OVERVIEW ON INTERNATIONAL EXPERIMENTAL PROGRAMMES ON POWER RAMPING AND FISSION GAS RELEASE

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Abstract

During the last years a number of internationally sponsored experimental programmes were initiated to study the LWR fuel behaviour during ramping and fission gas release at higher burnup levels. Common interest and the limited availability of experimental facilities and appropriate test fuel rods have led to valuable cooperation of many organizations throughout the nuclear community.

These programmes are performed by the experienced staff from research centers with their experimental facilities. Fuel vendors and several utilities contribute by supply and irradiation of test fuel rods.

The aim of this paper is to provide a synopsis of the following programmes:

- Studsvik Projects: Interramp, Overramp, Superramp, Demoramp I and II
- Petten, High Burnup PWR Ramp Test Programme
- Mol, Tribulation Programme
- BNWL, High Burnup Effects Programme
- Risö Fission Gas Project
- Related tasks within the OECD Halden Reactor Project

The objectives of the programmes, their work scope and main results will be summarized on the basis of presently available information. An outlook to future proposed programmes will be given.

The OECD Halden Reactor Project has for long times been the only internationally sponsored experimental programme to investigate specific aspects of the LWR fuel behaviour during irradiation. Many valuable experimental facilities and in-pile measuring instruments were and are being developed and applied in numerous irradiation experiments. In 1973 the Edison Electric Institute initiated the first international programme with only one specific objective, namely the investigation of the fuel densification phenomenon.

When the PCI problem was identified in the early 70's several private programmes were immediately started by fuel vendors to provide understanding of the problem and recommendations to the reactor operators in form of operational guide lines. Because of the high cost of these experiments and because of the limited availability of appropriate test rods the first international ramping project could be started 1975 in Studsvik, the Interramp Project. This Project had a clearly formulated technical programme and ended with the achievement of the technical goals. All later international ramping and fission gas release programmes followed the same scheme. Within this frame, cooperation of utilities, fuel vendors, research institutes, and licensing authorities has been achieved and their representatives in the Project committees provide the technical guidance to the Project Managers after intensive discussions.

The experimental programmes are performed by the experienced staff of the research centers, which have the proper experimental facilities installed in and around their research reactors. Test fuel rods are mainly supplied by fuel vendors and several utilities contribute in pre-irradiating the test fuel rods to the desired burnup in their power reactor.

Use of and rights to the results are regulated in Project Agreements. In most cases the results remain the property of the contracting parties and are kept confidential for the Project period. Public use of the data is normally granted to the contracting parties several years after the end of the Project.

A synopsis of the following programmes will be given:

- Studsvik Projects: Interramp, Overramp, Superramp, Demoramp I and II

- Petten, High Burnup PWR Ramp Test Programme
- Mol, Tribulation Programme
- BNWL, High Burnup Effects Programme
- Risø Fission Gas Project
- Related tasks within the OECD Halden Reactor Project

Since most of the Programmes are still going on or have not yet reached the state of free public use, the summaries contain more general information than detailed results. The interdependence of the programmes appears also from this information. For all of the above programmes a short summary is provided as Appendix 1 to 10.

Table 1 lists the international ramping programmes and indicates the relevance of their results in the terms of the RSST-approach[1)] for ramp test strategies shown in figure 1 (safe range, safe speed, safe step, safe time). The results of the programmes are summarized in tables 2 to 6.

Most of the programmes provide results on failure thresholds (safe range) which are important to provide limits for the reactor operation. The determination of a "safe speed" and a "safe step" is not a major objective in the programmes. Determination of the "safe time", important in case of operational power transients, seems not to obtain to much attention.

The programmes on fission gas release are listed in table 7 and their results are summarized in tables 8 and 9. With respect to the transient fission gas release, all ramping programmes add to the available information, too.

1) W. Vogl, R. von Jan, H. Stehle "Experimental Strategy of Fuel Performance Testing with Respect to PCI" Nucl. Eng. Des. 65, 307 (1981)

Table 10 lists the presently proposed future international programmes, one on transient testing (safe time) and one on the kinetics of the fission gas release after a fast power increase. Both programmes are technically interesting and should obtain broad attention.

Table 1 Overview on International Ramping Programmes

Project	Approx. Number of Tests	Objective	Results Relevant for Safe Range	Speed	Step	Time
Studsvik INTERRAMP Proj.	20	BWR Ramp Behaviour at 10 - 20 MWd/kg	X		X	(X)
Studsvik DEMORAMP I Proj.	5	BWR Combined Remedies	X			
Studsvik DEMORAMP II Proj.	9	BWR Mechanistic Studies, Short Time Transients			(X)	X
Studsvik OVERRAMP Proj.	39	PWR Ramp Behaviour at 10 - 30 MWd/kg	X	X		
Studsvik SUPERRAMP Proj.	44	BWR and PWR Ramp Behaviour at High Burnup > 30 MWd/kg	X	X	X	
KWU/CE/DOE High Burnup PWR Ramp Test Progr. (Petten)	20	PWR Ramp Behaviour at High Burnup > 30 MWd/kg	X	X		
TRIBULATION International Programme (Mol)	48	High Burnup Behaviour of PWR-Rods Subjected to Transients	(X)			X
OECD Halden Reactor Project	70	Ramp Behaviour and Mechanistic Studies on Experimental Rods	X	X	X	

Table 2 Main Results of Ramping Programmes

1. Safe Range

- Failure thresholds determined between 5 and 45 MWd/kg burnup
- Failure threshold decreases with burnup up to 20 - 30 MWd/kg. (Influence of higher burnup is being studied)
- Failure threshold depends on fuel rod design, e.g. e.g. BWR versus PWR, pellet/clad gap size, UO_2 properties
- No influence found of cladding mechanical properties, e.g. cold worked, stress relieved versus recrystallized
- Failure threshold coincides with onset of important fission gas release and fuel restructuring
- Pre-irradiation conditions, i.e. fast flux and cladding temperature may influence the ramping behaviour

Table 3 Main Results of Ramping Programmes

2. Safe Speed

- The failure threshold can safely be passed with slow ramp rates (investigated with unpressurized BWR rods)
- No conclusive data on PWR rods obtained (OVERRAMP Project)

Table 4 Main Results of Ramping Programmes

3. Safe Step

- The failure threshold can be passed with a limited power step if preconditionning is close to the failure threshold
- A criterical step of 70 W/cm has been determined for unpressurized BWR rods at 10 - 20 MWd/t (INTERRAMP Project)
- No results are available for PWR rods

Table 5 Main Results of Ramping Programmes

4. Safe Time

- During ramp testing failed rods release fission products to the coolant normally within minutes to some hours
- The "time-to-fission-product release" strongly depends on the power level above the failure threshold and on burnup
- The time for PCI-crack initiation and penetration of the clad wall seems to be in the order of minutes only (DEMORAMP II)

Table 6 Main Results of Ramping Programmes

5. Some Observations on the PCI Failure Mechanism

- Crack formation during ramping occurs obviously very fast after reaching the necessary power (fuel temperature) level
- Initial fission gas release at time of crack formation is rather small
- Only very little plastic strain is associated with PCI failure
- UO_2 properties (grain size, porosity, density) seem to have an important influence on the PCI failure threshold

Table 7 Overview on International Fission Gas Release Programmes

Project	Objective	Approx. Number of Rods
OECD Halden Reactor Project	Steady State and Transient Release, Detailed Mechanistic Studies, Instrumented Tests	108
BNWL High Burnup Effects Programme	Release after Power Reactor Operation and after Pre-Irradiation at Elevated Power Levels (Bumping)	81
Risø Fission Gas Project	Fission Gas Release after Base Irradiation and after Bumping at High Burnup	12

Table 8 Main Results of Fission Gas Release Programmes

1. Steady State Release

- Fission gas release and related UO_2 microstructural data from well documented fuel rods after operation in power and test reactors in the burnup range up to 45 MWd/kg (presently available)
- Rods under irradiation to extend data base up to 80 MWd/kg (HBEP and TRIBULATION)
- Significant release is only observed when the fuel temperature exceeds the level required to form grain boundary fission gas bubbles. This temperature decreases with burnup
- The feed-back effect of released fission gas on fuel temperature has been measured and appears to depend on size of the pellet/clad gap

Table 9 Main Results of Fission Gas Release Programmes

2. Transient Release

- Fission gas release after ramping and bumping (long hold times) has been and is determined for a wide range of power levels (~ 300 - 500 W/cm) and burnups (5 - 45 MWd/t)
- Instrumented tests confirm the square root time dependence of transient fission gas release after ramping (Halden)
- Transient fission gas release is strongly influenced by UO_2 grain size (Halden, OVERRAMP)

Table 10 Proposed Future International Programmes

Studsvik Transramp Project

(follow-on programme to Demoramp II)

Objective: Determine time to PCI crack initiation, crack penetration and fission product release after fast power increase above failure threshold

5 unpressurized BWR rods, ~18 MWd/kgU

Project planned to start in September 1982

Risø Transient Fission Gas Release Programme

(follow-on programme to Risø Fission Gas Project)

Objective: Study the kinetics of fission gas release after fast ramping

Test rods mainly refabricated and pressure instrumented from rods irradiated at Halden and Monticello

Project planned to start in December 1982

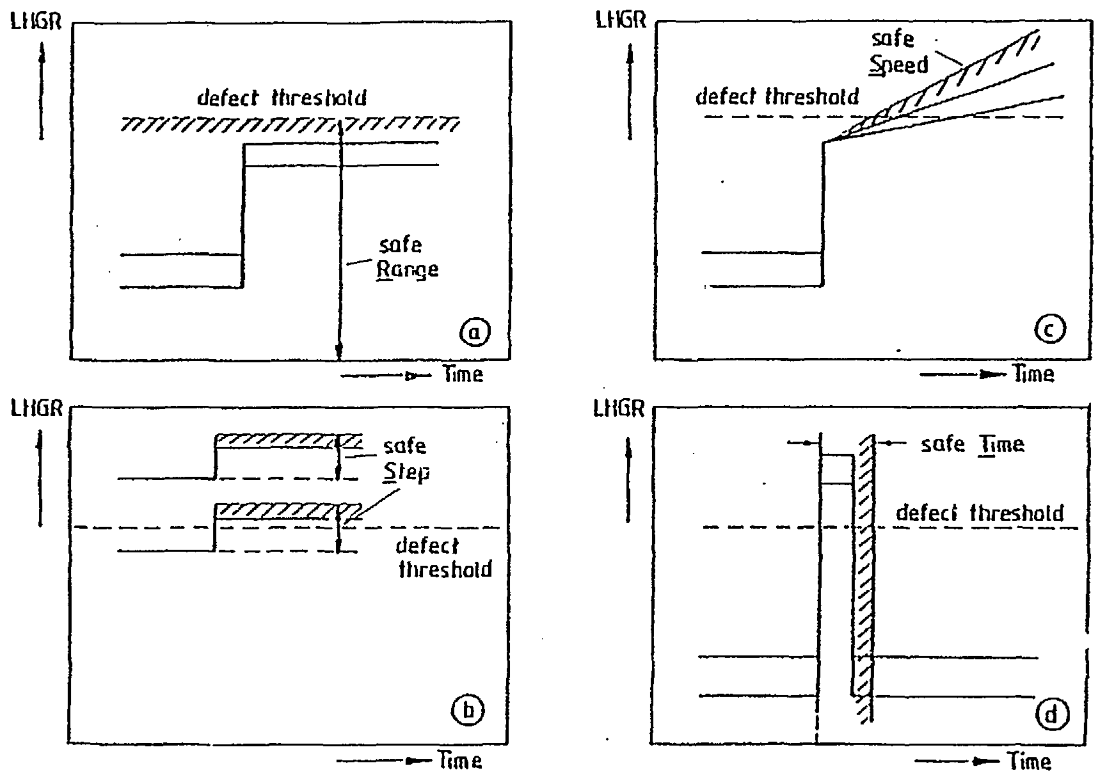

Fig.1 The RSST - Aproach in the Ramp Test Strategy

Appendix 1/1

Studsvik Interramp Project

1. Managing Organization

   Studsvik Energiteknik AB, Nyköping, Sweden

2. Objectives

   Ramp behaviour of unpressurized BWR test rods at 10 and 20 MWd/kgU burnup

   - Failure threshold of standard rods
   - Effect of design parameters
   - Failure mechanism and associated phenomena
   - Data base for fuel modelling

3. Fuel Rod Characteristics

   20 Zry-2 clad UO_2 rods (BWR, unpressurized)

   diameter: 12,5 mm

   length : 538 mm

   fill gas: 1 bar Helium

   design variables:

   - cladding condition (recrystallized, cold worked/ stress relieved)
   - pellet density (95, 93 % TD)
   - pellet/clad gap (80, 150, 250 µm)

4. Pre-Irradiation

   reactor : R 2, Studsvik, capsule BWR condition

   burnup levels: 9 - 23 MWd/kgU

   LHGR : 340 - 440 W/cm high power period
   200 - 300 W/cm low power period

   alternating power history, about 70 days duration at high or low level

5. Re-Irradiation

   reactor : R 2 Studsvik, loop BWR condition

   type of power history: ramping, single step

   preconditioning : 1 day at 230 - 410 W/cm (equal to last pre-irradiation period level)

   LHGR : 380 - 650 W/cm

   power change : 20 - 250 W/cm (relative to max. power level during pre-irradiation)

   hold time : 24 hrs (25 min one rod)

   power change rate : 40 W/cm min

6. Main Results

   - Failure threshold power at about 420 W/cm, independent of burnup (9 - 22 MWd/kg), defined by fuel rods preirradiated at ≤ 360 W/cm peak power
   - Safe power step above highest pre-irradiation power level found to be < 70 W/cm
   - Fission gas release increases sharply with ramp power level from 2 - 3 % below 420 W/cm to 14 % at 480 W/cm
   - Incipient cracks found in clad of unfailed rods with a ramp power step of ~ 70 W/cm
   - Clad condition (recrystallized vs. cold worked, stress relieved) and pellet/clad gap size between 80 and 150 µm did not influence ramp behaviour
   - Well documented data set for fuel modelling established
   - Consistent reduction of time to release of fission products from the failed fuel rod to the water coolant as function of power ramp increment above the failure threshold

7. Project Period and Status

   1975 - 1979

   complete, free public use of information granted to the participants

8. Sponsoring Organizations

* AB ASEA-ATOM	Sweden
Comitato Nazionale per l'Energia Nucleare and Nuclital	Italy
Commissariat à l'Energie Atomique	France
Electric Power Research Institute	USA
Exxon Nuclear Company, Inc.	USA
Institutt for Energiteknikk	Norway
Japan Atomic Energy Research Institute	Japan
Kraftwerk Union Aktiengesellschaft	Germany
Oskarshamnsverkets Kraftgrupp AB	Sweden
Risö National Laboratory	Denmark
Statens Vattenfallsverk	Sweden
* Studsvik Energiteknik AB	Sweden
Sydsvenska Kraft AB	Sweden
Technical Research Center of Finland	Finland

* also actively involved in experimental performance

9. References

1. G. R. Thomas, The Studsvik Interramp Project, Journal of Nuclear Materials 87 (1979) pp 215 - 226
2. H. Mogard et al., The Studsvik Interramp Project, an International Power Ramp Experimental Study, ANS Topical Meeting on LWR Fuel Performance, Portland, April/May 1979
3. H. Stehle et al., LWR Fuel Behaviour during Operational and Overpower Transients, ANS/ENS Topical Meeting on Reactor Safety Aspects of Fuel Behaviour, Sun Valley, August 1981

Appendix 2/1

Studsvik Demoramp I Project

1. Managing Organization

Studsvik Energiteknik AB, Nyköping, Sweden

2. Objectives

- Effect on ramp behaviour of a combination of "remedial" design modifications
- Comparison to Interramp data of failure threshold, cladding deformation and fission gas release
- Behaviour of hollow fuel pellets

3. Fuel Rod Characteristics

Zry-2 clad UO_2 rod segments, BWR 8 x 8

number of rods	:	5	
diameter	:	12.5 mm	similar to Interramp rods
length	:	528 mm	similar to Interramp rods

design specifics:

- annular UO_2-pellets (i.d./o.d.: 3.5/10.6 mm)
- large grain size by niobia addition (0.4 - 0.5 %)
- helium fill pressure: 3 - 5 bar

4. Pre-Irradiation

reactor: Ringhals I (BWR)
burnup : 16 MWd/kgU
LHGR : 250 W/cm

5. Re-Irradiation

reactor	:	R-2 Studsvik, loop BWR condition
type of power history	:	ramping, single step, except for first test (staircase ramp) to indicate level of possible failure threshold
preconditionning	:	250 W/cm, 24 hrs
LHGR	:	400 - 500 W/cm
hold time	:	24 hrs

6. Main Results

The project has met all it's objectives successfully

7. Project Period and Status

1979 - 1982 final report under preparation

8. Sponsoring Organizations

Electric Power Research Institute	USA
Japan Atomic Energy Research Institute	Japan
Studsvik Energiteknik AB	Sweden
Swedish State Power Board	Sweden

9. No public reference

Appendix 3/1

Studsvik Demoramp II Project

1. Managing Organization

Studsvik Energiteknik AB, Nyköping, Sweden

2. Objectives

Investigation of the PCI failure mechanism in transient type ramp tests with short hold times above the failure threshold

- Establish failure threshold with respect to Interramp data
- Study of fission gas release, fuel restructuring, clad permanent deformation and stress corrosion crack formation

3. Fuel Rod Characteristics

8 BWR Zry-2 clad (CW, SR) UO_2 rods

diameter	:	12.5 mm
length	:	~ 400 mm
fill gas	:	1 bar Helium
pellet/clad gap	:	200 μm
pellet density	:	10.5 g/cm^3

4. Pre-Irradiation

reactor: Würgassen (BWR)
burnup : 26 - 29 MWd/kgU
LHGR : 220 (290) ⤳ 180 W/cm

5. Re-Irradiation

reactor	:	R-2 Studsvik, loop BWR condition
type of power history	:	ramping and transient type tests (9 tests,one rod reramped)
preconditionning	:	300 W/cm, 24 hrs
LHGR	:	380 - 485 W/cm
power change rate	:	40 and 200 W/cm min
hold time (two tests)	:	24 and 1 hrs
time above preconditionning level for transient typ tests	:	1 to 10 min

6. Main Results

- Failure threshold bracketed relative to Interramp results
- Non-penetrating stress corrosion cracks formed in very short times dependent on power increment above failure threshold
- Fission gas release, fuel restructuring and clad permanent strain determined

7. Project Period and Status

1979 - 1981

complete, free public use of information by the participants not before January 1983

8. Sponsoring Organizations

Comitato Nazionale per l'Energia Nucleare	Italy
Institutt for Energiteknikk	Norway
Japan Atomic Energy Research Institute	Japan
Kraftwerk Union AG	Germany
Risø National Laboratory	Denmark

US Nuclear Regulatory Commission	USA
Studsvik Energiteknik AB	Sweden
Swedish Nuclear Power Inspectorate	Sweden

9. Reference

publication planned in Journal of Nuclear Materials, 1983

Appendix 4/1

Studsvik Overramp Project

1. Managing Organization

Studsvik Energiteknik AB, Nyköping, Sweden

2. Objectives

Ramp behaviour of PWR commercial type fuel rods
- Failure threshold as fct. of burnup
- Influence of design variables
- Influence of ramp testing parameters
- Provision of data for predictive fuel modelling

3. Fuel Rod Characteristics

39 PWR Zry-4 clad (CW, SR) UO_2 rods

rod group	number	type	diameter mm	length mm	remarks
1	24	16 x 16	10.75	~ 400	1) 2) 3)
2	15	17 x 17	9.5	~ 1,130	2) 4)

Design variables:
1) UO_2 grain size (4.5; 6; 22 μm)
2) pellet microstructure and geometry
3) clad condition (different final heat treatment)
4) Helium fill pressure

4. Pre-Irradiation

rod group	reactor	burnup MWd/kgU	LHGR (avg) W/cm
1	Obrigheim	12 - 31	200 - 250 ⇝ 180 - 250
2	BR-3, Mol	16.5 - 24	100 - 190

5. Re-Irradiation

reactor : R-2 Studsvik, loop PWR conditions
type of power history: ramping, single step
pre-conditionning : 300 W/cm, 72 hrs

rod group	LHGR W/cm	ramp rate W/cm min	hold time hrs
1	395 - 530	100 *)	24 (10 min)
2	375 - 450	100 *)	24

*) some tests with reduced ramp rates (0.5; 1; 5 W/cm min)

6. Main Results

- Failure thresholds were determined which lie between 420 and 520 W/cm depending on burnup, design and operating paramters
- Reduced ramp rates (~ 1 W/cm min) did not provide a distinct benefit in passing the threshold
- Fission gas release was strongly influenced by the UO_2 initial grain size
- A data base was provided for modelling on steady state and transient performance characteristics over a significant ramp of design and operating conditions

7. Project Period and Status

1977 - 1980 completed,
free public use of information by the participants not before January 1983

8. Sponsoring Organizations

* Combustion Engineering Inc.	USA
Comitato Nazionale per l'Energia Nucleare	Italy
Electric Power Research Institute	USA
Framatome	France
Institut for Energiteknikk	Norway
Japan Atomic Energy Research Institute	Japan
* Kraftwerk Union Aktiengesellschaft	Germany
Risö National Laboratory	Denmark
Statens Vattenfallsverk	Sweden
* Studsvik Energiteknik AB	Sweden
Valtion Teknillinen Tutkimuskeskus	Finland
* Westinghouse Electric Corporation	USA

* also actively involved in experimental performance

9. References

1. T. E. Hollowell et al., The International Overramp Project at Studsvik, *ANS Topical Meeting on LWR Extended Burnup-Fuel Performance and Utilization*, Williamsburg, April 1982

2. H. Stehle et al., LWR Fuel Behaviour during Operational and Overpower Transients, ANS/ENS Topical Meeting on Reactor *Safety Aspects of Fuel Behaviour*, Sun Valley, August 1981

Appendix 5/1

Studsvik Superramp Project

1. Managing Organization

Studsvik Energiteknik AB, Nyköping, Sweden

2. Objectives

Ramp behaviour of BWR and PWR commercial type fuel rods at high burnup (30 - 45 GWd/tU)

- Determine failure threshold for standard type fuel rods
- Investigate failure mode and related phenomena for comparison with lower burnup data
- Establish influence of design modifications on ramp behaviour (PWR subprogramme)
- Establish reduced ramp rates for safely passing the failure threshold (BWR subprogramme)

3. Test Rod Characteristics

28 PWR Zry-4 clad (CW, SR) UO_2 rods
16 BWR Zry-2 clad (recrystall.) UO_2

rod group	number	type	diameter mm	length mm	Helium bar	remarks
PK	19	PWR	10.75	~ 400	22.5	1) 2) 4)
PW	9	PWR	9.5	~ 1.130	13.8	3)
BK	8	BWR	12.5	~ 400	1	
BG	8	BWR	12.5	~ 980	1	4) 5)

design varibles:
1) UO_2 grain size (6; 20 µm)
2) UO_2 with 4 % Gd_2O_3 addition
3) annular pellets
4) small pellet/clad gap (100 - 140 µm)
5) reduced clad wall thickness (0.71 mm)

4. Pre-Irradiation

rod group	reactor		burnup MWd/tU	LHGR W/cm
PK	Obrigheim	(PWR)	32.5 - 45	200 - 250 - 200 - 130
PW	BR-3	(PWR)	35 - 40	120 - 180
BK	Würgassen	(BWR)	32 - 38	210 - 220 - 190 - 140
BG	Monticello	(BWR)	27 - 33	220 (140 max) (avg of 6 cycles)

5. Re-Irradiation

reactor : R-2 Studsvik, loop PWR or BWR condition
type of power history: ramping
preconditionning : 250 W/cm, 24 hrs

rod group	LHGR W/cm	ramp rate W/cm min	hold time hrs	remarks
PK	390 - 505	100	12	one rod, 10 min h.t.
PW	350 - 430	100	12	
BK	300 - 410	100	12 (24)	1) 2)
BG	up to 440	0.04 - 1.5	12	3)

1) two tests with preconditionning 180 W/cm, 24 hrs
2) some tests performed in power steps equivalent to an average rate of about 0,05 W/cm min

3) investigation of safe ramp rate above 270 W/cm

6. Main Results

- Burnup dependence of failure threshold evaluated relative to low and medium burnup data from Interramp and Overramp Projects
- Influence of design modifications determined
- Influence of clad temperature during ramping investigated
- Influence of preconditionning power level studied for BWR rods
- Ramp rates for safely passing failure threshold investigated (BWR)
- Fission gas release, fuel restructuring, clad permanent strain after ramping determined

7. Project Period and Status

1980 - 1982
- ramping nearly complete
- post-irradiation examination in progress
- final report to be finished beginning of 1983

8. Sponsoring Organizations

Babcock & Wilcox	USA
Belgonucléaire S.A.	Belgium
* Combustion Engineering Inc.	USA
Comitato Nazionale per l'Energia Nucleare	Italy
Electricité de France	France
Electric Power Research Institute	USA
Elektrizitätsgesellschaft Laufenburg AG (represents also three other Swiss utilities)	Switzerland
Exxon Nuclear Co	USA
* General Electric Co	USA
Institutt for Energiteknikk	Norway
Japan Atomic Energy Research Institute	Japan
Kernkraftwerk Philippsburg GmbH	Germany
* Kraftwerk Union AG	Germany
Rheinisch-Westfälisches Elektrizitätswerk AG	Germany
Risø National Laboratory	Denmark
* Studsvik Energiteknik AB	Sweden
United States Department of Energy	USA
Valtion Teknillinen Tutkimuskeskus	Finland
* Westinghouse Electric Corporation	USA

* also actively involved in experimental performance

9. No public reference

Appendix 6 / 1

KWU/CE/DOE High Burnup PWR Ramp Test Programme

1. Managing Organizations

Combustion Engineering Inc., Windsor/Connecticut, USA
Kraftwerk Union AG, Erlangen, Germany

2. Objectives

Ramp behaviour of high burnup PWR fuel rods (20 ramp tests)

- Failure thresholds of standard rods
- Operational conditions to safely pass failure threshold
- Effect of design modifications
- Influence of additional burnup after ramping on further ramp behaviour
- Background data report on 68 ramp tests previously performed (intermediate burnup range).

3. Fuel Rod Characteristics

18 PWR Zry-4 clad (CW, SR) UO_2 rods

diameter	:	10,75 mm
length	:	390 mm
fill gas	:	22,5 bar Helium

design variables:

- pellets without pore former, standard pellet/clad gap 190 µm
- pellets with pore former (20 µm grain size): standard and barrel shaped geometry; clad internally graphite coated

4. Pre-Irradiation

reactor: Obrigheim

burnup : 30 - 47 MWd/kgU

LHGR : 250 ⤳ 185 W/cm

5. Re-Irradiation

reactor	:	HFR Petten, capsule PWR condition
type of power history:		ramping (IS, ISM and repeated ramps after additional burnup accumulation)
pre-conditionning	:	200/250 W/cm, 72 hrs
LHGR	:	385 - 465 W/cm
hold time	:	10 min to 52 hrs
power change rate	:	normally 100 W/cm min; slow ramp rate 0,05 W/cm min

6. Main Results

- High burnup failure thresholds, dependence on burnup, conditionning power level, and design modifications
- Fission gas release, fuel structure changes, and general performance data after ramping, dependence on burnup, ramp power level, and hold time
- Report on background ramp test data at intermediate burnup levels

7. Project Period and Status

1980 - 1983

- 12 of 20 ramp tests performed
- post-ramp examinations started
- background data report nearly complete

8. Involved Organizations

Combustion Engineering Inc.	USA
Department of Energy	USA
* Joint Research Centre, Petten Establishment	EURATOM
* Kernforschungsanlage Jülich GmbH	Germany
* Kraftwerk Union Aktiengesellschaft	Germany

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* actively involved in the experimental performance

9. No public reference

Appendix 7/1

TRIBULATION International Programme

1. Managing Organization

Centre d'Etude de l'Energie Nucléaire, Mol, Belgium

Belgonucléaire S.A., Brussels, Belgium

2. Objectives

- Irradiation behaviour of PWR fuel rods with various design and fabrication parameters up to high burnups

- Fuel rod behaviour during fast transients with short duration at intermediate burnups
- Behaviour during further irradiation after fast transients

3. Fuel Rod Characteristics

UO_2 rods with Zry-4 clad, CW SR
number of fuel rods: 48 (10 groups of 3 to 7 rods)

diameter 9.5 mm
total length 1,136.0 mm

design variables:

- pellet:
  UO_2 powder conversion process (ADU, IDR, AUC);
  geometry (L/D = 1; 1.5; solid/annular)
- clad:
  wall thickness (s/D = 0.066; 0.059), heat treatment
- He fill pressure (1; 15 - 20; 30 bar)

4. Pre-Irradiation

reactor : BR-3, Mol

burnup levels: 20; 40; 60 - 70 MWd/kgU
(peak pellet)

LHGR : typical for 17 x 17 PWR design;
some rods ~ 490 W/cm

5. Re-Irradiation

5.1 Transients of Short Duration (at 20 or 40 MWd/kgU)

reactor	:	BR-2, capsule PWR condition
preconditionning	:	250 - 300 W/cm, 2 days
power change	:	70 - 210 W/cm
power change rate	:	5 - 10 %/sec
hold time	:	1 - 10 min

5.2 Irradiation after Transient

reactor	:	BR-3
burnup target	:	60 - 70 MWd/kgU
LHGR	:	typical for 17 x 17 PWR design

6. Main Results

Fuel rod behaviour as a function of burnup, after transients and after further irradiation:

- cladding diameter and length change, integrity
- fuel column behaviour
- UO_2 fission gas release and microstructural changes
- mechanical/chemical pellet-clad interaction

7. Project Period and Status

1980 - 1986

- pre-irradiation in BR-3
  partly complete and continuing
- first series of transients under way

8. Sponsoring Organizations

* Brown Boveri Reaktor GmbH	Germany
Babcock and Wilcox	USA
* Belgonucléaire	Belgium
* Centre d'Etude de l'Energie Nucléaire	Belgium
Department of Energy, U.S. Government	USA
Eidgenössisches Institut für Reaktorforschung	Switzerland
Electric Power Research Institute	USA
Electricité de France	France
* Fragema	France
Institute of Nuclear Energy Research	Rep. of China
Mitsubishi Heavy Industries (also representing two other fuel vendors and five utilities from Japan)	Japan
Nordostschweizerische Kraftwerke AG (also representing three other Swiss utilities)	Switzerland
Studsvik Energiteknik AB	Sweden
United Kingdom Atomic Energy Authority	Great Britain
* Westinghouse Electric Corporation	USA

* also actively involved in experimental performance

9. References

1. H. Bairiot et al., TRIBULATION High Burnup Behaviour of Fuel Subjected to Transients, CSNI Specialists' Meeting on Safety Aspects of Fuel Behaviour in Off-Normal and Accident Condition
Espoo, Finland, 1980

2. D. Haas, TRIBULATION, Objectives and Present Status, ANS Topical Meeting on LWR Extended Burnup-Fuel Performance and Utilization, Williamsburg, April 1982 (extra paper)

Appendix 8 / 1

Related Tasks within the OECD Halden Reactor Project

1. Managing Organization

Institutt for Energiteknikk, Halden, Norway

2. Objectives

2.1 Ramping

- Identify failure thresholds of unpressurized fuel rods as a fct. of design parameters and base irradiation power and burnup
- Characterize ramping behaviour of different fuel rod designs by in-pile measurement of diameter and length changes, fuel temperature and rod internal pressure (fission gas release)
- Correlate post-irradiation examination results with in-pile measurements

2.2 Fission Gas Release

- Investigate fission gas release during and after steady state operation and ramping
- Assess and seperate the effects of power and burnup
- Identify the effects of design parameters (e.g. gap size, Helium pressure, UO_2 grain size)
- Establish the kinetics of the release process over a broad fuel temperature range
- Correlate the release to the thermal state of the fuel, to the fuel microstructural characteristics and to time (burnup)

3. Fuel Rod Characteristics

~230 Experimental Zry clad UO_2 rods
active length: 390 - 505 mm

rod group	number	diameter mm	gap size µm	UO_2 density % T.D.	remarks
1 ramping	53	10.75 – 14.3	60 – 310	90 – 98	1)
2 ramping, mechanistic studies	71	9.5 – 14.3	60 – 250	94 – 96	2) 4)
3 fission gas release, instrumented rods	108	9.5 – 18.8	40 – 380	91 – 96	3) 5)

instrumentation:
1) clad extensometer, fuel thermocouples during base irradiation only
2) fuel thermocouples, pressure transducers, clad and fuel stack extensometers, diameter gauges
3) fuel thermocouples, pressure transducers, gas flow and γ-spectrometry

design variables:
4) annular pellets, UO_2 grain size (doped fuel), VIPAC and SPHEREPAC fuel duplex fuel, Helium pressure, non-penetrating i.d. cracks (2 rods)
5) Helium pressure, large grain size UO_2, duplex fuel

4. Pre-irradiation

reactor	:	HBWR, Halden
coolant temperature	:	240 °C
coolant pressure	:	34 bar
fast flux/LHGR	:	$5 \cdot 10^{10}$ [Wcms]$^{-1}$

rod group	burnup MWd/kg U	LHGR W/cm	type of power history	remarks
1	5.6 - 28.4	170 - 420	constant or decreasing with exposure	
2.1	6.5 - 22.5	250 - 360 (480)	constant power	
2.2	7 - 11	250 - 300	"	loop at PWR or BWR conditions
3	0 - 45	300 - 650	constant power and/or ramp	

5. Re-Irradiation

reactor: HBWR, Halden

rod group	LHGR W/cm	type of power hist.	ramp rate W/cm min	hold time hrs
1	350 - 650	ramping	0.06 - 30	4 - 20
2	430 - 550	ramping	20 - 50	10 - 500
3*	430 - 650	ramping	20 - 50	4 - 500

* only 36 rods ramped,
on 8 gas flow rods fuel temperature changed
by fill gas exchange (He, Ar, Xe)

6. Main Results

6.1 Ramping

- The failure threshold of HBWR experimental rods has been assessed (~650 W/cm at 5 MWd/kg, ~500 W/cm at 10 MWd/kg, ~480 at 20 MWd/kg)
- The pre-irradiation power level influences the failure occurence if it is less than 100 - 120 W/cm below the failure threshold
- Failure is often accompanied by permanent ridging (typically ≥ 0.1 %)
- Large gap size has a positive effect typically below 10 MWd/kg. At higher burnups the effect is cancelled
- Low density fuel exhibits more rapid relaxation of elastic clad deformation, resulting in higher PCI resistance (also true for Vipac and Spherepac rods)
- Annular pellets and duplex fuel operate at lower fuel center temperature accompanied by less mechanical interaction and fission gas release during ramping (to be confirmed for annular pellets)

6.2 Fission gas release

- Steady state fission gas release is primarily determined by the fuel temperature
- Significant release is only observed after an incubation period (burnup) which is strongly dependent on temperature (formation of grain boundary fission gas bubbles and bubble interlinkage)
- The feed-back effect of released fission gas on fuel temperature has been measured and appears to depend on gap size
- Steady state and transient fission gas release after ramping show a square root time dependence
- Only transient fission gas release at high centre temperatures after ramping (≳ 1600 °C) is influenced by UO_2 grain size (large grain size - low release)

7. Project Period and Status

OECD Halden Reactor Project started in 1958 with three years programme periods.
Present period 1982 - 1984

8. Sponsoring Organizations
(present programme period)

Signatories

Central Electricity Generating Board	Great Britain
Danish Ministry of Energy	Denmark
Finnish Ministry of Trade and Industry	Finland
Italian Comitato Nazionale per l'Energia Nucleare	Italy
Japan Atomic Energy Research Institute	Japan
Kernforschungsanlage Jülich GmbH	Germany
Netherlands Energy Research Foundation	The Netherlands
Norwegian Institutt for Energiteknikk	Norway
Swedish Nuclear Power Inspectorate	Sweden
United States Nuclear Regulatory Commission	USA

Associated Parties

Electric Power Research Institute	USA
General Electric Company	USA
Combustion Engineering	USA

9. References

Annual Reports from the OECD Halden Reactor Project, published by NEA

B. Aarset: "In Reactor Instrumentation for Fuel Behaviour Studies at the OECD Halden Reactor Project". Paper presented at the ANS Conf. on Fast, Thermal and Fission Reactor Experiments, Salt Lake City, USA (1982)

C. Vitanza: "Fission Gas Release from UO_2 Fuel". Paper presented at the ENC, Hamburg, Germany (1979)

K. Vilpponen: "In-Pile Measurements of Pellet Cladding Interaction and Relaxation". Paper presented at the IAEA Spec. Meeting, Blackpool, Great Britain (1980)

K. Vilpponen et al.: "Fuel Performance Under Ramping Conditions in the HBWR". IAEA Spec. Meeting, Risø, Denmark (1980)

High Burnup Effects Programme (HBEP)

1. Managing Organization

Battelle Pacific Northwest Laboratories, Richland, USA

2. Objectives

- High burnup behaviour of LWR fuel rods with emphasis on fission gas release
- Task 1: State-of-technology assessment
- Task 2: Fission gas sampling of existing rods
  (A) + (B) after commercial operation
  (C) after additional bumping to high power
- Task 3: Parameter effects study by irradiation and examination of new fuel rods

3. Fuel Rod Characteristics

81 Zry clad UO_2 rods

rod group	number	type	diameter mm	length mm	remarks
	Task 2 (A) + (B)				
1	9	PWR	10.75	~ 400	1) 2) 3) 4)
2	12	PWR	10.75	~ 1.130	4)
3	4	BWR	12.5	~ 400	
4	4	BWR	12.5	~ 980	
	Task 2 (C)				
5	12	PWR	10.75	~ 400	
6	4	BWR	12.5	~ 980	
	Task 3				
7	36	PWR	9.5	~ 1 130	1) 2) 4)

Design variables:
1) UO_2 grain size
2) annular pellets
3) Gd_2O_3/UO_2 pellets
4) He-prepressure

4. Pre-Irradiation

rod group	reactor	burnup MWd/kg U	LHGR (avg) W/cm
	Task 2 (A) + (B)		
1	Obrigheim (PWR)	23 - 46	280 ⇝ 180
2	BR-3, Mol (PWR)	36 - 46	475 ⇝ 130
3	Würgassen (BWR)	29 - 38	300 ⇝ 120
4	Monticello (BWR)	25 - 33	190 ⇝ 120
	Task 2 (C)		
5	Obrigheim	23 - 46	280 ⇝ 180
6	Monticello	25 - 33	190 ⇝ 120
	Task 3		
7	BR-3, Mol	31 - 80	410 - 320 - 190 1)

1) Three different power histories, generally decreasing with burnup

5. Re-Irradiation

rod group	reactor	type of power hist.	LHGR W/cm	hold time hr
	Task 2 (C)			
5	HFR Petten 2)	bumping 1)	300 - 492	48 (191)
6	R 2 Studsvik 3)	bumping 1)	375 - 450	48

1) Power change rate during bumping 5 W/cm hr

2) Capsule PWR condition

3) Loop BWR condition

6. Main Results

Task 1: Evaluation of published high burnup fission gas data (Ref.2)

Task 2: Fission gas release, fuel structure, general performance data after
(A) + (B) commercial power reactor irradiation and
(C) re-irradiation at high power level of short duration

Task 3: Fission gas release and fuel structure data for different fuel design parameters as a function of burnup above 30 MWd/kgU

Make data available in a computerized data base system.

7. Project Period and Status

1980 - 1987

Task 1: complete

Task 2: (A) and (B) nearly complete

Task 3: 1st irradiation cycle ends March 1983

8. Sponsoring Organizations

Brown Boveri Reaktor GmbH	FRG
Babcock and Wilcox	USA
* Belgonucléaire	Belgium
* British Nuclear Fuels Limited	Great Britain
Central Research Institute of Electric Power Industry	Japan
* Centre d'Etude de l'Energie Nucléaire	Belgium
Combustion Engineering, Incorporated	USA
Comitato Nazionale per l'Energia Nucleare	Italy
Department of Energy, U.S. Government	USA
Electric Power Research Institute	USA
Exxon Nuclear Company, Incorporated	USA
Framatome	France

* General Electric Company	USA
Hitachi, Limited	Japan
Japan Atomic Energy Research Institute	Japan
* Kraftwerk Union Aktiengesellschaft	Germany
Mitsubishi Heavy Industry, Limited	Japan
* Netherlands Energy Research Foundation	The Netherlands
Nuclear Fuels Industry, Limited	Japan
Risö National Laboratory	Denmark
* Studsvik Energiteknik AB	Sweden
Swiss Federal Institute for Reactor Research	Switzerland
Toshiba Corporation	Japan
Technical Research Center of Finland	Finland
Westinghouse Electric Corporation	USA

* also actively involved in experimental performance

9. References

1. M. D. Freshley, High Burnup Effects Programme - A Summary Status Report, ANS Topical Meeting on LWR Extended Burnup-Fuel Performance and Utilization Williamsburg, April 1982 (extra paper)
2. C. E. Meyer, An Evaluation of Published High Burnup Fission Gas Data, ANS Topical Meeting on LWR Extended Burnup-Fuel Performance and Utilization Williamsburg, April 1982

Appendix 10/1

Risö Fission Gas Project

1. Managing Organization

Risö National Laboratory, Risö, Denmark

2. Objectives

- Experimental data on fission gas release from high-burnup water reactor fuel

3. Fuel Rod Characteristics

12 Zry Clad UO_2 Rods

diameter: ~ 14 mm
length : 89 cm

4. Pre-Irradiation

Reactor	Burnup, avg.(peak) MWd/kgU	LGHR, avg. W/cm
Halden Reactor (Norway)	32 (44)	(390) 320 ~ 180

5. Re-Irradiation

Reactor	type of power hist.	peak LHGR W/cm	hold time hr
DR 3, Risö	9 rods "bump tested"	320 - 462	24 (one rod 72 hrs)

6. Main Results

Fission gas release (integral): Zero (below 400 W/cm)
0 - 16 % (400 - 462 W/cm)

Radial Xenon and Cesium distributions determined

7. Project Period and Status

1980 - 1981, complete

8. Sponsoring Organizations

British Nuclear Fuels Ltd.	Great Britain
Department of Energy	USA
Elkraft	Denmark
Elsam	Denmark
Exxon Nuclear Company	USA
General Electric Company	USA
Inspectorate of Nuclear Installations	Denmark
Institutt for Energiteknikk	Norway
Rheinisch-Westfälisches Elektrizitätswerk	Germany
Swedish Nuclear Power Inspectorate	Sweden
United Kingdom Atomic Energy Authority	Great Britain
Westinghouse	USA
Risö National Laboratory	Denmark

9. Reference

P. Knudsen, "The Risö Fission Gas Project - an Overview" ANS Topical Meeting on LWR Extended Burnup-Fuel Performance and Utilization, Williamsburg, April 1982