ELECTRON TRANSPORT CALCULATIONS

FOR X-RAY SIMULATION

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TABLE OF CONTENTS

I. INTRODUCTION

A new method of calculating the properties of electron transport and energy deposition is presented in this proposal. This method will have two very distinct advantages which make it unique among electron transport calculations presently being used or developed. First, it will run on the computer 50 to 100 times faster than the other methods while generating equivalent results with comparable accuracy. Secondly, all the physical data (cross sections, etc.), are built into the technique, so that only specific problem parameters are needed to implement a calculation making the calculational method very simple to use. The method has been tried on a limited scale and proven by a comparison with experiments.

The need for a means of calculating the properties of electron transport simply and inexpensively but accurately becomes very obvious when considering the advantages of using electron beams to simulate X-rays. The physical processes involved in the deposition of energy by electrons and by photons are sufficiently similar so that using electrons to simulate photons is valid when the correct experimental procedures are used.

Electron beams from existing equipment can be tailored to simulate very accurately the threat conditions imposed by low-energy photons. It is very difficult to produce sufficient quantities of low-energy

photons to simulate these conditions directly; it is practically impossible to simulate the threat accurately with high-energy photons which are available. Without developing new equipment, electron beams from existing flash X-ray units and linear accelerators can be used to simulate the following quite realistically: (i) charge transfer or internal EMP; (ii) thermal mechanical shock; and, (iii) TREE. In addition, there are other more subtle uses of electron beams; i.e., the radiation effects modeling of inertial guidance. However careful attention through quantitative calculations must be given to the problem of correlating X-ray effects with electron-induced effects. The calculational technique which we propose to develop here will provide a versatile tool for generating data needed to make accurate correlations.

To illustrate by example the calculational technique that will be developed,a parametric study of the yield from various anodes on flash X-ray units is included in the proposed work. This study will be designed to indicate the anode configurations which will produce the highest X-ray output. The immediate problem of inadequate yield from existing machines will be addressed. Solutions which involve the design and material composition of the anodes will be sought. The simulation of X-ray effects by X-rays is partly limited by the inability to achieve

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representative energy deposition levels. Any improvement in the output of flash X-ray machines would be well worth the modest effort this study will require.

II. SIMULATION

The physical processes by which electrons and X-rays deposit energy into a material are sufficiently similar that the electrons can be used to simulate X-rays. Photons with energies from a few keV to a few MeV lose energy in matter by either photoelectric absorption or Compton scattering. In either case, all or part of the incident photon energy is transferred to an electron. In Compton scattering events, in which the photon will lose only part of its initial energy, the remaining energy will be dissipated by successive Compton scatterings until the photon is eventually absorbed. In general, these processes convert photon energy into electron kinetic energy. There is a small but finite possibility a photon could lose enough energy in a single event with one atom to dislodge it. This would occur either in a high-energy photoelectron event, or in a wide angle coherent scattering event. Both events are very unlikely. Though the displacement of the atom has important consequences, the infrequencies with which it occurs in photon absorption precludes these consequences from being measurable among the consequences of the energetic electrons. Radiation effects from intense X-ray sources are predominantly the result of photon energy transferred to electrons.

Energetic electrons undergo collisions with other electrons and nuclei. They lose their energy by ionizing processes in which electrons

are stripped from atoms in electron-electron collisions. Very little energy is lost in nuclear scattering, except when a photon is generated through the bremsstrahlung process. The bremsstrahlung photons lose energy to the material via the mechanics described above. Eventually, this energy results in electron kinetic energy.

Therefore both initial radiations transfer their incident energy to electrons which eventually transfer this energy to the whole collection of electrons and atoms in the region. This distribution of energy will be manifested as heat and heat-related effects. The important point is that the eventual forms that electron or X-ray energy take in matter are indistinguishable. Therefore, the radiation effects observed after electron or X-ray irradiation do not depend upon the differences in the microscopic interaction mechanisms of the two radiations.

However, there can be considerable differences in the observed radiation effects due to macroscopic differences in the energy deposition by electrons and X-rays. These differences result from essentially geometric and atomic number dependencies. An extreme example that illustrates one type of difference is a situation where radiation is incident on a laminate of gold and aluminum. The energy loss per unit length for a 1 MeV beam of electrons is 1.505 MeV/(g/cm^2) in aluminum and 1.177 MeV/(g/cm^2) in gold. On the other hand a 30 keV X-ray deposits 0.036 MeV/(g/cm^2) in

aluminum and 0.69 MeV/(g/cm^2) in gold. Electrons deposit energy at about the same rate in both materials whereas 30 keV X-rays deposit energy at a rate 20 times higher in gold than in aluminum. Consequently if 30 keV X-rays are to be simulated with electrons in a gold-aluminum laminate, something must be done about the differences in deposition rate.

Before explaining how the proposed calculations can help to design a simulation experiment that overcomes this difficulty one other point should be made. If a photon spectrum from a flash X-ray machine is used the same problem will occur. Assume that the output from a machine like the AURORA is to be used to simulate a 30 keV X-ray in a gold-aluminum laminate. The average photon energy from such a facility will probably be greater than 300 keV, but let us use this energy as a lower limit. A 300 keV photon will lose 0.031 MeV/(g/cm^2) in aluminum and 0.09 MeV/(g/cm^2) in gold. Here the ratio of energy loss in gold and aluminum is about 3, a long way from 20 which is the value for a 30 keV X-ray. Consequently the same problem occurs with a photon beam from a simulator. Furthermore, there are very few things which can be done with the photon beam to accomplish a better simulation. However there are a number of things that can be done with the electron beam to solve this problem.

In order to illustrate both the advantages of simulation with electron beams and the utility of having the capability that the proposed

calculational technique would provide, let us indicate how the problem with the gold-aluminum laminate can be approached. The problem of simulating the high deposition in gold while maintaining a lower deposition in aluminum can be approached by altering the energy spectrum of the electron beam. If the beam were directed at the gold surface and the beam had a large low energy component, most of the energy would be deposited in the gold. To select the energy spectrum that would accomplish this a detailed electron transport calculation must be done. Since many alternatives need to be tried, a quick running code is imperative. In order to design an absorber that would generate the proper energy spectrum from the output of a generator a second set of electron transport calculations need to be run. For such a sequence of calculations, a rough cost estimate would be about $2000 if a Monte Carlo calculation were used. If the proposed calculational technique were used, the cost would be between $20 and $50.

Having discussed the physical processes leading to the conclusion that electrons can simulate X-rays, and having illustrated how electron beams can be tailored to solve at least one of the problems that seem to many as precluding the usefulness of electrons, it is appropriate to discuss unique advantages of the electrons. First, sufficiently intense electron beams are much easier to generate than sufficiently intense photon beams.

From the energy deposition rates quoted above it is seen that it takes about 50 photons at 300 keV to deposit energy at the same rate as a single 1 MeV electron. An optimistic figure for conversion of a 15 MeV electron into a useable photon is 10%. Therefore, the intensity of the electron beam used to produce bremsstrahlung in a simulation must be 500 times the intensity if the electrons were used directly. Since intense electron beams cause problems of their own, there is an important advantage to using the electron beam as a simulator.

A second, but correlated advantage, is the capability of achieving very high energy depositions. From the numbers quoted above an increase in deposition level of 500 can be achieved by using the electron beam directly. This is a significant advantage in materials response studies. Several groups around the country are actively involved in using electron beams to generate thermal mechanical shocks. These groups are presently using Monte Carlo calculations to give them energy deposition profiles. The codes they are using (mostly ZEBRA) are not versatile enough to account for non-normal incidence due to beam blow-up nor fast enough so they can be used in parameter studies. They are run in order to obtain energy deposition profiles which are necessary if material response data are to be extracted from the experiment. The output of these experiments could be significantly improved if the energy deposition calculations could be made more versatile and cheaper.

A third advantage of the use of electrons is the fact that they can be used to selectively deposit energy. In this application they are not being used as a simulator but as a heat source. A narrow beam of electrons can be directed at specific parts of a complicated instrument. By selectively heating only these parts often valuable parametric information can be extracted. This information can be tied together to provide a vulnerability picture of the instrument. The radiation effects modeling of inertial guidance systems are being pursued in this manner. Because of the close tolerances of the instrument it is impossible to selectively heat an operating gyroscope in any other way.

In fact, the calculational technique proposed here was first tried and proven feasible on an experiment with gyroscopes. The MIT Instrumentation Laboratory exposed an non-operative SABER gyroscope to an electron beam. The gyroscope was instrumented with a set of thermistors. A 60 MeV electron beam was used to selectively heat various parts of the instrument and the temperature rises were measured. A crude version of the proposed electron transport code was used to calculate these temperature rises. The results generally agreed quite well. In cases where there wasn't good agreement, the decrepancy could always be associated with one of the known inadequacies of the code. These inadequacies were the result of insufficient effort being expended in the

development of the code and were not due to some fundamental problem with the method.

The result of these experiments encouraged the gyroscope manufacturers to expand their programs to irradiate operating instruments and observe the drift rates caused by the heat deposited. The information they obtained will be coupled into a model which will allow them to calculate the drift caused by some arbitrary threat induced heat deposition. A necessity for the success of such experiments is the ability to calculate the heat deposited. This requires a versatile electron transport code. Since each set of experiments could require as many as 200 calculations (as we required in the pilot program), a fast running code is imperative. In fact, the increased cost of running a Monte Carlo code for this experiment alone would have paid half the cost of developing the code proposed here.

Another application where electron beams may have a unique advantage for X-ray simulation is in the investigation of charge transfer effects (internal EMP). This threat arises from the current flow from a surface close to electronic components. When X-rays irradiate a surface they may cause a charge flow from that surface. The current can create an EMP which is picked up by leads or other effective antennas. The result is a spurious electrical signed in the electronic apparatus.

Since these signals may be quite large it is important to study the effect. By carefully selecting an electron beam spectrum the charge flow across internal surfaces can be simulated with electron beams. The selection of the proper spectrum and the design of an absorber that will form the proper spectrum from the output of existing machines requires many electron transport calculations. Keeping in mind that these calculations should be repeated for every simulation experiment it is clear that only a fast running, easily implemented code will perform the task. To our knowledge this particular simulation has not been attempted but certainly it should be.

A last example is in the TREE's area. Here damage to crystals, lead bonds, and other components are a direct result of energy deposition. Presently most TREE's testing is done with hard X-ray beams from flash X-ray units. The quality of such tests could be greatly increased if the threat could be more accurately simulated. This can be done with electron beams. Flash X-ray units are limited in their capability to produce sufficiently soft X-ray spectra at sufficiently high intensity. Electron beams can provide the intensity. However, if the energy deposition profiles are to be realistic, calculations must be performed to determine the proper electron energy spectrum and to design an absorber which will generate the proper spectrum. The transport calculations must be able to handle

a variety of materials and must be inexpensive to run since many cases are needed in TREE experiments.

In this section the physical processes of electron and X-ray energy deposition have been discussed in order to point out the equivalence of the two radiations for simulation purposes. One of the most often raised problems of the simulation of X-ray by electrons is that large differences in energy deposition rates with different material have been discussed. This problem was used to exemplify the flexibility of the electron beam simulation by describing one way of circumventing it. It was also shown that the same problem exists in simulators using photon beams. However, with photon beams there is not sufficient flexibility to eliminate the problem. Finally, the application of electron simulations to thermal mechanical shock tests, gyroscope testing, charge transfer, and TREE testing were discussed. From this the discussion is clear that there are a number of uses for an electron transport code. It is also evident that many experiments would by bypassed or inaccurately done if such a code was not quick-running and easily implemented. If the whole area of simulation of electrons is to develop to its full potential, electron transport calculations must become routine and inexpensive.

III. ELECTRON TRANSPORT AND ENERGY DEPOSITION

The basic physics of electrons at near relativistic and higher energies was developed during the late thirties. The cross-sections for electron-electron, electron-nuclear, and bremsstrahlung production were accurately derived, although numerical results were subject to uncertainties imposed by the necessity to make analytic approximations. It remained for the availability of large computers two decades later to make broad use of the accomplishments of the early theorists. Since the interaction processes are Coulombic in nature, they have been known fundamentally since quantum electrodynamics was formalized in the late forties and early fifties. The research since then has been limited to the development of calculational and numerical techniques required to construct quantitative results from the basic theory.

But the extension of the basic theoretical knowledge to the properties of energetic electrons in bulk matter introduces a completely new set of important problems which have yet to be solved. The main difficulty is that electrons, while losing only a small amount of energy in most collisions, have a relatively high interaction cross section with either a nucleus or another electron. The dominant interaction is through electron-electron collisions in which the incident electron alone or the incident electron-target system will lose, on the average, only a few tens of electron volts per collision. Thus, if only these collisions are considered,

approximately 10^5 collisions are required before an electron with an initial energy of a few MeV comes to rest.

Electron-nuclear collisions do not help the situation; in fact, they further complicate it. Elastic collisions, of course, do not involve energy loss to the electron, but only change its direction of motion. Inelastic collisions, however, result in the production of bremsstrahlung, which must be included in the radiation transport problem.

Attempts to calculate electron transport in bulk matter are doomed if approached on an individual collision basis, even with large-memory, high-speed computers. The alternative approach of averaging over many collisions has been attempted and met with some success. Moliere[1] has developed a useful formulation for angular dispersion in the small-angle approximation.

Goudsmit and Saunderson[2] solved the problem in general, although their approach imposes calculational difficulties. The problem of energy loss fluctuations or energy straggling has been approached by Landau[3] and Blunck and Leisigang[4] who obtained expressions for small energy losses. There have been many other contributions to the solution of these problems; however, they all have the same drawback, namely, they are useful only at small angles and for small energy losses.

Another approach is to solve the problem using approximations correct in bulk matter at the limit where energy loss is appreciable and angular dispersion large. In general, these approaches have centered around computer programs in which the electrons interact with a series of many thin slabs of material. The most successful of these investigations was performed by Berger[5] at the National Bureau of Standards using a Monte Carlo technique. The variety of interactions available to the electron are sampled and tabulated for each slab; the process being repeated until sufficient accuracy is achieved. To date, this method is the only one which has successfully calculated many electron transport properties.

Another available Monte Carlo code, BETA[6], improves on this approach in that it has a generalized geometry capability, but has not been checked against test problems. It has the additional drawback that it requires extensive input. Other attempts to calculate energy deposition alone have also been made. These are all somewhat specialized and exhibit significant discrepancies among themselves. Therefore, one might think that the most advanced calculational technique would be Berger's[5] ETRAN-15 program or ZEBRA which is a specialized version of ETRAN-15.

A closer look at this work, however, reveals some rather important difficulties. Although all the programming errors have been eliminated in the six years required to develop the code, some discrepancy

remains. Most recently, a comparison of the transmission coefficient calculated with ETRAN-15 for 4.0 MeV electrons incident on aluminum was made with experimental data.[7] After careful evaluation it was concluded that the calculated values were in error by as much as thirty percent in the latter half of the range. Since the code is internally consistent, such a discrepancy will propagate to all the other calculated quantities, and a comprehensive investigation of the other comparisons indicates that the discrepancy is persistent. A discussion with Berger[8] resulted in the conclusion that there was something systematic and fundamentally wrong with the technique since the physics input can be assumed to be accurate. Thus, there is a fundamental difficulty in the most recent and complete solution to the electron transport problem, and it serves to indicate that a large investment in time and money does not necessarily insure a program which will yield correct answers. Experimental results must be consulted if accuracy is to be insured.

A drawback inherent with the Monte Carlo technique is that many histories are required to obtain meaningful results. For example, the ETRAN-15 code was recently run to generate the energy spectrum of 4.0 MeV electrons which had penetrated half range into tin. 2×10^4 histories, (requiring two hours of Univac 1108 time) were needed to obtain even marginal statistical accuracy. The basic and unavoidable drawback

of such a technique is that calculations are made sparingly and only after a careful selection of parameters. The code is, consequently, not at all suitable for an experimentalist or designer interested in examining many configurations.

IV. CALCULATIONAL APPROACH

We propose to develop a new and relatively inexpensive means of calculating electron transport and energy deposition, using available experimental data. First, the procedure recognizes that transitions from basic physical properties to the applied situation, involving bulk matter, are difficult and inadequately known, and, second, that theoretical techniques are not likely to be developed in the next few years.

Specifically, it is proposed that an effort initiated by the author be developed to its conclusion. In the previous work, which was government supported on several projects, a first-generation computer program was developed, using the above method, to solve specific problems which arose from experimental results obtained with an electron linear accelerator. Though the time and effort involved in this pilot program were small, the results were very encouraging. Predictions[9] were made of the temperature rises due to an electron beam directed at a gyroscope and compared with thermistor data. There was good agreement in cases where formulas from experimental data were used, but disagreements in cases where rather blind extrapolations were made by all too commonly used techniques. In the work proposed here we plan to use this previous experience as a valuable guide while expanding greatly the use of other evaluated data.

The code will be designed to treat incident electrons as a beam or a series of beams from several directions, mathematically represented as vectors depending on energy, polar angle, and axial displacement. Energy spectra of electrons can constitute the incident beam as well as monoenergetic electrons. The geometry will be 2-D. More complicated geometries would require several runs and not present a significant limitation by definition of our goals.

The target material will be treated as a series of slabs with thicknesses restricted to less than the range of the average incident electron. The code will have the capability of treating any elemental material, most composite materials, and any combination of these. The target slabs will be represented as matrices which operate on the incident beam vector to generate an emergent beam vector. The energy loss, particle loss, and angular dispersion characteristics of the electrons passing through a slab are manifested by this operation. This procedure of calculating the beam vector with successive slab matrices will be continued until either all the electrons are stopped or the irradiated object has been traversed.

The procedure can be expressed mathematically, as

$$S_{n+1}(E, \theta, y) = \int_{E'} \int_{\theta'} \int_{y'} F_n(E, E', \theta, \theta', y, y') \times S_n(E', \theta', y')\, dy'\, d\theta'\, dE' \qquad (1)$$

where S_n is the beam vector entering the n^{th} slab, F_n the response of the n^{th} slab, and S_{n+1} the beam vector emergent from the n^{th} slab. The variables E, θ, and y, of course, refer to the energy, angle and lateral displacement from the beam axis.

Resort to the substantial body of experimental data arises because of the need to define the responses of the slabs as parametric functions of the energy, angle of the incident beam, thickness and effective atomic number of the slab. Experimental data of the following kind will be utilized:

a. Transmission coefficients.

b. Energy spectra of transmitted electrons.

c. Range-energy data.

d. Backscatter coefficients.

e. Backscatter energy spectra.

f. Thick-target bremsstrahlung data.

In the previous work some of these data were used in the following manner to generate material response functions. The energy spectra and angular distributions were fit with exponential functions in such a way that the response function took the following form:

$$F_n(E, E', \theta, \theta', y, y') = f_t\, N\, (E-E_b)^2 \exp\left(\frac{E-E_b}{E_t-E_b}\right)^2 \exp(C\theta^2)\, I(y, y') \qquad (2)$$

where E_b, E_t, f_t and C are all functions of the incident beam parameters (E', θ', and y'), as well as the atomic number of thickness of the slab. The normalization factor is chosen such that,

$$f_t = \int_E \int_\theta \int_y F_n \, dy \, d\Omega(\theta) \, dE \qquad (3)$$

where f_t is the transmission coefficient. There are a number of fitted formulas available for f_t, none is completely satisfactory. We will improve on these formulas so that f_t will be more accurate over a wider range of energy, material thickness, and atomic number. This now becomes possible because of some rather extensive experimental work completed very recently. The lateral displacement function $I(y, y')$ was fixed geometrically from the angular distribution of transmitted electrons and the distance between slabs. The particular form of the function used in this early work was successful enough to convince us that the method could work, but not enough effort was expended to obtain sufficient accuracy. There are known errors in the mathematical function which can be eliminated only after systematically assembling the pertinent data. These formulas are presented as examples to illustrate how the method has been used; however, it is the purpose of the work proposed here to develop the approach with

a more extensive parameterization of the pertinent measured data. No attempt has been made so far to include the other items of data listed above. This would be a process which would require assembling and evaluating the existing data and then parameterizing it in the manner used with the energy and angular distribution of transmitted electrons. Radiative effects can also be included because of the recently increased availability of thick-target bremsstrahlung data. These effects are of secondary importance within the range of the incident electrons but dominate beyond that depth. It is within the context of this proposed work to provide a systematic analytical method for estimating the photon production using the data available and some rather extensive Monte Carlo calculations of the radiation yield. The penetration of the photons beyond the range of the electrons can be traced using simple experimental attenuation and appropriate build-up factors. The requisite data has been published in the literature.

Since the properties of bulk matter are measured in most cases, the chance of an inadvertant omission or miscalculation of a physical process is very small. When it is convenient and reasonable, theoretical derivations will also be used, but only when it is certain that no significant uncertainties will thus be introduced. From experience, we know it is possible to set up such a calculation which will run on the computer in

times two orders of magnitude shorter than Monte Carlo codes. We will achieve this speed without sacrificing accuracy because we are using the data which has been generated to check Monte Carlo codes.

It is planned that the code will generate various properties of the electron beam leaving each slab and various effects on the materials through which the beam passed. In a general version, the following data will be printed out:

a. Number of transmitted electrons.

b. Electron energy spectrum.

c. Angular dispersion of the transmitted electron beams from the n^{th} slab.

d. Backscatter from slab $n + 1$.

e. Radial distribution of the transmitted electron beam.

f. Energy deposition.

g. Deposited dose.

h. Net charge deposited.

Other quantities derivable from these can also be included if required in a particular application. Specifically, the temperature rise can be computed and printed out if the appropriate specific heats are available.

As was mentioned above an important application of this method for the calculation of electron transport is the use of the code to specify how an electron beam can be contoured to simulate a given photon deposition. This can be done because energy straggling causes the number of electrons transmitted to start decreasing at roughly one-third of their range. Half may be lost by the time they reach half range. This effect is very pronounced and energy dependent, but the numbers quoted are typical of 4 MeV electrons in aluminum. The straggling property can be utilized by taking electrons with different energies and adjusting their intensities so that the energy deposition versus depth approaches that of a low energy photon beam.

A simple example of this technique is shown in Fig. 1. Here, the dashed curves correspond to the energy deposition profile due to two electron beams of 4.0 and 8.0 MeV energy in aluminum. The solid line is the sum deposition. The dotted curve corresponds to a deposition profile for 40 keV photons using simple attenuative coefficients. Beyond about 1 g/cm^2, the photon deposition is well simulated with only two electron beam energies. Thus, if a spectrum of electron energies is correctly specified, a wide range of photon profiles could be simulated. It is also reasonable to propose shaping electron energy spectra since a multiple thickness absorber in an energetic beam can perform this task quite easily. In fact, the code would be used to determine how to design such an absorber

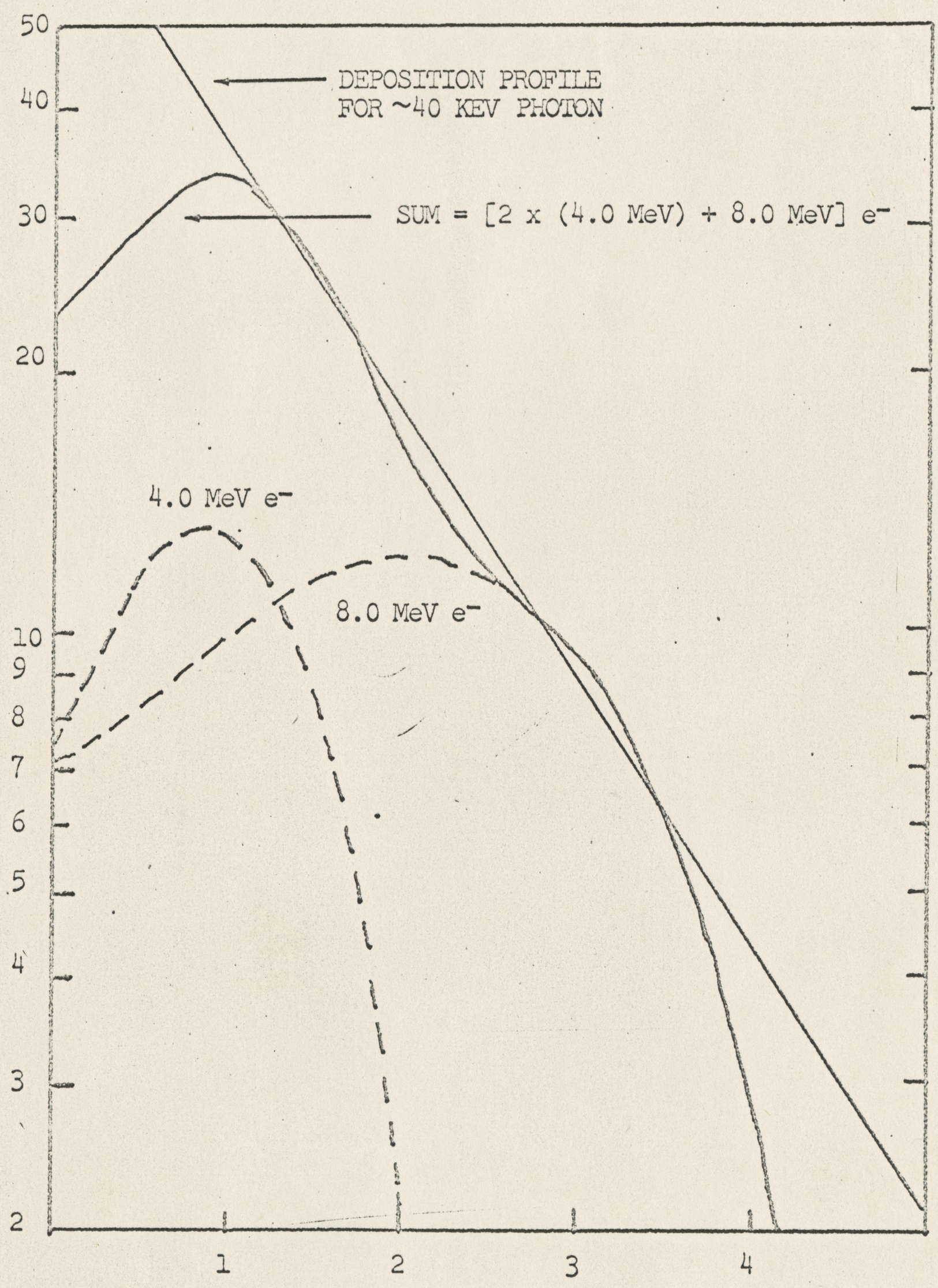

Figure 1: Energy Deposition Profiles

and to calculate precisely what the actual configuration produces. Given a typical photon deposition profile, an electron beam spectrum which produces the same energy deposition profile in matter can be calculated. Then, an appropriate absorber suitable for use on a typical flash X-ray unit or electron Linac could be designed.

V. SAMPLE PROBLEM--FLASH X-RAY OUTPUT

As an illustration of how the proposed computer program can be used, a specific problem will be run. The problem will be a parametric study of the output of photons from a flash X-ray unit. The parameters will be the constituents and design criteria of the target anode. The purpose of this study will be to determine if there is some optimum combination of materials laminated into an anode that would increase the photon output of these machines. Since energy loss, bremsstrahlung production and angular dispersion are all different functions of atomic number in the appropriate energy range, it is quite likely that there is some optimum target configuration that would yield a maximum output.

The output of GAMBLE II a flash X-ray machine to be made operable in the near future at NRL will be used as the electron input. Various configurations of target materials and thicknesses will be analyzed with the code to determine which results in the highest X-ray yield. The code will calculate the electron transport and photon production using a Bethe-Heitler cross section formula. The self absorption of the photon beam will be calculated. From this study it will become apparent first, if any significant gain can be realized in X-ray output by changing the target design and secondly what the changes required of the target design. From the data a specific design of the anode will be recommended.

This study will be written up in such a way that it can be repeated step by step for other input spectra. By doing this users and operators of other facilities then GAMBLE II can perform the same optimization for their facility. It is hoped that by careful design of the anode the conversion efficiency of X-ray machines may be significantly increased.

VI. SCOPE OF WORK

The contractor will use his best efforts in a program to develop techniques for calculating the transport properties of electrons. The program of work will include the following tasks:

1. All the available experimental data on electron transport will be assembled and evaluated.
2. The data will be correlated and incorporated in a computer program to calculate electron transport properties, including energy deposition through multi-material configurations.
3. The energy deposition results from this program will be presented in such a way that the data can be coupled easily with material response codes.
4. A parametric study will be performed to determine the most efficient anode configuration for a specific flash X-ray unit.

VII. PERSONNEL

It is expected that the principle investigator on this program will be Dr. James A. Lonergan. Dr's. J. R. Beyster and C. A. Stevens will be available for consultation. The resumes of these people are included in Appendix A.

VIII. PRICE AND CONTRACTUAL INFORMATION

Science Applications, Inc., suggests that the proposed work be conducted over a twelve-month period under a cost-plus-fixed-fee contract. The estimated cost for this program is shown at the end of this section.

The labor costs used in this proposal are based upon current average rate of the personnel expected to be employed in the proposed effort. No premium for direct overtime expense has been included in this proposal.

The overhead rate used in this proposal is provisional and consists of all of Science Applications, Inc.'s indirect costs and is adjusted for assumed unallowable costs. Overhead rates will be adjusted at the end of Science Applications, Inc., fiscal year to actual costs, excluding disallowables, as determined by Government audit. Science Applications, Inc., is under the audit cognizance of the Defense Contract Audit Agency, San Diego Branch Office, 5100 Federal Blvd., San Diego, California, 92105.

Unless previously withdrawn in writing, this proposal will remain valid for ninety days from the date on the cover.

Estimated Cost for a Twelve-Month Program

	Man Months	
Personnel Services		$23,651
Scientist 3	10	
Scientist 1/Programmer	4	
Overhead @ 100%		23,651
Fringe Benefits @ 20%		4,730
Computer Usage, 5 hrs. @ $600/hr.		3,000
Travel and Communications		1,200
Total Estimated Cost		$56,232
Fixed Fee		6,748
Total Estimated Cost Plus Fixed Fee		$62,980

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APPENDIX A--RESUMES

Dr. J. R. Beyster, President/Scientist 4

University of Michigan: B.S.E. (1945), M.S. (1947), Ph.D. (1950)

Dr. Beyster is an internationally recognized authority on the experimental determination and interpretation of nuclear and reactor properties using accelerators. His experimental expertise is strengthened by a strong theoretical as well as a practical background.

In the early 1950's, Dr. Beyster worked with the Westinghouse Atomic Power Division on the nuclear submarine program. Later, he joined Los Alamos Scientific Laboratory where he carried out research on the water boiler reactor in addition to measuring fast elastic and inelastic neutron scattering cross sections. In 1957, Dr. Beyster joined General Atomic where he soon established and managed a linear accelerator facility that grew to a five million dollar capital value with a one hundred forty man technical department, totally supported by basic and applied contract research. During this period, he made a number of fundamental contributions to neutron thermalization research. In early 1969, Dr. Beyster formed Science Applications, Inc., as a diversified R&D firm responsive to the needs of government and private industry in contract research and technical consulting.

Dr. Beyster is a fellow of the American Nuclear Society, has been chairman of its Reactor Physics Division and program chairman of the Shielding Division. He is also a member of the American Physical Society and the National Council on Radiation Protection.

Dr. James A. Lonergan, Scientist 3

University of Santa Clara: B.S. (1961)
University of Arizona: M.S. (1964), Ph.D. (1966)

Dr. Lonergan is an experimental nuclear physicist who has lately been measuring and evaluating electron and gamma ray transport through bulk media.

In 1966, Dr. Lonergan joined General Atomic where he performed some of the earliest gamma-ray shielding experiments utilizing monoenergetic gamma rays from in-flight positron annihilation. Later, he directed a program to measure the transport properties of high-energy electrons including bremsstrahlung production. He has used these results to develop computer techniques to calculate electron transmission spectra and energy deposition. He also studied thermal shock of concrete using uranium seeding techniques and initiated a program to measure x-ray transport in air.

Dr. Lonergan is a member of the American Physical Society and the American Nuclear Society and has authored several technical publications.

Dr. Charles A. Stevens, Scientist 3

New York University: B.S. (1957)
University of Michigan: M.S. (1958), Ph.D. (1962)

Dr. Stevens is a theoretical nuclear engineer with strong leanings towards computer applications in the nuclear reactor and weapons physics fields. His present interests lie in the application of neutron and gamma ray transport to the prediction of nuclear weapons effects.

In the early 1960's, Dr. Stevens worked on the NERVA nuclear rocket project at Westinghouse. In 1964, he joined General Atomic where he was engaged in reactor physics research and nuclear model calculations. Several computer programs which are used by reactor physicists today, throughout the United States, resulted from this research. In 1966, he served as Principal Investigator for the accelerator booster fast pulsed reactor program at General Atomic. Later, he participated in nuclear weapons effect research and, in particular, investigated the neutron contributions to the EMP problem. Presently, Dr. Stevens is leading research programs involving radiation fields from nuclear weapons. One program is aimed at the prediction of direct ground shock intensities. Another has the objective of predicting EMP intensities resulting from low altitude explosions.

Dr. Stevens is a member of the American Nuclear Society and has authored some thirty technical publications.