C. RESEARCH AND DEVELOPMENT - GENERAL ISSUES

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C.1. RADIATION DAMAGE

High-current medium-energy protons injected into the target generate, by spallation reactions, neutrons and charged particles with energies reaching the level of the accelerated protons. This causes severe radiation damage in the section of the window, the target, and the wall material surrounding the target. The most important type of radiation damage to materials stems from the displacement of lattice atoms resulting from the collision of the projectile particle upon the target atom or from the recoil energy that the atom receives upon emission of a nuclear particle, for example the atom recoil upon absorption of a neutron and emission of a capture γ-ray. When an atom is displaced from its lattice site and comes to rest in between lattice atoms, a vacancy and an interstitial have been created [1]. The vacancies may aggregate together, and similarly the interstitials, form vacancy-type and interstitial-type defect clusters. These defect clusters are primary agents for causing radiation hardening and embrittlement. The primary effects of concern with regard to the use of materials in the vicinity of the proton beam are changes in mechanical properties and dimensional stability. The major mechanical property changes are hardening and embrittlement, and the embrittlement manifests itself in several ways: radiation-produced defect clusters (aggregates of vacancies and interstitials), helium aggregation into bubbles and ductile-brittle transition defects. A further type of radiation damages consists of the impurities introduced by the formation of transmutation products [2].

The analysis indicate that the surrounding wall as well as the window suffers high radiation damage, so that the former must be replaced frequently in a transmuter with a high current accelerator.

The analysis of hydrogen and helium production indicates that hydrogen is deposited in the system by the spreading of the proton beam arising from multiple Coulomb scattering. Hydrogen generated as a secondary proton of (n,xp) or (p,xp) as well as deuterons and He generated through evaporation processes, are slowed down and deposited mainly in the target.

Because accelerated protons produce spallation neutrons and protons in the target and window areas with energies above the atomic displacement, and also produce hydrogen and helium, the problem of radiation damage is expected to be substantial when a high-power accelerator is used for a large subcritical reactor. Using the small proton current associated with small sub-criticality avoids this serious problem.

These findings indicate that, in designing the proton-accelerator based transmuter, the radiation damage to the beam window section and the side walls of the target should be investigated carefully. Moreover, the radiation damages in structural materials of the accelerator-driven system can be higher than in corresponding critical reactors because of the existence of high energy spallation neutrons [3][4]. Calculations of neutron energy spectra and fluxes are required so damage parameters can be determined and a better assessment of candidate alloys can be made.

REFERENCES

[1] Monroe S. Wechsler, Chubin Lin and Walter F. Sommer, "Basic Aspects of Spallation Radiation Damage to Materials", AIP Conference Proceedings 346 on International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, NV, July 1994, AIP (1995)

[2] Wechsler, M.S., Stubbins, J.F., Sommer, W.F. et al, "Selection and Qualification of Materials for the Accelerator Transmutation of Waste Project", Report LA-UR-92-12-1211, Los Alamos

National Laboratory, Los Alamos, NM, (1992)

[3] Takahashi,H., Takashita, H., and Chen, X, "Transmutation of High_level Radioactive Waste and Production of ^{233}U Using an Accelerator-Driven Reactor", AIP Conference Proceedings 346 on International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, NV, July 1994, AIP (1995)

[4] DeVan, J.H., DiStefano, J.R. et al., "Materials Considerations for Molten Salt Accelerated.based Plutonium Conversion Systems", AIP Conference Proceedings 346 on International Conference on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, NV, July 1994, AIP (1995)

C.2 NUCLEAR DATA CODES

Proper calculations of accelerator-driven systems require more elaborate computer models than modeling for conventional critical reactors. It is necessary to couple two transport problems: the transport of the medium energy charged particle (1-3 GeV) in the spallation target with the transport of neutrons down to low energy range. Neutron transport problems in the fission-range of the energies have been the subject of reactor physics for half of a century. Transport problems with the charged particles were mainly the domain of accelerator physics and radiation protection.

A description of fission neutron transport codes and burn-up codes is far beyond the scope of this report, we give here only a brief description of the codes which integrate/couple modeling of the charged particle transport and spallation processes with the neutron transport in the energy range up to the GeV region.

Due to interest in accelerator-driven systems, as well as in other areas of application, such as radiooncology, accelerator shielding, astrophysics, and radiation during space travel, the nuclear reactor community undertook new initiatives to assess the reliability of the current nuclear models and to develop better transport codes, for example, the OECD NEA meeting. (The findings are documented in the proceedings of a specialist meeting at Issy-Les Moulinaux, France, 30 May-1 June 1994).

When medium-energy protons collide with a nucleus, the nuclear reaction occurs by a two-step process of spallation and evaporation of the residual nucleus (see Fig.1 section B.2.). When the residual nucleus has a large mass and a moderately high excitation energy, then it might undergo fission in competition with the evaporation reaction. The third process is emission of the cluster and emission of the particle, the so-called pre-equilibrium emission particle, before reaching the thermal equilibrium state. Neutron and photon transport below the energy of 20 MeV has been accurately estimated in conventional reactor calculations which are very familiar to the nuclear engineer.

In the first step of the spallation process, the transport of the nucleon in the nucleus can be treated with the classical model because the nucleon's wavelength inside the nucleus is smaller than the average spacing. The collision of the nucleon with a nucleon is treated as a two-body collision . The π meson of π^+ and π^- which are created in the nucleon-nucleon collision are also included in calculations of the cascade process; thus, the basic data for a two-body collision between a pion and nucleon is required to describe the cascade process for the meson. In the nuclear cascade codes NMTC [1] and HETC [2], [3], the evaluation of a nucleon-nucleon collision is obtained from Bertini's [4] data, and the production of a meson is treated by using the Isobar model developed by Sternheimer and Lindenbaum [5].

Since the nucleon is a fermion, the nucleon which is scattered below the Fermi energy is forbidden as a real scattering event. Such events are discarded, and another scattering event is calculated. When the kinetic energy of the scattered nucleon through the nuclear surface is above the binding energy of the nucleon, this nucleon escapes from the nucleus with kinetic energy minus its binding energy.

When the nucleon's kinetic energy inside the nucleus is less than the binding energy , the nucleon gives kinetic energy to the nucleus as excitation energy. This energy thermalises the nucleus, and neutrons, protons, or other light nuclei are evaporated. When this excitation energy surpasses the fission barrier in the heavy nucleus, fission events will compete with the evaporation of light-element particles.

The particle emitted from the collision of the nucleus travels until its next nuclear collision (called an inter-nuclear cascade). This process is repeated until the energy of the particle falls below the cut-off energy. When the particle emitted or scattered from the nucleus is a charged particle, its energy is lost by exciting the electron surrounding its tracking path. As the particle slows down its wavelength becomes longer than the average distance between the nucleons; then, the reaction cannot be described as a two-body collision of the nucleon or meson, and must be described by quantum mechanics, using the optical potential model.

The NMTC and HETC codes are the system codes which calculate, by the Monte Carlo method, the nuclear reactions of protons, neutrons, and pions above the cut-off energy and the transport of these particles in heterogeneous media. In these codes, the cascade of a nucleon in the nucleus is calculated by the code MECC2, developed by Bertini; the evaporation process is calculated from the excited nucleus by EVAP developed by Dresner [6]. Particle transport within the heterogeneous medium is calculated by many subroutines developed in the O5R codes [7]. Furthermore, many subroutines were added to calculate the transport of the charged particle and the nuclear reactions associated with the pions.

The original NMTC and HETC codes cannot calculate high energy fission which is very important for targets with high atomic number, such as Uranium or the actinides. To treat this high-energy fission reaction, many authors have developed their own codes. By adding their own fission models to the NMTC code, the NMTC/JAERI [8]and NMTC/BNL [9] codes were generated. The LAHET code [10]was made by adding the Rutherford Appleton Laboratory (RAL) [11] and ORNL models [12] to the HETC code. Besides the NMTC and HETC, the ISABEL code [13] was developed from the VEGAS code [14] which can treat the refraction process. The LAHET code offers the option of using the ISABEL model in addition to the HETC code; LAHET treats the light mass nuclei's cascade by Fermi's break-up model. Furthermore NMTC/JAERI and LAHET (see section D) have the capability to handle the pre-equilibrium process based on the Exciton model.

Other nuclear cascade codes, such as FLUKA [15] (see also section D.3.) and CASIM [16] were developed by the high energy community and are continuously upgraded in order to be useful for ADS-calculations (e.g. through incorporation of the high energy fission processes).

At the OECD/NEA, conducted a study in two areas of microscopic nuclear physics, using the data from a thin target benchmark, and developing transport capability using thick target physics. Model codes such as ALICE92, PREQAQ2, GNASH, KAPSIES, FLUKA, FKK_GNASH, CEM92, and LAHET codes have been evaluated. In the evaluation of the thick target, the codes of LAHET(LANL) and FLUKA (CERN/Milano) and NMTC (JAERI) and HETC-THERMES (KFA-Jülich), LAHET-MCNP(LANL), CALOR(ORNL), SHIELD-SITHA(INR, Dubna) and SOURCE (Ansaldo, Italy) were discussed, as well as the group cross-section libraries -HILO86/400 MeV, LANL/800MEV and LAHI-KFA/2.8 GeV. As benchmark experiments, the following experimental data were described; COSMOTRON/ FERICON-LANL/CHALK RIVER, SUNNYSIDE-LANL, Stop Targets-LANL, Vassylkov experiments [17] (see also ICANS-XI, 1990, Shielding experiments at beam stop at PSI and LANL, a Japanese review of shielding experiments). For evaluating energy deposition and target heating, LANL-LANSCE and ANL/ RAL spallation sources provide very valuable data.

To evaluate calculations of radionuclide decay, it is desirable that the newly developed codes, such as ORIHET/PSI and CINDER 90/LANL, are available to the scientific community.

REFERENCES

[1] W.A. Coleman and T.W. Armstrong, "NMTC Monte Carlo Nucleon Meson Transport Code System", ORNL 4606 (1970)

[2] K.C. Chandler and T.W. Armstrong,, "Operating Instructions for the High-Energy Nucleon-Meson Transport Code HETC", ORNL-4744 (1972)

[3] Radiation Shielding Information Center, "HETC Monte Carlo High-Energy Nucleon-Meson Transport Code", Report CCC-178, Oak Ridge National Laboratory (1977)

[4] H.W. Bertini, "Monte Carlo Calculation of Intranuclear Cascade", ORNL-3383 (1963)

[5] R.M. Sternheimer and S.J. Lindenbaum, Phys. Rev. 105, 1974 (1957); Phys. Rev. 109, 1723 (1958); Phys. Rev. 123, 333 (1961)

[6] L. Dresner, "EVAP - A Fortran Program for Calculating the Evaporations of Various Particles from Excited Compound Nuclei", ORNL-TM-196 (1962)

[7] D.C. Irving et al., "O5R a General Purpose Monte Carlo Neutron Transport Code", ORNL-3622 (1965)

[8] Y. Nakahara and T. Tsutsui, JAERI Memorandum M82-198 (1982)

[9] H. Takahashi, "Fission Reaction in High Energy Cascade", BNL-NCS-51245 (1984)

[10] R. Prael and H. Lichtenstein, LA-UR-89-3014 (1989)

[11] F. Atchison, "Spallation and Fission in Heavy Metal Nuclei under Medium Energy Proton Bombardment", Meeting on Targets for Neutron Beam Spallation Sources, G. Bauer (Editor), KFA-Jülich, FRG, 11-12 June 1979, Jül-Conf.-34 (January 1980)

[12] R.G. Alsmiller, Jr. et al., "Neutron Production by Medium Energy (~1.5 GeV) Protons in Thick Uranium Targets", ORNL-TM-7527 (1981);
R.G. Alsmiller, Jr. et al, "A Phenomenological Model for Particle Production from the Collision of Nucleons and Pions with Fissile Elements at Medium Energies", ORNL-TM-7528 (1981)

[13] Y. Yariv and Z. Fraenkel, Phys. Rev. C, 20, 2227 (1979)

[14] K. Chen, Z. Fraenkel, G. Friedlander, J.R. Grover, J.M. Miller and Y. Shimamoto, Phys. Rev. 166, 949 (1968);
K. Chen, G. Friedlander, and J.M. Miller, Phys. Rev. 176, 1208 (1968)

[15] J. Ranft et al., "FLUKA82", CERN Divisional report TIS-RP/156/ CF (1985)

[16] A. VanGinnekin and T. Borak, IEEE Trans. Nucl. Sci. Vol. NS-18, No. 3, 746 (1971)

[17] R.G. Vassylkov et al., Atomnaya Energiya 44, 329 (1978)