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Engineering Effort Needed to Design Spacecraft with Radiation Constraints

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Abstract – *A roadmap is articulated that describes what is needed to allow designers, to include researchers, management, and engineers, to investigate, design, build, test, and fly spacecraft that meet the mission requirements yet, be as low cost as possible. This roadmap describes seven levels of tool fidelity and application: 1) Mission Speculation, 2) Management Overview, 3) Mission Design, 4) Detailed Design, 5) Simulation and Training, 6) Operations, and 7) Research. The interfaces and output are described in top-level detail along with the transport engines needed, and deficiencies are noted. This roadmap, if implemented, will allow Multidisciplinary Optimization (MDO) ideas to incorporate radiation concerns. Also, as NASA moves towards Simulation Based Acquisition (SBA), these tools will facilitate the appropriate spending of government money. Most of the tools needed to serve these levels do not exist or exist in pieces and need to be integrated to create the tool.*

I Introduction

The ability to design spacecraft optimized to mission requirements at the lowest cost is the ultimate goal of any mission and spacecraft design team (referred to as a designer). As will be shown in this paper, a major element of spacecraft design is the radiation protection element. All other elements of spacecraft design are understood enough to be engineering problems and not science problems; however, while we understand the propagation of radiation through materials, we currently do not have nearly enough ability to determine the risk of that radiation to humans, electronics, and other materials with a manageable uncertainty. We also do not yet have the ability to predict all particle ejection events associated with the sun. Therefore, the current design of spacecraft for radiation protection is based on conservative estimates of radiation damage. Research is occurring in the probability risk assessment methodology, but a production quality tool for boundary conditions or response functions is not ready. Production quality computational tools incorporating good engineering practices that a spacecraft designer could use to incorporate the radiation protection component in their design environment do not yet exist. Best estimate research tools do exist however. The current task is to convert these research tools to production tools based on the latest physics and risk limits.

The purpose of this paper is to describe the type of tools that have been identified to date and that the NASA Langley Research Center and others are designing to provide to the designer and other researchers. There are a few items that must be explained for those who do not deal with this subject every day in order to understand why this is an important subject and why every designer should have radiation protection as their second thought for every decision they make. Also, there are no models, experimental results, or computational data in the paper because most of these tools do not exist or do not exist in a coherent form to generate results as a designer should see them. However, without a written roadmap such as this, there is no organization to the effort to generate these tools and make them useful to and utilized by the design and research communities.

This paper is a culmination of ideas from many different people in the space radiation, design, engineering, and other communities. It has very few original ideas from the author. However, much more work has to be done to implement these ideas and put radiation protection in a place where is impacts the design process the least, but still produces a spacecraft that meets mission requirements.

I.A What is a Designer

There are many views of what a designer is suppose to be. In this paper, terms are used that will identify experts and non-experts. In the current design process, a radiation expert is needed to consult on designs, create models, and calculate values. Here, a radiation expert is a Ph.D. in physics or engineering and well versed in or the author of the code being used. It is inefficient to let this type of staff member continue in this role. This person would be better utilized in creating and upgrading the codes. A more appropriate staff member to preform this role is a BS or MS degreed engineer who has a good understanding of the codes and the theory behind it. However, this person is not an expert as defined above and therefore, is called in this paper a non-expert. In reality, the non-expert is not alone in their role. An expert is available and part of the design process reviews, but is not part of the day-to-day design tasks.

I.B Risk and Where It Comes From

For human activity in low earth orbit (LEO), the acceptable risk is defined as 3% excess risk of fatal cancer over a lifetime. The exposure limits associated with this risk are primarily based on the atomic weapon data from Japan, which is based on neutron and low LET[a] radiation: X and γ-rays.

For electronics, an empirical database and direct irradiation testing are used to define the functionality of parts to radiation.[1] That database is primarily based on low LET X and γ-rays, electrons, and some higher LET proton and heavy ion data. There is a view that if an electronic part can withstand a certain LET created with protons then it should be able to withstand **any** particle with the same LET. Figure 1 shows that at the same LET, higher Z particles have a very different effect in materials. There are no regulatory limits associated with electronics; however, loss of function is undesirable.

Materials have no record except that generated in the nuclear power industry – again, mainly low LET events; military results, if any exist, are classified and currently unavailable. These data do not represent the high LET radiation found in space. There currently are no regulatory limits associated with materials; however, loss of function is undesirable.

Space radiation is composed of numerous components. Galactic Cosmic Rays (GCR) are particles that are present everywhere in the solar system and are low intensity but are very high energy. They consist of fully-striped nuclei from hydrogen to uranium and are traveling near the speed of light; therefore, they have great penetrating power. GCR generally create a chronic risk to humans, electronics, and materials because of their low intensity. Solar Particle Events (SPE) are high energy, high intensity ejections of material from the sun. They can create an acute risk to humans, electronics, and materials.

In LEO, and near other planetary bodies, various magnetic fields exist that trap radiation as shown in Figure 2 for LEO. This radiation is mainly protons and electrons, but it does contain neutrons splashed out of the atmosphere (if one exists) and other charged particles. These splash neutrons decay with a half-life of 10-12 minutes into protons and electrons which populate the inner belts as shown in Figure 3. The outer belts are populated by infiltration of particles, mainly protons, from the solar wind and GCR. Depending on the orbit, they can produce an acute risk and a chronic risk. The earths magnetic field is depressed under the south Atlantic and allows more and higher energy particles at lower altitudes. This is the South Atlantic Anomaly (SAA) which is traversed by the normal Shuttle (STS) and Space Station (ISS) orbits. Other planetary bodies, like Jupiter, have other type of belts with different intensities and energies associated with them. These data will have to be compiled into a coherent model that can be programmed as a boundary condition to the transport engines for use within this roadmap.

Planetary bodies generate particle radiation. This radiation is generated within the soil and rock itself when GCR or SPE penetrate into the soil or rock and fragment. The lighter particles scatter and some scatter out through the surface. This is a hazard for operations on planetary bodies.

Figure 4 shows the components of space radiation while Figure 5 shows the GCR abundance and energy spectrum. This shows the depth of the nuclear and atomic physics needed to solve this problem and the transport methods needed to enable the proper response functions. The large energy spectrum that needs to be modeled and the number of particles that need to be tracked stress current technologies and methods. Larger, faster, and clustered computers only solve part of the problem. New methods and computing platforms are needed to complete production tools for the designer of spacecraft.

To achieve an acceptable risk to the humans, electronics, and materials (referred to as occupants in this paper), the shielding of these radiation components is essential. However, they are not shielded like terrestrial components by utilizing mass, time, and distance. The energy of the particles is orders of magnitude higher than any radiation shielded on the earth's surface. Therefore, the technique of putting mass between the source and the object is not appropriate. Also, the cost of launching the amount of mass necessary is prohibitive. The other legs of the shielding paradigm, time and distance, are not available strategies in the spacecraft design process. Therefore, other strategies are needed to shield these radiations. While electromagnetic shielding is being researched, its potential is questionable. That leaves the utilization of materials in an intelligent manner to reduce

[a]Linear Energy Transfer in keV/μm for other units

the damage caused by the radiation, and the protection of the occupant by special means: radio-pharmaceuticals for humans as an example.

These particles are traveling at energies sufficient to fragment when interacting with nuclei of any material surrounding the occupant (including the occupant itself). These fragments are also at high energy and are a direct function of the material in which they fragment. Therefore, the ability to shield these fragments and their primaries is a direct function of all the materials used to build the spacecraft. The materials also reduce the energy of charged particles and electromagnetic radiation (EMR) through a continuous interaction between the material's electron charge density and the charge of the particle or the EMR. Therefore, the larger the electron charge density, the faster a charged particle loses energy, EMR loses energy or is absorbed, or the particle is scattered away from the interior of the spacecraft. The electron charge density is dependant on the material. For neutrons and other neutral particles, only nuclear interactions are available, and therefore, the closer the target atoms are in mass to the projectile – say, a neutron, then the faster the projectile will lose energy and be absorbed or be scattered away from the interior of the spacecraft.

The last risk item that needs to be explained is the concept of ALARA (As Low As Reasonably Achievable). It is an operational constraint in a radiation environment, but it highly impacts the design process. The ALARA concept means that during operations with a radiation source, the operator must do what is reasonable to reduce the radiation exposure to its employees and equipment. This is **not** a check-off box for the designer. It is a real legal requirement and must be an integral part of the design process. It also places a constraint on the design team to work with operators to achieve a provable ALARA strategy that is reflected in the design.[2]

I.C Why is the Radiation Risk Important?

This is an important question since there are many risks associated with space flight. However, once the mission is over, the radiation exposure is the major risk for the astronaut. For electronics and materials, once the mission is over, the radiation exposure for these items is zero and so is the risk to the mission. Therefore, the astronaut's radiation exposure is a life-long risk and must be dealt with in the design phase of the mission along with the operations phase to minimize mission costs, keep the astronaut safe during the mission, provide an acceptable risk after the mission, and perform the mission requirements.

A designer makes many choices about components, materials, placement, operation, etc., ... in the design process. The primary function of a component usually drives these choices; however, if it does not, then what does? The assertion in this paper is that the radiation function of that component should then be the driver.

Why does every component have a radiation function? As stated above, every bit of material acts as a particle shield and a particle fragment generator. As the radiation travels through material, its characteristics change. The designer needs to set up an overall path for the particles so that the radiation's characteristics change to protect the occupant and the spacecraft still meets the mission requirements. Therefore, every non-primary function choice made should be made to reduce the radiation effects to the occupant.

Examples are needed to illustrate these design limits and their importance. For a typical mission with humans, a pressure vessel is needed. For nominal 7-14 day stays on the lunar surface, an aluminum structure for a habitat will meet dose requirements for the astronaut without an SPE. However, if the designer makes the choice of aluminum as the structural component based on their design comfort level, this is not ALARA. Other materials such as carbon composites should be considered and analyzed through trade studies before a final material choice is made. As another example, the placement of the astronaut's sleeping quarters may be made for esthetic qualities, and even though it still meets dose limits, ALARA dictates that the designer creates a place where dose can be minimized to place the sleeping quarters. Of course, there are other constraints that must also be considered. For example, surrounding the sleeping quarters with every refrigerator on the spacecraft (or other heavy components) may meet dose limits and ALARA; however, the noise associated with this arrangement may violate other regulations that the designer must consider. This is the test of reasonability inherent in ALARA.

Therefore, it is important for the designer to consider the primary function of the component being designed first, and the radiation risk associated with that component along with other life-long risks second. Other regulatory constraints are then considered third.

II Verification, Validation, and Accreditation (VV&A) vs. Best Practices

Of course, design is carried out in virtual space and therefore computational tools are needed to analyze the design to determine if design requirements are met and the ALARA principle is considered. It is these design tools that are the crux of this paper. The designer is by definition **not** a radiation expert, nor should they be; however, they need the knowledge of an expert while analyzing their design. A well thought out tool can bridge this gap between the non-expert and the expert. The non-expert designer is not designing in a vacuum. Experts are available for consultation and are part of the review process.

When computational tools are talked about, the last thing on a designer's mind is the applicability of this tool to the design question being asked. VV&A is a process[3] to manage uncertainty in the quantities computed for the design. What the management of uncertainties means to the designer is that they have full knowledge of the uncertainty during the design process and are therefore responsible to manage that uncertainty. Currently, most NASA designs are based on best practices (this is based on anecdotal evidence when asked about current computational practices at NASA Langley).[4] This means that a scientist or engineer has made as good of an estimate based on the relevant physics as is possible with the resources available. Therefore, when they pass the code to the designer (or as usually occurs, passes the results of the code to the designer), the designer has no knowledge of the uncertainty, cannot manage it, and cannot therefore be responsible for it. This places the responsibility of uncertainty management back with the scientist or engineer. The designer is designing without the information necessary to produce a good design.

Therefore, computational tools need to be more than the best estimate that can be made by the relevant physics and resources. An understanding of the uncertainty in the tool is necessary, and it would be best if a quantitative estimate of the uncertainty is part of the tool. This allows the designer to make choices based on a sound understanding of what is needed, what is understood, and how well it is understood.

For radiation tools, many parts are inherent in a design. Some of these parts are common with other engineering analyses like geometry. However, there are unique data and methods where the uncertainty must be understood. Good VV&A practices dictate that each dataset and each method be isolated and uncertainties of each be ascertained. Therefore, each method or dataset that determines cross sections or interaction probabilities, as an example, must be able to be formatted for all transport methodologies. In this manner, an understanding of the uncertainty for each component is directly related to the data or method. In this way, a designer can understand that when a particular tool is used, a particular uncertainty is associated with it, and the designer can then manage that uncertainty.

III Impact on the Design Process

With the design process highly coupled to radiation, other engineering disciplines must also be tied into the process since their results impact the radiation risk to the occupants. This is called Multi-Disciplinary Optimization (MDO). All disciplines that are needed to design the spacecraft must work together to enable the designer to create the lowest cost spacecraft yet still meet all mission requirements. The ALARA requirement is also part of this process. However, the designer asks different questions that can take different tools to generate an answer. Therefore, the design process can be broken up into various levels that take various fidelity tools. Again, a trade off occurs here. The lower the fidelity of the tool, the faster it runs. Also, different tools generate different types of answers. As an example, a low fidelity, fast tool may generate dose values somewhat accurately everywhere in a spacecraft, but a higher fidelity, slower tool may generate accurate angular flux values everywhere, couple all the particles together, and represent more physics than a low fidelity tool. The tool to use depends on the answer wanted. For an expert, it is (usually) no problem to choose the proper tool. For a non-expert designer, choosing the proper tool is a problem. Therefore, even though the computational engine might be the same, a different user interface is usually wanted to generate different outputs and help guide the designer to the proper tool. In this way, different levels of tools are created.

There are at least seven (probably more) levels of production quality analysis tools needed: 1) Mission Speculation, 2) Management Overview, 3) Mission Design (or requirements generation), 4) Detailed Design, 5) Simulation and Training, 6) Operations, and 7) Research. While these are very broad topics, the ability of each tool level to analyze the radiation element is important and the driving factor to the overall spacecraft design. The limitation of this list is the lack of experimental data to backup the recommendation offered here; however, these recommendations are logical and obtainable.

The description of these levels does not describe an exact interface between the tool and the user. NASA Standard 3000 will define the output numbers that are needed from a regulatory view and the physical situation will dictate the information that will need to be input. However, the designer's interface is not described in detail because the designer is integral to the design of the interface. Currently, the designer has not been incorporated into the tool interface process. Without designer approval of the interface, the tool will never be used.

III.A Mission Speculation

Mission speculation occurs when a designer: researcher, technologist, manager, citizen, etc..., wants to determine the major obstacles in performing a mission. Again, radiation is a major factor in any design, and if a new technology is being used to drive the mission, then that technology is going to have to be vetted against radiation concerns. A fast method of radiation risk determination is needed. The fidelity needed here is still a question. Much debate will occur on this level and may include access to all of the tool levels discussed below. Either a table look-up method from a depth versus dose curve or some other simple mechanism can be used to generate the answer wanted.

III.B Management Overview

Management overview is the analysis needed to present management with the mission overview or to perform a trade study or a paper study at the mission level. Usually, it is the science or technology that drives the choice of the mission. This is where a "quick and dirty" analysis is needed to determine if current technology or TRL 7-9[b] technology can suffice to supply the mission. Table lookups or simple pre-run transport solutions with a web or simple interface can be used to supply this level of information. At this level, especially for trade studies or requirement studies, a particular tool may not be as necessary to get the process started as a "rule of thumb" briefing to familiarize the design team with why radiation is important and how to mitigate this risk starting early in the design process. This is an important aspect of design and has been a problem at NASA. Some well known examples are the Viking and Skylab Missions.

Viking was designed and mass limits reached when it was determined that the solar cells were not large enough because they degrade from radiation, dust, and other environmental triggers. They were resized to accommodate the need. However, mass limits were exceeded, therefore secondary science experiments were eliminated. Other parts of the craft needed more shielding and again, since more mass was added, more secondary science experiments were eliminated. For Skylab, it was deemed that the film vault would not protect the film from radiation for the entire mission. Therefore, the vault was modified to meet requirements along with extra support structure to meet launch loads. The mission's life was shortened because the craft was heavier and its orbit decayed faster.

The moral to this story is that radiation concerns must be incorporated into the design process as early as possible. The problem to date is that the tools needed to incorporate these concerns did not exist or exist in a primitive or inadequate state. While dose versus depth curves for various materials do exist, these are not usually enough to give a good estimate of what is needed to generate and evaluate requirements.

III.C Mission Design

The mission design level is where the mission planners, after management approval of course, design the mission and lay-out the mission requirements. A relatively accurate analysis is needed, but it does not have to be detailed. Trajectory, material classes, and mass distributions are important. A web based package like SIREST,[5] based on the HZETRN code[6] for high energy charged particles, is sufficient to satisfy this level assuming approximate mass distributions and material classes are known.

In NASA parlance, this level of tool is sufficient enough to get the designer through the Preliminary Design Review (PDR). Because of the nature of the different tasks within this level, different interfaces may be needed to accommodate it. This can be anything from a simple material lay-up analysis to a full fledge mass distribution from a Computer Aided Design (CAD) model utilizing thousands of rays. The computational engine is the same, just the run time and the accuracy of the answer is different. For intermediate analyses, a series of spheres can be used where a simple upper and lower mass distribution can be analyzed all the way to 16 or 32 different segments.

The ultimate goal is to design a spacecraft that can meet the requirements for a PDR. Many changes will be made to the design in this process. A fast tool is necessary to achieve this goal. A perturbation or variational based analysis method would be the method of choice; however, because of the number of particles that must be tracked, this becomes slower than running a fast forward transport solver for each design. For example, SIREST has a multi-material transport engine that will fulfill the requirements for this level. Different interfaces or levels of fidelity of input data are needed, but these can be fully accommodated.

III.D Detailed Design

The detailed design level is where the details of the design that will be built and flown are to be optimized with all other technologies to be incorporated in the design. The designer's interface of choice is CAD. Most other engineering disciplines utilize some version of a finite element method of solution which is intimately compatible with the CAD interface. There is only one code that can utilize fully 3-D, CAD interface, tightly coupled particle, finite element, space radiation capable transport: ATTILA,[7] which is currently licensed by Transpire Inc. A 1-D finite element analysis is available through the University of New Mexico called LOBOTRN.[8] This 1-D method includes higher order phase space interpolation than ATTILA performs. Therefore, it is able to transport a beam and other scenarios much more accurately. Both of these codes have the Fokker-Planck operator[9] implemented to allow the charged particle to diverge in a 3-D manner. While these methods have not solved numerous space related problems to date, they show exceptional promise in solving these types of problems and need to be cultivated.

[b]Technology Readiness Level 7-9 are technologies that can be brought to flight readiness with a small investment

The other 3-D solution method utilizes the Monte Carlo method; however, currently no program exists that can be utilized in the CAD environment without severe geometry approximations. All these Monte Carlo codes utilize combinatorial geometry methods and have a problem modeling objects like a simple incandescent light bulb. Therefore, a second, Monte Carlo specific model must be created which adds another layer to the VV&A process and slows down the generation of an answer needed by the designer. It also introduces the need for an expert to generate that model.

Current Monte Carlo codes that can be utilized in the space environment, like HETC-HEDS,[10] do not incorporate variance reduction (biasing) techniques that reduce the number of particle histories, and hence runtime, to generate the same uncertainty as in the unbiased model. The biasing technique of choice is weight windows. There are two flavors of weight windows: local and global. For the local variance reduction method,[11] an adjoint deterministic solution can be used to steer more particles in the direction of interest like a detector. However, with this technique, the solution away from the detector converges at a much slower rate if at all. For the global variance reduction method,[12] a forward deterministic solution can be used to accelerate convergence in all parts of the model. With these weight windowing variance reduction techniques, a Monte Carlo calculation can be greatly accelerated. Preliminary results suggest that a 100 to 1000 times speedup is theoretically possible.[11, 12]

The stochastic and deterministic methods are a natural for a fidelity discussion. As the number of histories in a Monte Carlo run tends to infinity, the solution tends towards the correct solution for the physics modeled in the interaction probabilities. As the space, angle, and energy mesh size gets smaller for deterministic codes, the solution converges to the correct solution for the physics modeled in the cross sections. However, we cannot wait for an infinite number of histories or an infinite number of phase space mesh elements to compute. Each solution method has advantages and disadvantages. The secret is to know which one to use for the answer the designer is seeking. They can also work together to get a more accurate answer faster than either one alone: a hybrid methodology. The space radiation transport world needs to move in this direction to be able to be of use to the designer and enable an ALARA solution! Without this hybrid methodology, the designer will not be able to utilize either method because an expert will be needed to create an approximate model so that the solution time is something that can be tolerated by the design process. This is an unwanted outcome.

An unnecessary tension exists between stochastic (MCNPX, HETC-HEDS, FLUKA, MARS, PHITS, etc...) and deterministic (ATTILA, LOBOTRN, HZETRN, GRNTRN, ONELD, ANISN, etc...) camps within the space radiation field. Each method has its advantages and disadvantages. Fortunately, they are mostly orthogonal in this respect. Where one has an advantage, the other has a disadvantage. In short, each is useful and wanted at the detail design level. Both types of codes need to be brought to the same level of completeness for VV&A and utilization in the design process. It is always a prudent engineering strategy to have two different methods solving the same model to ensure nothing has been overlooked. If they work together, a hybrid method, then a stronger tools exists that did not exist before. This should be the goal of any transport method development effort.

For a hybrid method, a natural fidelity argument can be made with a combined tool. If the designer needs a medium fidelity answer, then the tool should run just a forward deterministic calculation. This is adjustable by the number of phase elements used in the model. If a high fidelity answer is needed at a point, then a hybrid method should be employed, for example, an adjoint deterministic solution accelerated Monte Carlo run. If a high fidelity global solution is needed, then another hybrid method should be employed, for example, a forward deterministic solution accelerated Monte Carlo run. Again, when a higher fidelity is used, it is assumed that the time to solution is longer.

The main foreseen problem with this level of fidelity is the uncertainty in the cross sections or the interaction probabilities. Currently, the uncertainty in these values is larger than the uncertainty in the higher fidelity transport methods. Therefore, if the uncertainty in the cross section data is not decreased, then these higher fidelity methods will not gain the designer any reduction in uncertainty for the answer being sought. This however should not be a stumbling block philosophically or in reality.

III.D.1 Human Models Currently within NASA, the CAM and CAF (Computerized Anatomical Male and Female) human models are the basis for dose equivalent (and associated quantities), and hence risk, for space calculations in SIREST and HZETRN. Currently, however, the CAM and CAF models cannot be used directly in any stochastic or deterministic model. These models can be converted to CAD format and utilized in the finite element deterministic codes with no further problems and can be used in the stochastic codes once spline surface particle tracking is implemented. Other efforts like the digital astronaut are looking at this area, and the results will be very useful for the detailed design level. This includes the voxel based human models that are being used in various medical areas.

Some problems do exist in the human response models. First, the science is still being performed. Therefore, we have no engineering limits for deep space. The current 3% excess fatal cancer risk for LEO may change due to new data being generated. Currently, we have no risk based response functions for humans in space, just exposure limits that represent the risk. The risk limit for humans will be changing in the near future. Instead of excess fatal cancers, the new limit will probably be based on Risk of Exposure Induced Death (REID) and should be between 3 to 5% with an uncertainty assessment for chronic and clinically significant risk for acute exposure.[13]

III.D.2 Electronics and Materials Incomplete and crude models for electronics and materials exist at this time. Much research is needed here to bring these models to the same level of completeness as the human models. Other papers[14] are beginning to address the electronics problem from a probabilistic methodology.

III.E Simulation and Training

Simulation and training are another level of design and take place after the Critical Design Review (CDR). This is where the design is tested, modified to as-built and tested, operational scenarios are created and tested, and people are trained to operate and maintain the spacecraft. Here, the interface to the computational tool is just as important as the computational tool. Virtual reality or an immersive environment is the best interface available. The user can be immersed in the environment and can be shown the effects of the radiation as they traverse the spacecraft and the mission. This psychologically brings the invisible radiation environment to the user, which is important because of the lack of physiological queues from radiation. The uses of this type of interface are numerous. Other interfaces, like those used in the detailed design level are also useful, but for a different purpose. Of course, if a major redesign is needed, then the process will revert back to the detailed design level until the updated CDR is completed.

How NASA uses the word "simulation" is a bit different than an engineer or scientist would use the word. For this application, the meaning is somewhat varied and at this moment in time, not strictly defined. Accordingly, a vague but descriptive definition will be given here. Simulation has combined two functions that were different in the past: verification and validation of the design and creation of operational and maintenance procedures. Training is then the teaching to and modification of those procedures with the users.

In the past, separate tools were created for all the tasks described in this section. However, with the advance of virtual environments, a single tool has the ability to work with the data generated in the detailed design step and provide all the necessary information assuming the design does not change. If the design changes enough to warrant the design data suspect, then a new set of data can be generated using the tools from the detailed design level. With the advent of a finite element, multienergy group representation of the transport process, an adjoint solution can be formulated for the spacecraft.

The adjoint solution represents the importance of a boundary condition to a particular function of interest inside the spacecraft. If the point of interest, for example, were the human lens on an astronaut, then in the detailed design phase, an adjoint solution would be generated at that point for all the relevant radiation encountered on the trip. With this pre-calculated solution, as the boundary conditions change, to fully solve the transport equation for the lens of the eye, the boundary condition is convolved with the adjoint solution (simple matrix multiplication) and the full transport solution (energy and angle) is realized. This is a quick and straight-forward way to generate a very accurate solution with a simple technique. Its down side is that if the design is constantly changing, then computer time is wasted generating adjoint solutions that are of limited value.

With this technique, the tasks of simulation and training can be completed in a virtual environment (or a non-virtual environment for that matter) with ease. Most virtual environments utilize the existing CAD drawing and project it into the interface: a wall, CAVE, or other device. The adjoint solution can be directly projected into this environment and with the right combination of computation devices, a near-real time "walk" through the spacecraft can be achieved. Users can be trained, designs tested against design basis accident scenarios, operation and maintenance procedures created and tested, etc.... This technique is powerful if the design remains constant.

III.F Operations

The last well-defined design level in this paper is operations. This tool is for operators and users to appropriately respond to radiation events during the mission. For this level, an adjoint model again is the best solution available because it utilizes the full transport solution from the as-built design. Once the boundary condition is applied to the adjoint solution, a quick determination of the proper action to take (prepared and rehearsed in the simulation and training section) is available to the operator and users. This is essential for long lunar stays and trips to Mars.

It is assumed that the appropriate infrastructure is available. Today, for LEO operations, NASA relies on satellites like SOHO and GOES and other information to help determine appropriate actions. In the Martian environment, some of the infrastructure, like a "GOES" satellite, does not yet exist. Either that infrastructure needs to be built, or other methods to gather the needed operation's information must be created.

III.G Research

This can be considered a catch-all category, but in reality, it has a specific function. This level of tool can vary from a low fidelity tool looking at a particular integrated phenomenon to a high fidelity tool tracing particle trajectories through a material. The interface can also be varied. The crux of this tool is that it is a tool set that all the other levels rely on to be a test bed and method checkout on top of answering questions that a designer does not ask, such as what are the detailed shielding characteristics material XYZ. Also, the response functions of the occupants are developed and tested here before deployment in the design level tools. This is an important category of tool. The VV&A level of this tool set is also not as high as the designer level tools. Here, a best estimate value could be the answer sought to allow an estimate of uncertainty for a method being deployed. Of course, as the research tool matures, its uncertainty is better understood and its VV&A level increases until it is ready to be deployed for use by designers.

IV Simulation-Based Acquisition

NASA is utilizing the Simulation-Based Acquisition (SBA) model for procurement. This model utilizes simulation of the mission to develop requirements for the procurement process. Therefore, a medium or high fidelity tool is not needed, but a low fidelity tool is the right tool for this task. The tool will be able to perform trade studies and other tasks needed to generate data that can be used to create a request for proposal, perform trade studies, and analyze a design. NASA will be using the NExIOM[15] data dictionary to establish communication between the various tools to prepare for an acquisition. It is unclear at this time how much MDO will be performed if any. This process is just now being clarified within NASA so details are scarce and changing. However, the SBA model will be used to acquire all hardware for Project Constellation (the current mission for lunar return and Mars).

V Conclusion

In conclusion, much physics and engineering work is needed to fully define and complete these levels of production codes in this roadmap. These levels do not have sharp distinctions. They bleed from one level to the next. Stochastic and deterministic codes along with the requisite cross sections and interfaces are needed to complete a tool set that can be used to generate an optimized spacecraft to meet mission requirements – at all levels and in all disciplines. The proper radiation analysis tools in the hands of designers and managers can solve the engineering problems needed to allow the lowest possible cost and safe access to space for the future. However, the designers will need to help by telling the tool programmers what the designers need to perform their design tasks. These tools also lay the groundwork for when the science of radiation damage is better understood and models created to determine risk from the radiation fields that better reflect the occupant.

References

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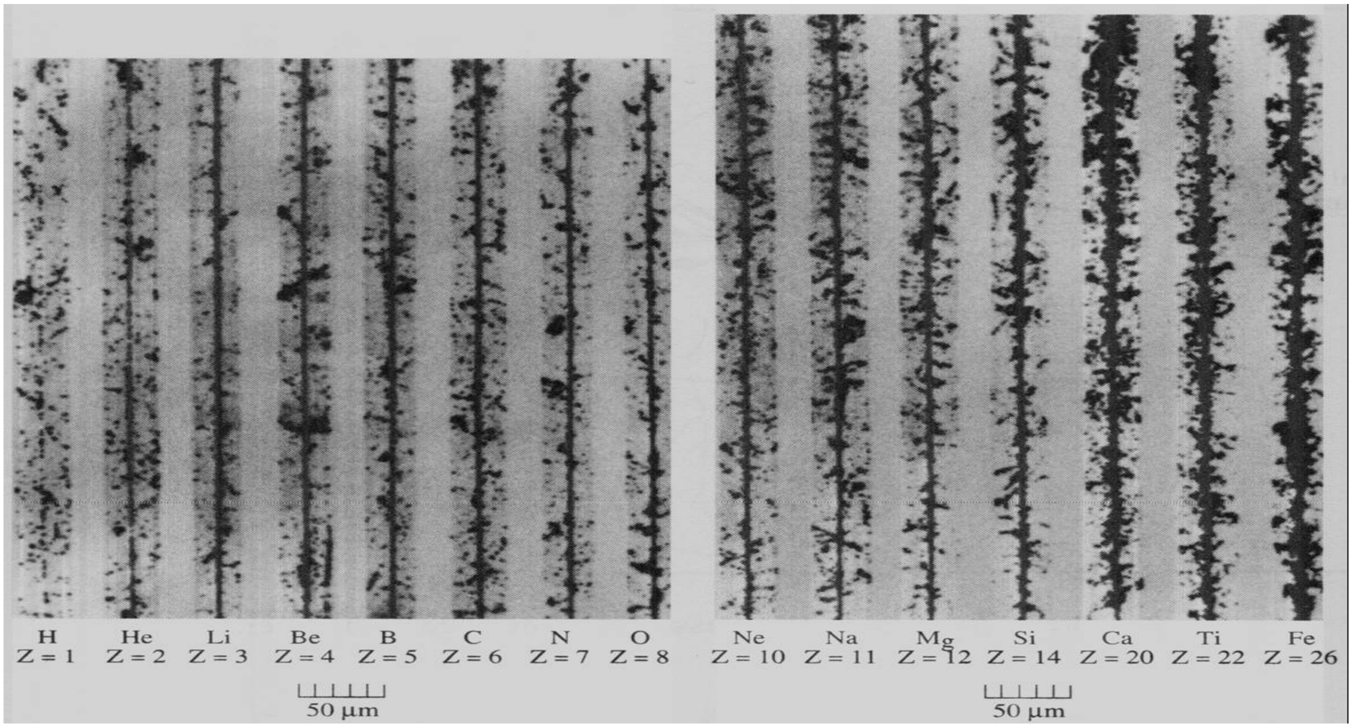

Figure 1: Nuclear Emulsion Effects of Constant LET versus Z

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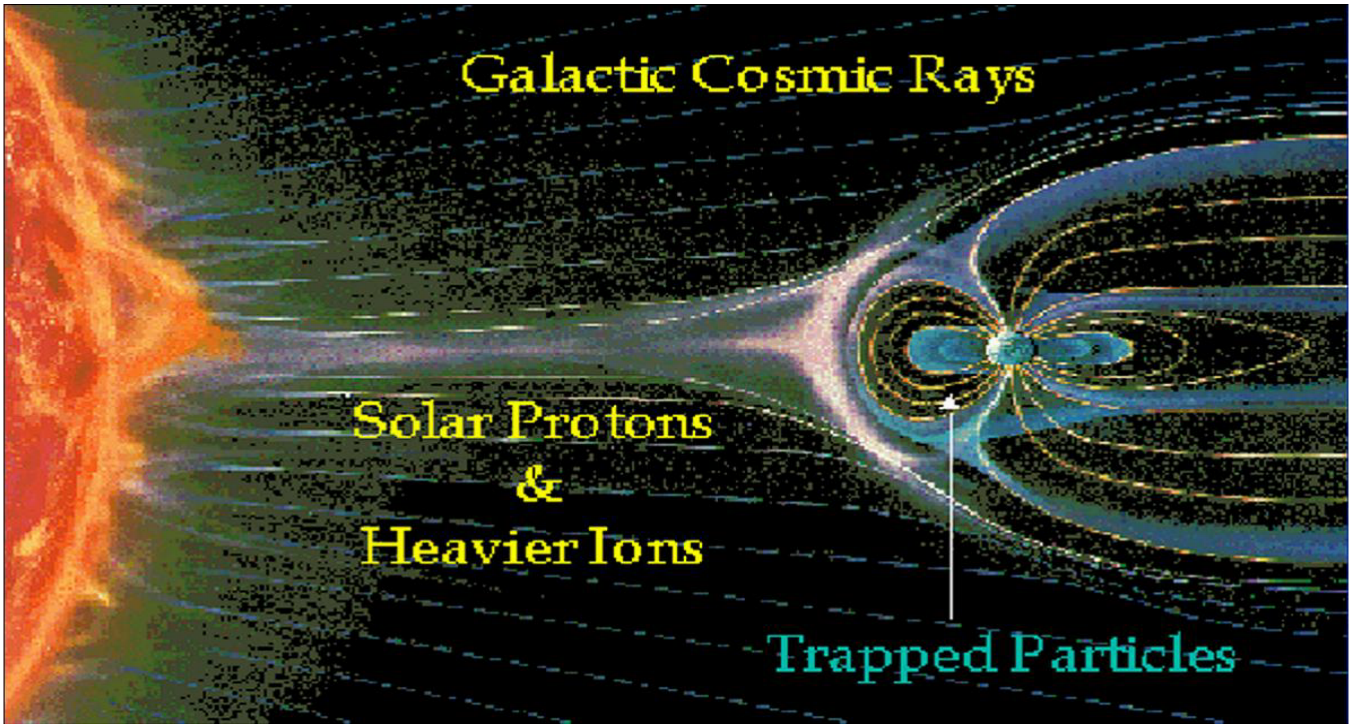

Figure 2: Magnetic Field for the Earth

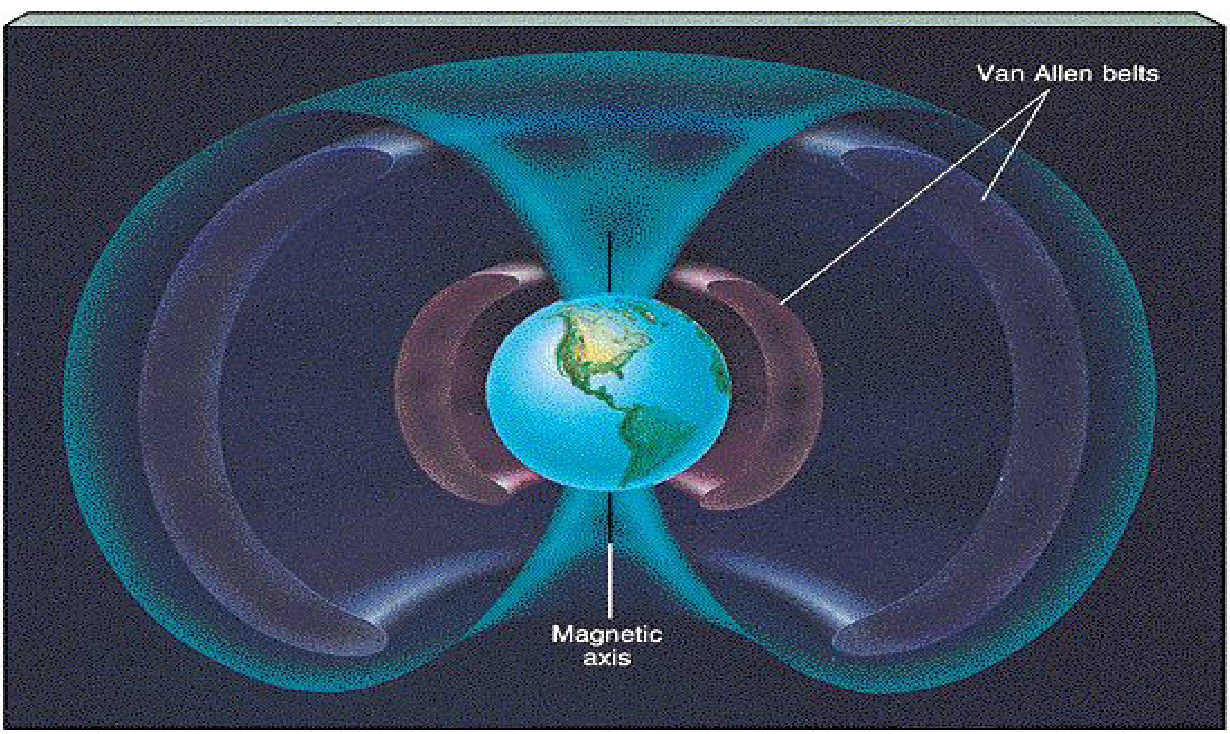

Figure 3: Magnetic Field for the Earth

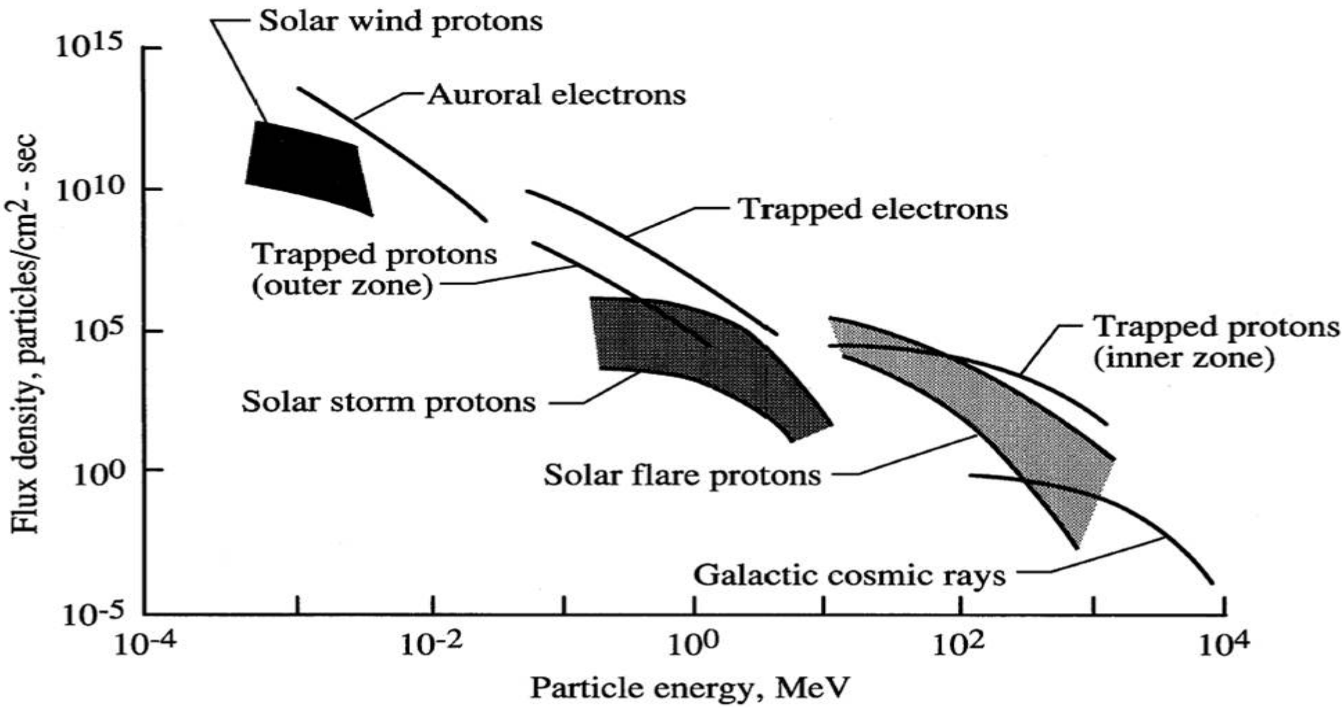

Figure 4: Energy Spectrum of Various Space Radiation Types

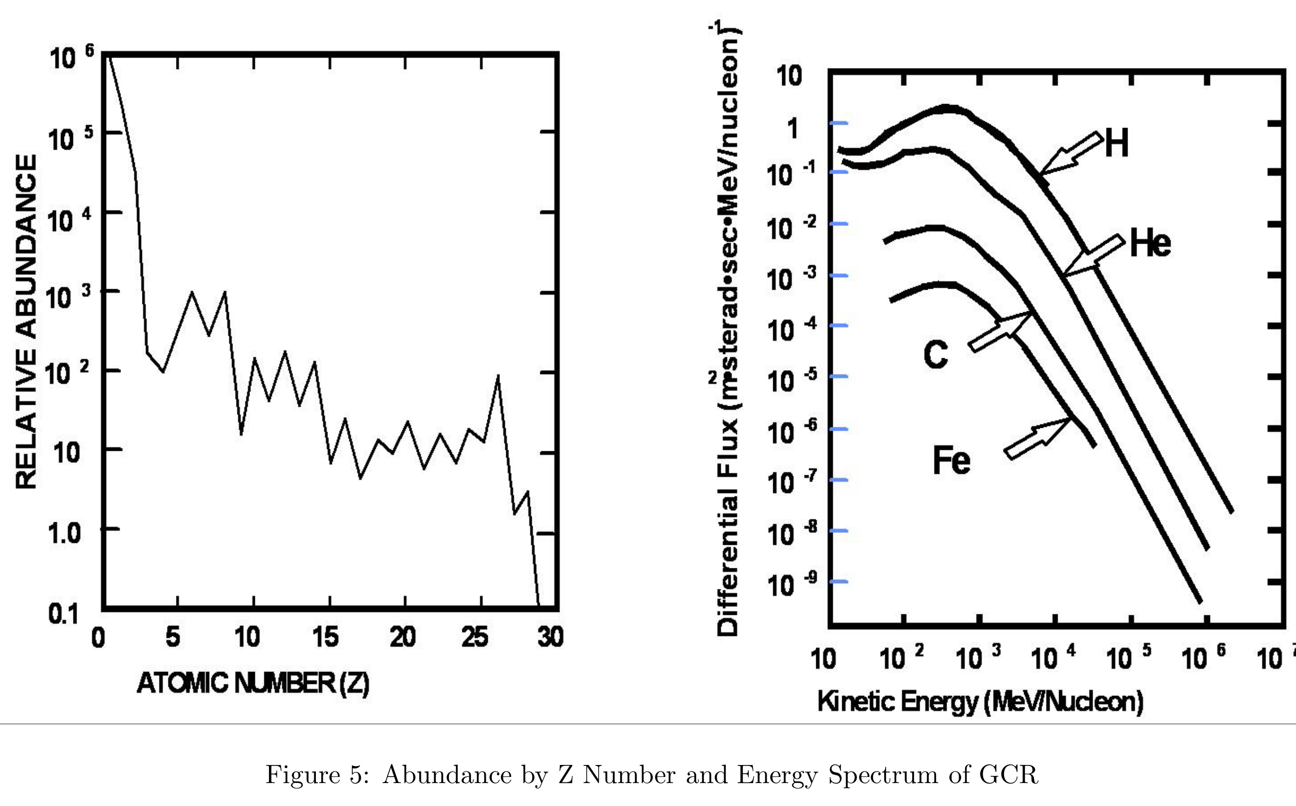

Figure 5: Abundance by Z Number and Energy Spectrum of GCR