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NUCLEAR DATA NEEDS FOR THE SPACE EXPLORATION INITIATIVE

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ABSTRACT

On July 20, 1989, the President of the United States announced a new direction for the U.S.Space Program. The new Space Exploration Initiative (SEI) is intended to emplace a permanent base on the Lunar surface and a manned outpost on the Mars surface by 2019. In order to achieve this ambitious challenge, new, innovative and robust technologies will have to be developed to support crew operations. Nuclear power and propulsion have been recognized as technologies that are at least mission enhancing and, in some scenarios, mission enabling. Because of the extreme operating conditions present in a nuclear rocket core, accurate modeling of the rocket will require cross section data sets which do not currently exist.

In order to successfully achieve the goals of the SEI, major obstacles inherent in long duration space travel will have to be overcome. One of these obstacles is the radiation environment to which the astronauts will be exposed. In general, an unshielded crew will be exposed to roughly one REM per week in free space. For missions to Mars, the total dose could exceed more than one-half the total allowed lifetime level. Shielding of the crew may be possible, but accurate assessments of shield composition and thickness are critical if shield masses are to be kept at acceptable levels. In addition, the entire ship design may be altered by the differential neutron production by heavy ions (Galactic Cosmic Rays) incident on ship structures. The components of the radiation environment, current modeling capability and envisioned experiments will be discussed.

I. INTRODUCTION

Since the termination of the Apollo program in the early 1970's, NASA centers, DOE laboratories, and universities have continued to study the technological requirements to develop a lunar base or complete a manned mission to Mars. On July 20, 1989, President Bush validated such efforts by announcing [1] a new direction for the U.S. space program. The goals of the new Space Exploration Initiative were declared to 1) establish a permanent base on the Lunar surface and 2) develop a manned outpost on Mars by the year 2019. The President also tasked the new National Space Council with formulating the SEI program.

Following the announcement, NASA completed a "90-Day Study" [2] which assessed technologies needed for a Mars Mission. In addition, the National Academy of Sciences reviewed both the 90-Day Study and some alternative technology options [3]. Both of these reviews produced a list of critical technologies which needed further development to support SEI goals. Two of the critical technologies identified by these committees were advanced nuclear propulsion and protection against the space radiation environment. Both of these areas will require improvement of the nuclear data bases that currently exist.

II. SPACE RADIATION PROTECTION

A critical component of SEI is a prior knowledge of the radiation field inside of complex geometries, including the human body, that have been exposed to space radiation. This knowledge could be obtained from tests of actual space modules at an accelerator facility that simulates space radiation. But, currently there are no facilities that can produce the desired radiation field and the cost of such tests would be prohibitive. Therefore, validated models will play important role in the design of spacecraft and human habitat modules and in providing an accurate representation of the radiation field inside these geometries. These models will encompass a wide range of nuclear physics disciplines, from medium energy to high energy and relativistic heavy ion physics. They will use state-of-the-art representations of radiation interactions with a wide variety of structural and biological matter, and experimental validation will be used in every stage of the development to help establish confidence levels for the results. The interaction physics must treat e, γ, n, and H through, possibly, U ions and particle energies from MeV to tens of GeV/amu. This multidimensional parameter space is too large to presume that data will be obtained on all particle types and energies. Instead, extensive use will be made of the models to define the critical parameters for a wide range of mission scenarios that include, for example, space stations, interplanetary travel, and permanent habitation of the moon and planets. These parameters will then be used to guide the experimental efforts for development of the radiation transport code and the radiobiological response data base.

There are two sources of radiation that are major drivers in the SEI program; they are, Galactic Cosmic Radiation (GCR) and Solar Energetic Particle (SEP) events. A calculation of the dose received by an astronaut inside of a spacecraft for a three-year mission to Mars illustrates the importance of the GCR and SEP sources. For such a mission, the calculated dose for just the GCR component is as high as ~100 rem [4] which exceeds the recommended three year occupational dose by a factor of 6.7. If an intense SEP event should occur during the mission, the astronaut could receive a lethal dose from some of the more intense SEP events.

The GCR is a persistent source of radiation that originates outside of the solar system. The intensity of the GCR varies by as much as a factor of two or more with the eleven year solar cycle, the maximum intensity occurs during solar minimum. The GCR is composed of ions from hydrogen to uranium with the most abundant ion being hydrogen. In Fig. 1, spectra are shown for classes of ions pertinent to SEI. Ions with $Z > 28$ are present in the GCR, but their relative biological importance is minimal. All ions have roughly the same energy distribution with the maximum in the distribution occurring at approximately 400 MeV/amu. Ion energies as high as 1000 GeV/amu have been measured, but their relative intensity is at least six orders of magnitude less than the peak intensity. The high-Z, high-energy (HZE) particles in the GCR are extremely penetrating and biologically destructive; for example, an iron ion with an energy near the peak of the distribution can effectively destroy every cell in its path in passing through the human body. Even though ions with $Z > 2$ represent less than two percent of the GCR fluence, they can contribute more than 50% to the dose. Nuclear data on high-Z projectile and target fragmentation processes and secondary particle production and transport are necessary to develop the radiation transport models, to build evaluated data libraries, and to validate the models.

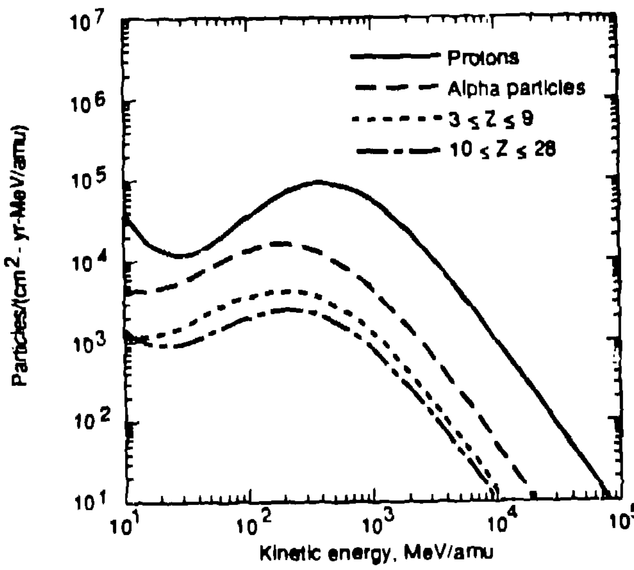

Fig. 1. Flux Versus Energy for GCR Ions During Solar Minimum [5]

The SEP events are spora and can last for hours to several days. These events are unpredictable but occur most frequently during solar maximum. They consist of mostly protons and alphas with energies as high as several GeV/amu. In Fig. 2, accumulative plots of proton intensity are shown for three characteristically different SEP events. The August 1972 event, which was the most intense SEP

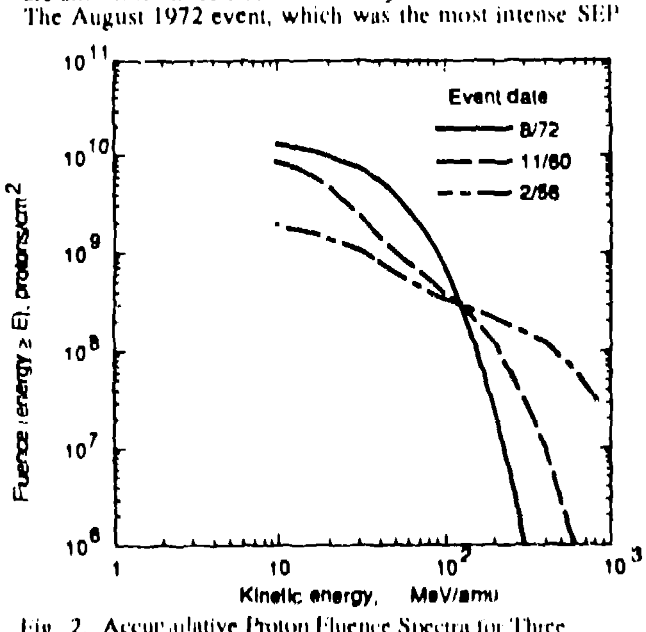

Fig. 2. Accumulative Proton Fluence Spectra for Three Large SEP Events [6]

event recorded prior to the October 1989 event, had a proton fluence of about 10^{10} protons/cm^2 and proton energies of several hundred MeV. On the other hand, the SEP event of February 1956 had a proton fluence of about an order of magnitude less, but it had protons with energies of several GeV. Shielding may be effective in protecting an astronaut from SEP events, but now secondary radiation, mainly high-energy neutrons, becomes important.

Secondary radiation occurs when GCR or SEP particles penetrate thick shields. This radiation manifests itself in the form of very high-energy neutrons and protons (hundreds of MeV). Calculations of the differential particle flux for particles at 100 g/cm^2 depth in carbon dioxide resulting from incident GCR at solar minimum are shown in Fig. 3. Similar spectra are obtained for other shielding materials including lunar regolith. Nuclear data will be required for total, elastic, and inelastic neutron processes for energies up to several hundreds of MeV. Furthermore, to calculate a dose, (n,z) cross sections will be required for materials found in the human body.

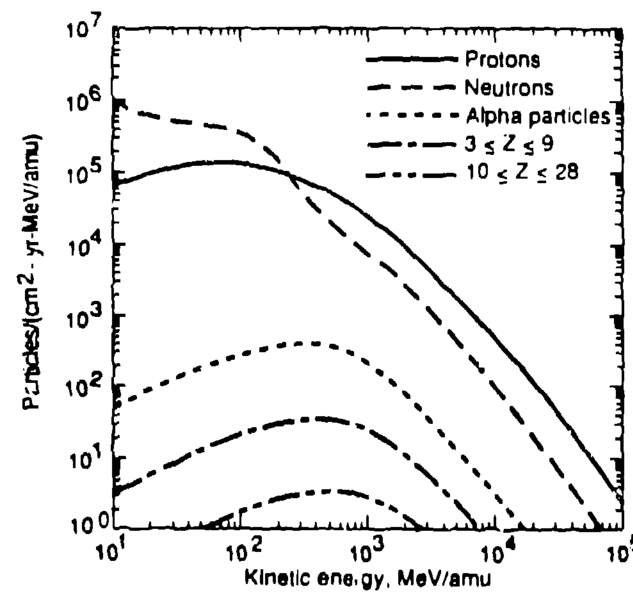

Fig. 3. Yearly Differential Flux Versus Energy for Particles at 100 g/cm^2 Depth in Carbon Dioxide Resulting from Incident GCR at Solar Minimum [7]

In this section we have ignored the man-made radiation from a nuclear reactor. If a nuclear propulsion system is used, then the total dose must include the effects from nuclear radiation. The nuclear data needs for calculating the radiation output from a nuclear propulsion system are addressed in the following sections.

III. SOLID CORE NUCLEAR PROPULSION

Although a nuclear rocket engine had been partially developed and tested during the ROVER/NERVA program [8,9] in the 1960's, substantial advances have occurred in several technological areas pertinent to nuclear propulsion systems. As a consequence, NASA and the DOE sponsored a pair of workshops in the summer of 1990 to examine all concepts for nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP). The purpose of the workshops was to allow a common panel of experts to evaluate several different reactor concepts, fuel forms, or engine systems. Approximately 60 individuals from NASA, DOE and the industrial community comprised 5 review panels, each reviewing all of the concepts. One of the primary findings of the panels was that NTP technologies for manned missions could probably be developed earlier than NEP systems but that higher operating temperatures would be required for the mission.

Subsequent to these findings, both NASA and the Department of Energy (DOE) have initiated a series of meetings to more completely examine the research needs in these areas. The more complete effort is a jointly NASA/DOE sponsored group of 6 Task Teams to examine nuclear propulsion from the perspectives of safety, mission benefit, nuclear thermal propulsion (NTP) technology, Nuclear Electric Propulsion (NEP) technology, fuels and materials, and test facilities. The NTP panel examines all technology needs including improvements in data bases necessary for high temperature nuclear reactor core operations.

The ROVER/NERVA program succeeded in performing 22 different reactor/engine tests between 1955 and 1971. The highest power engine tested was the Phoebus 2 at 4500 MW and a thrust of 1.1×10^6N. The hottest fuel temperature achieved during the tests was 2550K which corresponds to a specific impulse, Isp, (momentum delivered per unit mass) of about 850s. Because of the space radiation dose problem described in Section II, the manned flight to Mars must be made as quickly as possible to reduce GCR dose and potential solar flare coincidence. For example, in order to reduce the total round trip to around 1 year, an Isp of around 950 to 1000s must be achieved (for a reasonable mass of around 750 tons in Low Earth Orbit). Consequently, peak fuel operating temperatures of around 3200K would be required. To date, no institution has ever operated a critical system at steady state conditions at such temperatures.

During the ROVER program, computational modeling was used but with moderate success due to the complexity of the problem and the, then current, computer capability. Current constraints on the testing environment and the budget environment, however, will necessitate a much stronger dependence on computational simulation than before. Consequently, several improvements in cross section sets and computer code treatments will be required.

Although several different reactor concepts have been proposed, a generic geometry can be envisioned such that:

1) the reactor core will be a cylindrical assembly consisting predominantly (from the neutronics viewpoint) of UC_x ($x \geq 1$) with some ZrC intermixed with hydrogen coolant; and

2) the core is surrounded by insulator material (possibly aluminae) then reflector/moderator which is cooled by cold hydrogen gas.

Because of this geometry, moderated neutrons which are reflected back from the cold reflector will be upscattered by the insulator and fuel material. The upscattering kernels of aluminae, beryllium, and carbon need to be re-examined and probably improved. Accurate calculation of the neutron spectra will be necessary due to the strong dependence of the U^{235} fission cross section on neutron energy between 273K (σf =577b) and 3300K (σf =120b) temperatures. The spectral content of the neutron flux will determine the radial power profile in the core and thus engine life and performance.

Because of the need to achieve much higher fuel operating temperatures, new materials with higher melting points are being considered as flow channel coatings. The two most promising candidates are HfC and TaC which have melting points of 4120K and 4080K, respectively. These materials, however, also have significant neutron absorption cross sections. A review of the cross section data base between .01 to .3eV is needed. Furthermore, reactivity measurements of such materials in criticality assemblies will be necessary.

IV. ADVANCED PROPULSION CONCEPTS

As part of the effort of the Nuclear Thermal Propulsion Task Team, one of the authors (Howe) chaired a sub-panel to evaluate innovative propulsion concepts. The motivation to form such a panel was to investigate alternative methods of achieving much higher Isp's (> 2000s) in order to reduce Mars mission round trip times to 1-2 months. The goals of the sub-panel were to 1) evaluate a variety of concepts on a "level technological playing field", 2) identify critical research issues of each concept, and 3) identify proof-of-concept experiments for the leading concepts.

Because of substantial work performed in the 60's and 70's, the gas core nuclear rocket is the leading concept. Although several variations exist as to geometry, flow fields, and fuel forms, all of the concepts essentially involve the containment of a uranium gas or plasmoid surrounded by hydrogen coolant/propellant . Design chamber pressures range from 100 to 500 atmospheres. Uranium temperatures range from 5000K to 100,000K.

Neutronically, the upscatter problem is even more pronounced. Early findings indicate that the main fission generation region in a spherical uranium plasmoid will be a spherical shell at some radius inside the plasmoid radius. This effect is caused by the assumed upscattering of the reflected cold neutrons and may have a dramatic effect on the concept performance. Consequently, the upscatter cross sections for BeO, F, and U need to be accurately determined.

In addition, some of the concepts rely on mechanical containment of the uranium fuel and on radiative coupling to the propellant through a fuzed silica window. The opacity of the window as a function of neutron fluence has not yet been thoroughly investigated.

The sub-panel also considered several concepts for long-term propulsion systems for solar system exploration. Of these, fusion and antimatter annihilation ranked the highest. While the fusion reaction has been well studied, no data exist for the antiproton annihilation cross sections below 2MeV, except for the totally stopped, thermal data point. Many of the proposed antiproton storage concepts are extremely dependent on the annihilation cross section in the 100eV to 100KeV regime. Determination of these cross sections will be necessary to pursue this propulsion concept.

V. SUMMATION

The President of the United States has initiated a new space initiative which will require technological advances in several areas. Two of these areas, space radiation protection and advanced propulsion will require improvements in the nuclear data base. Accurate knowledge of the secondary products of relativistic heavy ion collisions produced by Galactic Cosmic Rays will be necessary to protect the crew , the electronic controls, and to design the placement of the spaceship's main components such as fuel tanks. Determination of neutron upscatter cross sections and absorption cross sections for specific materials must be made in order to design advanced propulsion systems such as solid-core or gas-core nuclear rockets. In addition, the antiproton annihilation cross sections below 2MeV are unknown and will need to be measured to develop even higher performance propulsion systems. Such systems will be necessary to reduce trip times to planets for human crews. If mankind is to explore the solar system, significant extensions of our current nuclear reaction data base will be absolutely essential.

References

1. G. Bush: "Remarks by the President at the 20th Anniversary of the Apollo Moon Landing," Washington, D.C., July 20, 1989. Published in the Space Exploration Initiative Fact Sheet

2. A. Cohen: "Report of the 90-Day Study on Human Exploration of the Moon and Mars,"NASA, Nov. 1989

3. G. Stever: "Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives," National Research Council, National Academy Press. 1990

4. "Guidance on Radiation Received in Space Activities. NCRP Report No. 98, July 989

5. J. H. Adams, Jr., R. Silberberg, C. H. Tsao, "Cosmic Ray Effects on Microelectronics. Part 1: The Near-Earth Particle Environment." NRL-MR-4506-PT-1, Naval Research Laboratory (Aug. 1981)

6. J. W. Wilson, "Environmental Geophysics and SPS Shielding," Workshop on the Radiation Environment of the Satellite Power System," (Edited by W. Schimmerling and S. B. Curtis), LBL-8581, pp.33-116, Sept. 1978

7. L. C. Simonsen, J. E. Nealy, L. W. Townsend, and J. W. Wilson, "Radiation Exposure for Manned Mars Surface Missions." NASA Technical Paper 2979, March 1990

8. J. H. Altseimer, G. F. Mader, and J. J. Seinart: Journal of Spacecraft, Vol. 8, No. 7, July 1971

9. Koenig, D. R., Los Alamos National Laboratory Report, LA-1062-H, May 1986