INERTIAL FUSION ENERGY AT DENIM (SPAIN)

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The paper describes the history and the research carried out in the field on Inertial Confinement Fusion (ICF) since 1966 at the Spanish Atomic Energy Commission (JEN) up to present time at the Institute of Nuclear Fusion (DENIM) of the Polytechnic University of Madrid (UPM). Late in the 70s, we developed the NORCLA code that was the first non-classified coupled code to analyze the different processes held in ICF. Since then, we have developed a set of more accurate codes such as the ARWEN (two-dimensional transport), JIMENA and ANALOP (atomic physics), ACAB (safety and environmental), material and reactor chambers and advanced fuels. The paper tells also the origins of DENIM and all the efforts made to achieve an international declassification in ICF research.

The first steps in inertial confinement fusion were taken in 1966 in the Spanish Atomic Energy Commission (JEN) when we developed a radiation-transport code, named ISLERO, to analyze a ellipsoidal microcapsule with uranium walls. In its interior there was a DT micropellet with a Pu layer and in the opposite extreme of the microcapsule there was a hole allowing the passing of a laser beam. To a certain extent, this microcapsule, holhraum-typed, was based on the H-bomb. Due both to the simplifications of the code Islero equations and the inaccuracy of the parameters, the results were not reliable. For that reason I gave up temporarily this research.

Eight years later, I organized a group with half-a-dozen of scientists to study the processes produced in the fusion of direct-driven targets based on the micropellet of DT with a layer of Pu, as I had previously done in the code ISLERO. We developed NORCLA code, the first non-classified coupled code, including time-dependent hydrodynamics and realistic neutron-gamma transport with adequate energy source from fusion and fission materials. Two modules composed NORCLA: NORMA (for hydrodynamics) and CLARA (for fusion-fission sources and neutron-gamma transport).

NORMA in its first version (adapted using CHART-D code from Sandia as a base) considered one-dimensional time dependent evolution of fluids/plasmas under flexible boundary pressure conditions, supposedly formed by laser-matter interaction with the pellet. By means of a lagrangian scheme, momentum and energy equations were solved including radiation diffusion and suprathermal electrons terms in a simple mode. Interchange of energy terms among the different species were also included. Equation of State (EOS) and atomic coefficients were considered through analytical solutions (ANEOS package) using the average atom ionisation model. Shock waves were treated using the concept of artificial viscosity (von Neumann & Richtmyer) by adjustment up to quadratic terms. The results from NORMA (density, temperature, velocity, position) for each computational zone were treated as the necessary input for the CLARA module of burnup and transport processes.

The CLARA module includes a detailed one-dimensional and time dependent treatment of the neutron-gamma transport equations. A key aspect in this module was the Legendre decomposition of nuclear data (cross section) in angular dependence (P_N) and the neutron fluxes studies in discrete ordinates modelling (S_N).

A modification of this NORCLA code was also considered by coupling the NORMA module with a MonteCarlo time dependent system (TIMOC-ESP/LIBERTAS) including also burnup equations for fusion and fission.

In 1980 the JEN focused all its efforts on nuclear fusion research in the magnetic confinement field. For this reason our group decided to leave the JEN and to create the Institute of Nuclear Fusion (DENIM) at the Polytechnical University of Madrid to continue with inertial fusion energy.

The nuclear countries classified from the very beginning the research on ICF, mainly about holhraum. Although necessary at first, this classification produced one negative effect. The prohibition for the American scientists to publish sensitive theoretical and experimental results, whereas scientists from Italy, Germany, Spain and specially Japan could publish their work without any restriction. Sometimes the works published by these scientists were already done by their American colleagues. This fact produced nuisances that affected negatively to the quiet environment and collaboration which are so important in any process of scientific research.

In this confusing and complicated environment, in June 1988 the 19th ECLIM was held in Madrid. Relevant scientists and directors of different laboratories devoted to the ICF participated in this Conference. Professors Chiyoe Yamanaka, Erik Storm, Vladislav Rozanov, Heinrich Hora and myself took advantage of this opportunity to write the **Madrid Manifesto** which was signed by over 130 scientists. In this Manifesto it was said:

Recent research results in Inertial Confinement Fusion (ICF) have put to rest fundamental questions about the basic feasibility of achieving high gain ICF, and make it clear that there should be an aggressive program to design, build and operate ICF facilities to demonstrate high gain fusion in the laboratory... The time has arrived to begin to seriously seek a new age in the development of ICF. The laudable goal of the international ICF community is to use the fullest possible collaboration among nations in order to provide the technological benefits from fusion that will serve all humanity.

In the spirit of the 19th European Conference on Laser Interaction with Matter (ECLIM) held in Madrid, we urge the international community to take action now.

In 1992 the Herald Tribune and the New York Times made public that *The Federal Government... is beginning to declassify some of the most sensitive* *aspects of its design and to let American scientists publish them in scientific literature. The reason for this reversal is not internal policy considerations, the end of the cold war or the collapse of the Soviet Union as a military threat. Rather it is foreign competition. Scientists in Japan, Germany, Spain and Italy... have openly published the "secrets" for years. Continued secrecy for similar research in the United States was seen as stifling the exchange of ideas, inhibiting progress and limiting international cooperation. At times American scientists have been ordered not to attend meetings with foreign scientists, because they would have run the risk of discussing classified information. As a result, the Department of Energy, the keeper of the secrets, carried out one round of declassification in 1990, and says it is readying another.* After this event, the US DOE decide to declassify almost all IFE research.

Since then, we have extended the research to the following areas: radiation fluidynamics (two dimensional transport code ARWEN); atomic physics (JIMENA and ANALOP codes, NLTE screened hydrodynamic model and detailed configuration code M3R); safety and environment (ACAB code); materials and reactor chambers and advanced fuels for IFE.

ICF TARGET DESIGN: PHYSICS AND COMPUTATIONAL SIMULATION

Radiation transport capabilities have been implemented into the ARWEN code. The transport equation is solved using the Discrete Ordinates (Sn) scheme in multigroups of energy. All the algorithms have been optimized for working under an AMR system. Data is calculated in every mesh, and then properly exchanged following an optimized ordering. The calculations take into consideration in a semi-implicit form the interaction between the material and radiation energy states in every time step. That keeps the accuracy of the emission term even under the case of large time steps, which allows to use larger time steps limited only by fluid dynamic considerations.

The resulting algorithms are accelerated by means of the Diffusion Synthetic Acceleration, which is implemented in the transport calculations. This method operates on the multigroup equation, accelerating both the angular and energetic convergence.

A new corrector method for the calculation of emissivities has been developed and implemented. It has a big importance in the calculation of the emission of radiation in regions with steep gradients, which is the case of, for example, ablation fronts.

The ARWEN code with radiation transport has been sufficiently validated by comparing its results to an analytical case (Su-Olson test), results from a reference code as it is LASNEX, and experimental measurements. The results are outstanding in the sense of not only reproducing the expected computational results, but also producing better agreement to the experimental data. The development of the radiation capabilities and futher testing has lead to a doctoral thesis.

The ARWEN code is currently being used for simulating studying recent target designs for several research areas:

- Ignition of ICF targets by jet impact.
- Laboratory study of the interaction of supernova remnants.
- Amplification of UV light in a plasma medium.
- Dispersion of debris from explosions.

In the near future, multimaterial calculations are to be introduced, as well as a already designed further optimization of the radiation calculations.

ATOMIC AND NUCLEAR PHYSICS

Main activity in this area was focused to develop and complete a set of codes for opacities in LTE and NLTE conditions in a range of densities and temperatures for inertial fusion targets.

Two LTE computer codes: JIMENA and ANALOP were developed. The first one uses self consistent calculations and the second one, parametrical potentials. Many comparisons with other codes and experiments were done in different Worshops for Opacity Calculations. Several doctoral thesis have been presented developing the parametrical potentials for opacity calculations.

During five years there existed a full participation in experiments for massive targets in the LULI experimental facilities, supported by a program for Large Installations of the European Commission..

Present theoretical and numerical work is focused to determine opacities for dense plasmas especially in NLTE using a detailed kinetic model with double excited states coupled to line radiation transport and with a screening hydrogenic model using parametric potentials. M3R computer code developed in collaboration with the Department of Physics of the Nevada University was coupled to ANALOP, giving a powerful tool to get populations in any kind of plasma and also opacities for dense plasmas. In this sense an international comparison of atomic opacities is under way, and final results will be published during this year.

NEW CONCEPTS

Physical phenomena in degenerate plasmas have been studied to assess the performance of Inertial Fusion targets working in such extreme conditions. It has been found that the theoretical ignition temperature is significantly lower in those cases, because of the reduction in bremsstrahlung losses. However, this reduction is only relevant for very high densities, over 10^{27} e/cm^3 for deuterium-tritium plasmas. For 10^{29} e/cm^3, the ignition temperature is about 1keV.

However, degenerate plasmas would have to be ignited by external beams (in the so called Fast Ignition model) and the advantage of these plasmas (lower ignition temperature) almost vanishes, because the target gain decreases as the target density increases, as most of the driver energy is invested in compression of the target. As a summary of this analysis, it can be said that plasma temperatures to start a fusion burning wave are smaller in degenerate plasmas than in classical ones, but this positive effect is counterbalanced by a shorter target gain, which is the dominant parameter in Inertial Fusion Energy.

A new target design is proposed on the basis of fast ignition. All previous models followed the pattern of a target implosion driven by a primary energy source (laser, ions) synchronized with a sudden deposition of energy by a secondary drive. The new model proposed performs the deposition of energy by the collision of a high velocity jet generated also with the main drive. This has the significative advantage of requirement of a single energy source, resulting in a simpler drive device.

The design is based on a typical target for fast ignition, where a spherical sector of the shell has been removed and changed into a guiding cone pointing outwards. On that stereoangle is placed another cone pointing inwards, in such a way that the illumination of the target will act on its external side. The implosion of this cone produces a cumulative process resulting in a hypervelocity jet towards the center of the target.

Upon correct design, the jet may arrive to the center in the very moment when the shell is in its most compressed state. The deposition of kinetical energy onto the shell produces a rise on temperature leading to target ignition.

The system has been simulated with ARWEN, showing as expected considerable heating on the collision area.

IRRADIATION DAMAGE OF MATERIALS

Work has been done in the last years conducting to identification of time-dependent neutron intensities and energy spectra from Inertial Fusion Energy (IFE) DT-targets. Those magnitudes allow a correct analysis of radiation damage in materials in Inertial Fusion Reactors. Total neutron intensity as a function of the time from the target emission in a Fe layer as structural wall has been obtained; an inner and outer Fe layer (10 cm thickness) for two types of protection (Flibe, Pb,Li) are considered demonstrating a different behaviour. When Flibe, the maximum is attained in the inner layer at the time interval 0.09-0.10 µs, while that maximum arrives at 0.10-0.11 µs in the outer layer. The intensity decreases very rapidly in both layers. On the contrary, when LiPb the intensity get its maximum at 0.2 µs, similar in both studied layers, with a new maximum at 1 µs much more pronounced in the inner layer.

Multiscale Modeling (MM) is getting a large role in obtaining predictive characteristic. That is true not only for fusion programs but for other nuclear industrial interests such as fission programs (advanced Fission Reactors / Generation IV and Accelerator Driven Systems for Transmutation). A common methodology work appears in both cases in spite of coincidence of analyzed materials. Key is the validation of MM against specific experiments step by step at the microscopic and macroscopic levels and real understanding of damage processes. A large collaboration is being routinely carried out on IFE activities at DENIM with Lawrence Livermore National Laboratory (Directorate of Chemistry and Materials Science and NIF design) and University of Berkeley (USA), SCK-CEN Mol (Belgium), Edf and CEA (France), University of Cagliari (Italy) and namely with Departamento de Física Aplicada of Universidad de Alicante and CIEMAT (Spain). DENIM is actively in MM for Fusion through European Fusion Development Agreement (EFDA), EFDA Technology Work Programme 2003 / Field: tritium Breeding and Materials / Area: Materials Development / Multiscale Modeling / Structural Materials: Modelling of irradiation effect, in years 2003 and 2004 through the Association CIEMAT/EURATOM for Fusion. Key microscopic parameters (by own DENIM models Molecular Dynamics, MD) that identify the effect of irradiation, new defects formation, are being generated for some specific metallic materials (Fe, binary alloys FeCr, FeCu, V...) and their diffusion conducted by MonteCarlo. Next step is being their interaction with dislocations (Dislocation Dynamics) and study of nucleation in the presence of He. The effect of He in FeCr alloys is also being pursued in a collaboration with Departamento Física Aplicada of Universidad de Alicante. We also derive macroscopic magnitudes using small scale MM models in short simulation times by using MD defect-dislocation studies under stress. DENIM modelled pulse radiation damage, and we have make progresses in the microscopic validation of Multiscale Modelling with experiments using pure and ultra-high pure Fe through the Simulation-Experimental Program in collaboration with CIEMAT named VENUS-II, that will follow 2004-2007 by REVE Spanish Project, and European Union / EURATOM Integrated Project PERFECT (6 Framework Program).

Our work is also being concentrated in two IFE key materials (SiO_2<>optics, SiC<>low activation advanced material). A molecular dynamics *tight binding* scheme has been fully developed for ß-SiC to understand the microscopic phenomena of the native defects and its diffusion at different temperatures. The knowledge of the migration energies at different temperatures allow to determine the diffusion coefficients D (Temperature). We reach an extraordinary good agreement among our calculated defects energetic and those results obtained using sophisticated and expensive method such as *ab-initio* At 2000K, we can observe how the ß-SiC crystal remains perfect with its typical cubic structure. We have shown that the carbon atoms does not diffuse into the crystal; the self-interstitial silicon atom prefers the relation with atoms of the same specie due to the effect that the repulsive force of the silicon atoms is larger than the repulsive forces of the carbon atoms. We are giving results on the other potential interstitial types into SiC. All simulations are carried out at 1800, 2000 and 2200 K with small simulation boxes of 65 atoms. Molecular dynamics is being used to study the defects produced in fused silica by energetic atoms, neutron and gamma irradiation. We determine the structure factor, the bond angle distribution, coordination and ring statistics, and we compare with results from experiments concluding that our results are in good agreement with measurement of fused silica glass. Threshold displacement energies have been computed as a function of the direction of movement of PKA, and cascades of 5 keV are being actually extended to 10 keV. Two modeling-experimental programs have been started in 2004 with CIEMAT for Silica analysis, which will be extended in the future to Alumina and other materials of first wall and ceramics insulators.

TRITIUM ENVIRONMENTAL ANALYSIS

A large and completely new work has been performed in the analysis of consequences of tritium release according with expected source emission from IFE Conceptual Reactors and others nuclear systems when considering all the chemical forms of tritium (HT and HTO) and their conversion to Organically Bound Tritiium (OBT) with soil processes and consequences of re-emission to atmosphere. The effect and consideration on primary and secondary (The secondary phase begins once the impoverishment of the tritium concentration takes place in the primary plume and the tritium is deposited in the soil and leaves of the vegetables. We report several important conclusions for the following processes) phases of tritium transport in the environment with final consideration of different time-dependent phases in dosimetry is a new approach that allows a more realistic and surprising more restrictive limit in tritium handling as classically assumed in conceptual systems. This methodology has also been successfully used in work for establishing Vandellós site for ITER under Contract with EFDA. The whole study of this phase drives to the conclusion that the behaviour of the tritium should be simulated using two well differentiated studies: deterministic and probabilistic. Deterministic calculations are based on a fixed meteorological data given ''a priori'', where the speed and directionality of the wind, class of atmospheric stability and rain intensity, as well as the boundary conditions of the means that surround to the atmospheric discharge (soil type, humidity of the air, temperature and solar intensity) are given. The probabilistic study is based on measured real meteorological analysis every hour, and the probability that individuals can present dose for internal irradiation of the tritium is considered. Our conclusion is that these probabilistic studies provide the real dynamics of the processes, which are different from deterministic case.

SAFETY AND ENVIRONMENTAL (S&E) ISSUES

In the field of computational modelling for S&E analysis our main contribution refers to the computational system ACAB that is able to compute the inventory evolution as well as a number of related inventory response functions useful for safety and waste management assessments. The ACAB system has been used by Lawrence Livermore National Laboratory (LLNL) for the activation calculation of the National Ignition Facility (NIF) design as well as for most of the activation calculations, S&E studies of the HYLIFE-II and Sombrero IFE power plants. The last two capabilities implemented in ACAB allows to model the different pulsed activation regimes present in all the different kind of inertial confinement fusion devices (ranging from test/experimental facilities to fusion energy power plants), and compute uncertainties on activation calculations due to cross section uncertainties: the sensitivity-uncertainty approach able to deal with the uncertainty of each of the reaction cross sections separately, and the Monte Carlo-based methodology dealing with the synergetic/global effect of the complete set of cross-sections uncertainties are implemented. In establishing an updated methodology for IFE safety analysis, we have also introduced time heat transfer (CHEMCON code) and thermal-hydraulics (MELCOR code) calculations to obtain better estimates of radionuclide release fractions. Off-site doses and health effects are dealt with by using MACSS2 and developing an appropriate methodology to generate dose conversion factor (DCF) for a number of significant radionuclides unable to be dealt with the current MACSS2 system. The activation code ACAB using as input the DCF library and the release fraction information provides the dose to the most exposed individual, population dose, early fatalities, and cancer fatalities.

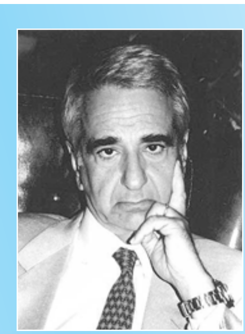
We performed LOCA and LOFA analyses for the HYLIFE-II design. It was demonstrated the inherent radiological safety of HYLIFE-II design relative to the use of flibe. Assuming typical weather conditions, total off-site doses would result below the 10-mSv limit. The dominant dose comes from the tritium in HTO form. In the Sombrero design, a severe accident consisting of a total LOFA with simultaneous LOVA was analyzed. Key safety issues are the tritium retention in the C/C composite, and the oxidation of graphite with air that should be prevented. The activation products from the Xe gas in the chamber are the most contributing source to the final dose leading to 47 mSv. We also analyzed the radiological consequences and the chemical toxicity effects of accidental releases associated to the use of beryllium, mercury and lead, as IFE materials under a HYLIFE-II framework scenario. For the tree material analyzed, the chemical safety requirements dominate strongly over radiological considerations. Also, the role of clearance as waste management option for HYLIFE-II was explored. For the confinement building, which dominates the total volume of the waste stream, all the material could be released from regulatory control for unconditional re-use after about one year of cooling following plant-shutdown. We also explored liquid wall options for tritium-lean fast ignition IFE power plants. Many single, binary, and ternary molten-salts were evaluated for their S&E characteristics, as well as for the required pumping power. In analyzing the impact of cross section uncertainties on the contact dose rate from the activated concrete-gunite outer shell of the NIF reaction chamber, it is shown that current cross sections allows a reasonably confidence in the results. Regarding IFE, uncertainties in the prediction of the neutron induced long-lived activity in all the natural elements shown that for the HYLIFE vessel a significant error is estimated in the activation of several elements, while the estimated errors in the Sombrero case are much less important.

EUROPEAN COLLABORATION AND EXPERIMENTS CARRIED OUT AT LARGE SCALE EUROPEAN FACILITIES

Interpretation of experiments done at LULI (Ecole Polytechnique) during 2003 supported by the European Union and by the CEA (France). This includes discussions and preparation of papers for Physics Review and JQRTS in collaboration with LULI, Universitie Paris-VI. (France), Universidad de Las Palmas de Gran Canaria, UNED (Spain) and University of Nevada. Reno (United States).

New experiments has been proposed in the new LULI-2000 installation for the study of new spectroscopic techniques of hot and dense plasmas.

With the collaboration of Professors J.M. Aragonés, C. Ahnert, P. Velarde, F. Ogando, E. Mínguez, J.M. Martínez-Val, M. Piera, P.T. León, J.M. Perlado, M. Velarde, J. Sanz, O. Cabellos and N. Carpintero.



Guillermo VELARDE

In 1956 he began to work in the Theoretical Physics Division of the Spanish Atomic Energy Commission (JEN) until 1981 as Director of Technology. Between 1957 and 1963 he studied nuclear energy at the Pennsylvania State University and Argonne National Laboratory, and afterwards he worked in Atomics Internacional, Ca. In 1973 he got the tenure of Professor Chair of Nuclear Physics at the Polytechnical University of Madrid. In 1981 he created the Institute of Nuclear Fusion. He is co-editor of 6 international books on inertial fusion and author of the book Quantum Mechanics published by McGraw-Hill in 2002. He has published 290 papers and has been member of scientific committees in 50 international conferences, being General Chairman and organizer of 6 of them. Since 1998 he is Chairman of the IFE Coordinating Committee-Technical Group of the European Union.
He is General of Division of the Air Force.
In 1997 he was granted with the Edward Teller International Award in recognition to his research on inertial confinement fusion and in 1998 he received the Archie A. Harms Prize for the development of emerging systems on nuclear energy.