-3024, 1967.

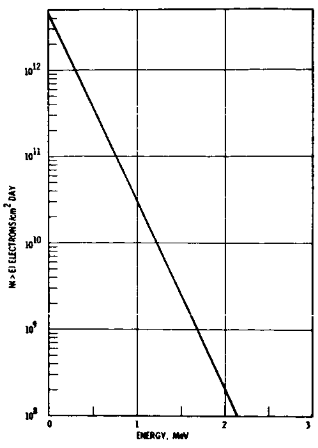


Fig. 1. Predicted electron spectrum for equatorial synchronous orbit.

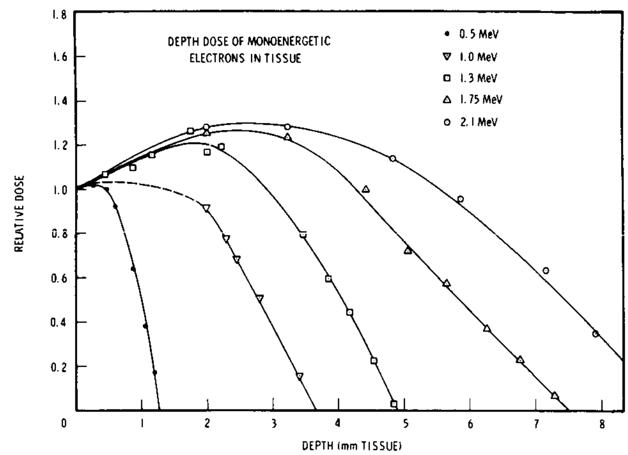


Fig. 2. Depth dose of monoenergetic electrons in tissue.

Since the space suit shielding is equivalent to 2.0 mm of tissue, electrons below 0.8 MeV cannot penetrate the space suit shielding of an astronaut and do not have to be considered.

From the depth-dose measurements taken during the first phase of the program, the penetration of a given energy electron may be accurately predicted. Figure 2 shows the characteristic penetration of electrons with energies in the region of interest taken during the first phase of the program. The data from Figure 2 may be presented in a more satisfactory manner to make interpolation between incident energies. By plotting the depths at which a given percentage of the incident dose is absorbed, a series of curves results. Figure 3 shows the relationship of absorbed dose and incident energy for 10, 50, and 90 percent of the incident dose levels. These curves exhibit a regularity that makes interpolation of depth patterns straightforward and simple.

These curves may be used to evaluate the penetration of any electron having incident energy from 0.5 to 2.1 MeV. By taking the predicted spectra of the synchronous orbit and dividing the electron spectra into small energy bins, the characteristic depth-dose relation may be calculated for each energy bin. The sum of these penetrations weighted by the number of electrons predicted in each bin then represents the total depth-dose pattern that would be expected from an electron beam whose energy spectrum is that of the synchronous orbit.

The number of electrons in each energy bin is multiplied by the value of $\frac{dE}{dX}$ in tissue for the energy of that bin from the tables of Berger and Seltzer(*) and the product then represents the absolute value of the dose-depth curve. The curves for all the energy bins are then added to get the resultant dose versus depth for the synchronous spectrum as shown in Table 1.

Table 1

Relative Dose	Depth In Tissue (millimeters)	Depth In Pig (millimeters)
1	0	0
0.67	0.5	1.5
0.42	1	3
0.25	1.5	4.5
0.13	2	6
0.04	3	9
0.01	4	12
0.006	5	15

*Additional Stopping Power and Range Tables for Protons, Mesons, and Electrons By: Berger and Seltzer NASA SP-3036

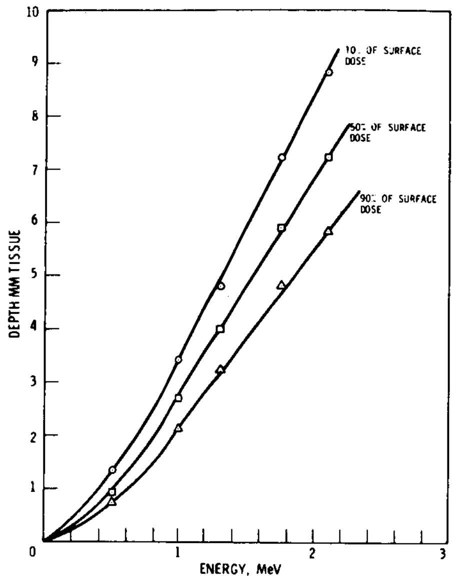


Fig. 3. Characteristics of penetration of monoenergetic electrons.

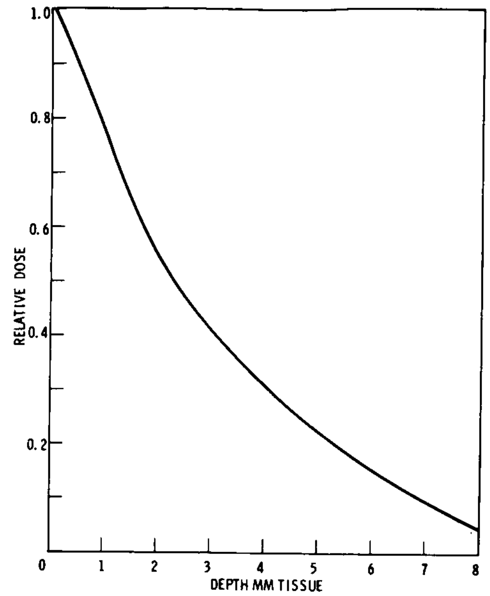


Fig. 4. Depth dose pattern from the predicted synchronous orbit spectrum.

From measurements of the skin characteristics of miniature pigs, the epidermis and dermis were considered approximately two to possibly three times thicker than the same relative layers in human skin. Thus, the relative dose desired in the target animal to simulate equivalent penetration in man occurs at the relative depths as shown in Table 1 and in Figure 4. Several monoenergetic electron energies could be selected such that the sum of their depth dose penetration curves would correspond to the predicted pattern of Table 2. A final selection of three monoenergetic electron energies was made to simulate the equatorial synchronous orbit spectrum. This selection appears in Table 3, which shows the predicted dose from the synchronous orbit spectrum, the simulation dose that would be deposited from the three monoenergetic electron irradiations, and the differences. The largest discrepancy is seen at a depth of 2 mm, where the simulation is 0.04 less than the predicted dose pattern, when normalized to 1.0 at the skin surface. The depth dose pattern that would be given by the simulation is shown in Figure 4.

During an electron irradiation the exposure was uniform to the trunk over an area 12 inches wide. The axis of rotation was approximately on a line from the head to tail, through the central mass of the animal. There is some variation in the distance from the skin surface to the exit window. To establish whether this variation made a significant change in dose deposition in relation to the 1-cc tissue-equivalent ionization chamber positioned near the exit window, the dose levels were measured as a function of distance from the window. The results, Figure 5 show that position of the central flank of the pig with respect to the exit window was not critical within ± 2 inches.

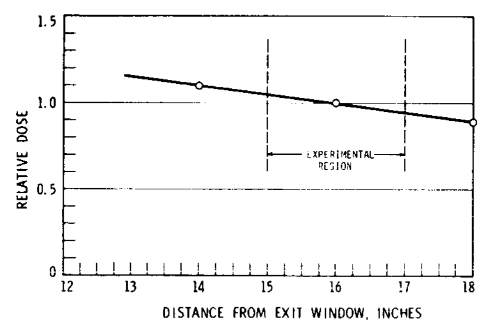


Fig. 5. Measured dose level variations with separation of the target animal from the exit window of the Dynamitron.

The procedure adopted in the first series for each pig irradiation was to make three irradiations on three successive days, with a different incident energy for each irradiation. In the second series the successive irradiations were made within 35-70 minutes. The sequence of incident energies was at random. Before each irradiation, a mockup of the pig's body surface was placed in the equivalent geometry and a relationship was established between the extrapolation tissue-equivalent ionization chamber shielded by the space suit and TLD's on the front surface of the space suit. During irradiation, the space suit shielding was placed over the pig's skin, and a matrix of TLD's was used to measure the intensity of dose over the total area being exposed.

Table 2. Depth Dose Values for Equatorial Synchronous Orbit

Relative Dose	Depth in Man (millimeters)	Depth in Pig (millimeters)	Relative Dose
27,600	0	0	1
18,600	0.5	1.5	0.67
11,700	1	3	0.42
6,990	1.5	4.5	0.25
3,550	2	6	0.13
980	3	9	0.04
340	4	12	0.01
170	5	15	0.006
55	6	18	0.002
9	7	21	-
4	8	24	-

Table 3. Comparison of the Depth Dose Pattern by the Predicted Synchronous Orbit to the Simulation by Three Monoenergetic Electron Irradiations

Depth (mm)	0	1	2	3	4	5	6	7	8	9
Predicted Dose	1.00	0.77	0.57	0.42	0.30	0.20	0.13	0.09	0.06	0.04
Simulation Dose*	1.01	0.77	0.53	0.43	0.32	0.22	0.14	0.10	0.05	0.00
Difference	+0.01	0.00	-0.04	+0.01	+0.02	+0.02	+0.01	+0.01	-0.01	-0.04

*Simulation Energies 1.0 MeV - 48% with space suit shield
1.75 MeV - 37% with space suit shield
2.1 MeV - 16% without space suit shield

To determine whether the uniformity of TLD measurements on the outside surface would correspond to a uniformity inside the shield of the space suit, a matrix of TLD's was placed inside and outside the suit and irradiated simultaneously. The results of the measurement are shown in Table 4. The uniformity represented by the measurements inside the space suit shielding shows that the measurement of dose on the surface of the space suit is a satisfactory measure of dose uniformity.

Table 4. Uniformity of Dose Deposition Inside and Outside Space Suit

MATRIX OUTSIDE

180		180		190
200	190	200	200	190
200		200		210
190	190	190	180	200
190	190	180	180	190
170		160		170

MATRIX INSIDE

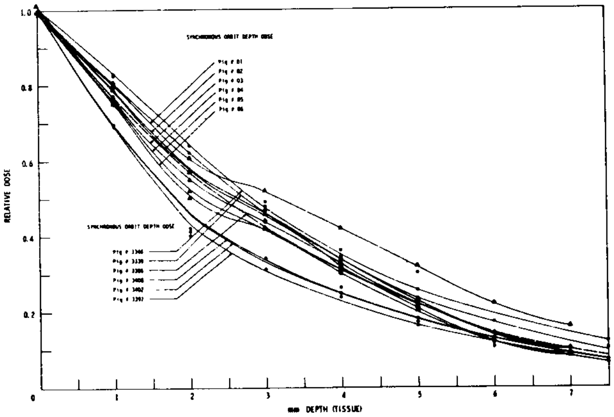
150		150		160
150	170	170	170	170
160		160		170
170	180	150	180	160
170	170	160	170	170
160		150		160

The CaF_2:Mn hot-pressed chips used for this program have a thickness of 550 mg/cm^2. This represents an equivalent thickness of tissue of about 4 mm. The differences among the readings in Table 4 of the TLD measurements inside and those outside the space suit can be predicted from the depth-dose curves in Figure 2. Since the TLD chips represent a target that is thin in comparison with the range of a 2.1 MeV electron the average dose measured by the TLD should be in reasonable agreement with the dose, as measured by the extrapolation tissue-equivalent ionization chamber. This agreement was established within 10 percent for the exposures at 2.1 MeV.

The depth-dose penetration achieved in the actual irradiations of the animals is seen in Figure 6. This Figure may be compared with that of Figure 4 showing the depth-dose pattern from the predicted synchronous orbit spectrum. In general the simulation is quite good. In all cases, the quoted dose is the actual rad dosage at the skin surface.

Figure 6

Comparison of Depth Dose Penetration of Actual Irradiations



Experimental Results

Monoenergetic Trunk Irradiations

A total of eleven pigs received monoenergetic trunk irradiations at either 1.3 or 2.1 MeV with a range in doses from 245 to 2650 rad, as shown in Table 5. No gross or microscopic evidence of a reaction in the skin was observed in the first post-irradiation year (Table 8) at the following doses: 245, 312, 650, 710, 930, 1020, and 1230 rad. At 1450 and 1660 rad distinct erythema was first seen at 87 days post-irradiation while on the 102nd day it was quite marked in the former and enormous in the latter.

The erythema and pigmentation subsided slowly at both doses and disappeared completely at about 200 days. With increasing dose, reactions were noted earlier. At 1700 rad there was moistness of skin felt grossly at 29 days post-irradiation and outer corium edema seen in the biopsy at that time. Distinct erythema appeared by the 71st day and was gone by the 100th day. Biopsies on the 376th and 465th days disclosed no tissue alterations. At 1980 rad, scattered focal areas of necrosis were noted grossly at the 18th day with erythema that subsided by the 52nd day. The highest dose of 2650 rad produced the most extensive lesion with central necrosis at the 12th day and widespread ulceration extending into the dermis by the 21st day. Gradually healing took place with residual erythema and pigmentation being gone at 5 months, although scaling in the irradiated area continued up to one year.

The irradiation effects may be summarized by stating that no recognizable lesion occurred until a dose of 1450 rad was administered. As would be expected, at higher doses reactions occurred earlier and were more severe. Even with rather extensive ulcerations that occurred at the highest dose of 2650 rad, healing developed within five months.

Table 6. Summary of Spectrum Irradiations Performed In 48-72 Hours

Pig No.	Date (July 1969)	Energy (MeV)	Average Total Dose On Side of Pig (rad_{tissue})		Dose in Central Flank Area (rad_{tissue})		Spectrum Composite (percent)
			Right	Left	Right	Left	
3339	25	1.0	1,130	1,000	1,180	1,060	40
	23	1.75	1,090	1,280	1,140	1,330	44
	22	2.1	450	430	460	440	16
			2,670	2,710	2,780	2,830	100
3346	25	1.0	730	830	760	850	40
	23	1.75	850	780	900	810	42
	22	2.1	340	340	370	390	18
			1,920	1,950	2,030	2,050	100
3386	14	1.0	860	950	880	990	48
	15	1.75	660	730	710	740	37
	16	2.1	270	320	280	340	16
			1,790	2,000	1,870	2,070	101
3392	17	1.0	1,250	1,240	1,390	1,320	61
	15	1.75	600	540	650	590	28
	16	2.1	200	230	230	270	11
			2,050	2,010	2,270	2,180	100
3402	17	1.0	790	760	840	820	59
	18	1.75	360	390	380	410	29
	16	2.1	160	150	180	160	12
			1,310	1,300	1,400	1,390	100
3408	17	1.0	520	660	570	720	60
	18	1.75	300	240	320	250	27
	19	2.1	130	120	150	130	13
			950	1,020	1,040	1,100	100

Table 5

Monoenergetic Trunk Irradiations

Pig Number	Date Irradiated	Energy (MeV)	Average Total Dose (Rad) Rt. Side	Lt. Side
3247	9-12-68	2.1	650	
3259	9-12-68	2.1		1700
3361	1-3-69	1.3	245	312
3340	1-3-69	1.3	1980	2650
3337	7-11-69	1.3	690	760
3334	7-10-69	1.3	1660	
		2.1		1450
3338	7-19-69	2.1	1110	740
3437	7-23-69	1.3	930	710
01	2-23-70	2.1	1420	
02	2-24-70	2.1		1020
04	2-24-70	2.1		1230

Trunk Spectral Irradiations Performed in 48-72 Hour Period

Six pigs were irradiated with a spectrum of 1.0, 1.75, and 2.1 MeV within a 48 to 72 hour period as shown in Table 6. Since only one energy was available at a single exposure, it was decided to give the total dose spread out over the period noted above. While being a spectral irradiation, when all energies had been used, it was of necessity also a fractionated scheme. Subsequent to this, another experiment was run in which the time period for irradiations was compressed into 35-70 minutes. This came closer to a true spectral arrangement, but as yet still consisted of three consecutive exposures at different energies so it also represented a fractionated scheme. The dose range was selected to be similar to that of the monoenergetic trunk irradiation series, as nearly as possible, extending from 950 to 2710 rad (Table 9). No gross or microscopic evidence of a reaction in the skin was observed in the first post-irradiation year at the following doses: 950, 1020, 1300, and 1310 rad. At 1790 rad and at 2000 rad no gross reaction was seen grossly but on biopsy on the 7th day in the former and at the 35th day in the latter minimal edema of the very outer corium was seen microscopically. More frequent biopsies might have disclosed alterations but certainly, if they existed, they were insufficient to produce a lesion that could be recognized on clinical examination.

In summary, by comparison with the monoenergetic series of irradiations, only a most minimal reaction occurred and that was not until a dose of 1790 rad was given. It should be mentioned, however, that the largest single dose component in the total 1790 rad exposure was 1330 rad. In the monoenergetic series the lowest single exposure resulting in a reaction was slightly higher than that being 1450 rad. Apparently this series responded, as one might expect, as a fractionated dose response and therefore the total dose effect was quite different from that of the total dose reaction when given as a single exposure in the monoenergetic series.

Trunk Spectral Irradiations Performed in 35-70 Minutes

This series of irradiations was designed and carried out after the spectral irradiations noted previously as being performed in a 48-72 hour period as shown in Table 7. The same energies were used; namely, 1.0, 1.75, and 2.1 MeV. The time period was compressed so that individual energy irradiations were given one after another and in a total period of between 35 to 70 minutes from first to last exposure. Again, it was recognized that this also was a fractionated scheme but might better simulate the theoretical situation in which the entire spectral irradiation occurred in one exposure. In addition, intermediate doses not given in the former spectral series were administered this time to correspond more nearly to the monoenergetic series. The purpose in this was again to find out the lowest dose at which a reaction might occur.

Table 7

Summary of Spectrum Irradiations Performed in 35-70 Minutes

Pig No.	Date (Feb. 1970)	Energy (MeV)	Average Total Dose on Side of Pig (rad_{tissue})		Spectrum Composite (percent)
			Right	Left	
01	23 (L)	1.0		430	39
		1.75		385	35
		2.1		280	26
				1,095	100
02	24 (R)	1.0	390		42
		1.75	400		42
		2.1	150		16
			940		100
03	24 (L) 25 (R)	1.0	580	460	44
		1.75	550	380	40
		2.1	200	170	16
			1,330	1,010	100
04	24 (R)	1.0	810		48
		1.75	650		38
		2.1	240		15
			1,700		100
05	25 (L) 26 (R)	1.0	240	1,290	43
		1.75	390	890	44
		2.1	120	270	13
			750	2,450	100
06	25 (L) 25 (R)	1.0	950	630	53
		1.75	520	510	29
		2.1	320	180	18
			1,790	1,320	100

Six pigs were irradiated in this series in a range from 750 to 2450 rad with the largest single component being 1290 rad. It is to be recalled that the lowest dose response in the monoenergetic series occurred at 1450 rad. Twenty biopsies were performed between the third and 150th post-irradiation day. This series has currently an eight month follow-up instead of one year for comparison with the earlier (48-72 hours) spectral series. No gross clinical reaction was observed at any dose. In a biopsy on the third post-irradiation day at 2450 rad spongiosis of the epidermis was seen but no edema of underlying dermis. The epidermal spongiosis may have been an artefact.

In summary, this spectral trunk irradiation series resulted in no post-irradiation reactions, except the very minor ones at 1790 and 2450 rad. These results differ substantially from that of the monoenergetic series in which a distinct reaction occurred at 1450 rad and at all higher doses through 2650 rad. It is suggested that the dose fractionation accounts for the lack of reaction in the two spectral series, since in the latter a number of total doses given were in the range in which prominent lesions developed in the monoenergetic series.

Table 8

Summary of Monoenergetic Trunk Irradiations

Pig Number	Date Irradiated	Energy MeV	Average Total Dose Rt. Side	Lt. Side	Post-irradiation day, Dose [ ], and Histopathology Code ( )
3247	9-12-68	2.1	650		29[650](1) 71[650](1) 177[650](1) 353[650](1)
3259	9-12-68	2.1		1700	9[1700](1) 29[1700](2) 71[1700](2) 157[1700](1) 376[1700](1) 465[1700](1)
3361	1-3-69	1.3	245	312	2[245](1) 7[245](1) 21[245](1)
3340	1-3-69	1.3	1980	2650	2[1980](1) 7[1980](1) 198[1980](5)
					21[2650](4) 263[2650](5) 353[2650](5)
3337	7-11-69	1.3	690	760	39[760](1)
					96[1660](2) 165[1660](5) 370[1660](1)
3334	7-10-69	1.3	1660		370[1660](1)
		2.1		1450	10[1450](1)
3338	7-19-69	2.1	1110	760	32[760](1)
3437	7-21-69	1.3	930	710	28[930](1)
01	2-23-70	2.1	1420		5[1420](1) 150[1420](1)
02	2-24-70	2.1		1020	150[1020](1)
04	2-24-70	2.1		1230	9[1230](1) 150[1230](1)

Histopathology code for Tables 8, 9, and 10. 1. No recognizable lesion. 2. Edema of outer dermis. 3. Epidermal necrosis. 4. Ulceration of epidermis extending into dermis. 5. Degeneration outer corium. 6. Fibrosis, dermis.

Table 9

Summary of Spectrum Trunk Irradiations Performed Within 48-72 Hours

Pig Number	Date Irradiated (July 1969)	Energy MeV	Average Total Dose Rt. Side	Lt. Side	Spectrum Composite (%)	Biopsies Post-irradiation day, Dose [ ], and Histopathology Code ( )
3339	25	1.0	1130	1000	60	151[2670](1)
	23	1.75	1090	1280	44	36[2710](2)
	22	2.1	450	430	16	
			2670	2710	100	
3346	25	1.0	730	830	40	
	23	1.75	850	780	42	
	22	2.1	340	340	18	
			1920	1950	100	
3386	14	1.0	860	950	48	4[2000](1) 35[2000](2)
	15	1.75	660	730	37	7[1790](2)
	16	2.1	270	320	16	
			1790	2000	100	
3392	17	1.0	1250	1240	61	158[2010](1)
	15	1.75	600	540	28	203[2050](1)
	16	2.1	200	230	11	
			2050	2010	100	
3402	17	1.0	790	760	59	
	18	1.75	360	390	29	
	16	2.1	160	150	12	
			1310	1300	100	
3408	17	1.0	520	660	60	33[1020](1)
	18	1.75	300	240	27	
	19	2.1	130	120	13	
			950	1020	100	

Table 10

Summary of Spectrum Trunk Irradiations Performed Within 35-70 Minutes

Pig Number	Date Irradiated	Energy MeV	Average Total Dose Rt. Side	Average Total Dose Lt. Side	Spectrum Composite (%)	Post-irradiation day, Dose [ ], and Histopathology Code ( )
01	2-23-70 Left	1.0 1.75 2.1		430 385 280 1095	39 35 26 100	Control, non-irradiated 2-5-70 150[1095](1)
02	2-24-70 Right	1.0 1.75 2.1	390 400 150 940		42 42 16 100	7[940](1) 150[940](1)
03	2-24-70 Left 2-25-70 Right	1.0 1.75 2.1	580 550 200 1330	460 380 170 1010	44 40 16 100	4[1010](1) 150[1010](1) 150[1330](1)
04	2-24-70 Right	1.0 1.75 2.1	810 650 240 1700		48 38 15 100	4[1700](1) 112[1700](1) 150[1700](1)
05	2-25-70 Left 2-26-70 Right	1.0 1.75 2.1	240 390 120 750	1290 890 270 2450	43 44 13 100	110[750](1) 150[750](1) 3[2450](1) 8[2450](1) 15[2450](1) 95[2450](1) 150[2450](1)
06	2-25-70 Left 2-25-70 Right	1.0 1.75 2.1	950 520 320 1790	630 510 180 1320	53 29 18 100	150[1320](1) 111[1790](1)150[1790](1) 150[1320](1)

References

1. Lippincott, S.W., Bender, R., Foelsche, T., Azzam, N., Montour, J. and Rogers, C.: Arch. Path. Vol. 89, 1970 p. 416.