SEP 12 1966

MASTER

CFSTI PRICES

UNCLASSIFIED

CLASSIFICATION LEVEL
(S, C OR U)

EC # 1.00; MN 50

ATOMICS INTERNATIONAL
A Division of North American Aviation Inc.

NAA-SR-MEMO COVER SHEET

REPORT TITLE

AUTHOR

NAA-SR-MEMO 11901

(This Document Contains 17 Pages.)
(This is Copy of Series)

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

CLASSIFICATION TYPE
(RD OR DI)

*NAA-SR-MEMOs are working papers and may be expanded,
modified, or withdrawn at any time, and are intended for
internal use only.*

THIS REPORT MAY NOT BE PUBLISHED WITHOUT THE APPROVAL OF THE PATENT BRANCH, AEC.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

UNCLASSIFIED

CLASSIFICATION LEVEL
(S, C OR U)

DO NOT REMOVE THIS SHEET

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ATOMICS INTERNATIONAL A Division of North American Aviation, Inc.		NAA-SR- TDR NO 11901		APPROVALS 	
TECHNICAL DATA RECORD		PAGE 1 OF 17		<i>C.A. Willis</i>	
AUTHOR DEPT & GROUP NO G. W. Spangler <i>D.W. Spangler</i> 731-14		DATE 4/20/66 <i>E. Donovon</i>		GO NO 7647 <i>E. Donovon</i>	
TITLE Fast Neutron Weighting Factors for Manrated SNAP Reactor Applications		S/A NO 1414		TWR	
PROGRAM SRIP		SUBACCOUNT TITLE Relative Biological Effectiveness		SECURITY CLASSIFICATION (CHECK ONE BOX ONLY)	
DISTRIBUTION		UNCL. ☒ AEC ☒ DOD ☒ CONF. ☐ SECRET ☐		(CHECK ONE BOX ONLY) RESTRICTED DATA ☐ DEFENSE INFO. ☐	
R. Alexander 4 R. Aronstein 2 E. Ash 2 R. Ashley 4 R. Audette 5 S. Berger 2 A. Campise 2 W. Carlson 2 D. Cockeram 2 W. Davis 2 W. DeBear 2 R. Detterman 5 E. Donovan 2 S. Fields 5 R. Galantine 2 R. Gerber 2 R. Gimera 5 C. Griffin 2 J. Hale 5 R. Hart 2 C. Hendricks 5 J. Hume 2 M. Huntsinger 2 R. Jetter 5 V. Keshishian 2 R. Koontz 4 W. Kunkel 4 J. Lang 4 L. Maki 5 D. Mason 5 W. Miller 4 L. Mims 5 D. Monnie 2 H. Morewitz 4 L. Moss 5 A. Piccot 5 M. Remley 4 J. Rohlf 5 H. Rood 5 K. Rooney 5 W. Sayer 2 J. Susnir 5 C. Willis(5) 5 R. Vollmer 4		AUTHORIZED CLASSIFIER SIGNATURE <i>C.A. Willis</i>		DATE 4-22-66	
STATEMENT OF PROBLEM In the design of a manrated SNAP reactor a fast neutron weighting factor must be chosen in order to appropriately optimize the shield design and power source configuration. Firmly established fast neutron weighting factors for space applications do not exist and it is probable that the basis for these factors would be different from those recommended for terrestrial radiation protection.					
ABSTRACT A review of the RBE problem is presented and its relation to fast neutron weighting factors for SNAP manrated reactor systems is discussed. Reasonably justified fast neutron weighting factors can be specified for particular SNAP reactor applications; however, there is insufficient experimental justification for a firm specification of general weighting factors.					

INTRODUCTION

The development of meaningful fundamental units for ionizing radiations has been in progress for over sixty years.⁽¹⁾ The various units that have been in use are based upon several radiation effects including; photographic film darkening, energy deposition in air, reddening of human skin, discharging of electrofied bodies, etc. A unit in common usage today is based on the energy deposition of an ionizing radiation in the material of concern. This physical unit of absorbed dose, the rad, is defined as the energy imparted by the ionizing radiation per unit mass of irradiated material, and has a magnitude of 100 ergs/gm.⁽²⁾ When doses to biological materials are based upon energy deposition, it is found that the different types of ionizing radiation have various efficiencies for producing similar effects.⁽³⁾ To account for this difference in efficiency the term Relative Biological Effectiveness (RBE) was introduced by H. M. Parker during the 1940's.^(4,5) Currently the RBE is defined as:⁽⁶⁾

$$\left[\text{RBE of a particular radiation} \right] = \frac{\left[\begin{array}{l} \text{200 kvp x-ray dose (rad) required to} \\ \text{produce an effect} \end{array} \right]}{\left[\begin{array}{l} \text{dose (rad) of that particular radiation} \\ \text{required to produce the same effect} \end{array} \right]}$$

The RBE is not an absolute value for any particular system, but depends on several factors including: the temperature, oxygen concentration, physiological state, and often on the exposure rate. One of the physical factors which effects the biological efficiency of a particular ionizing radiation, is the rate of energy deposition along the path of the ray or particle [i. e. linear energy transfer (LET)]. It has been found that for many biological effects, biological efficiency increases with LET reaching a maximum and then decreased with very high values of LET (Figure 1).^(7,8) Since its inception, the RBE was used as a weighting factor for high LET radiation and the unit used to describe radiation dose to man, the rem, was defined as, (Dose in rem) = (Dose in rad) x (RBE). A committee was appointed in 1960 by the International Committee on Radiological Protection and on Radiological Units and Measurements to study the concept and use of RBE in relation to radiation protection.⁽¹⁰⁾

In its report in 1962 the RBE Committee recommended, "that the term RBE be used in radiobiology only and that another name be used for the linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain for purposes of radiation protection a quantity that expresses on a common scale for all ionizing radiations the irradiation incurred by exposed persons."⁽¹⁰⁾ The name recommended for this factor is quality factor (QF). Provisions are made for other modifying factors. The product of absorbed dose (D), quality factor (QF) and other modifying factors is termed dose equivalent (DE) [i. e. $(DE) = (D)(QF)(\text{other modifying factors})$]. The major difference between RBE and QF is that RBE is a term to describe experimental results relating different types of radiation, whereas, QF is a factor "which ensures that the risk from a maximum permissible dose of high-LET radiation never exceeds that from a maximum permissible dose of low-LET reference radiation."^(10,11) It is noteworthy that QF is expressly inapplicable to doses larger than the ICRP criterion dose.^(10,11)

POSSIBLE BASES FOR NEUTRON WEIGHTING FACTORS

The most widely known basis for choosing neutron weighting factors is the recommendations used in industrial radiation protection work.⁽¹²⁾ The recommended values for quality factors are directly based on the linear energy transfer (Figure 2).^(9,12) Using the LET-QF relation as a basis and with a knowledge of the neutron energy spectrum, average quality factors can be derived.⁽¹³⁾ The RBE Committee Report noted, "The detailed relationship between RBE and LET, as it appears in the Recommendations, therefore, cannot be regarded as having other than a very slight experimental basis." As reported by Upton et al ⁽¹¹⁾ commenting on the RBE Committee Report, ". . . This summing-up still stands two years later. Newly available data on high energy radiations⁽¹⁴⁾ agree with earlier reports giving RBE values of ~ 1 for lethal and other acute effects in large animals exposed at high dose rates to neutrons or to protons and of ~ 10 or less for delayed effects of neutrons in mice and rats."

Quality Factors as a Function of LET
(Industrial Radiation Protection Recommendations)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901
DATE April 20, 1966
PAGE 6 OF 17

The National Aeronautics and Space Administration (NASA) is confronted with the problem of specifying weighting factors for the high-LET components of space radiation. A very active radiobiological research program is being supported by NASA in order to solve or clarify this problem.^(15,16) At the 1966 meeting of the Radiation Research Society, Dr. John Billingham presented the current position of NASA concerning the evaluation of radiation risk for manned space flight.⁽¹⁷⁾ Dr. Billingham presented a method for statistically combining solar flux data with assessments of the likelihood for biological response. This approach is a method of combining radiophysical and radiobiological data so that the balance between radiation, crew safety and mission success can be related to other hazards. A general conclusion that was stated is that on currently planned missions, with the currently recommended dose limits, space radiation is a minor problem. The major unknowns include the RBE and the validity of the currently recommended exposure limits. The stated NASA basis for current exposure limits is crew incapacitation during the mission. The weighting factor currently in use by NASA for assessing the hazards from high-LET space radiations is one.

Another possible basis for neutron weighting factors could be the various guidelines postulated by certain industries and agencies. In some of these guidelines (Figure 3) risk-limiting organs are specified.⁽¹⁸⁾ With the risk-limiting organ specified, appropriate values for QF and/or RBE can be inferred. Based upon these guidelines⁽¹⁸⁾ a QF of about five^(19,20,21,22,23,24,25,26,27) would be appropriate with the lens of the eye as risk limiting or a QF of about three^(1,7,10,27,28,29) for the skin or maybe a QF of one^(7,10,27,29,30) for the blood forming organs. The literature on the biological effects of the various ionizing radiation contains some conflicting data and wide diversities of opinion. Much of the difficulties in utilizing this experimental data arises from the lack of accurate and/or complete specification of the doses involved and the ambiguity of the effects reported. Despite the difficulties of interpretation a large quantity of experimental information is available.

FIGURE 3

RADIATION GUIDELINES FOR MANNED SPACE VEHICLES

(Suggested For Long-Duration Earth Orbital Or Interplanetary Missions)

Maximum Permissible Dose (Rem) Per Exposure Interval

Risk-limiting critical organ	Protracted or Fractionated				Single Acute	Emergency Acute	Integral Lifetime
	60 Days	3 Months	6 Months	1 Year			
Whole-body and blood-forming organs	50*	60*	75*	100*	50	150	500
Lens of eye	200	225	240	270	100	200	600
Skin of whole-body	275	300	350	400	100	400	1000
Skin of Extremities	600	650	750	900	250	600	1200

* Maximum exposure during any 20-day period not to exceed 25 Rem

The basic mechanisms for the production of biological damage by ionizing radiation is still not clearly understood; however, certain generalized hypothesis seem reasonable. "Large electric fields are suddenly brought into existence by the separation of positive and negative charges. These fields will, at first, influence the movement of electrons and all ionic species, and in a polar medium may break secondary hydrogen bonds and thus lead to disorder in macromolecules and possibly to denaturization of proteins."⁽³¹⁾ These basic physical and chemical phenomena take place in about 10^{-12} seconds. Certain of the chemical species produced by ionizing radiation have a long existence and may exert their influence at any time. However, if the biological system survives, elimination and repair mechanisms quickly begin to remove the unwanted products of irradiation. Irradiation altered macromolecules, such as DNA, may not be damaged sufficiently to cause their removal from the system and they remain exerting their influence for very long periods of time. On the cellular level this fraction of the radiation damage makes up most of the damage which is generally referred to as irreparable or non-recuperable. On the system or whole animal level the non-recuperable damage is far more difficult to describe; however, many measurements have been made and it amounts to about 10% of the total radiation damage.⁽³²⁾

It has been postulated that a major difference between the effects of low-LET radiation and high-LET radiation is that high-LET radiation produces more non-recuperable damage.⁽³³⁾ Krebs and Brauer⁽³⁴⁾ found, that as far as lethality effects are concerned, the non-recuperable damage caused by fission spectrum neutrons is the same as that caused by x-rays. They concluded, "that the relative biological effectiveness (RBE) of neutrons for causing permanent residual injury was the same as that for causing acutely lethal injury."

DISCUSSION

A review of the available literature gives RBE values for fast neutron irradiation of mammals from less than one to about thirty, with the majority

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901

DATE April 20, 1966

PAGE 9 OF 17

of these values falling between two and ten. This variation in weighting factor could change the shield weight by as much as 25%.⁽³⁵⁾ This 25% change in shield weight would probably require structural and configurational changes in the vehicle. The neutron dose weighting factors normally used in radiation safety work are quality factors, based on the extrapolation of the RBE data to zero dose rate. The quality factors are legislated values which probably will encompass new radiobiological data as it becomes available. This quality factor concept appears to offer an appropriate means for the control of the long-term, low-level exposure potential incurred in terrestrial reactor applications. In exposures of humans within the existing Maximum Permissible Dose (MPD) limits, the quality factors recommended by the RBE Committee appear sufficiently conservative to provide the necessary safety criteria.

However, there are several significant differences involved in space applications of reactor power sources. Included among these differences are:

1. the exposure rate can be known and the limiting exposure probably will not be based upon the potential exposure of a person during his entire working lifetime,
2. the neutron spectrum can be known and, therefore, the appropriate LET dependent factor (QF) may be accurately determined, and
3. the potential dose distribution within the exposed persons can be known which will allow the utilization of "additional modifying factors" to appropriately weigh the neutron exposures.

At the present time, for a clearly specified manned SNAP reactor mission, sufficient information is available for the determination of a reasonably justified fast neutron weighting factor which would be more realistic than the present QF values. An administrative selection of any of the possible bases, allows for a detailed determination of a particular fast neutron weighting factor. However, insufficient experimental data indicates that firm weighting factors cannot be specified at the present time, for either specific or general application.

ATOMICS INTERNATIONAL*A Division of North American Aviation, Inc.*NO. NAA-SR-TDR-11901DATE April 20, 1966PAGE 10 OF 17

One particular aspect of the basis of the QF concept, appears not to have been sufficiently investigated. The primary purposes of the RBE and/or QF in radiation protection work, is the biological weighting of different types of radiation so that their respective doses may be added. Although there is much experimental work reported and much still under way on the weighting concept, there appears to be little experimental data that demonstrates the validity of adding doses from different types of ionizing radiation for biological effects in mammals. A test of this concept can be made by experimentally determining the biological effects of a particular dose, in rem, with various neutron-to-gamma ratios.

It is recommended that additional experimental data be acquired in order to appropriately specify fast neutron weighting factors for SNAP manrated reactor designs. A fast neutron weighting factor is needed early in the design of manrated SNAP reactor systems. This data can be acquired by the initiation of a radiobiophysical research program utilizing the AI STIR facility.

TABLE I

RBE FOR SHORTENING OF LIFE SPAN

Test Radiation	Irradiated Object	RBE		Reference
		Acute	Protracted	
γ /Fission Neutrons	Mouse	5.8	14.4	33- Henshaw <u>et al</u> , 1946a; 1947
γ /Fission Neutrons	Mouse	1.8		33- Upton <u>et al</u> , 1954
γ /Fission Neutrons	Mouse	2.6		7- Storer <u>et al</u> , 1958
γ /Fission Neutrons	Mouse	2.2		5- Upton <u>et al</u> , 1960
γ /1 Mev Neutrons	Mouse	2.6	8.0	5- Upton <u>et al</u> , 1960
γ /Fission Neutrons	Mouse	2-3		33- Vogel, 1960; 1961
γ /Fission Neutrons	Mouse	1.70		33- Crotes & Gebhard, 1958
Roentgen rays/2 Mev Neutrons	Mouse	3.1		33- Nowell & Cole, 1959
Roentgen rays/8 Mev Neutrons	Mouse	1.56		33- Nowell & Cole, 1959
γ /2 Mev Fast Neutrons	Mouse		3.2	20- Evans, 1948
γ /2 Mev Fast Neutrons	Mouse		10	32- Neary, <u>et al</u> , 1957
γ /1 Mev Fast Neutrons	Mouse		13	32- Mole, 1957

The effect of the γ -radiation is diminished to 10 to 25% by distribution of the dose to many daily irradiations of 3 to 5 rad, while that of neutrons is reduced only little by fractionations - -
33- Hagen, 1962

ATOMICS INTERNATIONAL
A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901
DATE April 20, 1966
PAGE 11 OF 17

TABLE II
RBE FOR CATARACT FORMATION

Test Radiation	Irradiated Object	RBE		Reference
		Acute	Protracted	
X/1-2 Mev Fast Neutrons	Mouse	5		1- Leinfelder, <u>et al</u> , 1955
X/0.2 Mev Fast Neutrons	Mouse	5		3- Riley, <u>et al</u> , 1956
X/1-2 Mev Fast Neutrons	Mouse	4.5		3- Riley, <u>et al</u> , 1956
X/5-6 Mev Fast Neutrons	Mouse	2.4		3- Riley, <u>et al</u> , 1956
X/5-6 Mev Fast Neutrons	Mouse	4		3- Riley, <u>et al</u> , 1956
X/ 2.5 Mev Fast Neutrons	Mouse	4		3- Riley, <u>et al</u> , 1956
X/ 2.5 Mev Fast Neutrons	Mouse	4		3- Riley, <u>et al</u> , 1956
X/14 Mev Fast Neutrons	Mouse	3-4		19- Brown, 1960
γ /1 Mev Fast Neutrons	Mouse	3.6		24- Upton, <u>et al</u> , 1956
γ /4 Mev Fast Neutrons	Mouse	9.0		24- Upton, <u>et al</u> , 1956
γ /0.6 Mev Fast Neutrons	Mouse	3-4		24- Upton, <u>et al</u> , 1956
γ /1 Mev Fast Neutrons	Mouse	4.8		5- Upton, <u>et al</u> , 1961
γ /14 Mev Fast Neutrons	Mouse	2.1		5- Upton, <u>et al</u> , 1961
γ /Fission Neutrons	Mouse	5.8		26- Vogel, 1958
γ /1 Mev Fast Neutrons	Mouse		>3.2	20- Evans, 1948
γ /0.43 Mev Fast Neutrons	Mouse	7.3-8.9		22- Merriman, 1965
γ /1.0 Mev Fast Neutrons	Mouse	6.1-7.5		22- Merriman, 1965
γ /1.5 Mev Fast Neutrons	Mouse	4.6-5.2		22- Merriman, 1965
γ /1.8 Mev Fast Neutrons	Mouse	5.6-6.6		22- Merriman, 1965
X/1 Mev Fast Neutrons	Mouse		>10	14- Upton, <u>et al</u> , 1963
X/0.43 Mev Fast Neutrons	Mouse		10	14- Bateman, <u>et al</u> , 1963

TABLE III
RBE FOR ACUTE LETHAL EFFECTS

Test Radiation	Irradiated Object	RBE		Reference
		Acute	Protracted	
X/1 Mev Fast Neutrons	Mouse	1.6		33- Lawrence, et al, 1937
X/1 Mev Fast Neutrons	Mouse	6.2		33- Hagen, et al, 1950
X/Fission Neutrons	Mouse	3.6		33- Zirkle, et al, 1945
X/1 Mev Fast Neutrons	Mouse	3.2		20- Evans, 1948
X/1 Mev Fast Neutrons	Mouse	2.3-3.2		7- Storer, 1957
X/1 Mev Fast Neutrons	Mouse	1.7		33- Delihias, 1958
X/1 Mev Fast Neutrons	Mouse	1.2-2.1		3- Riley, 1956
X/Fission Neutrons	Mouse	1.6-4.6		24- Upton, 1956
γ /Fission Neutrons	Mouse	1.4		24- Upton, 1956
X/Fission Neutrons	Mongrel Dog	1.5		30- Ainsworth, <u>et al</u> , 1965
X/Fission Neutrons	Mammals	1.7		14- Fowler, <u>et al</u> , 1963
X/Fission Neutrons	Estimated for Man	1.6± 1.6		33- Harns, 1959
X/Fission Neutrons	Mongrel Dogs	0.9		14- Bond, <u>et al</u> , 1963
X/Fission Neutrons	Mouse	2.0		14- Bond, <u>et al</u> , 1963
X/Fission Neutrons	Rat	2.8		14- Bond, <u>et al</u> , 1963

An RBE between 2 and 3 can be assumed for acute lethal effects -- 33- Hagen, 1962

TABLE IV

RBE FOR ERYTHEMA PRODUCTION

Test Radiation	Irradiated Object	RBE		Reference
		Acute	Protracted	
X/ Fast Neutrons	Human Skin	3.0		27- Stone, <u>et al</u> , 1940
X/ Fast Neutrons	Human Skin	3.5		27- Stone, <u>et al</u> , 1947
X/ Fast Neutrons	Human Skin	2.4		7- Storer, <u>et al</u> , 1957
X/Fast Neutrons	Mouse Skin	1.8		28- Bewley, 1966
X/Fast Neutrons	Rat Skin	2-3		29- Fowler, <u>et al</u> , 1963
X/Fast Neutrons	Pig Skin	2.5±0.3		29- Fowler, <u>et al</u> , 1963

ATOMICS INTERNATIONAL
A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901
DATE April 20, 1966
PAGE 14 OF 17

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901

DATE April 20, 1966

PAGE 15 OF 17

REFERENCES

1. Glasser, Otto, "Medical Physics Volume I," The Year Book Publishers, Inc., 1944
2. "Radiation Quantities and Units, International Commission on Radiological Units and Measurements (ICRU), Report 10a," National Bureau of Standards Handbook 84, November 1962
3. Boag, J. W., "The Relative Biological Efficiency of Different Ionizing Radiations," National Bureau of Standards Report 2946, 1953
4. Glasser, Otto, "Medical Physics, Volume II," The Year Book Publishers, 1950
5. Glasstone, S., "Sourcebook on Atomic Energy," (second edition), D. VanNostrand Co., Inc., 1958
6. Bacq, Z. M., Alexander, P., "Fundamentals of Radiobiology," Butterworths Scientific Publications - London, 1955
7. Storer, J. B., Harris, P. S., Furchner, J. E., Landham, W. H., "The Relative Biological Effectiveness of Various Ionizing Radiations in Mammalian Systems," Radiation Research 6, 1957
8. Etter, L. E., "The Science of Ionizing Radiation," Charles C. Thomas Publisher, 1965
9. "Permissible Dose from External Sources of Ionizing Radiation," National Bureau of Standards Handbook 59, September 1954
10. Lamerton, L. F. et al., "Report of the RBE Committee to the International Commission on Radiological Protection and on Radiological Units and Measurements," Health Physics 9, April 1963
11. Upton, A. C. et al., "Radiobiological aspects of the Supersonic Transport," Health Physics 12, February 1966
12. "Standards for Protection against Radiation," Code of Federal Regulations, Title 10-Atomic Energy, Chapter 1-Atomic Energy Commission, Part 20
13. Keshishian, V., "Effective RBE of Fast Neutrons for Manned Systems Using SNAP Reactors," Il to J. D. Gylfe, dated January 31, 1966

ATOMICS INTERNATIONAL
A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901
DATE April 20, 1966
PAGE 16 OF 17

14. Proceedings of the Symposium on Biological Effects of Neutron and Proton Irradiations, held at the Brookhaven National Laboratory, 7-11 October 1963, vols. I and II, IAEA, Vienna 1963
15. Proceeding of the Second Symposium on Protection Against Radiations in Space, Gatlinburg, Tennessee, October 12-14, 1964, NASA SP-71, 1965
16. The Fourteenth Annual Meeting of the Radiation Research Society, Coronado, California, February 13-16, 1966
17. Billingham, J., Ewing, D., Robbins, D. E., "A Method of Evaluating Radiation Risk for Manned Space Flight," 14th Annual Meeting of the Radiation Research Society, Coronado, California, February 13-16, 1966
18. "Report on the Design Requirements for Reactor Power Systems for Manned Earth Orbital Applications," Task Area 1, Missile and Space Systems Division - Douglas Aircraft Co., Inc., Santa Monica, California SM-51965, January 1966
19. Brown, D. V. L., "Radiation Cataracts in Animals," Symposium on the delayed effects of radiation - John Hopkins University, October 29, 1959, ORD-SP-127, pp 51-58, 1960
20. Evans, T. C., "The Fast Neutron Hazard," Nucleonics 4, pp 2-8, 1949
21. Leinfelder, P. J., Evans, T. C., Riley, E. E., "Production of Cataracts in Animals by X-rays and Fast Neutrons," Radiology 65, pp 433-438, 1955
22. Merriam, G. R., Jr., Biavati, B. J., Bateman, J. L., Rossi, H. H., Bond, V. P., Goodman, L., Focht, E. F., "The Dependence of RBE on the Energy of Fast Neutrons; IV. Induction of Lens Opacities in Mice," Radiation Research 25, pp 123-138, 1965
23. Riley, E. F., Evans, T. C., Rhody, R. B., Leinfelder, P. J., Richards, R. D., "The Relative Biological Effectiveness of Fast-Neutron and X-Radiation," Radiology 67, pp 673-685, 1956
24. Upton, A. C., Christenberry, K. W., Melville, G. S., Furth, J. Hurst, G. S., "The Relative Biological Effectiveness of Neutrons, X-rays and Gamma Rays for the Production of Lens Opacities: Observations on Mice, Rats, Guinea Pigs and Rabbits," Radiology 67, pp 636-696, 1956

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-11901

DATE April 20, 1966

PAGE 17 OF 17

25. Upton, A. C., Conte, F. P., Hurst, G. S., Christenberry, K. W., Benedict, W. H, "Effectiveness of Neutrons, X-rays, and Gamma Rays for the Production of Lens Opacities Observations in Animals," Cancer Research 20 11,1960
26. Vogel, H. H., Jordan, D. L., Frigerio, N. A., "Studies of Relative Biological Effectiveness," Biological and Medical Division Semiannual Report, ANL-5916, 1958
27. Hollaender, A., "Radiation Biology, Volume I: High Energy Radiation," pp 315-350, McGraw-Hill Book Co., Inc., New York, 1954
28. Bewley, D. K., "Radiobiological Research with Fast Neutrons and the Implications for Radiotherapy," Radiology 86, pp 251-257, February 1966
29. Turner, B. A., Fowler, J. F., "The RBE of Fast Neutrons in Producing Intestinal and Skin Injury in Rats," The British Journal of Radiology 36, pp 77-121, 1963
30. Ainsworth, E. J., Leong, G. F., Kendall, K., Alpen, E. L., "Comparative Lethality Responses of Neutron- and X-Irradiated Dogs: Influence of Dose Rate and Exposure Aspect," Radiation Research 26, pp 32-43, 1965
31. Platzman, R., and Frank, J., Symposium of Information Theory in Biology, (ed. H. P. Yookey): Pergaman Press, London, p 262, 1958
32. Neary, G. J., Munson, R. J., Mole, R. H., "Chronic Radiation Hazards, An Experimental Study with Fast Neutrons," Pergamon Press - New York, 1957
33. Hagen, U., "On the Problem of the Relative Biological Efficiency of Various Types of Radiation Under Chronic Exposure," Atomkernenergie I, pp 275-283, 1962
34. Krebs, J. S., Brauer, R. W., "Residual Injury Caused by Irradiation with Fast Neutrons," Radiation Research 17, pp 855-863, 1962
35. Thomson, R. J., Personal Communication, Atomics International, Department 731, March 1966