(FINAL)
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Europa Missions: Generic Materials Test Methodology

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Radiation Introduction

Radiation

- Radiation in Europa missions: (a) natural Earth and Jupiter Environments (electrons and protons), and, (b) nuclear power source (neutrons and gamma ray photons)
- Effects: Predominant effects are Total Ionizing Dose (TID) and Displacement Damage Dose (DDD).
- Ionization: A photon or charged particle knocks an electron loose from an atom yielding an excited state.
- Displacement damage: An atom is knocked out of its position in a crystal lattice resulting in a vacancy (interstitial) and an atom (or pair) displaced to another location.
- Each radiation source has an energy spectrum that will dictate how much of each effect occurs as a function of energy and absorbed dose.
- Not all radiations do the same thing:

DAMAGE	Electrons	Protons	Gammas	Neutrons
Ionization	X	X	X	
Displacement	X	X		X

Radiation Damage

Ionization Damage

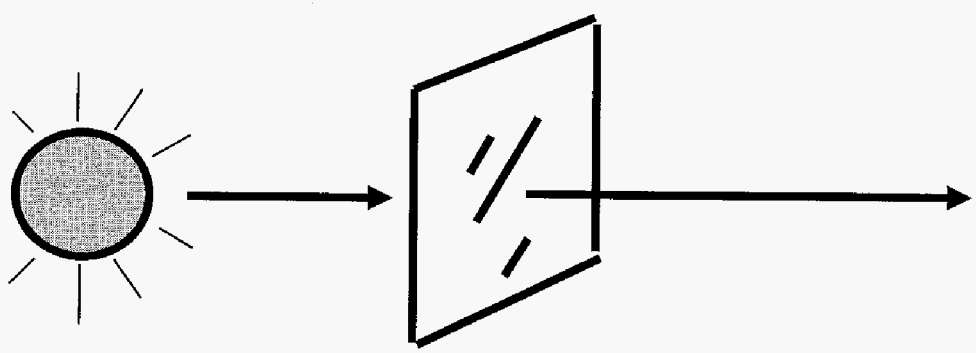
- Increase in temperature (non-ionizing loss heating).
- Polymers: crosslinking, chain scission, embrittlement, outgassing, loss of tensile strength, loss of elongation, destruction of elastomers.
- Wire and cable: fracture of insulation, loss of dielectric strength, change in dielectric constant, change in impedance.
- Lubricants: loss of lubricity, change in viscosity, outgassing.
- Thermal control paints: fracture and discoloration.
- Optics and glasses: darkening, internal charging, fracture, fluorescence
- Charge accumulation in dielectrics, possible internal arcing.
- Ceramics: may cause conductivity, loss of dielectric strength.
- Semiconductors: internal charge accumulation.

Displacement Damage

- Primary effect is damage to semiconductor devices.
- Density change, refractive index change and discoloration in glasses.
- Fracture and embrittlement of ceramics.
- Decrease in tensile strength and yield in some metals.
- Damage to permanent magnets.

Comments on Dose

- Papers rarely show how dose was determined (if it ever was!)
- You cannot transport a dose!
- Dose is the amount of radiation absorbed! (per unit mass)
- Example: A bright sunny day may give a flux of 400 W/m².
- Window glass is 95% transparent, consequently results in 5% absorption.
- The dose is therefore 20 W/m²
- Complete absorption would make the window totally opaque



380 W/m²
Transported flux

Not a dose!

400 W/m²
Incident flux

5% Absorption
equals 20 W/m²
Dose
(in mass of window)

Fluence Testing Approaches

- Fluence is the time integrated particle flux, or the total number of particles over the mission life.
- Testing goal: expose the component / material to the fluence of all particles, energies and types during the spacecraft mission.
- Fluence testing challenge: simulate "real" conditions in shorter time
- Understand that ionization and displacement damage may occur simultaneously
- The physics is what the physics is, so detailed understanding of degradation mechanisms may be desirable, but might not be required
- Be aware of uncertainties concerning particle equivalence testing (do 10 MeV electrons equate to 1 MeV gammas?)
- Includes the effects of secondary physics, such as bremsstrahlung, gamma ray production, Compton electrons, etc.
- The varied stopping power of materials, and differing penetration depth of electrons and protons, results in a *dose-depth curve*.
- Need for dosimetry and measurement of dose essential
- Due to their mass protons travel a much shorter distance than electrons. (At 1 MeV protons travel approximately 1/100 the distance of the electron)

Ionization Damage Exposure

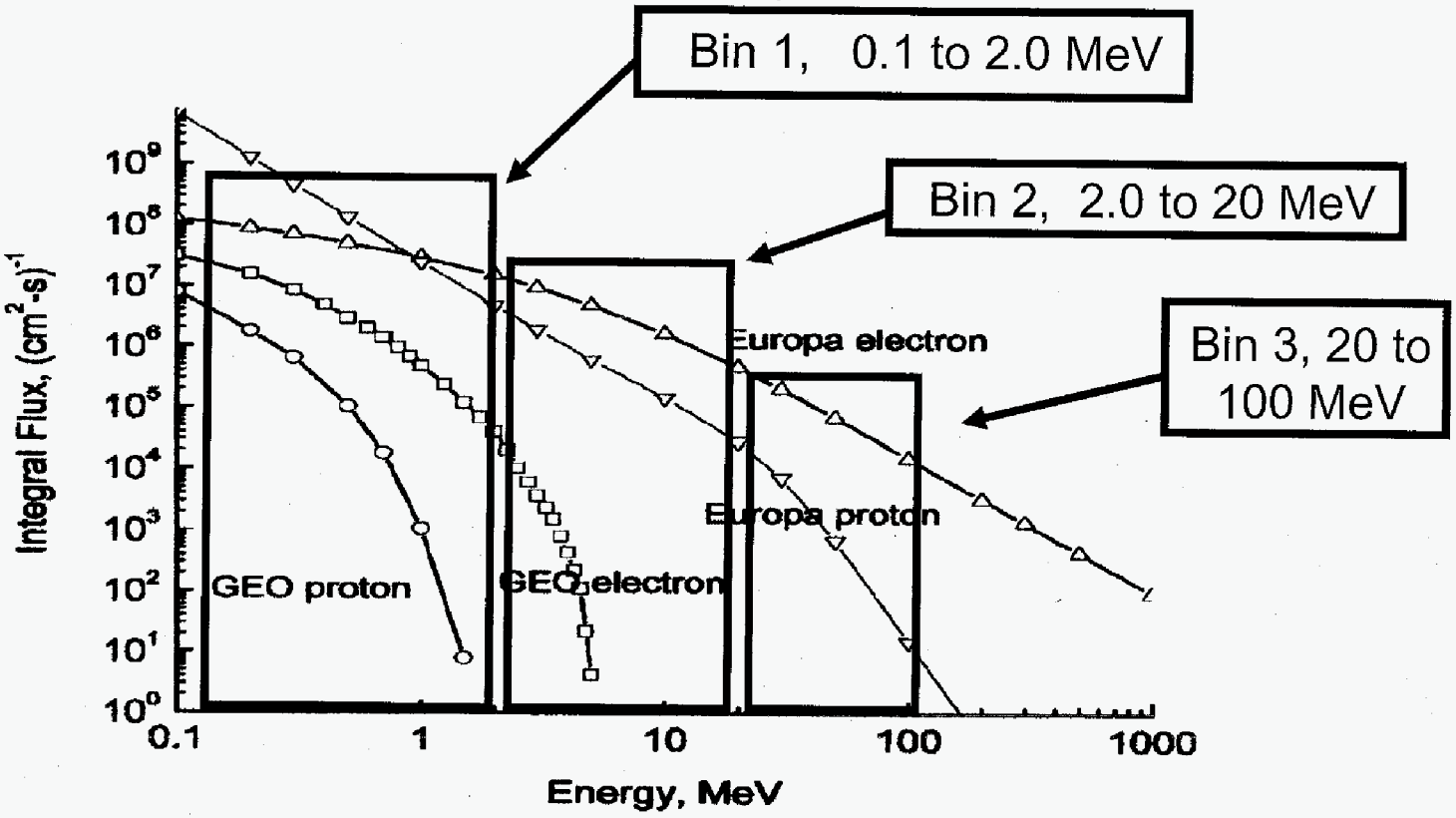
- Europa mission exposure due to ionization effects (TID) has been calculated (Dr. Insoo Jun, JPL).
- TID results from mission *electrons* and *protons*, plus contribution from reactor gamma radiation (25 krads).
- Gamma rays carry no charge, and consequently have much lower interaction with materials. This accounts for their high penetrating power and long path lengths.
- The absorption of gamma rays deposits an ionization dose, but the dose-depth curve is very different from electrons and protons.
- Protons will deposit all of their ionizing dose within the first millimeter; electrons will deposit all their ionizing dose with the first few centimeters; gammas may result in a lower, but uniform ionizing dose over a meter.
- Conclusion: although gamma rays are an ionizing source, the TID values imposed on Europa components cannot be realistically simulated with gammas due to the very different dose-depth curves.
- *Conclusion: Electrons and protons must be used to provide TID.*

Displacement Damage Exposure

- Europa mission Displacement Damage Dose calculated (Dr. Insoo Jun)
- Note that the DDD is *expressed* as the damage *equivalent* to 1 MeV neutrons, but is not *identical* to exposure to 1 MeV neutrons
- Displacement dose in Europa environment results from exposure to electrons <0.5 MeV) and protons. Different *dose-depth profiles* result in different spatial distributions
- Neutrons have very high penetration lengths because they require a near-direct collision with the atomic nucleus to impart their kinetic energy
- Protons and electrons cause displacement damage due to collisions with atomic shell electrons, and be deposited over <u>much shorter</u> path lengths that neutrons
- Displacement damage testing must therefore match the damage imparted by electron and proton fluxes representative of the Europa environment
- Exposure to 1 MeV neutrons will produce erroneous results
- Conclusion: The displacement damage requirements on Europa components *cannot be simulated with neutron* exposures due to the mismatch in dose-depth curves; *electrons and protons must be used to impart the Displacement Damage Dose*.

Europa Energy "Bins"

- Expose to mission fluence of electrons and protons
- Components: Power cables, com. cables, connectors, valves, sensors, etc.
- Selected Materials: "Teflon" FEP, Tefzel, DAP, Phenolic, MLI, thermal control paints, optical coatings, optics, composites, etc.
- Use "group fluence" approach (energy bins)



Rationale for Group Flux (Energy Bins)

Bin #1 (1 MeV test energy)

- Highest fluence and largest dose is found in this energy range
- Materials will all see high flux of low energy particles
- Low energy sources more easily located and less expensive to operate
- Physics well undestood; no displacement, nuclear capture, activation or induced radioactivity
- Good for screening; if materials/components don't survive the low energy spectrum they are not likely to survive the higher energies

Bin #2 (10 MeV test energy)

- Lower fluence and lower dose at these energies. Depends on dose-depth profile in the material
- Sources less commonly located and more expensive to operate
- Physics is now "mixed", resulting in ionization, displacement, defects, and secondary bremmstrahlung (hard X-rays)

Bin #3 (50 MeV test energy)

- Lowest fluence, but highest energy. Largest number of secondary events including neutron spalation, activation, gamma rays
- Most severe condition but with the lowest dose
- Facilities less common and most expensive to operate

Electron / Proton Group Fluences

- Europa fluence calculations (5 year mission) complete:

EUROPA FLUENCE SUMMARY						
BIN	ENERGY	RANGE	FLUENCE		FLUENCE	
NUMBER	Low	High	Electrons/cm2	(Rads/cm2)	Protons/cm2	(Rads/cm2)
1	100 KeV	2.0 MeV	**5.80E+15**	2.40E+08	**1.02E+17**	6.90E+11
2	2.0 MeV	20 MeV	**3.02E+14**	7.80E+06	**1.10E+14**	1.60E+08
3	20 MeV	100 MeV	**9.92E+12**	2.40E+05	**5.80E+11**	1.60E+05

- Expose to low energy electrons first. Sources available, relatively inexpensive, and all components will experience this exposure.
- Start with Bin 1; represents electrons and protons in energy range of 0.1 to 2.0 MeV (test energy 1 MeV, expose to 5.8 E+15 electrons/cm^2
- Dose-depth profile not identical to environment, but good start
- Exposures are relatively inexpensive, available, and provide good "pass/fail" test for cables and other components
- Do higher energy electrons later, and protons also if necessary (proton testing required if component passes electron testing)

Electron Beam Exposure Testing

- Electron beam testing applicable to "Bin 1". Example: E Beam Services, Cranberry, New Jersey; http://www.ebeamservices.com/
- Typical characteristics are:
  - Magnetic coils raster the beam to create a "curtain" of electrons
  - Dose controlled by exposure time
  - Energy range: 0.8 MeV through 10 MeV (w/ 150 Kw power at 5 MeV).
  - Minimum dose about 0.1 Mrads
  - Energies below appx. 10 MeV ; no activation
  - 4.5 MeV used instead of 1 MeV due to availability
- Conclusion: Commercial electron beam accelerators suited to deposition of both ionizing doses and displacement damage doses imparted in the "Bin 1" energy range (4.5 MeV electrons, test energy used).

Electron Beam Exposure Testing

- Electron beam testing applicable to "Bin 2", range: electrons 2.0 MeV to 20 MeV, and "Bin 3", electrons range 20 MeV to 200 Mev
- One source located: Gaertner Radiation Laboratory, Rennsalear Polytechnic Institute (RPI), Troy, New York: www.linac.rpi.edu
- Facility capabilities:
  - (a) Port #1, 5-25 MeV electrons, (b) Port #2, 25-60 MeV electrons.
  - Possible activation of trace elements, resulting in radioactive products, especially at the 50 MeV electron exposure
- Conclusion: This accelerator good for ionizing doses and displacement doses in "Bin 2" energy range (10 MeV, test energy), and fluences in "Bin 3" energy range (50 MeV, test energy).

Proton Sources

- Where components have survived electron exposures without damage, proton exposures are required.
- This is especially true for materials more susceptible to surface damage; eg. optics, optical coatings, thermal control surfaces, paints, MLI, etc. that may experience dramatic sputtering, cracking and general erosion.
- Proton sources for the three bins are:
- Bin 1 (1 MeV): Wittenberg University, Springfield, Ohio
- Bin 2 (10 MeV): Loma Linda University, Loma Linda, CA
- Bin 3 (50 MeV): University of California, Davis (48 – 67 MeV energy range) and possibly Indiana University Facility (IUCF)

However .....

- If displacement damage is not a strong consideration, it may be possible to simulate the proton contribution to ionization using electrons. The dose-depth curves will not match well, but may be adequate
- This will be explored further

Reactor Exposures

- Expose Europa components / materials only to reactor conditions that simulate the fluence and energy spectrum expected from an *NR power source*
- Current estimated Europa reactor contributions are:
  (a) fast neutrons, energy 1–5 MeV, (fluence 5 E+11 n/cm^2 at 25m from core)
  (b) gamma rays, energy 1(?) MeV, fluence 1 E+12(?) γ/cm^2, TID = 25 krad (Si)
- Do not attempt to determine overall mission displacement damage with reactor neutrons, or ionizing dose with reactor gamma rays!
- Make sure that reactor flux is well filtered (cadmium) to remove thermal neutron component (this will only result in activation)
- Replicate the Europa reactor spectrum as closely as possible
- Thermal neutron "activated" test specimens may become too "hot" to remove from the chamber for testing. Personnel exposure now a risk
- Reactor neutrons may thermalize passing through some spacecraft components anyway, but this will be a <u>real</u> outcome, not a testing artifact

Gamma Exposures

- If gamma rays are ionizing, but do *not* match the dose-depth profile for electrons and protons why test with them??
- Gammas (^{60}Cobalt, 1.25 MeV) are readily available, inexpensive, have relatively large target areas. Exposure is controlled by time and distance from the source
- Avoid atmospheric oxidation; essential that test specimens be exposed in sealed bags under inert gas (vacuum preferred), and dry (no moisture)
- Dose rate approximately 100 rads/second (Si) at a distance of about a meter. (One kRad in 10 seconds / JPL gamma source).
- This exposure may constitute a rapid *screening method* to identify early failures (should give *worst case* results), and is also ....
- A "standard" test method that correlates with other industry results
- Note: be aware of "false negatives"; a component may fail gamma that is acceptable for a Europa mission

Preliminary Exposure Findings

- "Representative" materials for Europa missions were exposed to 4.5 MeV electrons (appx. 1 Megarad/sec)
- Approximately the same dose-depth curves as 1.25 MeV ^{60}Co gammas
- Teflon PTFE and FEP maintained usable properties to 2 x 10^7 rads; <u>three</u> orders of magnitude better than literature values for ^{60}Co gammas in air
- EPDM and silicone rubber maintained usable properties to 2 x 10^8 rads; <u>two</u> orders of magnitude better than literature values for ^{60}Co gammas in air
- Fiber optics: pure silica and variations. No insertion loss at 50 Megarads surface exposure
- Kynar and Tefzel cable insulations began degrading at 2 Megarads, with evolution of corrosive hydrofluoric acid. Indicates that wire and cable insulations are at risk
- Kapton Torlon, PEEK, Vespel, IR grade quartz, sapphire and epoxy-graphite composites all showed no degradation at 1000 Megrads equivalent doses. Highly stable to ionizing environments

Testing Caveats

Caveats

- Accelerated dose rates may not represent reality, but it is all we have available.
- Group flux separation of the spectrum is the only realistic way to approach this problem.
- Varying dose rates may be desirable where dose rate dependency is suspected (eg. possibly internal charging in dielectrics; low dose rates may result in damage not observed in high dose rates).
- Actual spacecraft exposure is omni-directional, not a line source.
- Over-testing: (perhaps the case with gammas) may disqualify viable components and materials.
- Under-testing: may qualify a part that fails in service.

Preliminary Conclusions

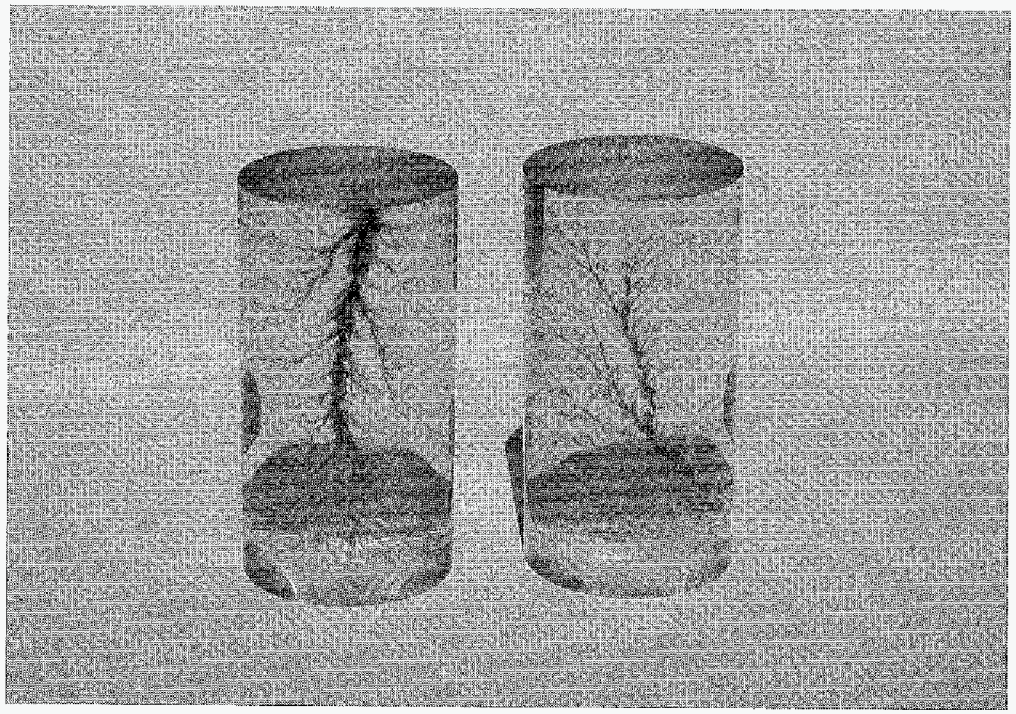
Conclusions

- Thermal control paints and blankets may be at the highest risk
- Some cable insulators (Kynar/Tefzel) may be at high risk
- Cable insulations are also at risk from internal charging and arcing
- Conventional wire insulations (Teflon PTFE and FEP) may survive high doses with no damage
- Many materials survive two to three orders of magnitude higher in dose under 4.5 MeV electron ionizing conditions than those reported for 1.25 MeV gammas
- Literature sources are forty years old; still relevant?
- Is the physics that different? Is it a dose-rate effect?
- Materials radiation resistance needs to be completely re-evaluated to qualify components for Europa missions

Internal Discharge

- Electrons deposit internally to an insulator resulting a “space charge”
- When the potential exceeds the dielectric breakdown voltage internal discharge, of “Lichtenberg” discharges form
- Electrons also impart conductivity; so low irradiation rates may be more damaging than very high rates

Lucite acrylic, 4.5 MeV electrons, 2 Megarad dose



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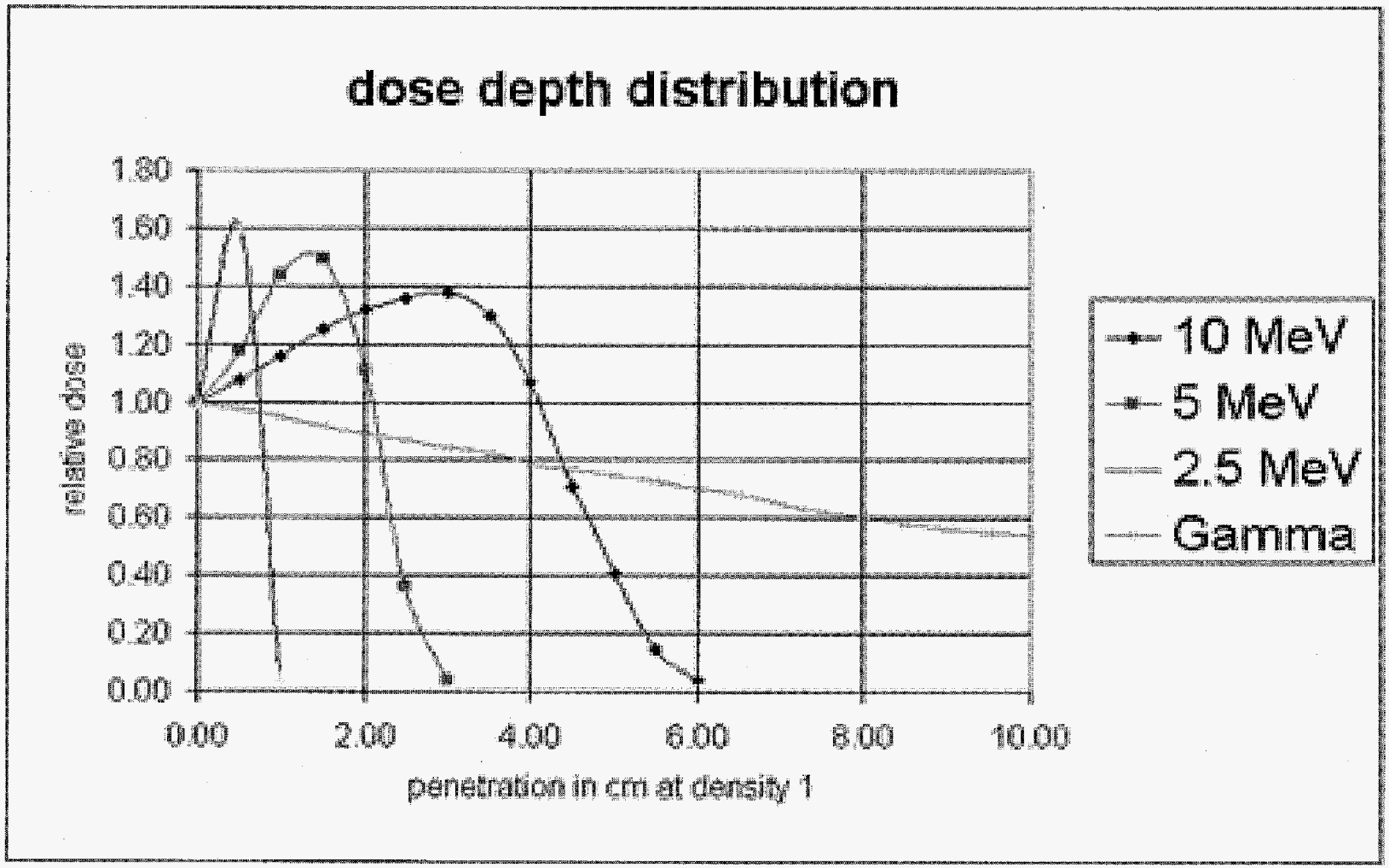
Electron Dose depth Curves