Radiation Effects on Spacecraft Structural Materials

Jy-An J. Wang*, Robert C. Singleterry Jr. **, Ronald J. Ellis*, and Hamilton T. Hunter*
***Oak Ridge National Laboratory,§ **NASA Langley Research Center**

International Conference on Advanced Nuclear Power Plants (ICAPP)
Embedded International Topical Meeting
2002 ANS Annual Meeting
June 9-13, 2002 - Hollywood, Florida

Abstract -*Research is being conducted to develop an integrated technology for the prediction of aging behavior for space structural materials during service. This research will utilize state-of-the-art radiation experimental apparatus and analysis, updated codes and databases, and integrated mechanical and radiation testing techniques to investigate the suitability of numerous current and potential spacecraft structural materials. Also included are the effects on structural materials in surface modules and planetary landing craft, with or without fission power supplies. Spacecraft structural materials would also be in hostile radiation environments on the surface of the moon and planets without appreciable atmospheres and moons around planets with large intense magnetic and radiation fields (such as the Jovian moons). The effects of extreme temperature cycles in such locations compounds the effects of radiation on structural materials. This paper describes the integrated methodology in detail and shows that it will provide a significant technological advance for designing advanced spacecraft.*

This methodology will also allow for the development of advanced spacecraft materials through the understanding of the underlying mechanisms of material degradation in the space radiation environment. Thus, this technology holds a promise for revolutionary advances in material damage prediction and protection of space structural components as, for example, in the development of guidelines for managing surveillance programs regarding the integrity of spacecraft components, and the safety of the aging spacecraft.

I. BACKGROUND

Manned and unmanned space exploration missions will be planned for distant destinations and will include orbital and lander roles. The spacecraft and modules will most likely be powered by RTG or, for longer and more power-intensive missions, by nuclear reactor systems. During such missions, the spacecraft structural material, personnel, and electronic systems will be subjected to a variety of radiation fields, including the radiation from the reactors or RTGs. The success of extended mission spacecraft technology depends critically on an effective surveillance program to monitor the degradation of the materials during service. The aging and subsequent degradation of structural materials used in spacecraft due to radiation are of particular concern because radiation embrittlement is the leading factor in spacecraft integrity failure, which relates directly to safety and operating costs.

I.A. Materials and Radiation

Property changes in materials due to radiation-induced displacement damage are a function of the incident particle type and energy spectrum, fluence and flux, and temperature, as well as the pre-irradiation history, chemical composition, and microstructure. Each of these parameters influences radiation-induced microstructural evolution. These factors must be considered together to predict reliably radiation embrittlement of structural components and to ensure the structural integrity of the spacecraft on long-duration missions. Based on embrittlement predictions, decisions must be made concerning operating parameters, possible spacecraft life extension, and the potential role of thermal annealing or other mitigation processes. Therefore, the development of embrittlement prediction models for the spacecraft is a very important issue for the aerospace industry regarding safety and lifetime extension of the aging spacecraft during its service. This is especially important for human missions since

§ Managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy.

the spacecraft also acts as a pressure and radiation barrier.

I.B. Space Radiation

Spacecraft are subject to bombardment by subatomic particles (charged and neutral) and electromagnetic radiation from both external and onboard sources.[1-5] The high-energy nature of the external radiation penetrating the vehicle skin will also contribute to the internal environment definition. In both cases, emission of secondary radiation must be considered. Sources of external radiation include magnetically trapped radiation, solar particle events, solar wind, solar electromagnetic radiation, galactic cosmic radiation (GCR), distant neutrino and gamma bursts, planetary magnetic storms, and auroral radiation.

The occurrence and magnitude of magnetic storms on the sun are often difficult to predict despite the general cyclic history of solar storms. Types of external radiation include energetic electrons, photons, protons, alpha particles, neutrinos, neutrons, and all naturally occurring isotopes. Typical onboard sources of radiation include nuclear reactors for propulsion and electrical power, and radioisotope-fueled power sources (RTGs). Important onboard radiations include neutrons, gamma rays, and beta particles. When energetic charged particles (with energies large compared to their rest energies) are decelerated over a very short distance in interactions with spacecraft materials, bremsstrahlung radiation [braking radiation] is produced.[6] Bremsstrahlung radiation (x- and γ-rays) is generally more penetrating than the incident particles that lead to its production. The energy associated with the bremsstrahlung is inversely proportional to m^2, with m the rest mass of the particle. For energies of up to 100 GeV, bremsstrahlung contributes substantially to energy loss in matter for electrons. Other particle/γ interactions are also important to the microstructure of the material.

II. MEASUREMENTS AND EFFECTS

The ESA Hipparcos satellite operated in a near-geostationary orbit between August 1989 and August 1993. Its telescopes and detectors were sensitive to background signals induced by energetic electrons and protons, and by bremsstrahlung. The observations led to a long-term data-set which represents the structure of the radiation belts, their dynamics and the effects of solar particle events.

In interplanetary space, the background (cosmic) radiation has been estimated and reported in numerous sources at about 10 rad (0.1 Gy) per year. This is higher than for most work environments on Earth, but should not be a problem for crewmembers for an extended exposure period. However, solar flares and high-energy heavy ions in cosmic rays would be problematic for crew and for spacecraft structural materials. Late effects from the high charge and energy (HZE) ions present in the galactic cosmic rays (GCR) including cancer and the poorly understood risks to the central nervous system constitute the major risks for exploration missions.

Accurate predictions of aging response of space structural components depend critically on the proper estimate of the radiation environment and the corresponding well-designed mechanical database. Service failures due to inaccurate characterization of aging responses could result in potentially costly repair or premature component replacement, and in the worst scenario, may result in catastrophic failure of the craft and loss of life. The general degradation mechanisms of the aging behavior that need to be considered include: microstructure and compositional changes, replacements and displacements of atoms, time-dependent deformation and resultant damage accumulation, environmental attack, the accelerating effects of temperature cycling, and the synergistic effects among all of the above. The complex non-linear dependencies observed in typical material aging data as well as the existence of large uncertainties and data scatter make the modeling of aging material behaviors and phenomena a difficult task by conventional statistical and deterministic approaches. A new information fusion approach was recently developed at ORNL to tackle this issue,[7-10] and will be used in this research.

II.A. Material Degradation

In general, the phenomena of material degradation via radiation embrittlement include increased yield strength and reduced fracture toughness. Fracture toughness, K_{IC}, represents the key information regarding material degradation; however, the test methods that are currently used to evaluate the fracture toughness of materials do not include the fracture mechanics based K_{IC} Method. The reason is that specimen sizes required to achieve complete plane strain control, so valid K_{IC} can be obtained, are almost always prohibitively large. Instead, fracture toughness is assessed using test methods that were developed several decades ago, most of which predate the development of fracture mechanics. Hence, if critical flaw size and/or safe design stress calculations are desired, K_{IC} must be inferred using correlations that relate these non-fracture mechanics values to K_{IC}. Such correlations inherently contain large uncertainties and, if K_{IC} is obtained in this way, large factors of safety must be attached to the computed results. If a testing procedure is found that can maintain a controlled plane strain constraint using small specimens, K_{IC} can be obtained directly with currently existing laboratory equipment. The advantage here is that safety factors that are currently applied in design and safety analysis can be relaxed with good justification.

Numerous test materials exist that have been in space for many months, and are being used in space. These include, but are not limited to, Long-Duration Exposure Facility satellite (LDEF) trays (see http://setas-www.larc.nasa.gov/LDEF/index.html) and experiments, which were in space for 69 months, and experiments that have been on MIR and ISS or are still on ISS. New materials are being developed to reduce the mass, and hence the cost of a spacecraft. The properties of these materials are still being determined and can benefit from this integrated testing. The methodology will also enable designer materials to be created to optimize mass, strength, radiation damage tolerance, and ultimately cost and safety.

NASA has conducted many experiments measuring deterioration on the surfaces of the now-defunct Russian space station Mir. Researchers have tested samples of thermal control paints, chemical coatings, mirrors, optics and other materials being considered for future enhancements on the International Space Station (ISS). During spacewalks, astronauts have attached external experiments to the outside of the Mir and used instruments to scan Mir's surface coatings. These studies have yielded vital understanding of the contamination that spacecraft face in their orbiting environment.

In a more recent event, the outer layer of Teflon fluorinated ethylene propylene (FEP) multi-layer insulation (MLI) on the Hubble Space Telescope (HST) was observed to be significantly cracked at the time of the Second HST Servicing Mission (SM2), 6.8 years after HST was launched into LEO. Comparatively minor embrittlement and cracking were also observed in FEP materials retrieved from solar-facing surfaces on HST at the time of the First Servicing Mission (3.6 years exposure). After SM2, a Failure Review Board was convened to address the problem of degradation of MLI on HST. In order to determine possible degradation mechanisms, it was necessary to consider all environmental constituents to which the FEP MLI surfaces were exposed. Based on measurements and various models, environmental exposure conditions for FEP surfaces on HST were estimated including; number and temperature ranges of thermal cycles; equivalent sun hours; fluence and absorbed radiation dose of x-rays, trapped protons, and plasma electrons and protons; and atomic oxygen (AO) fluence. Thus, a well-defined surveillance program that covers irradiation environments, dosimetry and fluence evaluation, and monitoring degradation of aging spacecraft structural material during the service is needed to ensure integrity and safe operation of spacecraft.

III. CURRENT RESEARCH

A quantitative and predictive understanding of how materials degrade or become passivated in the space environment is a critical research area given the large and increasing dependence on satellites and manned spacecraft that reside in, or pass through, the low-earth orbit (LEO) space environment. The physical and chemical environment at LEO is not benign, but rather presents a highly aggressive materials oxidation and degradation situation, ensuring that this will remain a key long-term technical issue as long-duration space activities become even more common than at the present time. For such orbits the interaction of atomic oxygen with thin-film coatings and both structural and nonstructural materials plays a dominant role in the long-term viability and performance of orbiting spacecraft. This situation is further complicated by: (*a*) the high kinetic energy of gas-surface collisions in LEO, (*b*) the synergistic chemical effects which will occur due to the presence of intense levels of solar radiation, (*c*) the presence of electronically excited neutral and charged particles, which may further perturb the expected interfacial chemistry, and (*d*) the presence of nanoscale interfacial defects produced via sputtering by high-energy particles.

III. A. Radiation Damage

The principal effect of radiation on metals and alloys is the creation of lattice vacancies and interstitial atoms in an otherwise perfect crystal.[11] In general, this results in an increased yield strength and reduced fracture toughness. As for elastic properties, tests have shown that the elastic moduli of metals are not appreciably affected by fast neutrons below a fluence of 10^{17} n/cm².[1,2]

Plastic properties of metals are markedly affected by radiation. In general, metals exhibit reduced plasticity and ductility and increased hardness following irradiation. As a possible explanation of the foregoing observations, it has been suggested that because plasticity is associated largely with the motion of dislocations, any mechanism that impedes this motion can produce the class of effects observed in irradiated metals.

Tests conducted to determine the effects of neutron irradiation on the mechanical properties of metals and alloys have shown that temperature of exposure, time at temperature, fluence, energy spectrum, and material properties (i.e., composition, degree of cold work, prior heat treatment and quenching, and grain size) are important variables. Engineering data on property changes of reactor-irradiated structural metals are available in many open literatures.[12,13]

The principal effects of neutron irradiation on the mechanical properties of metals are tensile and elongation properties; and the effects of neutron irradiation on fatigue, hardness, and reduction in area. The transition from brittle-to-ductile fracture occurs at higher temperatures as a result of neutron irradiation. The creep-rate and stress-rupture properties are generally affected by neutron irradiation. The direction and magnitude of changes in these properties depend on the particular metal and such factors as fluence, test and irradiation time, and temperature.

One important outcome of the radiation embrittlement of structural materials is the reduced fracture toughness. The degradation of the fracture toughness needs to be properly monitored through a surveillance program during the lifetime of the spacecraft to ensure safe operation. Furthermore, the embrittlement prediction model needs to be developed to provide basis for lifetime estimate, or/and lifetime extension, and to develop effective surveillance program for aging spacecraft.

III. B. ASTM Test Standards

Based on American Society for Testing and Materials (ASTM) Standards, the valid fracture toughness requires fracture tests to be carried out in a plane-strain condition. Normally this requires a fairly large test sample, in many cases, the required sample sizes of a valid toughness test are always prohibitively large, especially for ductile materials. This inevitably adds a tremendous burden to the surveillance program. Thus, miniaturization of fracture toughness samples is an important goal for spacecraft surveillance program. Periodic evaluation of fracture toughness on aging component materials is an effective and prudent approach to warrant the structural integrity. This requires a large supply of specimens to support the long-term surveillance program. Therefore, substandard-size specimens are desirable to make the best use of available material and limited space available.

III.C. Mixed-Mode Fracture

Tensile fracture (Mode I) is often considered as a major rupture failure mode. However, it is known that rupture failure occurring in a mixed mode of Modes I and III may be more likely than rupture failures occurring purely in Mode I for some materials. Complex 3-D space structures, including the overall vessel, 3-D piping or plate structures, and their joint components are most likely subjected to combined bending and twisting.

It is suspected that changes of rupture mode from Mode I to a critical mixed mode may be possible due to the radiation embrittlement, thermal cycle fatigue due to thermal swing and gradient, and service loading conditions. From the recent mixed mode fracture study,[14] which utilizing a complex testing set-up with a special machining CT specimen, test results indicates that mixed-mode (Mode I + Mode III) toughness and tearing modulus reduced to 50% and 30% of that from Mode I alone, for some ductile materials. Therefore, the combined impact of flexural normal stress (Mode I fracture) and the torsion shear stress (Mode III fracture) to the fracture toughness of the materials used in the structural hardware must be reassessed. In viewing of the economic testing, developing simplified testing procedure and test sample are essential to the success of material aging research regarding mixed modes failure.

III. D. Material Modeling

The complex nonlinear dependencies and large data scatter observed in radiation embrittlement data make the embrittlement modeling a difficult task. The conventional statistical and deterministic approaches have proven to result in large uncertainties, in part because they do not fully exploit the domain specific knowledge. The domain models built by researchers in the field, on the other hand, are not able to fully exploit the statistical and information content of the data. As evidenced in previous studies, it is unlikely that a *single* method, whether it is statistical, non-linear or domain model will outperform all others. Considering the complexity of the problem, it is more likely that certain methods will perform best under certain conditions.

In order to resolve the above mentioned issues, new thinking and innovative testing and analysis procedures are needed.

III. E. Multi-Discipline Approach

ORNL has an established expertise in reactor physics and radiation transport and nuclear cross section measurement and evaluation. Neutronics calculations and assessments have been completed for many types of nuclear reactor systems including space reactor applications. ORNL has had a long association with radiation and shielding studies of space reactors since the 1950s. Recently, ORNL has been involved in DOE/NASA shielding and reactor physics studies of space and surface fission power surfaces as part of the SPFT program.[15,16]

Specifically, a new WWW site has been established for the explicit purposes defined in the new American Nuclear Society's Aerospace Nuclear Science and Technology (ANST) working group**.** This News and Technology WWW site is located at RSICC, ORNL where legacy and new data, proceedings, and papers related to space radiation and its effects can be reviewed by the public.[a]

At ORNL, state-of-the-art modeling techniques and computer code systems (physics, radiation transport, fuel depletion) have been used in assessments of nuclear reactor concepts for planetary (e.g. Mars) surface landers and rovers and for spacecraft nuclear reactor systems. Fast spectrum and thermal spectrum reactors have been analyzed at ORNL for these applications. As an example of an intermediate spectrum reactor operating at 20 MW_{th} the equilibrium radioactivity level of the core inventory is about 98 MCi.

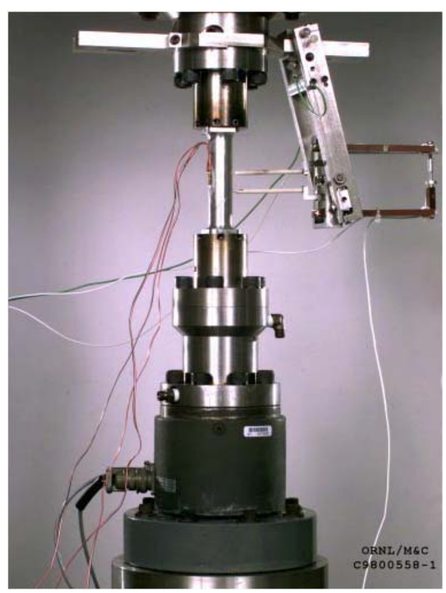
IV. SPECIFIC FUTURE RESEARCH TASKS

A major onboard source of radiation is the nuclear reactor or any RTG system in place on the spacecraft. There are a variety of potential designs for space-borne reactors with different neutron energy spectra and different radiation fields. The extent and type of neutron and gamma shielding used varies in each design. A very important criterion is the mass of the reactor power system and this leads to creative designs and choices for shielding and structural materials. The radiation sources and fields for current postulated space reactors would be assessed and appropriately considered with emphasize on the effects on structural materials. The radiation source and field calculations will be performed with the latest models and reactor physics and radiation transport code systems in use at ORNL.

IV. A. Special Testing Method

An innovative fracture toughness testing method, spiral notch torsion test (SNTT) system,[17-20] was developed recently at ORNL and will be utilized in this research, which also has the advantage of application to mixed-modes fracture toughness research, and for inhomogeneous material and interfacial fracture toughness studies.

The SNTT System measures the intrinsic fracture toughness (K_{IC}) of structural materials. Fracture toughness is a critical design element for structures such as reactor pressure vessels, where safety is a paramount concern, and for materials used in spacecraft and assemblies bound for space, where the change of fracture toughness properties due to extreme temperature swings and severe irradiation environment are major concerns. The SNTT System operates by applying pure torsion to unique cylindrical specimens, which are machined with a notch line that spirals around the specimen at a 45° pitch (See Figure 1). Toughness results are obtained with the aid of TOR3D-KIC, a three-dimensional finite-element computer code developed at ORNL.



Fig, 1. ORNL SNTT System Apparatus.

[a] ANST WWW site is located at ORNL http://www-rsicc.ornl.gov/anst_site/anst_news_tech.htm

The SNTT system is suited to test a wide variety of materials, such as metals and alloys (including the heat-affected zone of welds, for which fracture toughness is virtually unknown), ceramics, composites, polymers, carbon foam, and concrete. The SNTT system does not require fatigue precrack to obtain valid toughness results for the brittle samples. Furthermore, due to pure shear loading of SNTT, the crazing behavior of polymer materials will be minimized and more reliable toughness data will be obtained.

Mixed-mode fracture testing of structural materials can be carried out with current SNTT system configuration with little or no modifications to the specimen and testing equipment. Due to the complex 3-D spacecraft structure, the 3-D out-of-plane structural loading is likely to introduce torsional shear stress fields into the in-plane structures, besides the existing flexural normal stress fields during the service. Moreover, upon launch and reentering the earth orbit, the violent turbulence will certainly result in a mixed-mode loading to the spacecraft structure. Thus, the long-term fatigue aging effect of the combined flexural normal stress and torsion shear stress needs to be assessed.

Miniaturization is an important goal for material testing and surveillance program. This is made possible because the K_{IC} values determined by SNTT are virtually independent of specimen size (see Fig. 2). A cursory review of the stress and strain fields in a CT specimen indicates that the key information needed for determining the K_{IC} values is manifested within a small region (shape of a cylinder) near the crack front; therefore, the rod specimen can be miniaturized substantially without the loss of general validity. The purpose of the vast volume of the material outside the critical zone in conventional samples is to poise the ideal far field of stress and to provide a means to accommodate loading devices. This redundancy is eliminated to the optimum condition in the round rod specimen; therefore, the specimen miniaturization is achievable.

Fig. 2. SNTT Test Samples

The structural materials surveillance program requires a large number of tests to monitor the temporal change of the fracture toughness, K_{IC}, of spacecraft structural components, nuclear reactor vessels and piping systems, etc. To accommodate the large number of test specimens in the limited space available in the spacecraft and nuclear reactor, the test samples must be as small as feasible and practical to generate meaningful results. Specimens used in the SNTT system can be optimized to a diameter as small as practically possible without the loss of general validity.

IV. B. Information Fusion Modeling

The general degradation mechanisms of the material aging behavior that need to be considered include: microstructure and compositional changes, time-dependent deformation and resultant damage accumulation, environmental attack and the accelerating effects of elevated temperature, and synergistic effects of all the above. These complex nonlinear dependencies make the modeling of aging material behaviors a difficult task. The recently developed ORNL information fusion technique is an integrated technology that can be used to predict material non-linear behavior by utilizing a combination of nonlinear estimators including domain models, neural networks, and nearest neighbor regressions.[7] This new approach combines the conventional non-linear statistical methods and mechanism-based approaches into an integrated methodology for predicting material aging processes. The combined system has the potential to perform at least as well as the best of the constituents by exploiting the regions where the individual methods are superior. Such a combination of methods became possible due to recent developments in the measurement-based optimal fusers in the area of information fusion.[9,10] The ORNL information fusion technique can be a powerful tool in assisting the development of embrittlement prediction models for aging spacecraft.

The U.S. Power Reactor Embrittlement Database was used in the fusion technique program development to predict embrittlement levels in light water reactor pressure vessels.[21] The results indicate that the ORNL linear-fuser model for embrittlement prediction achieved about 56.5% and 32.8% reductions in the uncertainties for General Electric Boiling Water Reactor plate and weld data compared to Regulatory Guide 1.99, Revision 2, respectively (See Figs 3-4).

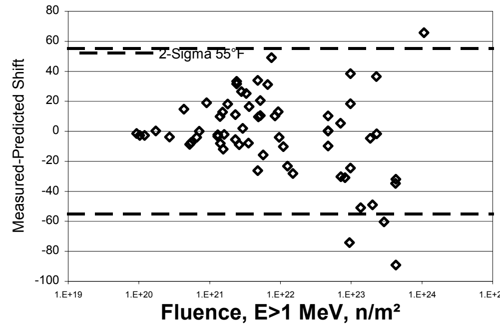


Fig. 3. RG 1.99/R2's residual for base GE BWR.

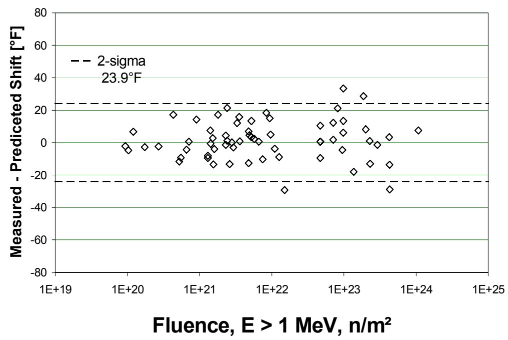


Fig. 4. Fuser Model's residual for base GE BWR.

The complementary approach proposed here proved better than the other conventional models because of its ability to handle the non-linearities included in the data that are hard to capture by other existing models. By using a wide spectrum of methods, the proposed tool for embrittlement predictions can handle the subtle non-linearities and imperfections, and can serve as a calibration and benchmark for the existing models. The predictions generated by this system have great potential for providing efficient, reliable, and fast results for such evaluations, and can be an essential part of the overall safety assessment of material aging research.

IV. C. Modeling Particle Transport and Analysis

Using radiation transport and physics code system methodology including state-of-the-art code packages in use at ORNL (such as HELIOS, SCALE, DORT, TORT, MCNP), calculations will be performed to simulate the radiation fields from various space or planetary nuclear reactors.[22-26] This will lead to assessments of shielding arrangements and the effects on spacecraft and lander structural materials.

A leading unique center called Radiation Safety Information Computational Center has stewardship and access to codes that span the relationships between materials and radiation effects. Located at ORNL, RSICC has spent the last forty (40) years collecting NASA, DOE, and NRC analytical tools for materials, nuclear physics, and experimental data related to neutron, photon, proton, electron, and light to heavy Z material interactions for dose and radiation transport.[b]

Strategies to minimize high energy γ-radiation from bremsstrahlung by appropriate choices of structural materials (lower atomic mass) or target materials that give preferential production of lower energy photons than higher energy (cut-off) photons, albeit there will be a greater flux of the lower energy photons. Also, perhaps necessary high Z materials can be shielded by materials that will help minimize subsequent bremsstrahlung radiation. The code BEBC was developed in the mid-1960s to analyze electron bremsstrahlung effects in spacecraft shielding materials. Another useful code was SHIELDOSE for space-shielding radiation dose calculations. It determines the absorbed dose as a function of depth in aluminum shielding material of spacecraft, given the electron and proton fluences encountered in orbit. Future work will look at further effects and consequences of bremsstrahlung radiation in spacecraft materials and living spaces.

IV. D. ORELA, Earth-Based Radiation Tests

The most useful developments in materials for structural and semi-conductor are direct testing using the fluences and particles of concern. At ORNL, an electron-linear accelerator (ORELA) is used to impinge and create protons and neutrons at a well-characterized target of tantalum. Used for cross-section measurements, highly differentiated beams of particles traverse long-distances to detectors and accurate transmission, scattering, and absorption properties of any material are directly measured.

The advantage to this accelerator is the rapid, controlled fluences[c], energy spectral adjustments, well-proven high-accuracy measurements, rapid shutdown and access to testing materials, and the possibility of adding in situ solar-cycle temperature

[b] RSICC WWW site is located at ORNL http://www-rsicc.ornl.gov/rsic.html

[c] ORELA WWW site is located at ORNL http://www.phy.ornl.gov/orela/orela.html

and mechanical vibrational effects to further test the environmental effects with and without the influence of radiation.

V. BENEFITS AND SPINOFFS

The predictions generated with the above methods from this work will have a great potential for providing efficient, reliable, and expedient results for spacecraft safety evaluations. This directly enhances the spacecraft design process to allow a strong, robust, and inexpensive spacecraft design with an abundant resource of materials for spacecraft structure. Also, the operating procedures for spacecraft integrity have a firm base of reliable data and models for age extension and parts reliability. This methodology system will allow the timely assessment of novel and out-of-the-box designs for ambitious extended manned and unmanned space expeditions including missions with lander or space nuclear reactors.

VI. REFERENCES

1. H. Shulman, W. S. Ginell, "Nuclear And Space Radiation Effects On Materials," NASA SP-8053, June 1970.
2. M. Kangilaski, "The Effects of Neutron Raidation on Structural Materials," REIC Report No. 45, June 1967.
3. Anon.: * Solar Electromagnetic Radiation. NASA Space Vehicle Design Criteria (Environment), NASA SP-8005, 1965.
4. Brown, R. P.: Natural Space Radiation Effects to Sensitive Space System Components and Materials. Vol. I of Space Radiation Environment, Rept. D2-90037-1, The Boeing Co., 1963.
5. Hess, W. N.: The Radiation Belt and the Magnetosphere. Blaisdell Pub. Co., Inc. (Waltham, Mass.) 1968.
6. Bjorken, J. D. and Drell, S. D. "Bremsstrahlung." §7.6 in *Relativistic Quantum Mechanics.* New York: McGraw-Hill, pp. 120-127, 1964.7.
7. J. A. Wang and N. S. Rao, "A New Technique for the Prediction of Nonlinear Material Behavior," *Journal of Nuclear Materials*, Vol. 301/2-3, pp. 193-202, March 2002.
8. J. A. Wang, "Development of Embrittlement Prediction Models for U.S. Power Reactors and the Impact of the Heat-Affected Zone to Thermal Annealing," *Effects of Radiation on Materials*: 18th Volume, ASTM Special Technical Publication 1325, pp. 525-540, March 1999.
9. N.S.V.Rao, Multiple sensor fusion under unknown distributions, *Journal of Franklin Institute*, 1999, vol. 336, no.2, pp. 285-299.
10. N.S.V. Rao, Multisensor fusion under unknown distributions: Finite sample performance guarantees, in *Multisensor Fusion*, A.K. Hyder (editor), Kluwer Academic Publishers, 2001.
11. L.K. Mansur, "Mechanisms and Kinetics of Radiation Effects in Metals and Alloys," ed. by Gorden R. Freeman, *Kinetics of Nohomogeneous Processes*, 1987, John Wiley & Sons, Inc.
12. J. A. Wang, "Analysis of the Irradiated Data for A302B and A533B Correlation Monitor Materials," ASTM Special Technical Publication 1366, pp. 59-80, March 2000.
13. G.R. Odette, P.M. Lombrozo, J.F. Perrin, and R.A. Wullaert, "Physically Based Regression Correlations of Embrittlement Data From Reactor Pressure Vessel Surveillance Programs," EPRI NP-3319, Electric Power Research Institute, 1984.
14. H-X. Li, R.H. Jones, J.P. Hirth, D.S. Gelles, Fracture toughness of the F-82H steel-effect of loading modes, hydrogen, and temperature, *Journal of Nuclear Materials,* 233, (o), pp. 258-263, 1998.
15. ORNL/SPFT/LTR-003, "Concept Evaluation Report: 3-kWe Heatpipe/Stirling Concept for Mars Surface Power Applications", draft, 2001.
16. S.J. Zinkle, J.J. Carbajo, L.J. Ott, R.T. Wood, D.T. Ingersoll, R.J. Ellis, M.L. Grossbeck, and J.F. King, ORNL/SPFT/LTR-004, "Space Fission Technology Assessment Report: Surface Power and Nuclear Electric Propulsion Technologies, with a focus on a 3-kWe Heatpipe/Stirling Concept for Mars Surface Power Applications", draft, 2001.
17. J. A. Wang, K. C. Liu, D. E. McCabe, and S. A. David, "Using Torsion Bar Testing to Determine Fracture Toughness, K_{IC}," Journal of Fatigue & Fracture for Engineering Materials and Structure, Vol. 23, pp 45-56, 2000.
18. J. A. Wang, K. C. Liu, and D. E. McCabe, "An Innovative Technique for Measuring Fracture Toughness of Metallic and Ceramic Materials," *Fatigue and Fracture Mechanics*: 33rd Volume, *ASTM STP 1417*, W. G. Reuter and R. S. Piascik, Eds., 2002.
19. K. C. Liu and J. A. Wang, "An Energy Method for Predicting Fatigue Life, Crack Orientation, and Crack Growth under Multiaxial Loading Conditions," *International Journal of Fatigue*, 23 (2001), S129-S134.
20. J. A. Wang, K. C. Liu, and G. A. Joshi, "Using Torsion Bar Testing to Determine Fracture Toughness of Ceramic Materials," ASME

Proceeding of ETCE 2002 Conference on Composite Materials Design & Analysis, February 3-4, 2002, Houston, Texas.
21. J.A. Wang, Embrittlement Data Base, Version 1, NUREG/CR-6506 (ORNL/TM-13327), U.S. Nuclear Regulatory Commission, August 1997.
22. RSICC CODE PACKAGE CCC-077, “BEBC: Electron Bremsstrahlung Penetration Code for Space Vehicles”, 1964.
23. Seltzer, S. M., SHIELDOSE, A Computer Code for Space-Shielding Radiation Dose Calculations, National Bureau of Standards, NBS Technical Note 1116, U.S. Government Printing Office, Washington, D.C., 1980.
24. Seltzer, S. M., Electron, Electron-Bremsstrahlung, and Proton Depth-Dose Data for Space-Shielding Applications, IEEE Trans. Nuclear Sci., 26, 4896, 1979.
25. Seltzer, S. M., Updated calculations for routine space-shielding radiation dose estimates: SHIELDOSE-2, NIST Publication NISTIR 5477, Gaithersburg, MD., December 1994.
26. Francis A. Cucinotta, Walter Schimmerling, John W. Wilson, Leif E. Peterson, Gautam Badhwar, Premkumar Saganti , and John F. Dicello **“**Space Radiation Cancer Risk Projections for Exploration Missions: Uncertainty Reduction and Mitigation”**,** DOE/NASA Radiation Investigators' Workshop, Washington, DC, June 27-30, 2001.