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Preparatory Study:

Nuclear Power Plant Ageing and Plant Life Extension (PLEX)

Report to Global2000, Vienna

Dr. Helmut Hirsch, Scientific Consultant

Hanover, February 2001

Content:

1. Introduction: What is Ageing, Where does Life Extension Begin?

In any industrial plant, material properties are deteriorating during operation due to the loads the components are subjected to. The International Atomic Energy Agency (IAEA) defines ageing as a continuous time-dependent loss of quality of materials, caused by the operating conditions[1].

Ageing processes are difficult to detect because they usually occur on the microscopic level of the inner structure of materials. They frequently become apparent only after a component failure, for example break of a pipe, has occurred.

Failure rates generally are high after start-up of a plant, when construction errors or design shortcomings become evident. In this phase, considerable efforts are usually undertaken to correct all problems, since there is a high economic incentive to achieve smooth plant operation as soon as possible.

During the 'middle age' of a plant, problems tend to be at a minimum. Later, as ageing processes demand their due, there will be a gradual increase of failure rates. This is a process which is not always easy to recognise and to follow, and which increases plant risk considerably. For a nuclear power plant, the ageing phase will begin after about 15 or 20 years of operation. Those, however, are rule-of-thumb numbers only and ageing phenomena can begin earlier.

As the world's nuclear power plant population gets older, there are efforts to play down the role of ageing. Those effort include conveniently narrowing of the definition of ageing. In a recent German study, ageing-related damages are limited to damages caused by unforeseen loads during operation, in spite of design and operation being in accordance with the requirements. Damages occurring after longer operation because design, manufacturing, commissioning or operation are not in accordance with requirements are not regarded as ageing-related[2].

On this basis, according to a recent study, only a small percentage of failures in German NPPs appears to be due to ageing. This restriction, however, is not acceptable. The restriction is artificial and arbitrary since it is not possible to completely avoid deviations from requirements in components of nuclear plants; their possibility always has to be taken into account during plant operation. On the other hand, failure to foresee a load in the design phase could well be regarded as a design error.

Thus, ageing will be understood in a comprehensive manner here, according to the IAEA definition quoted above.

There is also a certain lack of clarity regarding the definition of PLEX. This does not apply to the USA where operating licenses are granted for 40 years and life extension clearly begins after this time. In the UK, operating periods are likewise

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[1] Safety Aspects of Nuclear Power Plant Ageing; TECDOC-540, International Atomic Energy Agency, Vienna, 1990

[2] Liemersdorf, H. & F. Michel: Sensitivity of German NPPs to Ageing Phenomena; GRS/IPSN-Fachgespräch, Berlin, November 10, 1998

fixed (for example, originally 30 years for the Hinkley B AGRs). Similar rules apply in Russia and Eastern and Central European countries.

In many countries, on the other hand, operating licenses are not explicitly limited in their validity. Assumptions concerning the lifetime usually will be contained in the proof of safety for a nuclear power plant, giving, however, a considerable amount of flexibility.

In France, for example, 30 to 40 year appears to be have been generally recognised as the expected plant lifetime in the past; longer periods are now under consideration. The situation is similar, e.g., in Spain and Germany. In the latter country, there is a ceiling for the amount of electricity to be produced by each NPP, roughly corresponding to the commercial lifetime as generally envisaged. Amounts of electricity can be transferred, however, from older to newer plants, thus providing leeway for life extension.

The distinction between measures to make sure that the lifetime originally planned is reached, and measures aiming at prolonging the lifetime becomes indistinct in many countries – particularly so since the measures are basically the same in each case. This complication has to be well kept in mind.

It seems advisable to include ‘hidden’ life extension (i.e. measures which are to enable a plant to reach the lifetime originally envisaged, which could otherwise not be reached due to ageing phenomena, or, in cases where the original lifetime was not clearly defined, to reach the upper limit of the range of possible lifetimes) in the study of PLEX in general.

Another aspect which ought to be included in the study of PLEX is upgrading of NPPs. In many countries (e.g., Finland, Germany, Sweden, Spain), the output of nuclear power plants has been increased by hundreds of megawatts, by comparatively simple and inexpensive measures. The possibility of upgrading can significantly influence the economics of PLEX.

As nuclear power plants are being operated for decades, their design, quite apart from ageing, also becomes more and more obsolete. Reactor materials are developed further over the years, standards for containment are increasingly raised, the whole layout of the plant can become obsolete (as, for example, increasing degrees of physical separation are demanded). Furthermore, new results on possible seismic loads can lead to higher requirements regarding seismic safety, etc.

In some cases, obsolescence can be remedied by backfitting (if the financial means required are available). In other cases, for example regarding containment and protection against external events, the scope for backfitting is limited.

Obsolescence is an aspect quite distinct from ageing. It is not the main focus of this study. However, it should not be completely ignored in the context of PLEX and ageing hazards.

2. Main Areas of Nuclear Power Plant Ageing:

The influences leading to ageing processes in a nuclear power plant are[3]:

- Irradiation
- Thermal loads
- Mechanical loads
- Corrosive, abrasive and erosive processes
- Combinations and interactions of the processes mentioned above

Ageing can occur in many different manifestations, the most important ones being:

- Embrittlement of metals or organic materials (e.g. cable isolation)
- Stress corrosion cracking of steel components
- Erosion corrosion
- Change of electrical characteristics (e.g. by irradiation or thermal loads in electronic components)
- Mechanical or thermal material fatigue of metals, concrete and plastics

For exposed concrete, weather influences can also contribute to ageing.

Generally, ageing problems primarily concern passive components, i.e. components without movable parts.

Regarding active components like pumps and valves, deterioration usually manifests itself in a more obvious manner, and exchange of components can often be performed during regular maintenance work. Nevertheless, ageing of active components cannot be completely neglected as a risk factor.

There is no generally recognised procedure to determine the admissible lifetime of a nuclear power plant. Decisions are usually based on economic reasons as well as on general engineering practice.

Various individual ageing-related problems have been studied in some detail in the past. A number of mechanisms are known; nevertheless, they are not completely understood.

For example, the so-called dose rate effect in steel irradiation embrittlement has been known for years; but it still cannot described reliably and quantitatively today, giving rise to an increased risk of pressure vessel failure in older NPPs. Another problem not fully understood is the propagation of fatigue cracks in austenitic steel pipes.

All in all, it is clear that the global risk of a reactor accident grows significantly with the number of nuclear power plants which are in operation longer than about 20 years.

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[3] Meyer, N., D. Rieck & I. Tweer: Alterung in Kernkraftwerken; Greenpeace, Hamburg, 1996, revised version 1998

3. Countermeasures to Ageing – Plant Life Extension (PLEX):

As pointed out above, basically the same measures are required to counter non-anticipated ageing phenomena during the planned lifetime of an NPP, and to extend this lifetime.

When discussing countermeasures to ageing, a distinction has to be made between replaceable and non-replaceable components. There is a wide consensus among plant operators that in principle, all components crucial for safety can be replaced except two: The reactor pressure vessel (rpv), and the containment structure[4].

The reactor pressure vessel appears to be the component decisive for limiting a nuclear power plant's lifetime. Therefore, in recent years, investigations have been performed whether rpv replacement could not be possible after all. Siemens studied this option[5]; a feasibility study was also undertaken in Japan[6].

For the measures available, three levels can be distinguished:

- Exchange of components: This is often the only option in case of obvious shortcomings, leakages developing and other problems which directly influence the power plant operation. Even large components like steam generators and reactor pressure vessel heads can be exchanged.
  The costs of measures at this level usually are high.

- Reduction of loads: This applies primarily to the reactor pressure vessel where replacement is not an option. To avoid thermal shock, emergency cooling water can be preheated. To reduce neutron irradiation (and hence the progress of embrittlement), neutron fluency in the vessel wall can be reduced by putting dummy elements or highly burnt-up fuel elements in outer core positions. In principle, measures of this kind could also be applied to other components. Costs are moderate at this level.

- Reduce safety margins: By reducing conservatism in proofs of safety, longer lifetimes result – at least theoretically. Ageing effects in materials can be 'compensated' by more frequent examinations, on the optimistic assumption that cracks will be detected before they lead to catastrophic failure.
  The costs of such measures are usually relatively low.

The option to repair components has not been included here since repairs are largely part of the measures required regularly during plant operation anyway, independent of PLEX. One noteworthy exception is the annealing of reactor pressure vessels as practised in Eastern and Central Europe, a method to reduce embrittlement which is however questionable regarding the longer-term benefits, since there is no sufficient knowledge to date on the re-embrittlement behaviour of a vessel after annealing.

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[4] See, for example: Rapport sur le controle de la surété et de la securité des installations nucléaires; Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques, Séance Mercredi, 4 Mars 1998, www.senat.fr

[5] The decline of nuclear power; WISE News Communiqué 499/500, Amsterdam, October 10, 1998

[6] Daisuke, I.: A Feasibility Study on Nuclear Reactor Vessel Head Replacement; International Conference on Nuclear Engineering 7, Tokyo 1999, www.icone-conf.org

It is the tendency of NPP operators to remain at the two lower levels (reductions of load, and of safety margins). However, exchange of large components has been practised extensively whenever the remaining lifetime was sufficient to amortise the investment. For example, steam generators have been exchanged in nuclear power plants in most countries with NPPs with pressurised water reactors, and reactor vessel heads are being exchanged in France[7] and other countries.

Increasingly, on-site storage of spent fuel is practised or being implemented for lack of alternatives (in the USA, Germany, Central and Eastern European countries and others). In the countries concerned, a necessary precondition for PLEX, which has received very little attention so far, is the increase of storage capacity, leading to a corresponding increase of the radioactive inventory later.

Upgrading is an economically attractive option for NPP operators which usually goes largely unnoticed by the public. For example, Upgrading turbines and steam generators yielded an additional 4 % of nuclear generating capacity in Spain between 1995 and 1997; 7 % more are to be gained until 2004. Capacity was increased by 600 MWe in Sweden[8].

The output of the Finnish NPP Olkiluoto was boosted by 23 %[9]. In Germany, output of a number of plants was increased. For example, Brokdorf NPP increased capacity, in 1997, by 3.3 % by means of turbine modifications. An application to increase thermal reactor power by 2.26 % was rejected by the licensing authority[10].

4. Economic Aspects:

The economic evaluation of PLEX measures is complicated and depends on the concrete circumstances for each plant. In several studies, substantial benefits are described. For example, a US analyst recently claimed that the costs of PLEX for a US nuclear power plant are about 10 – 50 US$/kW, whereas construction of the cheapest non-nuclear alternatives would cost 325 – 405 US$/kW. Life extension of a coal fired power plant, for 20 more operating years, would cost 100 – 250 US$/kW[11]. New nuclear capacity would be considerably more expensive than all those options (far above 1000 US$/kW).

Russian authors, quoting US sources from the late eighties, reported considerably higher costs for PLEX measures: 125 – 300 US$/kW[12].

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[7] See footnote #4

[8] Varley, C. & J. Paffenbarger: Electricity Market Competition and Nuclear Power; Uranium Institute London, 1998, www.uilondon.org

[9] Plans for New Reactors Worldwide; Nuclear Issue Briefing Papier 19, Uranium Information Center Melbourne, January 2001, www.uic.com.au

[10] Jahrbuch der Atomwirtschaft; handelsblatt fachverlag/inforum verlag, Düsseldorf/Bonn, issues 1995 - 2000

[11] MacDougall, R.: US Nuclear Power – Can Competition Give It Renewed Life?; Numark Associates Inc., 1998, www.numarkassoc.com

[12] Baranenko, V.I. & V.A. Gashenko: The Problems of Extending the NPP Designed Service Life in the Russian Federation; Jahrestagung Kerntechnik, München, 26.-28. Mai 1998

French Industry Secretary Pierret, advocating life extension for French reactors, stated that each year of operation beyond the nominal 30 years-lifetime would bring a gain of 500 million FF (about 70 million US$)[13]. Compared to this, the cost of PLEX for one NPP according to the lowest estimate quoted above (10 – 15 million US$) appears to be more than reasonable; the highest estimate, however, corresponds to costs of 300 to 400 million US$ which represents a considerable investment which would not be worthwhile unless about two decades of additional operating time are guaranteed.

Taking into account that a complete steam generator replacement alone, for a four-loop PWR plant, costs about 165 million US$[14] (91 million US$ for a two-loop plant[15]), it seems plausible that the costs of PLEX measures will be closer to the higher estimates quoted above – if safety is given high priority and all practicable measures to counteract safety decreases due to ageing are in fact taken.

It is frequently emphasised that there are considerable uncertainties involved in PLEX. Safety and licensing problems can interact with economy in ways not anticipated by the applicant, as became apparent in case of the US lead plant Yankee Rowe, where a license renewal procedure ironically lead to premature shut-down. This gave rise to uncertainty among US reactor owners[16]. There is increasing optimism, however, since the first extensions were granted in spring 2000 (for Calvert Cliff and Oconee) and license renewal appears to be speeding up in the US[17].

The OECD Nuclear Energy Agency recognises this ambivalent situation by stating that *"major and expensive upgrades will be unlikely in competitive electricity markets."* Nevertheless, *"competitive electricity markets likely will increase the incentive for life extension and upgrades of nuclear power plants*."[18]

To sum up, PLEX (and upgrading) certainly are economically attractive if they can be performed cheaply ('PLEX light'). They can loose all attraction, however, if the whole spectrum of measures to counteract ageing is to be implemented, requiring large investments in a situation where the further economical and political development is difficult to predict.

5. The Scope for Life Extension:

Potentially, PLEX could be an interesting option for the operators of most nuclear power plants in the world. Indeed, it is seriously considered in all major countries operating nuclear power plants.

In the USA, as has been pointed out above, the first licenses for life extension have already been granted. Life extension (from 40 to 60 years) could be an attractive

[13] NucleonicsWeek Vol. 41, No. 47, November 23, 2000
[14] American Electric Power: 1999 Annual Report, Columbus, Ohio, 2000, www.aep.com
[15] News Release concerning Kewaunee Steam Generator Replacement, Public Service Commission of Wisconsin, July 2, 1998, www.psc.state.wi.us
[16] NucleonicsWeek Vol. 38, No. 50, December 11, 1997
[17] NucleonicsWeek Vol. 41, No. 38, September 21, 2000
[18] Nuclear Power in Competitive Electricity Markets; NEA-Report, 2000, www.nea.fr

option for the operators of up to 80 % of US nuclear power plants if it can be performed without major replacements.

In France, life extension is being studied with increasing emphasis. 'Hidden' life extension has already taken place insofar as officially, 40 years is quoted today as nominal plant lifetime[19], in contrast to the span of about 30 to 40 years usually given earlier. A recent study investigated two variants – 41 and 45 years. 50 – 60 years are regarded as achievable[20].

In Japan, an extensive research program an PLEX has been performed in the 90s[21]. A range of 40 – 70 years is regarded as confirmed life span[22]

In the UK, life extension has already been extensively practised. For example, the operating life of the reactors at Calder Hall and Chapel Cross was extended from 20 to 40 years[23], and of Hinkley B and Hunterstone from 30 to 35 years[24].

In Russia, life extension is being studied since 1992. Extension from 30 to 40 years is planned for all reactors, to avoid shutting down 8 plants until 2005, and 7 more between 2006 and 2010[25] [26].

Thus, in the five countries with about 2/3 of all the power reactors in the world (USA, France, Japan, UK and Russia), PLEX is actively pursued as an option and has already been implemented in some cases. The same holds for other countries with operating nuclear power plants, for example Sweden, Finland and several countries in Central and Eastern Europe.

The plans, recently announced, for life extension and power upgrade at Paks in Hungary (4 VVER units) even go beyond current plans in Russia since two variants for life extension are under consideration – from 30 to 40, or to 50 years[27].

In concluding, it can be assumed that PLEX certainly could be an option for more than half of the world's operating nuclear power plants, and perhaps for as many as 70 or 80 percent. Therefore, the risks associated with PLEX potentially could dominate nuclear power plant risks in the coming decades.

6. Available Independent Studies:

A certain number of studies has been performed by independent experts working for NGOs, regarding the problems and hazards of ageing.

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[19] A. Villemeur: Measures for Increasing Life Time; atomwirtschaft 45. Jg., Heft 1, Januar 2000, pp. 20-22
[20] See Footnote #4
[21] See, for example: Kosugiyama, S. & K. Takeuchi: Plant Life Management Activities in Japan; International Conference on Nuclear Engineering 7, Tokyo 1999, www.icone-conf.org
[22] See Footnote #9
[23] See Footnote #9
[24] NucleonicsWeek, Vol 40, No. 5, February 4, 1999
[25] See Footnote 12
[26] NucleonicsWeek, Vol. 42, No. 4, January 25, 2001
[27] NucleonicsWeek Vol. 42, No. 5, February 1, 2001

Most noteworthy is a report by three German experts for Greenpeace Germany which was compiled in 1996 and updated in 1998 (see Footnote #3). The problems of ageing are treated in-depth; however, the scope is restricted to the foremost ageing problems of metallic materials – rpv embrittlement, cracks in austenitic pipes (including steam generator tubes) and cracks in rpv heads.

A comprehensive, but very brief overview on ageing is given in another study of the early 90s[28]. Case studies of individual aspects of ageing have been performed by Pollard (Union of Concerned Scientists) in the mid-90s[29].

Furthermore, there is a considerable number of independent, critical studies on reactor hazards containing references to problems of ageing and obsolescence, for example, a recent German study dealing with safety problems of eight old German reactors[30].

All this work provides a good basis for further investigations into the problems of ageing and PLEX. However, there appears to be no comprehensive study of all aspects of ageing, and no detailed study of the hazards of life extension.

7. Focus for Future Work:

In view of the importance of the topic, and the lack of comprehensive, independent studies, further investigations are required, focusing on the following points:

1. The scope for ageing and PLEX should be investigated further – with the aim of a detailed identification of the nuclear power plants actually and potentially concerned world-wide, including 'hidden' PLEX. As far as practicable, the distinction between 'hidden' PLEX and backfitting should be elaborated and criteria for this distinction formulated.
   It is very likely, however, that this will be possible to a very limited degree only, since the measures for backfitting to reach to originally planned lifetime on the one hand, and for PLEX on the other had, are virtually the same in many cases and a distinction can be made on a plant-specific basis only.

2. One finding of this preparatory study was that PLEX is economically attractive, but only if implemented cheaply, setting economy before safety. This point should be investigated further in detail; the cost range in which PLEX is still attractive should be defined, taking into account country-specific factors (for the major countries). More detailed economic investigations could focus an the four technical issues listed below.

[28] Panten, Th., I. Tweer & H. Hirsch: The Game of Hazard; Greenpeace International, 1998
[29] Pollard, R.: US Nuclear Power Plants – Showing Their Age; three case studies, Union of Concerned Scientists, 1995
[30] Hirsch, H & O. Becker.: Atomstrom 2000: Sauber, sicher, alles im Griff? Aktuelle Probleme und Gefahren bei deutschen Atomkraftwerken; report for BUND (German section of FoE), Hanover, 1999

3. Given the technological and the economical limits to counteract ageing, the risks of PLEX, particularly if performed cheaply as ‘PLEX light’, should be investigated in detail, concentrating on the following issues:
   (a) Reactor pressure vessel embrittlement
   (b) Steam generators (particularly VVER reactors)
   (c) Containment (a crucial structure definitely not replaceable), including concrete ageing
   (d) Spent fuel storage – if on-site storage is implemented: Problems of large inventories accumulating during an extended lifetime
   The first two of those issues (rpvs and steam generators) have been subject to numerous studies by official institutions, which are, however, often not conservative and do not treat all details adequately. The third and forth issues (containment and spent fuel storage) have been generally neglected so far. Questions connected to obsolescence of older reactors (as distinct from ageing) should also be addressed in the context of those issues.

The role of upgrading reactor power in connection with PLEX should be included in the investigations wherever appropriate.

The points mentioned should be treated in a further study (‘main study’), starting from the results of this preparatory study and taking into account the independent work an ageing which has already been performed.

8. Resources Required for Main Study – Estimates:

The issues outlined above require in-depth study by competent experts. To use financial resources as efficiently as possible, it is advisable to install a small core group of nuclear experts doing most of the scientific work. This core group can call upon qualified consultants regarding special questions which require highly specialised competence, for example:

- Important country-specific issues

- Particularly involved technical and/or economic issues

This restriction to a small number of researchers, supported by consultants which are called upon in a well-aimed and specific manner, will permit to make the most of a budget which will of necessity be rather limited.

This core group could, for example, consist of the following four scientists:

- Dr. Ilse Tweer, scientific consultant, Buxtehude, Germany
  Dr. Tweer has been working on ageing problems of reactor materials for many years and is co-author of an important study on ageing (see Footnote #3).

- Dr. Gordon Thompson, Institute for Resource and Security Studies, Cambridge/Mass., USA.

Dr. Thompson is a recognised expert on reactor and spent fuel storage hazards with a profound knowledge of the US nuclear power situation.

- Dr. Helmut Hirsch, scientific consultant, Hanover, Germany
  The author of this preparatory study is a nuclear safety expert with extensive experience working both for NGOs and Governments, particularly as principal investigator and co-ordinator of complex studies.

- N.N., economist with experience in the fields of economic assessment of nuclear power, depreciation and amortisation of NPPs, financial reserves of NPP operators and other related topics.

The study could optimally be performed within 6 months from the date of confirmation of commissioning. The duration could be reduced, if necessary. The potential for reduction is limited, however, since the acquisition of information as well as the calling in of consultants necessarily requires certain lead times.

A comprehensive final report will be compiled, with a brief summary for the layperson.

The budget required would be about EUR 60,000,-- (plus VAT). This sum includes all costs of the study – the fees of the core group and the consultants, acquisition of information and travel costs for meetings and research, as well as all costs arising in connection with a presentation of the final report of the study to representatives of the commissioning organisations.