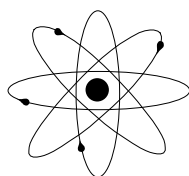
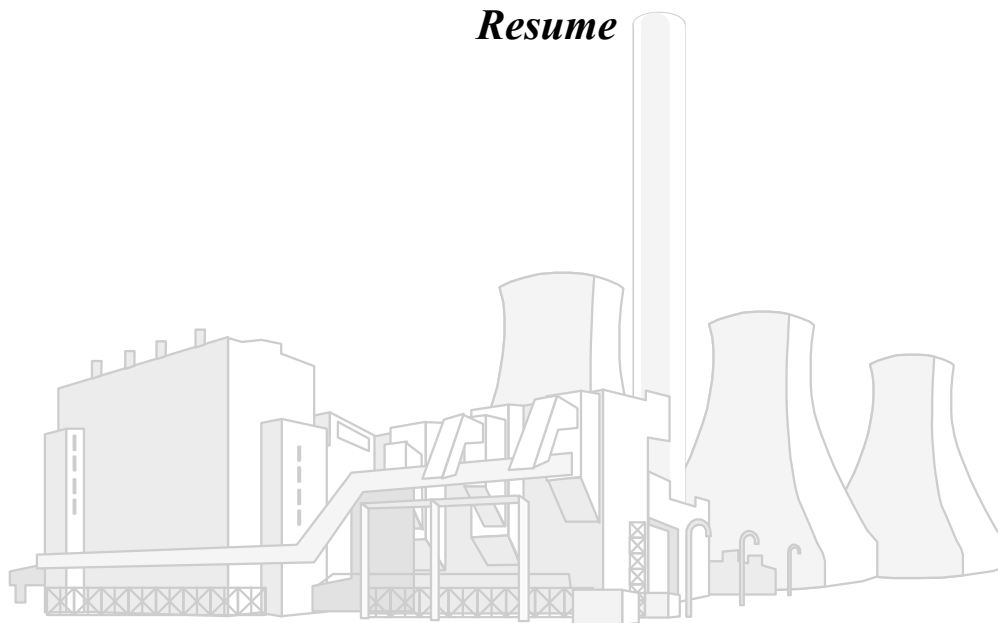


IN-REACTOR THERMAL BEHAVIOUR OF NUCLEAR FUELS



Resume



by

GILBERT FAYL

2000

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THE RESEARCH WORK

The author's research, supported by extensive literature studies¹, resulted in novel findings and plausible models in complex systems, and led to proposals for new and targeted research.

BACKGROUND

In designing nuclear fuel pins of optimum performance, it is necessary to have thorough knowledge of the initial fuel thermal conductivity and gap conductance as well as the influence of reactor operation (burn-up, power cycling, etc.) on these two key parameters.

Still today, the in-reactor thermal behaviour of nuclear fuel pins are under intensive study².

1. There is a complex interaction between the various physical parameters within a fuel pin operating in a nuclear reactor³. At a given heat load and cooling conditions, the operating temperature of each point within the fuel is determined by two key parameters: the **fuel thermal conductivity** and the **fuel-to-cladding heat transfer (gap conductance)**. The operating temperatures influence the fuel's physical state. But the physical state (density, porosity, cracks, fuel relocation, fuel swelling, etc.) in turn influences the fuel thermal conductivity and gap conductance.
2. At a given heat load, the fuel mean temperature determines the stored energy in a fuel pin. The stored energy and its distribution in the event of power excursions are essential parameters for safety calculations. Until the early 1970's, the criterion regarding fuel temperature applied in *thermal reactor* fuel design stated that no part of fuel should be brought to melting (about 2800°C) under maximum operating conditions. During 1972-73, evaluations of nuclear reactor safety in the USA led to the introduction of a more stringent criterion related to the fuel pin behaviour under 'loss-of-coolant/emergency-core-cooling' accidents. This new design criterion required that the fuel cladding temperature should never exceed a value at which rapid oxidation occurs (about 1200°C). Regarding advanced fuel for *fast breeder reactors*, there were indications and experimental evidence – but not sufficient knowledge – of the existence of a critical temperature above which such a fuel could, during irradiation, dramatically increase its initial volume ('swell') with a potentially detrimental impact on fuel pin integrity. Improved knowledge about the in-reactor thermal behaviour of nuclear fuel pins was thus required for safety and economic reasons.



A more complete list of references can be found on page 6 of this document.

¹ G. Fayl, *Out-of-pile and In-Pile Thermal Conductivity of Uranium-Dioxide Pellets*, Risø Report M-950, 1969.

² *Achievements of the Halden Project Programme in the 1997-1999 Period*, OECD Halden Reactor Project, February, 2000.

³ As an example for a vibratory-compacted fuel pin, a model describing this highly complex interaction is suggested in the publication – G. Fayl, *In-Reactor Study of Thermal Behaviour of Vibratory Compacted Uranium-Dioxide Fuel*, Halden Report, 1974.

THE AUTHOR'S RESEARCH

The author's research provided new knowledge regarding the thermal behaviour of fuel pins for light water reactors.

For fuel pins, pelletized and vibratory compacted, the author suggested plausible models explaining their complex behaviour during irradiation. Based on experimental evidences, operational schemes were suggested in order to obtain optimal utilization of fuel pins.

3. The research work was carried out in four different establishments⁴, the irradiation experiments in as many different research reactors⁵, all in all, located in six countries – a truly European effort.
4. In fuel pins for thermal reactors, pelletized uranium-dioxide's thermal conductivity as a function of temperature decreased with burn-up to a significantly higher temperature than reported in the literature: up to about 1000°C as compared to the reported value of about 500°C⁶. As a consequence, fuel temperatures increased with burn-up at constant linear power⁷. This finding suggests that a new look must be taken on the dynamic behaviour of fuel thermal conductivity during in-reactor operation.

The effect of fission gases on the fuel-to-cladding gap conductance was less pronounced than models predicted⁸. In one case, the resulting fuel temperature increase was about half of the calculated value. This finding indicates that models underestimate the significance of enhanced solid-to-solid contact between fuel and cladding.

Stabilisation of fuel temperatures after a certain burn-up, at the same linear heat load, was a clear indication of the combined effects of in-reactor operation on the fuel thermal conductivity and the gap conductance became saturated.

5. Currently used models could not fully account for the phenomena observed above. The author suggested that a combination of several processes might explain the findings and that a new look should be taken at the dynamic behaviour of fuel pins during in-reactor operation⁹. A plausible model was suggested in which fuel cracking and associated relocation of initial void between fuel and cladding to the fuel interior is the

⁴ The Danish Atomic Energy Commission's Research Establishment, Risø, Denmark; the A.B. Atomenergi, Stockholm, Sweden; the OECD Halden Reactor Project, Halden, Norway; and the European Institute for Transuranium Elements, Karlsruhe, Germany. (Some of these organisations have since changed their names.)

⁵ DR3 Reactor, Risø, Denmark; HBWR Reactor, Halden, Norway; High Flux Reactor, Petten, The Netherlands; Siloe Reactor, Grenoble, France.

⁶ G. Fayl and K. Hansen: *In-Reactor Determination of the Thermal Conductivity of UO₂-Pellets up to 2200°C*, Risø Report N° 269 (1972).

⁷ G. Fayl and K. Hansen: *Observations of Increase in Fuel Centre Temperatures with Burn-Up in UO₂/Zr-2 Fuel Rods*, Risø Report N° 415 (1974) presented at the Enlarged Halden Programme Group Meeting, Sandefford/Norway, 3-8 June 1974.

⁸ G. Fayl, K. Hansen and B.S. Johansen: *Effect of Released Fission Gases on Uranium-Dioxide Fuel Temperatures*, Report Risø-M-1782A (1975) presented at the Enlarged Halden Programme Group Meeting, Geilo/Norway, 16-21 March 1975.

⁹ G. Fayl: *An Explanation for Fuel Centre Temperature Increase at Constant Linear Heat Rating*, Paper presented at the Enlarged Halden Programme Group Meeting, Sanderstølen/Norway, 19-23 March 1973.

main mechanism. The driving force is provided by differential thermal expansion of fuel. In-reactor fuel densification seems to play a major role. Secondary factors such as fuel creep and fuel eccentricity together with external restraint of fuel, as well as fuel fabrication method, may influence cracking patterns. As irradiation proceeds, fuel swelling and fission gas release could have additional influences. It was suggested that fuel temperatures can be stabilized by inducing a more homogeneous in-reactor fuel densification at high power during initial operation.

6. Contrary to pelletized fuel pins, vibratory compacted uranium dioxide fuel pins underwent significant fuel temperature decrease at constant linear power during initial operation, followed by some temperature increase¹⁰. The complex thermal and mechanical behaviour of fuel pins was explained through a comprehensive model in which partial fuel densification plays a significant role. In this process, material transport yields structures similar to those in pelletized fuel. Calculation accuracy can be increased through the introduction of an 'overall thermal conductance'.

The author suggested using a soft densification scheme in order to obtain optimal utilisation of the fuel densification effect, while avoiding extensive forces between fuel and cladding.



In advanced fuel pins for fast breeder reactors, the author's research revealed a simple relationship between key parameters. Based on the experimental evidence, a series of experiments were suggested to establish a comprehensive equation combining the most relevant main parameters.

7. Contrary to the uranium-dioxide fuel pins where the dominant thermal resistance is within the fuel itself, under the experimental conditions employed, the dominant thermal resistance within advanced fuel pins for fast breeder reactors is between fuel and cladding. In both mixed (uranium-plutonium) -nitride¹¹ and mixed-carbide¹² fuel pins, the fuel-to-cladding gap conductance increased with linear power. The increase was even more significant with burn-up. For both cases, a linear relationship existed with gap conductance.

Another novel observation in the experiment analysed by the author was that single power cycles of limited duration, experienced after some irradiation, did have a limited, if any, influence on the fuel-to-cladding gap conductance. This was contrary to consecutive full power ramps where some improvements were observed, suggesting that more extensive fuel cracking and relocation in radial direction might have taken place during such controlled power increase and decrease so that the intimate contact between fuel and cladding increased.

¹⁰ G. Fayl and K. Hansen: *In-Reactor Determination of the Thermal Conductivity of UO₂-Pellets up to 2200°C*, Risø Report N° 269 (1972).

¹¹ G. Fayl: *Heat Transfer Coefficient between Mixed-Nitride Pelletized Fuel and Stainless Steel Cladding with Helium Bonding*, Transuranium Institute Report (1974).

¹² G. Fayl: *Heat Transfer Coefficient between Mixed-Carbide Pelletized Fuel and Niobium Cladding with Helium Bonding*, Transuranium Institute Report (1976).

The author suggested a series of co-ordinated experiments to study gap conductance and to establish an equation applicable to main fuel pin design parameters and operational conditions.



Theoretical considerations indicated that, for studying the thermal resistances within a fuel pin, sufficient information can be derived from fuel temperature fluctuation around a mean value or from fuel temperature changes induced by neutron flux changes. The author's research confirmed this.

8. Changes in heat transfer characteristics of fuel pins may occur under irradiation as a result of changes in fuel density, composition, geometry and thermal conductivity as well as gap conductance¹³. Theoretical considerations and experimental results showed that fuel pin parameters as well as operational conditions have a measurable influence on the dynamic characteristics of fuel pins¹⁴. It was concluded that the dynamic method seems to be suitable for studying more precisely how fuel restructuring due to irradiation influences fuel pin temperatures.

Based on the dynamic measurement technique of in-reactor thermal properties of uranium-dioxide fuel pin, the author proposed a systematic experimental study.



Ultrasonic thermometers have opened the way to studying fuel pin thermal characteristics at extreme high temperatures.

9. The experimental findings discussed above were obtained with refractory metal thermocouples. These exhibit a relatively short life and de-calibrate under irradiation conditions.

Experiments demonstrated that ultrasonic thermometer is an alternative solution; promising results were obtained in reactor experiments¹⁵. If further developed, determination of the fuel thermal response to power transients, by means of ultrasonic thermometer, may be a powerful tool for further studying the in-reactor thermal characteristics of fuel pins.



¹³ G. Fayl: *Application of Dynamic Temperature Measurements to Determination of Thermal Resistance within Fuel Rods*, Halden Report (1974).

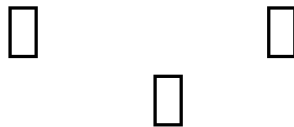
¹⁴ T.F. Bjørlo, G. Fayl and E. Rolstad: *Determination of Thermal Characteristics of Fuel Rods through Dynamic Temperature Measurements*, Paper presented at the Enlarged Halden Programme Group Meeting, Sanderstølen/Norway, 7-12 March 1976.

¹⁵ H. Tasman, H.E. Schmidt, F. Richter, M. Campana and G. Fayl: *The TRESON Experiment: Measurement of Temperature Profiles in Nuclear Fuels by means of Ultrasonic Thermometers, High Temperatures-High Pressures*, 1977, Volume 9, pages 387-406.

POST-SCRIPTUM

Any human activity is associated with a certain degree of risk. The population has the right to expect that every effort be made to minimise the risk. This necessitates a continuous improvement of the related knowledge.

10. The author's work illustrates the importance experimental research has in the nuclear energy field where the public demands that the satisfactory safety level must be constantly enhanced because of the potential consequences on human life. The above information may therefore be seen as an invitation to maintain an appropriate level of research in this area, for the sake of protecting our societies and their future. This must be done even if the current political climate seems to indicate that we might less and less rely on nuclear energy in the coming years or even decades. Nuclear energy is widely produced and there should be a continuous concern that this production is carried out under the safest possible conditions dictated by the state-of-the-art knowledge.



PUBLICATIONS

(Because of the confidential nature of in-reactor thermal behaviour of fuel pins for commercial nuclear power plants at the time the research was carried out, my publications remained internal to institutions and restricted conferences in most cases.)

Publications relating to In-Reactor Behaviour of Fuel Pins:

K. Hansen, G. Fayl, *Beskrivelse af Rig Til Måling af UO₂'s Varmeledningsserve*, Risø Internal Report 12, July 1967.

G. Fayl, *Iltoverskudsbestemmelse i Urandioxid*, Risø Report M-704, February 1968.

K. Hansen, G. Fayl, *Bestrålingsforsøg med Risø UO₂-Pellets i DR3*, Risø Report M-713, February 1968.

G. Fayl, *Mulige Årsager til Temperaturstigning i Varmeledningsrig Nr. 1*, Risø Report B-73, October 1968.

G. Fayl, *Out-of-Pile and In-Pile Thermal Conductivity of Uranium-Dioxide Pellets*, Risø Report M-950, 1969.

G. Fayl, K.W. Jones, O.T. Sørensen, *Capsule Irradiation Testing of Danish UO₂-Pellets*, Risø Report M-1260, May 1970.

G. Fayl, *Undersøgelse af Årsagen til Stigning af β -Strømmen i Varmeledningsrig Nr. 1*, Risø Report B-158, July 1970.

G. Fayl, *The Irradiation of the Japanese Test Fuel Assembly IFA-225 in HBWR*, Halden Working Paper EP-1225, January 1971.

G. Fayl, *The Irradiation of the Danish Test Fuel Assemblies IFA-201 and IFA-202 in HBWR*, Halden Working Paper EP-1201/1202, May 1971.

G. Fayl, *Results from In-Pile Calibration of IFA-201*, Halden Working Paper EP-1206B, May 1971.

G. Fayl, *Results from In-Pile Calibration of IFA-211*, Halden Working Paper EP-1211B, June 1971.

G. Fayl, *Results from In-Pile Calibration of IFA-201*, Halden Working Paper EP-1207B, September 1971.

G. Fayl, *Results from In-Pile Calibration of IFA-223*, Halden Working Paper EP-1223B, October 1971.

G. Fayl, *Comparison between Measured and Calculated Power in Test Assembly Containing Burnable Poison*, Halden Working Paper IDG-Note 1758, October 1971.

G. Fayl, *Early-Life Fuel-Canning Interaction in IFA-223*, Halden Working Paper IDG-Note 1760, November 1971.

G. Fayl and K. Hansen, *In-Reactor Determination of the Thermal Conductivity of UO₂-Pellets up to 2200°C*, Risø Report N° 269, 1972.

- G. Fayl, *Proposal for Post-Irradiation Recalibration of Fuel Thermocouples*, Halden Working Paper, IDG-Note 1849, August 1972.
- G. Fayl, *Comparison between Estimated and Calculated Powers*, Halden Working Paper, November 1972.
- G. Fayl, H. Devold, E. Kolstad, *In-Reactor Temperature Measurements*, Paper presented at the Enlarged Halden Programme Group Meeting, Sandestølen, Norway, 19-23 March, 1973.
- G. Fayl, *An Explanation for Fuel Centre Temperature Increase at Constant Linear Heat Rating*, paper presented at the Enlarged Halden Programme Group Meeting, Sanderstølen, Norway, 19-23 March 1973.
- G. Fayl, H. Jensen, *Post-Irradiation Examination of Thermal Conductivity Rig N° 2*, Risø Report B-308, April 1973.
- G. Fayl, *Proposal for Comparative Study of In-Reactor Thermal Behaviour of Fuel Rods*, Halden Working Note N° 105, October 1973.
- G. Fayl, *In-Reactor Study of Thermal Behaviour or Vibratory Compacted Uranium-Dioxide Fuel*, Halden Report, 1974.
- G. Fayl and K. Hansen, *Observations of Increase in Fuel Centre Temperatures with Burn-Up in UO₂/Zr-2 Fuel Rods*, Risø Report N° 415, 1974 presented at the Enlarged Halden Programme Group Meeting, Sandefjord/Norway, 3-8 June 1974.
- G. Fayl, *Heat Transfer Coefficient between Mixed-Nitride Pelletized Fuel and Stainless Steel Cladding with Helium Bonding*, Transuranium Institute Report (1974).
- G. Fayl, *Application of Dynamic Temperature Measurements to Determination of Thermal Resistance within Fuel Rods*, Halden Report, 1974.
- H.A. Tasman, M. Campana, G. Fayl, H.E. Schmidt, *In-Pile Ultrasonic Thermometry Experiment Treson*, Paper presented at the International Colloquium on High-Temperature In-Pile Thermometry, Petten, The Netherlands, 12-13 December 1974.
- G. Fayl, K. Hansen, B.S. Johansen, *In-Pile Experiences of High Temperature Measurements* at Risø, Denmark, Paper presented at the International Colloquium on High-Temperature In-Pile Thermometry, Petten, The Netherlands, 12-13 December 1974.
- M. Campana, G. Fayl, *Mesure de Transport d'Energie en Pile par Méthodes Soniques*, Transuranium Institute Technical Paper, February 1975.
- G. Fayl, *Calculated Fuel Temperatures in Fast Reactor Fuel Pins*, Transuranium Institute Report, 1975.
- G. Fayl, K. Hansen and B.S. Johansen, *Effect of Released Fission Gases on Uranium-Dioxide Fuel Temperatures*, Risø Report M-1782A, 1975, presented at the Enlarged Halden Programme Group Meeting, Geilo, Norway, 16-21 March 1975.

F. Caligara, M. Campana, M. Coquerelle, G. Fayl, J.F. Guenguon, J. Richter, K. Richter, H.E. Schmidt, H.A. Tasman, *Ultraschall-Thermometrie in Miseleoxid-Brennstäben*, Paper presented at Reaktortagung, Nürnberg, Germany, 8-11 April 1975.
M. Campana, G. Fayl, J. Richter, H.E. Schmidt, *Proposal for Instrumented Carbide Irradiations using Ultrasonic Thermometers*, Transuranium Institute Technical Note ESSIR/57, February 1976.

M. Campana, G. Fayl, R. Mandler, K. Richter, *Proposal for Power Cycling Experiments with Advanced Fuel Pins*, Transuranium Institute Technical Note ESSIR/58, February 1976.

T.J. Bjørlo, G. Fayl and E. Rolstad, *Determination of Thermal Characteristics of Fuel Rods through Dynamic Temperature Measurements*, paper presented at the Enlarged Halden Programme Group Meeting, Sanderstølen, Norway, 7-12 March, 1976.

G. Fayl, *Heat Transfer Coefficient between Mixed-Nitride Pelletized Fuel and Stainless Steel Cladding with Helium Bonding*, Transuranium Institute Report, 1974.

F. Caligara, M. Campana, M. Coquerelle, G. Fayl, J.F. Gueugnon, J. Richter, K. Richter, H.E. Schmidt, H.A. Tasman, *In-Pile Test of Ultrasonic Thermometers*, Transuranium Institute Report, October 1976.

G. Fayl, *Observations on Fuel-to-Cladding Gap Conductance for LMFBR Fuel Rods*, Transuranium Institute Technical Note KO277023, 1977.

H.A. Tasman, H.E. Schmidt, J. Richter, M. Campana, G. Fayl, *Measurement of Temperature Profiles in Nuclear Fuels by means of Ultrasonic Thermometers*, Transuranium Institute Technical Note KO277012, August 1977.

H. Tasman, H.E. Schmidt, J. Richter, M. Campana and G. Fayl, *The TRESON Experiment: Measurement of Temperature Profiles in Nuclear Fuels by Means of Ultrasonic Thermometers*, High Temperatures-High Pressures, Volume 9, 1977.

G. Fayl, *Fuel-to-Cladding Gap Conductance Determination*, Joint Research Center Headquarters Working Paper 5478, May 1978.

Further information: The author's most recent publications relating to Research Programme Evaluation:

L. Durieux, G. Fayl, *The Scheme Used for Evaluation of the European RTD Programmes*, paper presented at the OECD Conference on Policy Evaluation in Innovation and Technology, Paris, France, 26-27 June, 1997.

G. Fayl, Y. Dumont, L. O'Sullivan, L. Durieux, I. Karatzas, *Evaluation of RTD Programmes: A Tool for RTD Policy Design*, paper presented at the NATO Advanced Research Workshop on Quantitative Studies for S&T Policy in Transition Economies, Moscow, Russia, 23-25 October, 1997.

Karatzas, Y. Dumont, L. O'Sullivan, L. Durieux, G. Fayl, *Evaluating the European Commission RTD Programmes: Responding to the Needs of a Changing World*, paper presented at the NATO Advanced Research Workshop on Science Evaluation and its Management, Prague, Czech Republic, 25-28 November 1997.

G. Fayl, Y. Dumont, L. O'Sullivan, L. Durieux, I. Karatzas, *Data for RTD Programme Evaluation*, paper presented at the CEIES Seminar Statistics on Research and Development, Aarhus, Denmark, 3-4 December, 1997.

- G. Fayl, I. Karatzas, *Evaluation of Research Efforts at European Level*, Università Ricerca, Italy, March 1998.
- G. Fayl, *Measuring the Impact of EU Framework Programme at National Level*, paper presented at the International Expert Meeting on Evaluation, Vienna, Austria, 3-5 July, 1998.
- G. Fayl, Y. Dumont, L. O'Sullivan, L. Durieux, I. Karatzas, *Evaluation of Research and Technological Development Programmes: A Tool for Policy Design*, Research Evaluation, August 1998.
- Y. Dumont, L. O'Sullivan, L. Durieux, I. Karatzas, G. Fayl, *Evaluate Programme Impact: A Means to Address New Challenges and Meet Human Capital Needs*, paper presented at 3rd European Evaluation Society Conference, Rome, Italy, 29-31 October, 1998.
- Y. Dumont, L. O'Sullivan, L. Durieux, I. Karatzas, H. Teuber, G. Fayl, *Overview of the EC RTD Monitoring and Evaluation System*, contribution to the ETAN Working Group Report: Options and Limits for Assessing the Socio-Economic Impact of European RTD programmes, January 1999.
- G. Fayl, *Towards a European Evaluation Culture*, paper presented at the International Conference on Evaluation of Science and Technology in the New Europe, Berlin, Germany, 7-8 June, 1999.
- G. Fayl, *Conclusions* at the Socio-Economic Impact Evaluation Workshop, Helsinki, Finland, 26-27 November, 1999.
- G. Fayl, *Experience with EU RTD Programme Evaluation*, paper presented at meeting on La Valutazione della Ricerca, Rome, Italy, 4 February, 2000.
- G. Fayl, *Evaluation Cultures in a European Perspective*, paper presented at the conference on the Impact on Academic Institutions of Research Evaluation Systems, Lisbon, Portugal, 23-24 June, 2000.
- G. Fayl, *EU RTD Evaluation Networks*, paper presented at the European/US Workshop on Learning from S&T Policy Evaluation, Bad Herrenalb, Germany, 11-14 September, 2000.
- G. Fayl, *The Role of Independent Experts in the EU RTD Evaluation*, paper presented at Expertise and Interfaces Workshop, Budapest, Hungary, 2-3 October, 2000.
- G. Fayl, *The Role of Evaluation in the Governance of the Research System*, contribution to Round Table at the conference on Strategic Evaluation, Lyon, France, 9-10 October, 2000.
- G. Fayl, *Evaluation: Engine or Break for Reform*, paper presented at 3rd Annual Meeting of the German Evaluation Society, Berlin, Germany, 23-24 November, 2000.
- Karatzas, G. Fayl, *The Catalytic Effects of EC RTD Evaluation Activities on Trans-European Co-operation*, Research Evaluation, December 2000.



GILBERT FAYL



Date and place of birth: 18 March, 1937, Budapest, Hungary
Married, 3 children

Current position: Head, Relations with Scientific Advisory Bodies under Directorate General Research at the European Commission, Brussels, since January 2001.

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- 1967 Graduated from the Technical University, Copenhagen, Denmark, Master of Science.
- 1967-69 Post-graduate research fellow at the National Research Centre, Risø, Denmark.
Post-graduate courses in reactor technology, reactor physics, health physics.
Represented Denmark in a Scandinavian co-operation on in-reactor thermal conductivity of uranium-dioxide fuel.
- 1970-74 Danish representative and researcher at OECD Halden Reactor Project, Halden, Norway.
Main responsibilities included planning and conduction of reactor experiments and evaluation of their experimental data, in particular in the field of LWR fuel pin thermal behaviour.
- 1974-76 Researcher at the European Commission's Joint Research Center Transuranium Institute, Karlsruhe, Germany.
Main responsibilities included designing in-reactor experiments with LMFBR fuel pins and evaluation of their experimental data.
- 1976-81 Scientific Co-ordinator at the Headquarters of the Joint Research Centre, European Commission, Brussels, Belgium.
Main responsibilities included co-ordination of nuclear activities in the fields of plutonium fuels and trans-uranium research, reactor safety, and radioactive waste management.
Represented the European Commission in the International Fuel Cycle Evaluation exercise (1978-79) in the sub-group dealing with research reactors (as rapporteur) and another dealing with spent fuel disposal.
- 1981-89 Senior Administrator, DG Science, Research and Development at the European Commission, Brussels, Belgium, and member of the core team which was responsible for the conceptual formulation of the first European Community's RTD Framework Programme.
Main responsibilities included aspects of nuclear energy, and health and safety.
- 1989-94 Science, Technology and Education Counsellor at the European Commission's Delegation to the USA, Washington, D.C.
Invited lecturer at several US Universities.
- 1995-2000 Head, Programme Evaluation, DG Research and Technological Development at the European Commission, Brussels, Belgium.
Chairman of the European RTD Evaluation Network.
Represented the European Commission at the CREST Evaluation Sub-Committee.

Co-organised several international scientific conferences.
Represented the European Commission, and previously Denmark, in various international fora.
International Space Camp Award, 1991, and US Space Academy Award Teaching of Future, 1991.
Salzburg Seminar Fellow 1994 and 1999.

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TO WHOM IT MAY CONCERN

I hereby confirm that Mr. Gilbert Fayl (born 18 March, 1937 in Budapest) was employed as a post-graduate research fellow at the Riso National Laboratory in the period from January 1967 to December 1969.

He received a research grant for his project on "In-Reactor Thermal Conductivity of UO_2 -Pellets".

Mr. Fayl successfully completed his research/studies at our Laboratory. In continuation with his research, Mr. Fayl was nominated to represent our organisation at the OECD Halden Reactor Project, Norway.

Yours sincerely,

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Comments on the research work of Mr. Gilbert FAYL on the In-Reactor Thermal Behaviour of Nuclear Fuels

Mr. Gilbert Fayl's research work has concentrated on the In-Reactor Thermal Behaviour of Nuclear Fuels over a period of about ten years more than two decades ago. During this period, in my capacity as the Head of the Materials Research Department at the Danish National Laboratory and as member of various international research advisory bodies, I had the opportunity to closely follow Mr. Fayl's work and advise him. In the following, I will present my views and assessment thereon, from the point of view of its scientific and technological quality, relevance for related research, and its actuality.

1. Scientific and technological quality:

Let me start by stating that Mr. Fayl's work, due to its confidential nature, has been the subject of numerous peer reviews in selected, closed international circles. His work has been carried out in several internationally recognised establishments under strict control and advice:

- * In February 1967, Mr. Fayl started his research work in my Department as a post-graduate fellow with the aim of determining the in-reactor thermal conductivity of UO_2 fuel. The experimental facility used was the Danish DR3 Reactor. These efforts were supported by his out-of-pile thermal conductivity measurements carried out at the Fuel Laboratory of the Swedish Nuclear Research Centre, located (at that time) in Stockholm, Sweden. The overall effort was a joint Scandinavian project, where the results obtained were systematically presented to and discussed by the participating partners. Prior to his in-reactor experiments, Mr. Fayl carried out a substantial literature study that guided him to focus his experimental work.

During the entire period in my Department, Mr. Fayl – who was under my supervision – systematically reported on the progress of his research. In addition, the work was regularly discussed at my Department's seminars in which my collaborators, together with visiting scientists, participated. My advice and the peer discussions helped to ensure the focus of his work and its scientific and technological credibility.

- * As a logical continuation of his research in my Department, I encouraged Mr. Fayl to pursue his work at the international OECD Halden Reactor Project in Norway where Denmark is a participating partner. This organisation was – and still is – one of the world's leading focal points for nuclear fuel research. Mr. Fayl, while being the Danish representative at the Project (1970-74), became one of the collaborators to promote research on in-reactor thermal behaviour of Light Water Reactor (LWR) fuel pins. His research, which contributed to enhanced knowledge on the irradiation influence on the fuel temperatures in pelletized and vibratory compacted LWR fuels, was presented at several international conferences organised by the OECD Halden Reactor Project and discussed by international peers. I wish to mention that these focused events – then and now – were restricted to experts from the countries participating in the Project.

Peer reviews and discussions at the Projects' regular conferences are one of the main instruments that guide the research work. In addition, together with my colleagues in the international OECD Halden Programme Group (composed of senior researchers and senior research managers from the participating countries in which I represented Denmark), we had the task of advising the Project to ensure the quality and orientation of its research. In the context of the above, Mr. Fayl's efforts were highly appreciated and helped to maintain the attention on this important issue – the in-reactor thermal behaviour of LWR fuels.

- * After Denmark joined the European Communities, Mr. Fayl moved to the European Commission's own research centre - the Joint Research Centre's Transuranium Institute - in Karlsruhe, Germany in early 1974 and remained there for almost three years. There he continued his research on the in-reactor behaviour of nuclear fuels and, corresponding to the focus of the Institute's research programme, concentrated his work on advanced fuels for Fast-Breeder Reactors (FBR). Again, I had the possibility to follow his work, firstly as a member of the Institute's Advisory Committee for Programme Management (ACPM), and later as its Chairman (both times as representative for Denmark). I wish to mention that the ACPM had the same high-level composition as the OECD Halden Programme Group.

Guidance of the ACPM was one of the key instruments in maintaining the focus of the Institute's work and its internationally recognised high quality. This was particularly important, as the Institute is the sole one in Europe that devotes its research exclusively to transuranium elements and advanced nuclear fuels incorporating them. In the context of the ACPM's function, Mr. Fayl's work was also followed and assessed. It is noteworthy that Mr. Fayl recognised the need and possibility to study the in-reactor thermal behaviour of advanced fuels within the Institute's work programme.

2. Relevance for related research:

At the time Mr. Fayl started his research on thermal conductivity of UO_2 in my Department, literature data suggested that in the lower temperature range, it was decreasing with increasing neutron doses and reaching maximum values at a relatively low doses, after which it stabilised. Published experimental data also indicated that the irradiation effect on the thermal conductivity was decreasing with increasing temperatures so that above about 500°C , no significant effect was measured. On the other hand, at high temperatures, notably beyond 1500°C , the literature data was inconclusive. Against this background, Mr. Fayl's work had to concentrate on in-reactor measurements of thermal conductivity at even higher temperatures and extended in-reactor operation.

The more stringent reactor safety rules introduced in the US in the early 1970's (post-accident heat removal, etc) necessitated additional experimental and theoretical effort on the in-reactor thermal behaviour of LWR fuels. As very little reliable and relevant experimental data were available at that time, the data produced by Mr. Fayl's work (which was confidential and restricted) became of high relevance. In addition, the theoretical calculations he made at the OECD Halden Reactor Project on the basis of previously obtained but not yet evaluated experimental data, revealed features that had to be taken into account in reactor safety calculations. I agree with Mr. Fayl's conclusions that his investigations "*supported by extensive literature studies, resulted in novel findings and plausible models*" for the thermal behaviour of LWR pelletized and vibratory compacted fuels. I would like to emphasise Mr. Fayl's contribution to using the dynamic measurement technique to study in-reactor fuel pin thermal properties.

At the Transuranium Institute, Mr. Fayl's work helped to extend the research to include FBR fuel thermal behaviour. His useful contribution was notably, the identification of simple relationship between certain design and operational parameters as well as the evaluation of in-reactor experimental data obtained using ultrasonic thermometer.

3. Actuality

The Report, issued by the OECD Halden Reactor Project in February 2000, on the Project's achievement during the period 1997-1999, identifies the determination of the thermal conductivity of UO₂ fuel and the rate of thermal conductivity degradation with accumulated burn-up, as an important research subject. Obviously, Mr. Fayl's investigations conducted more than twenty years ago, are still actual and valid contributing elements to the overall analysis of the subject.

Another interesting feature of Mr. Fayl's work is that he is probably among the few persons who dealt with in-depth studies of different kinds of fuels' thermal behaviour (LWR and FBR) using various measurement techniques (thermocouple and ultrasonic thermometry), under diverse experimental conditions. Indeed, his research was carried out in four establishments, the irradiation experiments in as many research reactors, all in all located in six European countries. Of course, this comprehensive research was the result of Mr. Fayl's readiness for mobility rather than any predetermined research plan. Nevertheless, his Anthology is a valuable publication giving insight into nuclear research at a time when this was still considerably supported.



As a final comment, I wish to note that Mr. Fayl's research work with my Department was a post-graduate fellow programme, which he successfully completed. For a similar programme at the Danish Technical University and after successful completion, the research fellows were awarded the Danish title "Licentiate". Subsequently, in the context of European harmonisation on academic education and title, this was recognised as a Doctorate title (PhD). This possibility was, however, not an option for our Research Centre.

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