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ITALIAN PROGRESS ON LWR FUEL DESIGN, MANUFACTURING, TESTING AND MANAGEMENT

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INTRODUCTION

The activities carried out in Italy since the last Geneva Conference (1971) for the design, fabrication, testing and management of LWR fuel aimed on one hand at gaining wide knowledge (not only through licensing agreements, but also through significant independent development both in the field of design methods and of fabrication and materials technology), and on the other hand at industrial type accomplishments,which have permitted the enlargement of the acquired experience.

The operation of ENEL (Ente Nazionale per l'Energia Elettrica)Trino Vercellese 270-MWe PWR and Garigliano 160 MWe BWR stations led to the acquisition of highly significant experience, also because the information directly obtained from the normal operating activities were supplemented by specific ad-hoc tests and follow-up programs.

The activities were related to the reloads for the two reactors already in operation and the first core of the Caorso reactor (ENEL IV) and will go on with the reload for the Caorso station, plus the fuel for the four newly ordered stations.

At present the GE license for BWRs is held by AMN-Impianti Termici e Nucleari, whilst the activities relating to PWRs are carried out by BREDA and FIAT, licensees of Westinghouse.

The two groups are responsible for the supply of the initial loads, included in the order for the nuclear island.

As a part of its involvement in the nuclear fuel cycle, AGIP Nucleare (AGN) is concerned with the reload supply to all reactor systems: to this purpose it has been granted up to now a GE license for BWR reload fuel supply. At present, the fabrication of reload fuel for BWRs and PWRs is performed by FN (Fabbricazioni Nucleari) (with AGN as a major shareholder) and COREN respectively.

The research and development activities have been performed by the aforesaid companies and by ENEL, both independently and in cooperation with research institutes, particularly with the Comitato Nazionale per l'Energia Nucleare (CNEN). In this connection, CNEN and AMN-Impianti Termici e Nucleari formed a company called NUCLITAL to broaden their knowledge of BWR cores.

A similar cooperation on the development of PWR Cores is on the way of accomplishment between CNEN and SIGEN, a company formed by Breda Termomeccanica and FIAT.

A specific Cooperative Agreement was set-up between CNEN and ENEL for the evaluation of the fuel behaviour in the ENEL reactors.

Finally it is worthwhile to mention an Agreement executed by the Italian Government and the European Economic

Community for the utilization of the ESSOR reactor as a test facility for fuel, both in nominal conditions and in transient and accident conditions; to this purpose, irradiation test loops are being built which reproduce conditions of interest. After the completion of these loops, a valuable tool will become available to test fuel assemblies on a large scale so as to achieve a wider knowledge of fuel assembly mechanisms of failure and behaviour.

DESIGN AND ENGINEERING

The design of the initial load for Caorso power station (ENEL IV) and some reloads of the Garigliano and Caorso power stations was entrusted to the Joint Venture GETSCO and AMN-Impianti Termici e Nucleari.

In this connection, AMN personnel cooperated in the activities carried out at General Electric's facilities.Since 1975 AMN has been assisted by NUCLITAL, a consortium formed by AMN and CNEN.

For the initial load of ENEL VI and ENEL VIII power stations equipped with BWR, AMN will partecipate directly in the design of the core and fuel assembly, while NUCLITAL will be encharged with all development activities.

In this connection AMN and NUCLITAL are carrying out the preparatory actions associated with the future commissioning test of Caorso BWR, and with the interpretation of the related data that will be obtained.

AMN and NUCLITAL have a staff for core and fuel design of about a hundred qualified engineers and more than 130 calcolation codes in operation; most of the engineers had a long training at GE.

Recently AMN and G.E. have achieved an accord to further strengthen the BWR technology through a new technology development agreement;NUCLITAL will carry out all core and fuel technical activities of this agreement.

Besider the experience acquired with the program for the design and development of a core for naval applications and with the fabrication (in cooperation with AEG), of fuel assemblies of the second core of the Otto Hahn nuclear ship, FIAT carried out studies and analyses on the core of the Trino Vercellese station, both in steady-state and transient conditions in view of the possible replacement of the SS cladding with Zircaloy.

BREDA TERMOMECCANICA and FIAT will partecipate through their associated SOPREN S.p.A. in the nuclear, thermohydraulic and mechanical design of the fuel for the PWR stations (ENEL V and ENEL VII).

In the prospect of a sole supplier of the reloads for all the power reactors, AGIP Nucleare has specifically set up its organization and resources so as to be in a condition to supply BWR reload fuel with all the pertinent warranties from 1979 onwards.

The calculation methods and codes used by the above-mentioned companies for the nuclear fuel design and by ENEL in the area of core management were set up and verified on the basis of the results of the experimental activities, which will be dealt with in the following chapter.

RESEARCH AND DEVELOPMENT

The research activities carried out in Italy in the past few years on light-water reactor fuel have been expanded significantly to gradually widen the knowledge of the fuel behaviour and thus permit the independent development of the whole area of design and fabrication techniques, including materials performance, as well as core management and safety problems.

In this connection, two parallel lines are being followed, the first aiming at developing provisional models to be used as tools for core performance evaluation and the second aiming at taking full cognizance of fuel design techniques. As regards the former line, great efforts have been made by CNEN, particularly with ENEL under the aforesaid Cooperation Agreement.

Three main areas of interest were developed 1) neutronics and core management; 2) thermohydraulic analysis of the whole core and of the sub-assembly, with specific interest on the assessment of margins against burn-out; 3) thermomechanical behaviour of fuel pins and mechanical design of fuel assemblies, with specific interest on spacer grids; 4) equipment for on-site NDT of irradiated fuel.

Sources of information on these items were: test on prototype fuel assemblies and rods (out and in-pile experiments, and post irradiation examinations) including "ad hoc" experiments on fuel assembly of the ENEL power reactors so as to fully exploit the information on fuel behaviour available to the utility from operation (i.e.gamma scanning for power distribution, NDT examination and specific post-irradiations examinations in hot cells).

The out-of-pile experiments on test fuel have consisted of: critical experiments to check neutronics codes for both reactivity and power distribution evaluations also in the presence of Gd and Pu [1] , thermohydraulic tests including burn-out experiments for BWR conditions with different axial shapes performed at CISE to assess the CPR approach to burn-out margin analysis and tests on turbolent mixing performed at Studsvik laboratory ; pressure drop measurements on different types of spacer grids; analysis of vibrating modes and amplitudes of fuel assemblies in different environments and with various flow conditions.

Irradiation experiments, besides several Halden assemblies, including critical over ramp tests, consist of sixteen prototype assemblies for the Garigliano Plutonium Demonstration Program and three assemblies irradiated respectively in the Agesta (one) and Kahl (two) reactors. Moreover, Gd-poisoned, U and Pu fueled pins were irradiated in the Siloè reactor.

Extensive post-irradiation examinations performed on fuel pins from the assemblies mentioned above have not only confirmed the expected performance of the fuel [2] but also given very interesting data on burn-up predictions [3] , fission gas release at high burn-up, gadolinium depletion rate, variation of cladding mechanical properties vs irradiation, fission product and plutonium migration and so on.

Besides, fuel thermal conductivity, gap conductance, dimensional variations, cracking, relocation and densification have been investigated by means of instrumented rigs in several European reactors as ESSOR (Ispra), SILOE' (Grenoble), HBWR (Halden), R2 (Studsvik), as well as by means of out-of-pile apparatus and hot cell equipment in the Italian nuclear centers.

The following results are an example of feedback into calculational methods from experiments:

- Updating of the computation techniques for the core management of light water reactors, with particular reference to fuel assemblies containing a burnable poison, and including the evaluation of the thermohydraulic parameters of the core and fuel assembly, and the thermomechanical analysis of the fuel rods.
- The development of a prototype set-up to perform the non-destructive measurements on irradiated fuel in the fuel pond of the stations, on the basis of experience acquired by ENEL in this field. Goals of the design were reliability and accuracy of measurements, reduction in measuring time, and personnel exposure as well as no interference with refueling operation [4]
- A sub-channel analysis is no longer necessary for BWR burn-out predictions in case of standard local power distribution.

The research activities carried out by AMN-Impianti Termici e Nucleari and by Consortium NUCLITAL concern the widening of the knowledge of BWR fuel design. In particular, the following aspects are being examined:

a) Neutronics - Correlation analysis between LPRM signals and fuel assembly power distributions, U-Gd (1%-6%) fuel depletion experiments vs burn-up, analysis of critical tests carried out in the Kritz facility on BWR/6 configurations, and dynamic and ATWSstudies;

b) Thermohydraulics and safety - Code development for operational transients and accident conditions, design correlation development based on full-scale experiments related to the CPR (critical power ratio), subchannel coolant mixing, operational transients and experimental activities on the LOCA (Loss of cooling accident) and ECCS (Emergency core cooling sistem) for which a new test facility is planned.
c) Thermomechanics - In-pile and out-of-pile experiments on fuel cladding creep-out and creep-down at nominal and high temperatures, measurements of axial and radial deformations on BWR/6 fuel rods under irradiation, fuel rod power ramp test analysis, Zircaloy channel creep investigation, fuel bundle design verification under seismic and blowdown conditions and preconditioning studies.

The PWR fuel design techniques have been developed by FIAT that concentrated its efforts on three basic aims: acquisition of the necessary knowledge and experience for the nuclear, mechanical and thermohydraulic design, acquisition of the know-how for the various technological phases of the fabrication process, and systematical application of the methods and techniques of Q.A. BREDA TERMOMECCANICA and FIAT are planning to perform this type of activity in the future through their associated company SOPREN.

Within the framework of a joint research program with Euratom, a fuel assembly of the type used in nuclear power stations such as Trino Vercellese, consisting of a SS sheath with Zr-clad fuel rods, has been developed and fabricated by FIAT. The grid constraints to the external sheath are arranged so as to prevent the latter from collapsing following a differential thermal expansion of the steel and of the Zircaloy at the operating temperature.

Furthermore, equipment and processes suited to commercial fabrication of these assemblies have been studied.

The development activities of AGIP Nucleare have been carried out with the support of its laboratories, where the most important steps of the fabrication process, the control procedures and the mechanical tests on materials and components can be performed under controlled conditions. These activities have been mainly devoted to the following areas that are largely for fuels of different reactor systems:

- fuel rod performance under operating and transient conditions
- sintering and densification behaviour of fuel pellets
- creep collapse of Zircaloy tubing
- basic materials properties and technology development.

FABRICATION

Two enterprises have been undertaken in the field of nuclear fuel fabrication concerning the fuel for BWRs and PWRs. The magnitude of the efforts for BWRs was greater as a result of the construction of the 850-MWe BWR at Caorso (ENEL IV).

For the fabrication of fuel for boiling water reactors, Fabbricazioni Nucleari was created in 1967 by General Electric and AMN - Impianti Termici e Nucleari. Construction of the factory started in March 1972 over an area of 200,000 m^2. Production started two years later, namely in May 1974.

AGIP Nucleare first became a minority shareholder and then replaced General Electric in the partnership.The present shareholding is 85% to AGIP Nucleare and 15% to AMN-Impianti Termici e Nucleari.

FN has acquired fabrication experience with Garigliano last two reloads (4th and 5th) and the first core for Caorso. FN's plant handles the whole fabrication cycle starting from the UO_2 powder. Conversion of UF_6 to UO_2 in situ will be handled in the near future. The plant can handle fuel with a maximum enrichment of 4%.

The plant throughput is 200 tonnes/year, but provisions have been made for enlargement of the critical components of the plant to a throughput of 500 tonnes/year.

Seventy percent of the equipment was designed and manufactured in Italy. The plant design incorporated innovations over pre-existing plants which have proved satisfactory over more than one year of operation.

With General Electric's advisory assistance, FN has set up a comprehensive system of procedures covering all the operations related to quality assurance during fabrication, from supplier qualification to field inspection upon delivery. These procedures were followed both for the fourth Garigliano reload and for the Caorso first core. Since General Electric's withdrawal from the partnership, the responsibility for fabrication and quality control lies with the Italian industry; however, General Electric still supplies consulting services under the licensing agreement.

The fourth Garigliano reload comprised forty-six assemblies in an 8x8 array of the "plutonium-island" type. The thirty-one mixed-oxide rods per assembly were only assembled by FN, and the operation had to be performed in a special room having the features of a controlled area, because of the presence of plutonium. The dose absorbed by the personnel during the forty-five days required for this operation was 0.12 rem per person (versus the 0.625 rem/ person allowed). The transport of the plutonium rods from

Belgonucleaire's fabrication plant and the shipment of the final assemblies to the power station have not given rise to any particular problems.

FN then fabricated the 560 UO_2 assemblies for the first core of the Caorso reactor. At present, FN is fabricating the fifth reload of UO_2 enriched assemblies for the Garigliano reactor.

As concerns PWR fuel, Breda, FIAT, and Westinghouse, created in 1967 the COREN Company,which started immediately its activities by assembling the fuel bundles for the first reload of the Trino Vercellese PWR in 1968. Then COREN has supplied all subsequent reloads, including also rod fabrication. The manufacture of all mechanical components has been performed by FIAT.

Further steps have not been taken so far because the present workload (12 tonnes of uranium every 14-15 months) is not large enough to render pelletization a profitable proposition. Nor is it conceivable to install a pilot plant considering that the pelletization technology is by now well proven and established and that other organizations are engaged in research and development.

The fabrication effort was conditioned by the moderate size of the internal market, consisting so far of the supplies for only one reactor of medium rating (270 MWe). Orders for initial charge and 8 reloads for ENEL V and VII have been placed to COREN in 1974, but the fabrication schedule is not yet defined, pending decisions on the locations of the stations.

The policy followed has therefore been cautious by securing the structures required to fulfil the existing orders avoiding in the meantime a not sound and anti-economical factory operation. However, the efforts have been continued and the bases are now laid down for the short-term fulfilment of fairly sizeable orders.

Since vertical expansion was not justified for the reasons given above, COREN has not overlooked any opportunity for horizontal expansion in respect of collateral aspects very important to the fabrication process. In fact, major efforts have been devoted to quality control, personnel qualification and supplier qualification.

The organization set up for quality control conforms with the American standards universally accepted for nuclear plant manufacture. To avoid getting operation in the red, rather than using the manpower in unprofitable jobs during low-load periods, it is transferred to other departments when fuel fabrication is completed. This makes it necessary to train new operators for each fabrication campaign,as the same persons are not always available. The training courses are held by supervisors who have been trained in Westinghouse shops during low-load periods in all the stages of the fuel fabrication process, including pelletization.

On the basis of the acquired experience and of the development programs on hand, it will be possible to enlarge the facilities and outfit them to handle the supplies required for the PWRs included in ENEL's plant construction program.

CORE MANAGEMENT

As a whole, the operating experience with ENEL's LWR fuel proved satisfactory.

Only seven out of the 228 fuel assemblies of the Garigliano first core, including the spares , have shown suspected leaks (sipping). These assemblies produced 15,700 MWd/t on an average, though they had originally been designed for 13,200 MWd/t. The residence time in the reactor for some assemblies totalled about 10 years. The highly satisfactory behaviour of the Garigliano first core may be attributed to both the low linear heat loads (max. 8-9 kW/ft) and to the type of the fuel. Each rod consists of four segments about 70 cm long, which minimizes the possibility of ratcheting because of pellet-clad interaction.

The reload assemblies, inserted since 1968 form four batches of sixty assemblies each. The failed assemblies are listed in the Table, which also indicates the operating cycles before the detection of the damage.

Table

Reload	One cycle	Two cycles	Three cycles	Total of failed assemblies
First	4	5	zero	9
Second	9	13	not applic.	22
Third	zero	not applic.	not applic.	zero

It should be pointed out that the third batch performed very satisfactorily in the only cycle in which it resided in the reactor; the good behaviour may partially be justified by a greater care in load variation, mainly at startup,and by improved fabrication techniques.

No failures have been located in the sixteen plutonium prototype assemblies of the 1st and 2nd reloads. Operation with the 46 reload fuel assemblies inserted in 1975 has been very smooth so far.

In the Trino Vercellese reactor, whose core is stainless-steel clad, no damages have been detected so far, though the core has long attained the equilibrium burn-up (30,000 MWd/t after three residence cycles); therefore, the experience with the SS fuel at Trino is outstanding.

In 1976 eight fuel assemblies with all-plutonium rods have been inserted in the Trino reactor; the fuel behaviour has been satisfactory.

Considerable experience has been gained in core management also because of the presence in the electrical network of two different types of LWRs that involved different operational problems. During this period there has been a shift in the relative importance of two conflicting ends of core management, namely, full and continued availability of the reactor capacity on the one hand, and the best exploitation of the energy content of the fuel on the other. The great increase in plant costs, the high expenditures incurred for replacement energy, the lowering of the operating limits (e.g. max power density) caused the former end to prevail.

In this connection the activity carried out by ENEL in the field of core performance evaluation is indispensable for the development of proper core management. This activity has mainly aimed at determining the actual operating limits of ENEL's stations, at ensuring that the fuel behaviour does not jeopardize the capacity, and at widening the knowledge of the actual nuclear steam supply system dynamic characteristics, including the control and protection systems.

ENEL gathered and processed data on fuel and core performance both separately and in conjunction with CNEN under the above-mentioned cooperation agreement.

These data were used to verify and improve the reliability of ENEL's integrated calculation system for core management [5] . The bulk of experimental data combined with adequate calculation tools enabled the operator to cope with the problems that arose during operation of the two stations with a fuller awareness of the capabilities and limitations of the nuclear system.

An example was the outage of one of the two recirculating pumps of the Garigliano reactor. On that occasion, an exhaustive thermohydraulic analysis was carried out, which was also based on the results of the high-void operation tests performed during the first operating cycle. It was thus possible to establish that the maximum power level at which the station could operate on one pump was 90% of rated, a value that is definitely higher than the limit initially set.

Another interesting example is the procedure adopted to cope with the lowering of the limit on the maximum linear power density of the two operating stations as a result of the recent regulations on the loss-of-coolant accident. In the case of the Garigliano station, the supplier was requested to design the fuel assembly so as to ensure a lower axial peak factor through the use of gadolinium on the one hand, and to facilitate heat removal during the heat-up phase following the loss-of-coolant accident, by means of a more appropriate fissile material distribution inside the assembly on the other.

As regards the Trino Vercellese reactor, the power distribution measurements on the assemblies performed through gamma scanning cycle by cycle permitted a partial compensation of the lower power density limit by reducing the uncertainty factor associated with the power distribution evaluation. A penalty on the power level was also avoided by providing operational procedures for load variation, which allow a limitation of the effects of the xenon axial redistribution and consequently of the increase in the axial power factor. The effect of this provision has been assessed on the basis of a theoretical analysis and of experimental data on the variation of the power axial forms measured during the first operating cycle encompassing a large number of situations. On the other hand, this limitation on the station operating flexibility is acceptable, since this station covers the basic load demand of the Italian electric network.

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