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Fifty years of nuclear corrosion in Europe: from the pioneer period to a safe and mature industry[1]

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The discovery of radioactivity by Pierre and Marie Curie at the beginning of the 20th century had wide ramifications leading to large advances and changes in areas as different as defence, medicine, etc., and energy production. Just after World War II, the military developments of nuclear submarines had important implications for power generation as they use Pressurised Water Reactors (PWR), first used in the US Nautilus submarine, which were to become the most widely used type in civil nuclear power. The first nuclear power plant was connected to the national power grid in Soviet Union, at Obninsk in 1954. It was a RBMK reactor type (a water-cooled reactor fuelled with natural uranium and with graphite moderator). This type of reactor has never been developed in the West as it was not considered as safe: the reactor that exploded in 1986 at Chernobyl was a RBMK… .

But back to the end of the 50s and the 60s, the nuclear power generation had a flying start, as shown in the timeline of the first industrial nuclear power plants (Fig. 1):

- In 1954, the UK Atomic Energy Authority (UKAEA) was set up for the development of nuclear technology and two years later, the Calder hall reactor was connected to the UK power grid. It was a Magnox prototype which is fuelled with unenriched uranium metal and used magnesium alloy as cladding material.
- In 1946, the Atomic Energy Commission initiated in USA a development program for nuclear power reactors which lead to the first power plant, a PWR, operated by a private company (the Dusquesne Light Company) in 1957 at Shippingport.
- In 1945 the Commissariat à l'Energie Atomique (CEA) is created in France and developed its own graphite-gas reactor (UNGC type) which used natural uranium and a fuel cladding made with magnesium-zirconium alloy. The first UNGC reactor to go on-line was G-2 in Marcoule in 1959.

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[1] This article was written for the EFC Series No. 52: Progress in corrosion - The first 50 years of the EFC, edited by P. McIntyre and J. Vogelsang, Maney Publishing, September 2009, Hardback, 240 pages, ISBN: 978 1 906540 34 0.

- First nuclear power reactors were implemented in many European countries as shown in figure 1: Germany, Belgium, Italy, Sweden, Spain, the Nederlands, Switzerland, Czechoslovakia, Bulgaria, Finland had nuclear power reactor(s) connected to the national grid before the end of the 70s.

During that pioneer period, the nuclear technology for peaceful purposes was largely developed. It was during these pioneer days for nuclear energy that the European Federation of Corrosion was created (1955). In Europe, the treaty establishing the European Atomic Energy Community (EURATOM) was signed in Rome in 1957 and started large scientific and technical exchanges and co-operations between the signed founding States (Belgium, France, Germany, Italy, Luxembourg, and the Netherlands). Materials issues were key points in nuclear technologies not only for nuclear power plants (NPP) but also for all the civil nuclear activities, from the uranium enrichment (UF_6 is quite aggressive) to the nuclear waste reprocessing where materials have to face nitric acid at high temperature and high concentration. International exchanges were important and mainly on EURATOM or bi-national bases. In 1965, Professor Dieter Behrens (Dechema, Germany) asked Henri Coriou, Head of the "Corrosion department" at the CEA, to create the Working Party (WP) 4 on "Nuclear Corrosion" which was officially established in 1967 with 12 countries: Austria, Belgium, Denmark, France, Germany (Federal R.), Hungry, Italy, Nederland, United Kingdom, Spain, Sweden, Switzerland. EURATOM was associated to the WP (Fig. 2). During the twenty first years, the WP 4 was mainly organized like a "private club" with one meeting each year, with speeches on relevant items, free discussions and oral exchanges but no reports and no minutes. It could be noticed also that up to 1986, all the meetings of the WP 4 were in French (one of the 3 official languages of the EFC with English and German). Good food and good wines were generally provided by the host country of the meeting… . This was a good organization during that pioneer period, but, as shown on Fig. 3, the global nuclear capacity was increasing fast in Europe, Japan and the USA. During mid-eighties, the nuclear industry in these countries was becoming a mature industry. When Henry Coriou retired, Philippe Berge (EdF) was elected to chair the WP 4: during his chairmanship, nearly 10 years (1986-1994), he introduced, with Gérard Pinard-Legry (CEA) as Secretary of the WP, great changes which were in accordance with the new challenges of the nuclear industry: English became the exchange language inside the Working Party. Debates were opened to the scientific community. The WP was structured into nine main topics where corrosion played a major role: pressurized water reactors (PWR), boiling water reactors (BWR), fuel elements (cladding), high temperature reactors, liquid metal fast breeders, fusion reactors, reprocessing and waste management. It could be noticed that even today these topics are still very actual and important. During one of the first EUROCORRs, in Frankfurt (EUROCORR 1987), nuclear experts reported on the nine topics and decided that the WP 4 annual meeting will be during EUROCORRs. On the basis of their contributions, the first book of the EFC series (green book N°1) has been edited. It is significant of the dynamism of the WP 4 that this EFC series N°1 is a working party report on corrosion in the nuclear industry. The first workshop was held in Switzerland, at Handeck in 1991 on the "corrosion problems related to nuclear waste storage" and lead to the EFC series N°7 which was during ten years the main reference of researchers and engineers facing the long-term corrosion for nuclear waste management. The first session on nuclear corrosion occurred during EUROCORR 1992 in Espoo (Finland).

When François de Keroulas (EdF) was elected new chairman of the WP 4 in 1994 with Gérard Santarini (CEA) as Secretary, the Working Party had 140 members which were very active on the different matters related to nuclear corrosion. It was then decided in Nice (EUROCORR 1996) to have a session on nuclear corrosion during each EUROCORRs. The second workshop of the Working Party occurred ten years after the first one and was co-organized by Damien Féron (CEA) and Digby Macdonald (State University of Pennsylvania, USA) at the "maison d'hôtes" of the CEA centre of Cadarache in Provence (South of France), which is an old castle from the Middle Age and was the ideal location for the subject: "Prediction of long term corrosion behaviour in nuclear waste systems".

After the chairmanships of François de Keroulas (1994-2000) and of Jacques Daret (CEA, 2000-2002), Damien Féron (CEA) has been elected chairman of the Working Party during EUROCORR 2003 in Budapest with Yves Rouillon (EdF) as the Scientific Secretary (2000-2005), while Mylène Belgome (CEA) is acting as secretary since 2003. Nearly 30 years after its foundation, and nearly twenty years after the re-organization conducted by Philippe Berge, the revival of nuclear energy occurred in Europe, as shown, for instance, by the construction of two new European Prototype Reactors in Finland and in France, by the decision of building the ITER machine (fusion machine) in Cadarache (France), and, in the world, with the new deal of "Generation IV" (roadmap of ten nations preparing today the nuclear energy of tomorrow). These external evolutions of the nuclear environments lead the working party to adopt in Budapest (2003) an active three years plan in order to follow the nuclear "renaissance" which occurs at the beginning of this new millennium. The three main objectives are the following:

- To provide links between European teams and EU funded programs in nuclear corrosion field, with an opening on to the world.
- To initiate and stimulate opportunities of exchanges on scientific & technical subjects related to nuclear corrosion, particularly on today main nuclear research areas: waste systems, water reactors, generation IV and fusion reactors.
- To promote corrosion science and technical developments by events such as seminars, workshops, publications, etc.

Since the adoption of this plan, one or two WP meetings occurred each year: a spring meeting at the beginning of the year with only the WP 4 members and the fall meeting during EUROCORRs where everybody is welcome.

The relations between the EFC WP 4 and the OCDE/NEA (Nuclear Energy Agency) have to be underlined and contribute to the efficiency of the WP and to its reputation.

Publications have been also encouraged in the EFC series and also with other publishers, as shown in the Appendix where are listed the WP 4 sponsored publications. The objective to publish

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one book a year has been over passed. The website of the EFC include a subsidiary for the Working Party where are the announcements of new events, of new publications and also the minutes of our meetings.

From the pioneer period to the new age of nuclear energy at the beginning of this new millennium, the nuclear corrosion community had to face many challenges. In the earlier period, the selection of appropriate materials has been the major activity, as media were quite different from gaseous UF_6 for isotopic separation to concentrated nitric acid at high temperature for reprocessing plants. Perhaps at that time, water reactors were not supposed to have the most aggressive environments… . Nevertheless, corrosion in water reactors became rapidly one of the major concerns. Stress corrosion cracking (SCC) has been one of the main challenges since nearly the beginning of boiling water reactors (BWRs) and also for pressurized water reactors (PWRs). Even if the materials and the chemistries are not the same, the corrosion engineers and scientists succeed to mitigate these phenomena: extensive research efforts and collaborations have been needed to mitigate SCC. All types of commercial reactor experienced flow accelerated corrosion (FAC) which led also to large research and redevelopment programs and large collaborations in Europe and outside. Even if these phenomena are today under control, they are still are still major concerns for the life time life extension of nuclear power plants (NPPs).

The objective to extend the time life of many NPPs is an illustration of the generally good material selection and technological choices made by the nuclear community during the pioneer period. It is nevertheless one of the main challenges that the corrosion community has to face nowadays: it leads not only to have experimental data, but also to know the mechanisms of the corrosion phenomena. Two other major challenges may be identifying today: (i) the prediction of corrosion over millenniums for nuclear waste management which is a necessity for save waste storage and for the acceptability of nuclear energy by the people; (ii) the behaviour of materials at high temperature in gas, liquid metals or molten salts for the new reactors of “Generation IV”.

Nuclear power is part of the answer of the global energy challenge: to produce more energy while reducing CO_2 emissions. With its past experience, the EFC Working Party 4 “Nuclear Corrosion” may have the ambition to contribute to the success of this challenge.

One cannot close this short review of the activities of the 40 years old Working Party, without expressing our gratitude to all its past and present members, who have achieved a remarkable progress in the field corrosion in the nuclear technology. This was done in a perfect and friendly sense of international cooperation, where no room for personal or national interest took place.

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Appendix: Books published under the authority of the EFC WP 4 *(as of 2007)*

In the EFC series (published or planned):

1. EFC series N°1 "Corrosion in the nuclear industry" - 1989
2. EFC series N°7 "Corrosion problems related to nuclear waste disposal" -1991
3. EFC series N°36 "Prediction of long term corrosion behaviour in nuclear waste systems" - 2002
4. EFC N°48 "Corrosion of metallic heritage artefacts: investigation, conservation and prediction for long term behaviour" - 2007
5. EFC N°49 "Electrochemistry in light water reactors: focus on reference electrodes, measurements, corrosion and tribocorrosion issues" - 2007
6. EFC N°51 "Corrosion issues in light water reactors: stress corrosion cracking"- 2007

In other series:

1. Proceedings of the second workshop "Prediction of long term corrosion behaviour in nuclear waste systems" (ISBN 2-95-10108-6-9), published by ANDRA - 2005
2. Proceedings of the workshop on " Corrosion and long term performance of reinforced concrete in nuclear power plants and waste facilities", Journal de Physique IV, N°136 – 2006

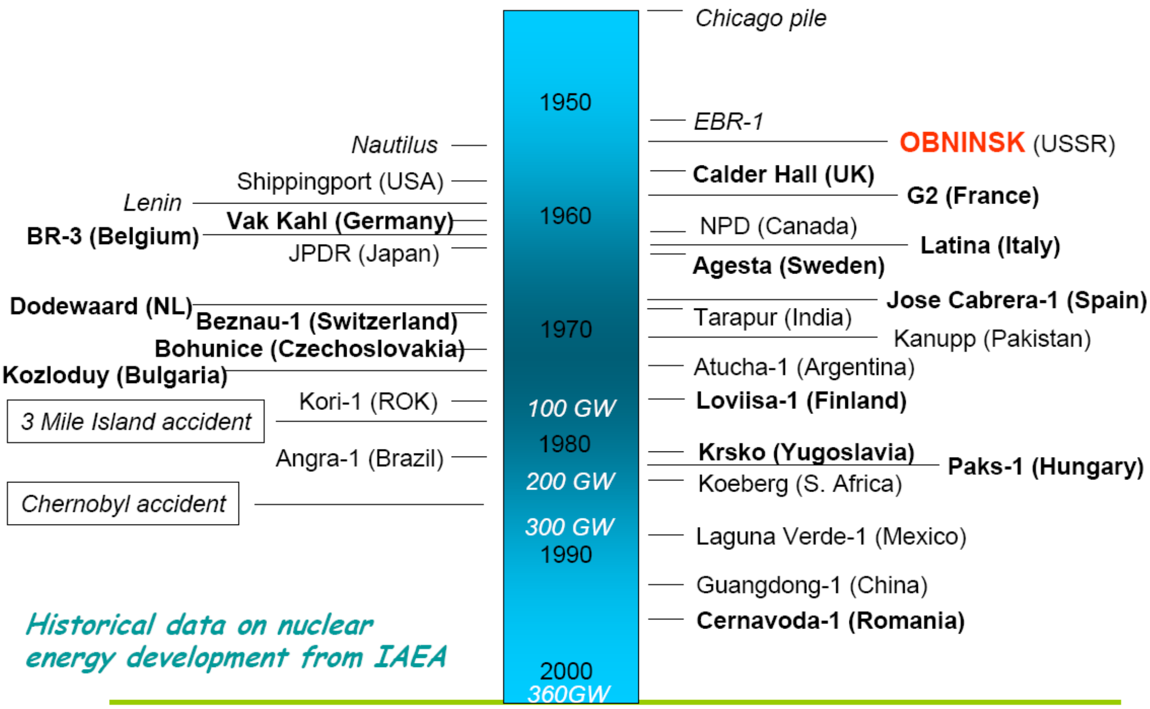

Figure 1: Timeline of the first industrial nuclear power plants (*in italics are main events: nuclear submarines and accidents*).

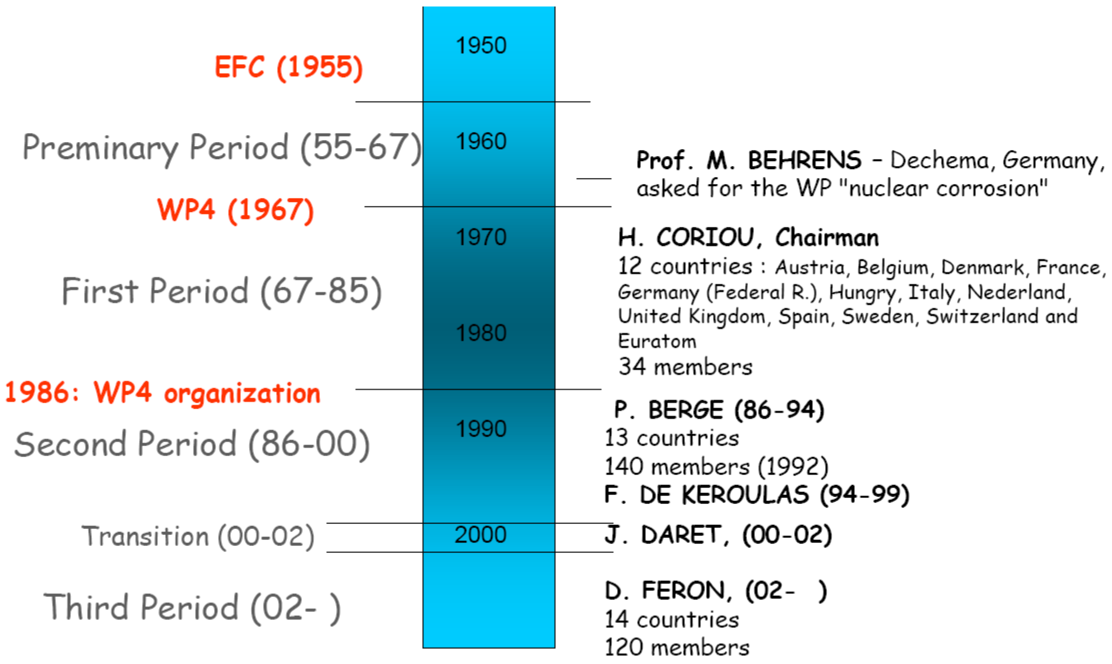

Figure 2: Timeline of the Working Party 4 Nuclear Corrosion, with chairmen periods.

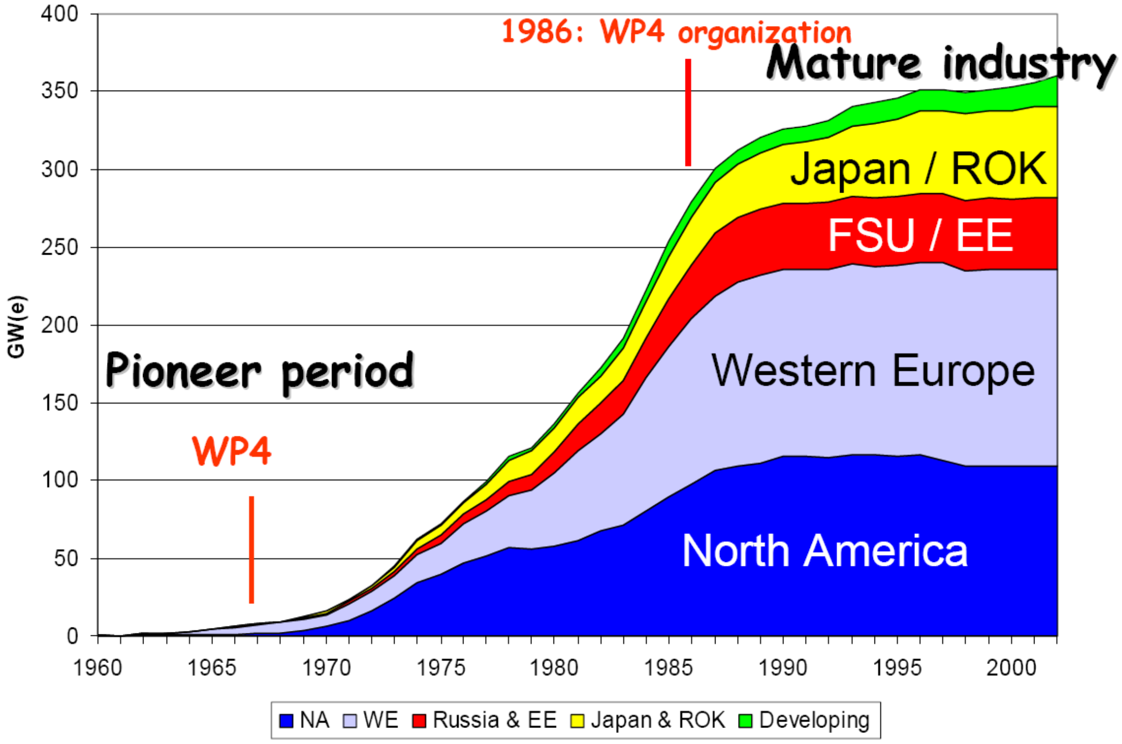

Figure 3: Evolution of the global nuclear capacity (data and curve from IAEA).

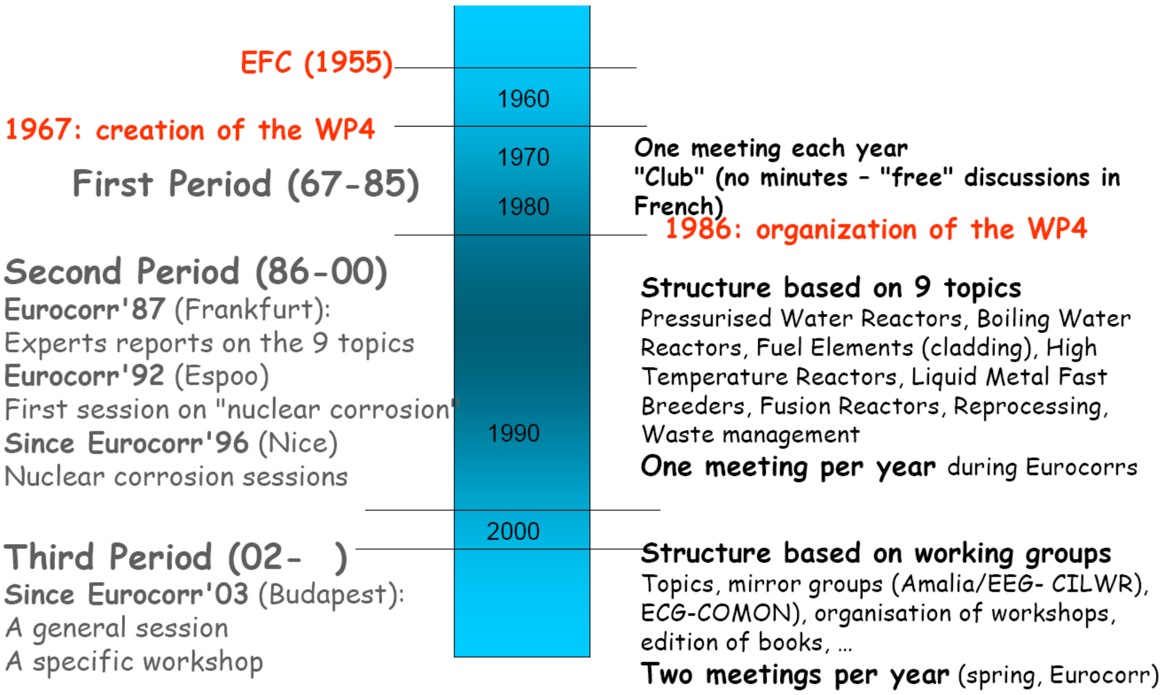

Figure 4: Evolutions of the organizations of the European Federation of Corrosion (EFC) and of the Working Partry on Nuclear Corrosion (WP 4).

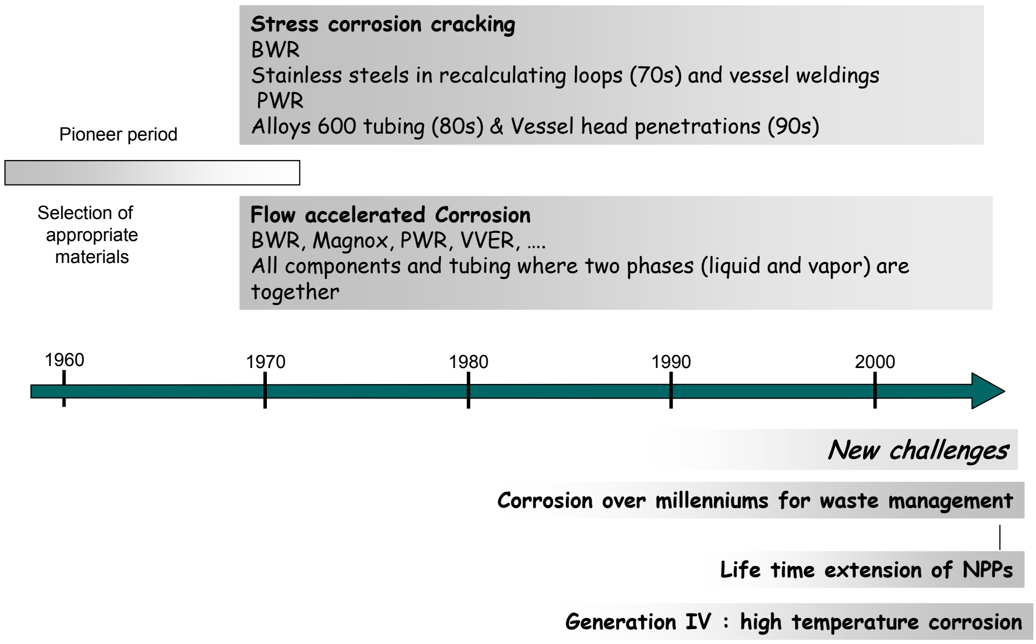

Figure 5: Main corrosion challenges faced these last 50 years in nuclear corrosion and future challenges.

EFC WP4 "NUCLEAR CORROSION" (AS OF 1 JANUARY 2017)

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