PANC-164 PUERTO RICO NUCLEAR CENTER GAS STOPPING POWER MEASUREMENTS FOR ALPHA PARTICLES Eddie Ortiz and Gilberto M. Arenas Rositlo May 1973 (OPERATED BY UNIVERSITY OF PUERTO RICO UNDER CONTRACT NO. AT (40-1)-1833 FOR US ATOMIC ENERGY COMMISSION ---Page Break--- University of Puerto Rico Mayagüez Campus GAS STOPPING POWER MEASUREMENTS FOR ALPHA PARTICLES by Gilberto M. Arenas Rositlo A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science (Nuclear Engineering) May 1973 Meeting Bigestar of Department ~~ 7 “Director, Graduate Studies Date ---Page Break--- A method has been developed to measure the stopping powers of gases for alpha particles using a (Si) semiconductor detector mounted opposite a natural Am" alpha source in a gas chamber and a 102-channel data acquisition system. By varying the gas pressure and taking an energy loss measurement at each pressure, the stopping powers and molecular stopping cross sections were calculated; also, range-energy relationships were measured simultaneously. Experimental data are given for air, He, O2, CO2, N2, Ar, Kr, Ne, and CH4, for alpha particles in the range 0.63-5.0 MeV. The section ranges from approximately 4-5 percent at the highest energies to approximately 9-10 percent at the lowest energies. The estimated probable error in the ---Page Break--- ACKNOWLEDGMENT It is the author's wish to express his sincere gratitude to those who helped me to complete this project. To Dr. Bodie Ortiz, Senior Scientist, Nuclear Engineering Division, Puerto Rico Nuclear Center, for suggesting the problem, for his dedicated guidance and competent supervision of the work. To Mrs. Aviva B. Córdova, Professor, Nuclear Engineering Department, UPR, for her constructive criticism and for her valuable advice. To Dr. Donald S. Sasscer, Head of the Nuclear Engineering Department, UPR, for his sincere interest in the author's work. To the Colombian Ministry of Mines and Petroleum - ICSTE Foundation for granting the

financial assistance needed for completion of this project for the personnel of the Library and Reproduction office of the PRIC for their extraordinary cooperation, ---Page Break--- dedicated ‘To my dear Esther and Alejandro ---Page Break--- TABLE OF contents ---Page Break--- LIST OF TABLES ---Page

Break--- Last of FIGURES Figure 1.401— Schematic diagram of the experimental arrangements 42 Report horizontal setup for stopping power and range 4.3 Close-up picture of the experimental setup. 'Oh accumulation chamber and instrumentation. 45 Calibration curve for the stopping power measuring system. 46 Several energy spectra of alpha particles after traversing a certain path corresponding to the chamber gas pressure for air and hydrocarbons, see, 48 Remaining energy of 5.7 MeV alpha particles after traversing a certain path corresponding to the chamber gas pressure for air, oxy and Freon. 49 Remaining energy of 5.7 MeV alpha particles after traversing a certain path corresponding to the chamber gas pressure for air, nitrogen, and Freon. 4-10 Energy loss of alpha particles in air, O2, and CO2 411 Energy loss of alpha particles in He, Ar, and O2 499 Energy loss of alpha particles in the Key 10 and 08 the 5th Range curves for the alpha particles (5447 MeV and for alpha particles after passing very thin Al and Ta foils in air. 32 35 ---Page Break--- 417 etc 419 An beat has 423 be, 3 ator 2 in latiane (GI) Range curves for the 1x1 keV particles initial kinetic energy and for alpha particles after passing very thin Al and Ti foils in air. Range curves for the 1% particles (5.47 MeV) initial kinetic energy and for alpha particles after passing very thin Al and Ti foils in Propylene. Range curves for alpha particles (5.47 MeV) in several atmospheric gases (air, O2, N2). Range curves for alpha particles.

gizha partioles (5e47 Nev) tn COgy eg and Zoom the sections of air, Oni and Yolecular etovning cress sections of Gi, O2ii, and O3lig for alpha particies. * Range-energy relation of elow alpha particles in air at standard conditions Page 7 a ar 33 ---Page Break--- Guprr 1 perromvorro In recent years there has been considerable interest in data relating to stopping power of charged particles in various materials. The significance of this parameter may be particularly appreciated by elementary-particle physicists and nuclear physicists in view of the fact that the precision with which nuclear reaction cross sections can be measured often depends on the section of the target = accuracy with which the stopping cross section is known. Health physicists need stopping power measurements for radiation protection purposes because biological, chemical and physical effects produced by the charged particle deposition in a tissue like human soft tissue (of composition 10613, 0.124%, 1.4% and 0.73% by weight) depend among other things, on the absorbed dose and on the Linear energy transfer of the charged particle involved. Energy deposition in the material through which the radiation is passing (stopping material) is closely related to the energy loss by the penetrating radiation. The energy loss of the penetrating charged particle per unit path length in the stopping material is called the stopping power of the material. Stopping power depends upon the various mechanisms in which radiation interacts with the individual atoms and molecules and is an expression of the average rate of a large number of individual interactions ---Page Break--- Stopping power measurements have been carried out in various solids, liquids and gases as stopping materials. In this work, a method is developed for measuring the stopping power of several organic semiconductor detectors. By varying the gas pressure and taking an energy loss measurement at each pressure, stopping power curves and molecular stopping cross sections as a function of alpha energy have

boca calculate. Also, range curves and range-energy relation = ehip for 0.3 ~ 5.4 MeV alpha particles in air and hydrocarbon gases were developed simultaneously. Results agreed within a 5 to 10% of accuracy with respect to literature-related data. ---Page Break--- As indicated by recent professional literature, there is a renewed interest in the variation of stopping power of gases for heavy charged particles (with a mass very much greater than the mass of the electron). A large amount of experimental work has been done and theoretical expressions for stopping power have been developed showing various degrees of accuracy. R.B.J. PAIR obtained Linear Energy Transfer (LET) curves for 1 to 8 MeV alpha particles in hydrocarbon gases and hydrogen. E.

ROTONDT measured stopping powers for 0.1 to 5.3 MeV alpha particles in N_2, O_2, He, and CO_2 by differentiating the range-energy curves of those gases obtained by means of a variable-pressure gas cell in which format particles lose part of their energy and were detected by a semiconductor detector. These measurements have quoted accuracies of 8 percent between 0.1 and 0.5 MeV, 5 percent at 1 MeV, and 3 percent at higher energies. P.D. BOURLAND, W.K. CHU, and D. POWERS measured stopping power relations for alpha particles in a differentially pumped gas cell system from 300 keV to 2.7 MeV using N_2, CO_2, Ar, Kr, and (He). G.D. KERR, L.R. RATER, M.E. UY ROD, and A.I. WALTER reported experimental data for air, N_2, Ar, Kr, CO_2, for alpha particles. ---Page Break--- From the energy range 100 keV ~ 5 MeV, molecular cross sections of the above cases were calculated within an accuracy of approximately 4 percent of probable error at the highest energies to approximately 12 percent at the lowest energies. P.J. WALSH measured molecular stopping cross sections for 0.3 to 5 MeV alpha particles within a 10 percent of accuracy at the lowest energies, using a variable-pressure gas cell and a constant separation.

distance between the alpha source and detector. WP, JESSS and J. SADAUSSIS (7) determined range-energy curves in the region 0 = 5 MeV for alpha particles with a collimating absorption call and an ionization chamber. The ionization change from a single alpha particle is collected in the ion chamber and amplified by means of the vibrating reed electronometers. A. BETIE (3) reported range-energy relations for 0 to 6 MeV alpha particles and developed a theoretical treatment on stopping power for heavy charged particles (See Section 3.3). ---Page Break--- CURRENT THE INTERACTION OF ALPHA RADIATION WITH MATTER All radiation measurements depend on the interaction of the radiation with matter. The nature of these interactions therefore forms the basis of a discussion of the measurements themselves, and an outline of the principal interactions of charged particles like alphas is developed in this section. The primary mechanism of energy loss in penetrating charged particles is due to Coulomb interactions between atomic nuclei and electrons with the charged particles; to a lesser extent elastic and inelastic collisions with electrons and nuclei are also of significance. If the energy transferred to an electron is only enough to raise it to a higher level in the atom, the process is called excitation; if the electron is given enough energy to separate it completely from the atom, the process is called ionization. The two processes are closely associated and together they constitute "energy loss by collision." At energies several times the rest energy of the moving charged particle, excitation and ionization account for the major part of the energy loss in all materials. Some of the electrons ejected in the ionization process have enough energies to produce further ionization themselves; such electrons are called secondary electrons. ---Page Break--- If other phenomena occur when alpha particles traverse matter. Interactions with the Coulomb fields of atoms, and particularly with atomic nuclei, result in changes in the direction of motion.

of ‘the heavy particle (tho tora Theavy particle" shall afterhere refer to a particle of a mass greater than that of the electron). Inelastic collisions with electrons are by far the most important processes by which a penetrating heavy charged particle loses its kinetic energy when the velocity of the particle, v, is much greater than the velocity of the electron (in hydrogen v■ = 2.183 x 10■ e/sec, while for α = 1.623 x 10■ e/sec). If kinetic energy is conserved, the process is called elastic scattering; such scattering is of minor importance for heavy particles but of great importance for electrons. Scattering through a large angle entails a large acceleration of the charged particle. This in turn may result in the emission of a quantum of electromagnetic radiation, known as bremsstrahlung, which becomes important when electrons are involved. 31 Coulomb Loss and Stopping Power. According to the classical point of view, a moving charged particle loses energy to an electron by imparting to it an impulse proportional to the strength of the Coulomb force and to the time during which this force acts. Since the momentum acquired by the electron is proportional to the time during which the interaction takes place, it is inversely proportional to the velocity v of the moving particle. The energy acquired by the electron, and hence the energy lost by the particle, must therefore be proportional to 1/v. This on the classical picture implies energy loss shows to be proportional to the electron density in the medium and inversely the energy loss per unit path length is proportional to the square of the velocity of the particle. When the penetrating particle is moving too slowly (v < v■) that as the average charge approaches zero, the average energy loss per unit length of path to electrons decreases to zero, proportional to the velocity of the penetrating particle if the average energy loss due to elastic nuclear collisions is increasing proportional to 1/2. The charged particles moving

throwch matter transfer thetr snerey preferentially to tices alectrons that are closer to their tracts. The farther an electron fron the track of the alpha par tele, the sneller tho imulce it can receive, and hence tio onaller ‘the energy that can be transferred to it. If that energy 4 just less ‘Shan the acount required to raise a K-electron to a highor energy low ely no energy will bo lost to a Keloctron at that distance. Sone stint farther any losses to Laloctron wlll becone tnposaible, and 20 ote The nore tightly bound the atonie electrons (Ju: the atoste mumter), the shorter vill be the higher 10 "cutnoff" distances end the ecaller tho rate of enorgy loss. Concoquently the rate of energy Joss 1s expected to show sone dependence on atonic nunber, being svaller at high atoste mabers. ---Page Break--- At valoctttes approaching the velocity of Light, the 1/e2 dex Pandance ie modified ty a relativictte of ects The relativistic con traction of the electric field of the coving alpha particle makes posathle mezzy Lose: Fate of energy Loos inom t creator distances, and in consequence the os slowly at very high energies. The stopping power to defined us tine anercy lost by the heavy charged particle (alpie, in ou cass) por unit path An the stopping subotance and is given ty the expression: 8(B) =~ (a5/ax) where E is the classical Kinetic mercy of the particles Stopping pover varies with the energy of the particle end the Fango of tho particle can be calculated byt Spe | os Be f f sa) “2 wdifax (G2) where B is the rango and Zp is tho initial Kinetic eneray of the par tele, Stopping pover can be detornined o:pertaontally ty measuring the enerey of the particles, which have gone throwh a certain thick ‘Reso oa substance, If the rango ie Imcim ag a Amction of Z, the stopping power can be obtained frost a 4 = 6.3) a s(e) ---Page Break--- 3+2 Stomrin: Cro-3 Sections Tho aolecwer stopping cross section « 4s defined as the enercy loss solecule per unit ares normal to the path of the particle, tees: 4) there 62/3x 49 the

energy loss per unit path length or Linear stopping power and n is the number of molecules per unit volume. The stopping cross section is used since it is a quantity independent of gas pressure or temperature. If the distance traveled by the particle is held constant and the number of atoms along a path of the particle becomes the variable on which the energy loss depends, the above equation should be written in this format:

e = -1428 (2.1 GeV) (6.5)

In both equations, E1 represents the energy of the incident particle on the material and E2 represents the reduced energy after penetrating through d atoms per unit area normal to the path of the particle. An expression can be derived for in terms of the variables measured in this investigation by the use of the Law of Avogadro, Boyle, and Charles with the following relationship:

a = (3.8)

---Page Break ---

here p is the density of the stopping material, W is the atomic weight and A is Avogadro's number. Also, we can deduce from the atomic theory: Rg = mz (0.7) sharing 40 the electronic density and Z is the atomic number of the substance. From Eq. (3-2) we follow:

Row E (1/2) = f (1/n^9) (3.8)

But n is directly proportional to the density of the materials, so the range R will be proportional. From the general law of gases, PV = nRT (G09) where M is the molecular mass, R is the gas constant, P is the pressure and T is the temperature in the volume V. Rearranging the last expression we get:

F = ae (10)

From Eq. (3-10) we can see that (P/T) is directly proportional to n or inversely proportional to the range R. Written in the other way, we have:

F = constant (G1)

---Page Break ---

Rearranging the last expression (13) where the subscripts "o" means standard conditions and B = (6.13)

Inserting B into Eq. (3.12) into Eq. (3.14), the molecular stopping cross section can be calculated from the collected experimental data using the resultant formula:

σ = RRAB (3.14)

where the mean residual energy of the alpha particle after traveling the distance d with...

a pressure Py in the chamber 4e Ey and the 'mean residual energy Ea is the decreased energy of the particle after reversing the chamber at the pressure Py (AP = Py = Py } Bp By)e 343 Eatho's Theory. (See reference 14) Bothe's theoretical treatment of the energy loss 42 based on Born's approximation, applied to the collision between the heavy (alpha) particle and the atomic electrons In this theory the differential cross section for the process in which the alpha particle transfers a given amount of energy to the atomic electrons is given by the square of the matrix element of the Coulomb interaction between appropriate initial and final states. Plane waves are used for the incoming and scattered alpha particle, the kinetic energies being E and E' (S-E), respectively. ---Page Break--- 2 The condition of the atoms is described initially by the perturbed atomic wave function for the ground state and finally by the wave function for one of the excited states. Multiplying the cross section for a given energy loss by the energy lost and integrating over all possibilities gives the final expression for the average energy lost per centimeter of path. The use of the Born approximation requires that the amplitude of the wave scattered by the field of the atomic electron shall be small compared to the amplitude of the undisturbed incident wave. As it is well known the criterion for this is that: wo, (3.15) where zo and v are the charge and velocity of the primary particle, respectively and ■ is the Planck constant. The condition is well satisfied for large velocities and small charge of the incident particle. Equation (3.15) is also essentially the condition for the particle to have its full charge when Eq. (3.15) is not fulfilled, the particle tending to capture electrons. The calculation of the stopping power is made much simpler for the velocity of the incident particle not only fulfills Eq. (2.15) but is in addition large compared with the velocities of the electrons within the atom, 4. as in Eq. (3.16) where E.

ts the easy the Anofdent particle, 243 the donfeation, ---Page Break--- B potential of the elestrona, and Mand s the aasceo of the tnetdent partlete and the electron, respectively. Tnder those conditions and tor xomralativistic velocttien the path or "topping power der 2 -a- ate os G17) B= ti EE) (.170) average enorzy loss par centizeter vith Hare ¥ 4s the velocity and 20 the charge of the incident particle, the munter of atoas por cubic centtaater of the material, the micleer charge, I the average excitation potenticl of the atoa, and the dizen stone: Jogarithnic term B the "stopping number", For relativistic velocitios of the incident particle 4t 13 show by Bethe that: Bow 2 (tog BE tog (4-22) = 2 G18) whore $= v/s and c 40 the valocity of Light. Although Equations (3617) end (3.18) vare derived for otmple "hydrogenlike" atons, it ean be apaliod to other absorbers by adjusting I. The value of Tis dest dotamined from know ranzewnery data, from vich 4 4s found ‘that I (given in electron volts) io related to 2 ty: Ios ns for Z <0 19) I+ sez for 2 > 30 ---Page Break--- % ‘Fron Equstion (3.17) the following relationships are evident: (a) Stopping power 1s proportional to electron density of the nedium (WZ), (b) Stovotng power 4a proportional to the equare of the charge of the incident particles Gey the stopping powar for prow tons 4s 1/4 that for alpha particles having the eazs valo= city. (Velocities are the sano for protons having 1/4, the energy of alpha particles), (c) Stopping povur increases vith decreasing particle valoc!ty. ---Page Break--- 6 A Mock dingras of the detection eysten used tn this project 19 given tn ficwe fete A nochanieal om PND vm wed to lovar the pr ewe dn the chatbers The prose sae within the center as sousured wth @ cereury canocoter, Leake #20 of stoppin; cas into the chester vas controled ty a manifolds 49 alpha source scimce uae placed opzoeite a soateontuetor detector in the gas chante: ‘The munber of colecules along the path of the Particle vaich provide the anergy loca nechanisn (

couloubie inter. eetions with the clestrons) we varied by changing the gas pressure in the che: The detectable energy of the alpha particles after ‘traversing the separation distance between the source and detector, at a low case temperature and pressure, is determined from the alpha spectra obtained from an analyzer system consisting of a semiconductor (Si) detector, a high power supply, a miller, a preamplifier, an amplifier, and a multichannel pulse height analyzer. A schematic of the laboratory setup is shown in figure 42 and a close-up can be seen in figure 43. The alpha particle source used in this experiment was a calibrated 0.1 microcurie Ho 5™T source, which had a negligible self-absorption and a minimum backscattering. This alpha source decays by emitting a 5.477-MeV alpha particle which was assumed to be SALSBAIOe (13.6 ---Page Break--- 6 fem] [oy - vacuum pump preamp detector collimator Ly collimators | Tt—adjustments | height cylinder | red chamber Figure Yo 441: Schematic diagram of the experimental arrangements ---Page Break--- Figure 4.2 1 Experimental setup for stopping power and range measurements. ---Page Break--- Figure 4.3 + of the experimental setups ---Page Break--- 9 percent) on 5.37AUioy (1-4 percent). The detector used was of the sensitive area of 1 cm² and a level of approximately 200 angstroms (© which is almost entirely to the gold electrode on silicon surface barrier type with typical insensitive business of the surface. A crash of safety does 41 the dead layer varies alpha particle linear stopping power of gold for alpha particles() attenuated by the dead layer thickness. The data showed that = 5.5, 140 and 042 alpha particle incident on the total energy was constructed using the detector suffered an energy loss in penetrating the dead layer of 10, 15 and 8 KeV, respectively. Thus, the detector was essentially free of complicating "window" effects. It has been shown that the response of solid state detectors is linear for alpha particles over the energy range of our experiment. The source and the detector were

mounted in line within the chamber and the separation distance could be varied by means of an adjustable rod upon which the source is mounted. Source and detector are shown in figure 44. Also, an aluminum collimator was placed over the alpha source and the detector in order to get a collimated beam of alpha particles. 4-2 Bronze Loss measurement: The calibration factor in Kor/channel for the energy analyzing system was obtained by means of a pulser observing first the zero energy position and then by observing the location of the 5.477 MeV alpha peak while the chamber was under vacuum. The results and factor obtained are shown in figure 45. The calibration factor (7.77 Sev/channel) was also measured after ---Page Break--- oo Figure 4.4 + Vacuum chamber ---Page Break--- summary/aey 114 gon Pourqo zoyo8y woRRMMTTH *woRkTwY Abroue ToD Feel ¥ PUY sOETR ABzotO WO 30 saves 4q pourrge ‘uesete SupisveN amod Supddoye or OF eam woRIVIATTED # Sry emIts ¥aEWAN T2NNVHD oo8 009 ‘oor oz AOW ‘AOWIN3 asInd ---Page Break--- 08a ceascrenents, Yo significant drifts were observed in the energy position. The temperature of the laboratory was maintained within 1°F of a mean temperature (75°F) so that it was possible to average several sets of energy loss measurements on each gas. Using the 5.477 MeV energy particle and a fixed source detector distance, energy spectra at various different pressures were taken for each of the gases considered. Information on the gases used in the experiments is given in Table 4.1, and an example of several energy spectra of alpha particles after traversing 5.4 cm of air at various gas pressures and at 2°C is shown in figure 4.6. Multiplying the calibration factor (Kov/channel) by the channel number of the alpha peak, we found the averaged peak energy of the alpha particles reaching the detector after traversing through the stopping gas at a given chamber pressure. Using a simple relation derived from Eq. (3-12) we got an expression for calculating the equivalent distance traversed by the alpha particle.

at chamber conditions. In other words, Bo. Poh Xotp Fe = ae FS 1) shore the subscripts "0" and "ch" mean standard and chamber conditions respectively, and 4 is the separation distance between the alpha source and detector within the chamber. The last expression ---Page Break--- TABLE 41 ‘SOME CIRCULATORY AND PHYSICAL PROPERTIES OF GASES USED IN THIS WORK case. structure’ MOLECULAR WEIGHT” STANDARD DENSITY Mt (g/mol) 0 (g/ex) aR 28.97 1.293 a 39.95 1.789 Me 23.01 1.251 & 83480 36736 02 316998 16429 2 g/cm3) 197 m0 aMaategs Freon 1 170.92 7.036 5 i, neG-a 16.04 0.717 HH ue coy Be 28.05 1.252 BE 2% BGpe 30.07 4.342 ¥ EEE eat 1878 ¥ Rg e383 Beta 4009 1.967 ea Given by Pauling (92), unless otherwise specified. 21 ahvon By toast (15)," ao) ja): Given by Orvillo-Thonas| (b): Given by Bont (2). ---Page Break--- *ogte 48 pue comnsoext 928 emoTsaA 90 To 30 00 795 Buyszwanny so45e COTOF} TOI MAITU Jo wjoeds ABzuUD Tesanas 1977 OIE WaGWAN 13NNVHD oor 009 oos oor oo, wu 19% aus 612, wu 61 | [SH wus 1 3 2 3 g WIL 2AI1 "235 OOP NI 13NNVH2 Yad SINNOD 8 ---Page Break--- may be rearranged as follows t «4.23 (hota) Tetp = 4 Fo assuming that the temperature quotient (To/Teh) is approximately equal to unity. Experimental energy and chamber pressure data for each of the gases mentioned in Table 4.1 were taken by varying the gas pressures on the chamber at intervals of 1 to 10 centimeters of mercury and the results were plotted in figures 4.7, 4.8 and 4.9. By altering these curves graphically, the stopping power parameters were calculated taking ox = 1m, and an average value for the corresponding energy. In other words, Af AE = Ey = Eyy Egyor = (B1 + £2)/2. Finally, the stopping power (~ d8/éx) was plotted against Eaves for each gas. The results are given in figures 410 to 4e13e Ranges of alpha particles with energies between 2.60 and 5.47 MeV were determined simultaneously with the stopping power measurements by counting the number of alpha particles of a certain energy reaching the detector in a fixed period.

of tino at a given gas pressures In order to decrease alpha energies, very thin metal foils (out 0.00004" and 0.000125" to 0.00015" and 0.0002" thick) were placed over the 5./7aev alpha source and the energy peaks coming from the decreased energy particles show acceptable broadening averaging 23, 4002, 34535, 3427 and 2.60 obtained using Andi ‘viduel and combined metal foils. Ax and hydrocarbon gases were ---Page Break--- a *e9eu uoqrvoospAY pus ITU JJ emesosd ou zoqrvyo om 04 BuFpucdsorz0s ¢ CICy aed upep.eo © Buyssaausy amaze woTOTTI MITE yyy AMK LY*G 30 Kiseue IurUTwORY t Ley ome “rus "Py 04 Buspucdsosso> ‘dary, z ° € t new OURN WHETY ---Page Break--- og puw % é2y ty soy osnos0ad v3 zoqueyo om 04 Fuypuodsoss0o +458y ted upezt09 v Superman, soy ze soToyzrod MTU | Ry ARIL7*G 30 Azo Dupuyeaey t gry emits ‘suis “Pg 04 Guspuodsossos *dtsy i e zg 1 "ROW ‘AOWINA VHTY ---Page Break--- qirtoont Pee tn ary soy omssord cv8 seqavys om 04 Iuypuedeozros “Sy yyod upeyTos © Buyssoaen aeaze soToTaaed MUTE | UY amieU7"S 30 KAsoUe DpuyouOY + Gry OmdEE ssw ‘4% 04 Guypuedsossos ‘4i8y. © z 1 "ASW “AOUINA VHT ---Page Break--- 5 u “Fafo pum ky tape vy soporiswd walye Jo s9oy ABzeHy t OLY eins “NOW ‘9U3N3 WHET t t f i a “un /ROW'AIMOd ONIddOLS ---Page Break--- “new ‘ROWINA VHaTY + ° “w2/how “WIMod oNIaois ---Page Break--- ” § 09 puw Zo ‘2y uy copoyysed ytre Jo ssoy sour t ziry oman ‘ROW ‘OWING VHdIV su2/A9W ‘YIMOd ONIddOIS ---Page Break--- rh moons pum ofa Zax “Rie wy eoToTa Tad melTe Jo ssoT Sew 1 Chey oT “Now ‘kON3NT VHGIV z ---Page Break--- B chosen for this part of the experiments and the results are tabulated in Table 4.2 and plotted on Figures 4.14 to 020. Additional range data for other gases such as O25 M2, 002, A2, Erp, MgO and Freonet4 48 presented on Figures 4.21 and 4.22 for 5.47-Viev alpha particles. Range curves were calculated by normalizing the total counts using the ratio of total counts and maximum total counts recorded by the scalar for the same period of time. Table A.1 (see Appendix) is a record of

the things of the instruments used on the experimental Measurements. 4-3 Gross Section Calculations. and hydrocarbon gases (C1, C2H4, C3H8, C3H6, C3H5) were calculated by means of Equation (3.14) and the following constant values: Avogadro's number (A): 6.024 x 10^23 molecules/mole Standard Temperature (T): 273°K Molecular cross sections for air Standard Pressure (P): 760 mm of mercury. Source to detector distance (d): 5.4 cm. Molecular weight and standard density values for each gas to be inserted on Equation (3.14) are given in Table 4.2. Cross Sections for air, methane, ethane, propane, ethylene and propylene for 0.3 = 5.0 MeV alpha particles are tabulated in Table 4.3, and curves of Molecular cross sections (10^-9 MeV/molecule/cm^2 versus alpha energy (E) were drawn in Figures 4.23 and 4.24 ---Page Break--- REMEDY RELAT PARTICLE BERT, MeV 5047 5.04 48h, 423 4.06 3653 3638 227 2.60 1643 3.89 3653 3432 28 2.63 2.10 141 TABLE 4.2 a 427 3674 3652 242 1.92 178 SIP OF AIR AND HYDROCARBONS FOR ALPHA PARTICLES® Rue, cus a, alg 2.96 2.38 - 213 2.00 1631642. 1531435 W19 1.06 0.69 0.68. * These values are plotted in Figure 4.25 GASES 2.05 157 4.51 1.03 0.92 0.62, or 0.70 0.613 ---Page Break--- 38 sandy vary by error FOR TL Pim nO UTI uw (A mixture of Supply Theory A same Sao nee soars 07m edsowing aoasU soToFIZOd WydTS s0y sororszed sutte ns 01% 10J coamo oRMy sYL+y omigg sm Py on Et 1 i Surpuodsosso “Aisy. (s4un02 -xou/ssun0>) Olayy ---Page Break--- sa0y wy teonuA Ho woE somo amy uO comIpE *(Ya0) OweNOK UF OTROS KL puW nO UIIA ArOK Suysesdsony amaze coTorired wate TOF Pew (Cisous OFOUET THRAFEE aml L7°6) GoTo wylT | ey OU 205 CoamD OOMY 4 SLH7 OmdEE San EE SUEDE EPEAT SE URL eee Fun Py 01 Buypuodscison “Airy t ou syuno>) DLAVe (snunes * ---Page Break--- 7 os He | t say UF foonpes Msous wooH soAm2 OWN Wo EoD TE *Ci®o) oumna wy stTos FL pu ng UT fren BuyecHdsen aoyse soToTAcod wydTe Joy uw (A208 OpROUTy THFRFUT Ami LY°S) SOTSTA TEL BUITR | RY om JO soamo euMy 1 GLY omITE Su

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04 Surpuodse. oO (24un02 -xow)sune>) O1vy ---Page Break--- < sami wy teougeA ABzau9 wee seams omy WO CORTE +@afo) eundorg wy sTTos WE PHO TO UTI Lx0n Jupoodoon aoqJv coToTyTed wdTE TOF Paw (Gisoue OTOUFE THFATUT a0H LY°6) FOTOHAIOL MRT | Aa omy op coaMD oUNY t LLY amdys SH Jo sur ‘aunssaya uzewvH “Ys os or or ox a jun) OUVA |” (Sunes ous ---Page Break--- » Cio) ovovtina wy sos FL ee Pov (£35000 STOUT THFETU AOL) os wHeD osu “1G poo of Buspuodsesso> “45. aire 03 woamo odimy + ghry oma or ese 2 2 (squno> -xow /syuno2) Dive = = ---Page Break--- g *(i9) oworkoas up oTFOE FL PED ny os conte Kin even cone of vo eomdRE 9a SupeceLIONy xOAJO COTATI mAIPU GOs uD (4Bx0us OTROUTL TERA FUT AM TOTATE WSTY | HY Om OF Som eum IGLe7 omiry 8H fo sup ‘gunssaua wagwvH> “YY ov or ot a ouvea ” 8 2 (s4und2 “xu /ssunoy i su “04 Buipuodsesso> “4ity ---Page Break--- RANGE, ems 1 i 2 ALPHA ENERGY, MeV Figure 4.09 + Ransom: crete tone a Calg Coty CoH, CoHs 5 6 ba particles underd condi ---Page Break--- (ou paw % ey 24) woees ovmszouy Texwaer uy (40H L7*5) woTeTAEM MYSTY j,_t7 sO} Conan BDU 1 1Z~y emoqs Sy 4o sus ‘“aunsszus usewvHd “Pa 9 os ov ge L oz ot ° sun "y §, buypuodsosso> “dasy © > Youve (s4tin09 oui /syuno: ---Page Break--- 7h wo0ag pas a oo wr (a5 LYS) seTONIOd wHET® 7 403 Boasmo eBUWY t ze+7 OTE 6H fo sus ‘sunssaua wagwrno “Ps os op oe Sr m stuns) O1LWs to (squno> -xoui | ---Page Break--- TABLE 4.3 MOLBOULAR STOPPING CROSS SDOTIONS OF AR #11D HYDROCARBOW GASES FOR ALPHA PARTICLSS* anh, tay tae OCOe 0.3 - - 13.5 196 235 26.0 Oh - - 16.0 213 28.5 27.0 05 55 - 1762 225 21 215 ob aks mse er ee 12 9 1S 265 16.0 15S 22.6 166 5S 663 1064 1267 We Wd 2.0 8.0 55 cy) 10.6 1267 1406 28 55 AS 7600 8.0 10-1 Wed 32 “7 rd 72 93 1065 ---Page Break--- CONT. TABLE 443 nem oo, vat at 36 ae 40 42 bs b6 be 50 * Those values are plotted in Figures 4.23 and 4e2be am be 403 bet 39 28 Be 37 366 35 MOLECULAR, STOPPING CROSS SECTION (10-4 ev/aolecule/en*) my 309 308 36 35 33 32 3A 3.0 29 Cai, 6.2 6.0 58 566 Soh, 50 5.0 49 he ale 69 67 665 63, Gt 569 BT 56

55 ORG 89 8.6 83 8.0 18 16 Th 13 ms Cig 10.0 7 Qh 9.0 87 8.6 8.4, 8.0 ---Page Break--- a4 8 MOLECULAR CROSS SECTION, 10 eV/molecule 3 1 2 3 4 5 ALPHA ENERGY, MeV Figure 4.23: Molecular stopping cross sections of air, Opsis and Gilg for alpha particles: ---Page Break--- ar 3 8 8 MOLECULAR CROSS SECTION, 16 eV/molecule/cm² 3 ALPHA ENERGY, MeV Figure 4.24: Molecular stopping cross sections of Gly, Cyi{, and O38 for alpha particles. ‘ar Cal, ---Page Break--- CHAPTER RESULTS 21D conclusions ‘The accuracy of the stopping power and molecular cross sections calculated in this investigation depends on the following quantities: ‘Je~ Gauge Pressure: The difference between the two columns of the Mercury Barometer could be read to an accuracy of ± 0.5 mm of mercury. ‘Thus, the error in P ranged from 0.4 percent for the largest pressure intervals, to 6 percent for the smallest pressure intervals. The pressure intervals ranged from 113 mm of mercury at the highest energy loss to 8 mm of mercury at the lowest energies. 2 Gas Temperature: A mean temperature of 21°C was used in calculations and the temperature of the laboratory varied ± 1°C from this mean. Therefore, the fractional error was approximately 4.0 percent. 3r= Separation Distance of source and detector! The error in the measurement of the separation distance was of the order of 0.8 percent. Residual Energy of the alpha particle! This error was the most important in these experiments and the hardest to estimate. However, the estimate of this error was reasonable from the spread of the experimental data obtained from the energy loss spectra. The uncertainty in estimating the peak channel of the energy spectra was a major source of error in determining the average. At which residual energies, the resolution of the energy system was very good and the error: Locating of the energy ---Page Break--- 49 spectra was noted: » straggling of the particles caused the energy spectra to broaden and the peak could

not be located with as much accuracy. In this » the error

was esti- sated to be 2 chamela, or 0.23 per cast at higher energies and 5.5 percent at the lower residual energies. The most probable error of the calculated values based on the experimental data was determined by taking the square root of the sum of the squares of the maximum fractional error in each experiment. At higher residual energies, the most probable error (mean standard deviation) found was of the order of 4-5 percent and 9-10 percent for lower residual energies, respectively. The values proposed by the author on the basis of this investigation for the stopping power of 13 cases are given in figures 4.10 to 4.13 as a function of alpha energies; also, for the molecular cross sections of methane and hydrocarbon gas (Gly, Calg, C26, CHR, Osis) which are tabulated in Table 5. Those energy correction values were obtained from smooth curves drawn through the experimental data points and probable errors (figures 4.23 and 4-24) as a function of alpha energy; this is true also for the stopping power and range curves. The method used in this investigation gives values that are in excellent agreement with those found when the gas pressure within the chamber is constant and the scattering factor distance is varied at the energy region where a comparison is possible. Table 5.1 is an example of a comparison of molecular cross section calculations given by different authors and this work showing a good correlation within ---Page Break--- U6 670 seen on ort ru cron oe ove ore oe zo bg ah ug ek ae oe 9 rot eu sa ote teh ee sest oe Stak vor v Ms z9 ow. we $6 oro. 6% Ea be 29 ber es or 29 ze oe ba 8 re 66 $6 se ore se or at ot mm zn on 80 90 RAT Wee ay Te 8 uly execu Sioa way SRUQUVILT? MO GNOOE VAVO LIA SYNGE NOLLOaS sooND UVINLETOH go NOsTEVAHOD bs save, ---Page Break--- 51 ow cL BT wr 6 He se oe ors oe LS sae re ue ore or Be 9S ss HE ue ore or ov Te ST | AE ay FE) SIETDEC Cro) annie ary gio/OTAOTOH/AW OL *NOLICES SOND WrUNATION ---Page Break--- the = 5:0 sav alla energy reston for some hydrocarbon gases and air, This

vo: should be extended indefinitely for additional cold outer cross sections in calculations using the information on inorganic gases (ty, Copy 0, note) given in this work or including as many inorganic and organic research and industrial gases as desired. In the same way, comparisons with theoretical calculations using the Bethe equation (Eq. 3+17) across show the residual alpha energy above 1 MeV (Figure 5.1). In the radiolysis of a gaseous system, it is possible to measure the number of ion pairs formed by absorption of radiation. The yield of a given reaction can therefore be expressed in terms of the number of molecules formed per ion pair produced. The ratio NAIL is commonly referred to as the ion pair yield, where M is the number of molecules changed per ion pair and Ny is the number of ion pairs formed. M may designate a species of a given kind disappearing or being produced, and in some cases, M may be expressed either as the total number of ions or as the number of ions of a given kind. The latter calculation is based on knowledge of stopping powers and the energy required to produce an ion pair in the individual gases. Related research could be developed simultaneously like gas radiolysis, determination of chemical reaction mechanisms, or yield measurements, etc., using the values given in this work for inorganic and hydrocarbon gases. ---Page Break--- Alpha Energy, Me Figure 5.1 Reference: 3 jethe slow alpha particles ---Page Break--- cf he om 10.- BIBLIOGRAPHY ALLIS Seis and W:RSEAN, $.D. The Stopping Cross Sections for Protons, O+1 to 6.0 MeV} Rev. Mod. Phys 25, 779 (1953). BRIT, HAs: Chemical Structures of Inorganic Gases} J. Baue. 37, 616 (1960). BENE, HA, The Range-Energy Relations for Slow Alpha Particles and Protons in Air} Rev. Mod. Phys 2p 213 (1950). + GHD, Weis and POWERS, D.t Stopping Cross Sections for Alpha Particles from 0.3 to 2.0 MeV Phys. Rev. B 8, 3625 (1971). COLARD, Js and GAL, J+ Silicon Surface Barrier Type Semiconductor Detectors; Nucl. Instrum. Methods 16, 195 (1962) BOURLAND, Pe

DEARIALEY, G.: Semiconductor Molecular Particle Detectors; National Academy of Sciences ~ National Research Council Publication 871 (Edited by J.W.T. Dabs and FeJe Walter), pp. (1961). JESSE, W.P. and SADADSEIS, J., 'The Range-Energy Curves for Alpha Particles and Protons; Phys. Rev. 72, 1 (1950). KERR, G.D., HATRR, L. My, UNDERWOOD, MN, and WALTER, 4 Molecular Stopping Cross Sections of Air, Kr, 002 and Cl, for Alpha Particles; Health Phys. 12, 1475 (1956). EMD, S.0.1 Radiation Chemistry of Gases Reinhold Publishing Corp. New York, pp. 123 (1961). ORVILLE, WSs and THOHSS, Tet Sade Spaeteye 3, 589 (1955). ---Page Break--- 55 WEE PALER, BBS The Stopping Power of Nitrogen and Hydrocarbon Vapours for Alpha Particles over the Energy Range 1 - 8 MeV; Proc. Phys. Soc. 87, 681 (1966). Y= PAULING, tt The Chemical Bonds; Cornell University Press, Ithaca, NY, pp. 58 (1967). Bee ROTONDT, S. Energy Loss of Alpha Particles in Matter; Radiation Base 33, 1 (1968). Vem SEGRE, B (Bitter): Experimental Nuclear Physics vol. 1, part II, pp. 166 Wiley (1953). Wen MALAH, Pad. Energy Loss of Alpha Particles, Protons and Electrons in Matter; Ph.D. Thesis, University of North Carolina, Chapel Hill, H.C. (1962). WEAST, R.C. (Editor): Handbook of Chemistry and Physics; Chemical Rubber Co., Cleveland (1966). ---Page Break--- 56 ---Page Break--- 57 TABLE AT INSTRUMENTATION EQUIPMENT SETUP FOR EXPERIMENTS Joe DETECTOR BIAS SUPPLY Ortec Model 423 Gate Ar 50 volts. Ortec Model 719 Ortec Model 486 Coarse gain: 16 volts Fine gain: 6.5 volts Window: 10 volts Lower Level: 0452 volts other settings as per operating instructions. dew Station Ortec Model 484 Threshold: 0.4 Other settings as per operating instructions. ANALOG TO DIGITAL CONVERTER Molecular Data Fine: 0.10 volts Coarse: 10.0 volts. ---Page Break--- 58 TUBE AT Conversion Gains 102% the Upper Level Discriminator: 10 volts, Lower Level Discriminator: 0.49 volts other settings as per operating instructions. Gem MASTER CONTROL Nuclear Data Output time: 400 seconds. Other settings

es per operating instructions. 'Tom READ-TA/OUT DISPLAY Macloar Data Settings as per operating instructions. ---Page Break--- TABLE A.2 ROE AND ECMOE Loos mpEanscrrat data for 5.477100 aT anrma PARTICLES DN ATR ona of Hg = MeV os tm tam oak 10.5 1643 0.962 0.746 622 ABS re 1669 1603 0.939 14200 557 432 3067 1644 0.963 20181 423 3629 3563, 1623 0.950 2.508 373 29 3903 1621 9.949 2792 33 2650 427 1627 06953 3.033 2 210 M7 1629 06954 36318 wz 1.00 5103 1549 06907 3a6h4 13 0.87 5360 1085 0.635 36765 R O71 5he8 36 0.002 3.893 2 0645 ---Page Break--- TABLE A.3 AOSE gm Remar toss mr=noewes, pava FoR 5.477N6v ax?41 goon PARTICLES TY i, caasaR 'tora, CRANE = QUTVALENT sta, comms RAN Sure 'BIEGY, cas of Hg = We nk 16 1.000 0.028 eg 5h 5.0. 163804954 0.355 gy 52 3.0 170.973 0.639 a5 5.01 1364 169% 04937 o.930 5 478 1k 16690972 1.236585 454, 22 1639 0.955 1.506 56 432 25eh 1628 0.954 14804 502 4.05 32h 1603 0.934 2502462 3659 36.2 1686 0.982 572 yap 3.32 ed, 1580 0.92 aur gre 2.89, 09 105 0.935 3.332 2645 5204 WI 0435 371g 1093 5307 71 0.040 3.815 at 1663 Boor a.843 - - 8 04004 3.986 179 1.39 104000 4227434 1.02 10,000 kez70 8 0.65, ---Page Break--- TABLE AL SANOZ AND DWERGY 10SS EXPERIMENTAL DATA FoR 5.47-¥EV an arena PARTICLES Di Cig cmeen ora, can, EQUIVALENT rasssuss, courts, «ATO Inte za, 'ENERO, cas of Hg os Mav oe 1663 0.999 0,056 698 Seka 36 1602 0495004255662 5h 10 1636 06974 a ho82 907 1685 1.000 ons 586 455 127 1583 0.999 got 542 bez 1564 1584 0.940 14093505 3692 18.6 168 06954 14320 ass 355 216 1518 0.936 14533408 3.17 2b 20.956 6353 2.1 2.0 Kb 0.976 4.968 a7 245 316 1567 0918224319 148 3h8 ee 0.408 KB 0.56 3504 58 00m 25133 0433 36.0 © 0,000 24556 5 0.19 ---Page Break--- TABLE a5 RANGE aD ENERGY Loss EXPERDENTAL para POR 5.47-NEV An2%1 ana cE PRessuas, esa of Be 1.0 3.0 25.5 26.3 'ror, cours 1613 1631 163 1643 15% 1604 1565 1952 us? 1430 546 202 1 RATIO 0.959 1.000 06965 oom 0.949 0.954 0.930 04923 ong 04850 06324 0.120 0.000 PARTICLES TX O3iig ee o.071 0.355 0.540 ov7e8 1.072 1s 148 46541 1.669 ame 1.769 nen

1.850 cae BER 693 623 573 503, an 35h 224 uo 2 65 8 BqUIvALENT ‘Bier, Mev 5638 8h, eks 3490 3.20 2.75 2.20 wn 1.08 0.95 ont 0450 oont ---Page Break--- TABLE 6, RKRS AND BRmey 109s exrsenc: PAXTIOI ral DATA FOR 5.4.77 an%47 popag Ti Cait, Ri TOME cum, agora cE, COUNTS RATION yp, © NRE “BIEAGT % Ea Mev 07 1699 0.990 0.049 m2 5eh5 29 WHS 4.000 0.206 69 5.27 509 1705 049% 0.419 as 5.04 89 Wet 04980 0.632 616 4 19 1682 0.900 0.045 sz 452 Med 1604 04935 1.058 33 heat 12.0 168104980 1.207 504 3.98 21.0 W641 04956 14492 465 3662 200 1680 0.989 44705 re) 3.28 21.0 Wis 0.960 1.918 380 2.95 30.0 15610910 291 325 252 33.2 162004980 24358 267 2.07 36.0 1503 0.876557 206 1.60 3700 15K5 0,900 2.608 m4 1635 3807 150604878 a9 190 4.01 4004 1254 O71 2.849 88 0.68 4009 200 0.116 2.906 5h ona 43 0.012 2.934 52 040 au? 10,0005 2.962 x» 0.23 ---Page Break--- LE 7 RAWE AKD EER 1089 DOAROGTAL DATA FOR 5-4 7-30V an41 arpea canaER FRESSIRE, ens of Ez 0.8 38 68 38 128 15.9 18.9 2109 25.0 21.0 2.8 Bh 28.8 RATIO 1.000 O.9h4 0.959 04985 0.976 0.981 0.962 04943 04932 ow7es 0.207 0.002 0.000 PARTICLES Dt Cg Tatpy eae 0.056 0.270 04483 04696 04909 1.129 1.343 16555 177% 1918 1.915 2.017 2.046 cue, HOGER 6% 653 oo 550 494, 431 360, 186 105 R 32 SquaaT 'RIERGY, Mev Soh 5.07 467 beet 3683 3634, 2.79 2.28 ohh 0.81 0655 0624, 0615 ---Page Break--- SE AND oO? Det 67 10.1 1363 1669 20.8 25.8 324 Bue? 38 35.7 36.1 369 TUBULE 8 Y L083 EAPERDSEMAL ATA FoR 5.4770 aT arena TOTAL cours 16 1706 1670 167 1653 1685 1619 1565 1592 1532 1399 s92 153 10 2 PARTICLES TH 0 RATIO 0.991 012 0.991 04993 0.981 1-000 0.960 0.950 0.945 0.910 04830 0.707 0.090 0.005 0.000 94050 04220 06476 ont 0.945 1.200 wart 1.833, 1.925 2.280 2.420 2.472 2.536 2.565 24621 REER 699 667 62 sm 530 45 27 on 169 109 92 & 49 BRUIvalrr ‘BIERGY, Xe¥ 50h 5018 4083 hel an 3668 3624, 2.67 2.10 4.31 0684, ont 0652 0.38 0.20 65 ---Page Break--- 1528 1454 120 TABLE A.9 ISLES TW 02 RATIO 1.007 0.995 0.957 04959 o.ous 1.009 0.958 ome 0.960 04970 068% 0.901 04904 0.860 0.275 0.071 0,000 cua, RBI 703 232

133 DATA FOR 5.47=RCV An°%47 aupna EQUIVALENT ‘BERY, Nov Sekb 53h 5.06 4480 bokh beth, 38h, 308 3605 2.70 2.16 1.80 1.07 0.87 0656 0.42 0.26 ---Page Break--- 88 m8 8 2.8 32.8 Ih 41.0 45.0 Mae 506 52.0 5208 5309 5563 5548 56.2 1697 1758 1688 1652 1588 1624 1567 1651 1607 1626 16% 1560 1513 173 ea) 1939 389 ‘TABLE a-10 RATIO 1.000 1.035 06994 0.973 0.935 0.956 04923 0.973 0.947 04964 0.951 0.919 0.891 0.9% on8e3 0.789 6dr o.217 0,010 0.001 Tater 0.056 0.341 0.625 1.051 1.477 1.762 2.046 24330 2.657 2.913 2197 36467 34595 34694 3.751 3.829 3.826 3.929 3.964 3.993 msm 705 or 67 590 53h, 496 458 412 361 3h 203 m 138 1% a2 n 56 ar S2ITAL DATA FOR 5047-4 ant apna PQUIVALENT BHEROY, Mav Soll? 5622 9h, 458 hath 3.85 3655 3.20 2.80 2043 2,02 157 1033 1.07 O97 0.76 0463 0655 0643 0.36 67 ---Page Break--- 5545 5643 5965 599 TaBte At EPrEnm PARTTSISS Tra Xstor o.170 06454 o.n7 1.001 146342 1.612 1.911 2.223 2.479 2.263 36133 36431 3.701 e255 crane, mma 690 659 598 559 523 182 125 102 52 TAL DATA FOR 5.,77%MEV An? urna EQUIVALENT ‘BERGE, Mev 5636 512, 487 dob beh, 4.06 31h Bet 3et2 2663 2.20 1.87 et om 0.79 0654, 0440 0.20 ---Page Break--- TABLE At? 04998 0.970 1.000 0.980 0.994 0.974, o.o71 04959 o.g71 0.934 0.907 0.927 0.919 o.922 0.892 04566 0.025 0.000 ‘a 0.028 0.099 0.227 0.362 06518 06675 nese 1.072 1.321 1.463 16 1748 1918 207 26344 2.499 2.570 2.644 came, UGE 700 687 669 640 615 588 505 BRR ERS 1st 22 56 SRESTTAL DATA POR S477 aT gpa PARTICLES TN Op PQUIVALETT ‘SERGY, av 5h 5633 5.18 4 am 4456 422 3.92 3655 69 ---Page Break--- TABLE 2.13 PAIGE 27D EVEGY Loss E@IMETAL para Por 5.47ev An? appmy PARTICLES Tt Ee cana PRESSURE, cas of Ee O64 bok 94 Boo 18.9 25 22 31.0 33.0 35.0 3569 3667 3803 rom conts 1657 1687 1662 1662 1567 Mah 104 conn a 8 ER RATIO 0.982 1.000 04985 0.985 0.928 0.880 0.832 0.798 06138 0.017 0.004 0.000 (0.000 0.000 0.000 ‘stor 0.028 04312 0646 0.987 16342 1.669 1.932 2202 26344 26415 26486 2.550 2.607 a1

2.842 cua, OS 4, SQUIvALErT ‘BERG, Mev Solet 5.08 4063 hts 3.67 3.1% 2%, 2.20 1684 “7 1.60 1643 1.30

1404 0463 ---Page Break--- 8 38 68 10.1 12.9 15.9 18.7 19.8 200k 21.0 RY Less ror TABLE etd SPERD IAL pan PARTICLES Tr cours —Rarro 1679 1683 1645 1656 1630 1625 154k 103 112 0.968 0.4965 0.917 0.714 0.1086 (0.000 ron s.c77—v an arpa 693 3662 2.96 217 116 0.70 648 0.25, n ---Page Break--- ---Page Break---