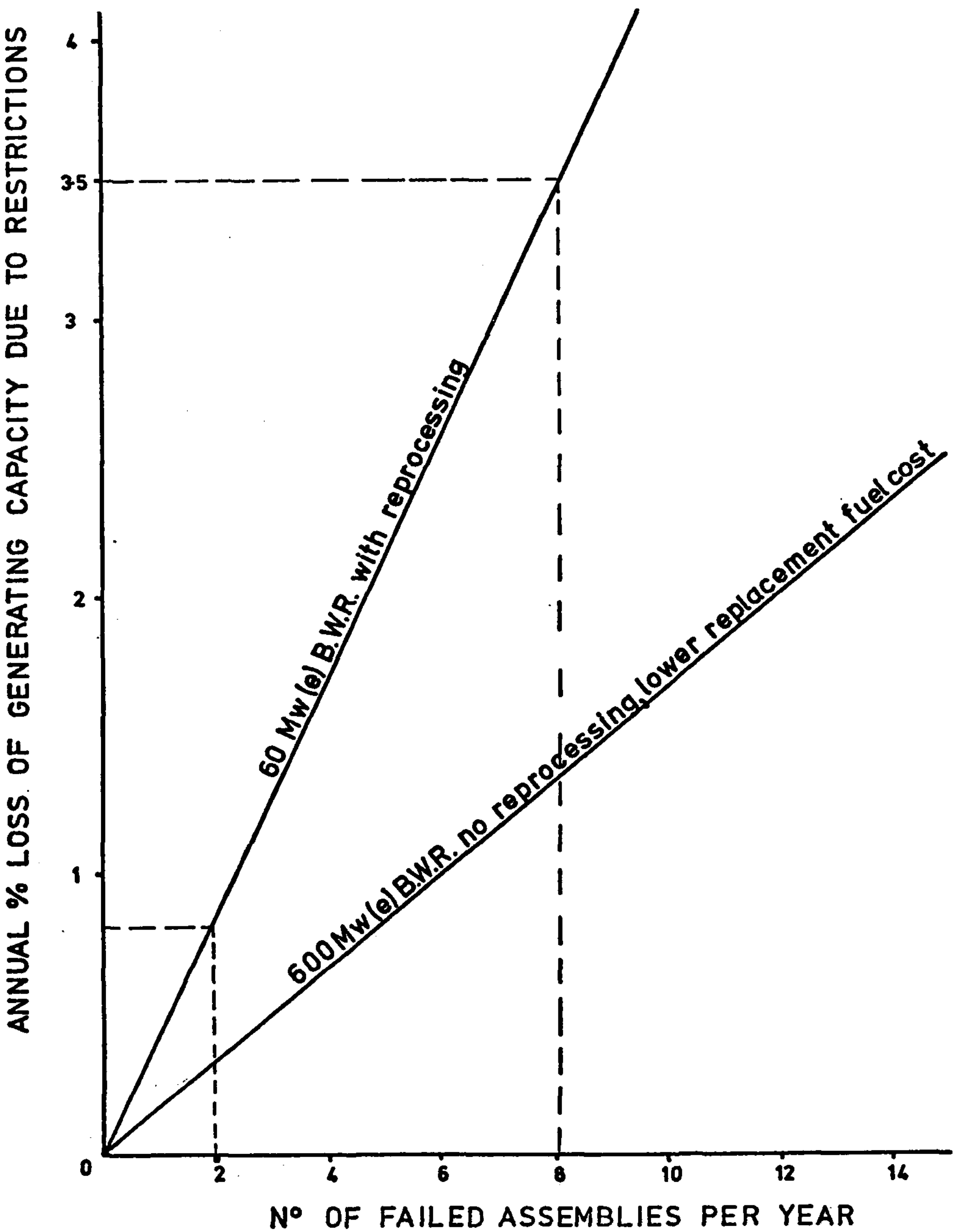

FIG.5. BREAK-EVEN RELATIONSHIP BETWEEN COST OF FAILURES AND COST OF RESTRICTIONS

THE COMBINED USE OF TEST REACTOR EXPERIMENTS AND POWER REACTOR TESTS FOR THE DEVELOPMENT OF PCI-RESISTANT FUEL

S. JUNKRANS, G. VESTERLUND, O. VĀRNILD
ASEA-ATOM AB,
Västerås, Sweden

ABSTRACT

The theme of this paper is that for development of PCI-resistent fuel acceptable from the commercial and licensing aspects, extensive and time-consuming work is needed both in a test reactor and in power reactors.

The test reactor is necessary for ramp testing to power levels not allowed in power reactors and with the aim of generating fuel failures. It is also used for other special irradiation experiments. The access to power reactors is necessary to generate information on performance in a real LWR core and to incubate at a reasonable cost the large amount of rods required for test reactor ramping.

Selected results from the ASEA-ATOM work are used to support these conclusions.

PCI IDENTIFICATION

for ASEA-ATOM the work in the PCI area started about 10 years ago. The first set of ramp experiments performed took place in the R2 reactor in early 1971. The aim was to reproduce the PCI-failures and to study the mechanism and its impact on LWR fuel (1).

Since these early experiments covered a range of rod designs and pre-irradiation conditions, it was suspected that PCI was a generic phenomenon affecting all types of Zircaloy-clad UO_2 fuel and that the failure propensity in principle was increasing with burn-up and power rating.

However, in the early 70's it was not clear what would be the quantified impact on the ASEA-ATOM BWRs with low-rated 8 x 8 fuel and maximum linear heat rating of 41.5 kW/m. To study this an extensive program was executed. This program consisted of three parts, namely:

- o pre-irradiation in power reactors (Ågesta 80 MW PHWR and Oskarshamn-1 440 MW BWR) of segmented test rods inserted during 1971-1974. The rods were of standard design or included minor design changes. Approximately 200 of these rods have later been ramp tested in R2 in Studsvik.
- o ramptesting in R2 of standard KAHL BWR fuel rods supplied by ASEA as part of a commercial delivery and irradiated to relatively high burn-up. Rods from 2 assemblies were used for this purpose and burn-up covered was up to 25 MWd/kg U.
- o to provide the link between the R2 test reactor ramp experiments, an exaggerated inpcore ramp was performed in the Oskarshamn-1 power reactor shortly before the summer shut-down in 1975.

Some significant results have been published previously (3, 4, 5, 6). The main conclusions serving to identify the PCI problem and quantify its impact for further use in the development work were:

- PCI failure levels in R2 ramps for medium burn-up fuel (15-25 MWd/kg U) comprising some tens of test rods is typically of the order of 45 kW/m.
- When some thousends of full size rods are exposed to fast ramps a small number of low-probability failures are found at lower power levels.
- By far the most powerful way of reducing the probability of PCI-failure was found to be to restrict the ramp rate and to avoid step-wize power changes. This reduced the impact on the ASEA-ATOM BWRs to a 0.4 % loss in capacity factor for non-failure fuel operation.
- There is reasonable agreement between results from ramp tests in a test reactor, e.g. R2, and in a power reactor provided corrections are taken for

  i) low-probability failures,

  ii) that the power increase rate in a power reactor may be much faster than in a test reactor,

  iii) that the power profile in a power reactor may be axially distorded during the ramp in a power reactor.

In figure 1 there is a comparison between a typical R2 ramp and a peak dury rod in the Oskarshamn-1 ramp experiment.

These conclusions were reached primarily through power reactor irradiations and tests and with the R2 test reactor rather as a necessary complement. The importance of the Oskarshamn-1 ramp experiment should be strongly emphasized (4).

PCI FAILURE MECHANISM

In the early days it was believed that PCI was mostly a mechanical phenomenon involving overstraining of the cladding. However, later fuel rod experiments revealed that failures occurred without plastic deformation of the cladding and that the cracks contained both a transgranular and an inter-granular portion. Stress corrosion testing of irradiated and unirradiated Zircaloy specimens in simulated fission product environments produced the same kind of cracks. Thus it was concluded that the failure mechanism was fission product induced stress corrosion cracking (SCC).

From these tests it was also concluded that

1) the most probable agressive agent is iodine as laboratory tests in iodine give cracks with both trans and intergranulor portions as also found in failed fuel rods,

2) A iodine concentration of only ~2 $\mu g/cm^3$ and thus low fission gas release is sufficient for SCC,

3) minor changes of the cladding such as texture, heat treatment or surface treatment were not effective remedies to the problem.

Considering test vs power reactors it is recognized that very important information has been derived from inspection of power reactor fuel rods. It has been shown that PCI failures in principle (although with low probability) can be generated at power ratings below 40 kW/m and that they are not necessarily accompanied by either plastic deformation of the cladding, exessive fission gas release or UO_2 grain growth. This would not have been easily found in test reactor experiments only.

DEVELOPMENT OF A NEW DESIGN

In developing a new fuel design that is accepted both from the commercial and from the licensing point of

view, several steps have to be taken.
These include

- theoretical analysis of the remedy design,
- laboratory testing both with respect to PCI resistence and to other effects,
- manufacturing process development,
- incubation and ramp testing of a significant number of rods to quantify the improvement or establish a conficence level. This is necessary since variations in behaviour may be found for any remedy due to variations in quality, irradiation history, burn-up, etc.,
- special irradiation experiments as deemed necessary, for instance operation of defect fuel,
- lead test rods or assemblies,
- large scale demonstration in a power reactor.

Basically there are two kinds of PCI remedy concepts illustrated by some concepts presently under development in Sweden. They are

- "improvement by kind" such as in the case of copper-plating the inside of the cladding providing a barrier between the fission products and the cladding metal,
- improvement by degree such as in the case of annular pellets.

In the first case the integrity of the remedy element under all conceivable operating conditions and with large scale production quality has to be demonstrated. In principle this may result in the verification of a PCI-immune fuel rod but requires a broad program with many different kinds of tests.

In the second case, the PCI situation is basically retained but the failure level is displaced. Thus the major task here is to quantify the improvement, which requires a large amount of tests in a more narrow program.

An illustration to the fact that an improved fuel design needs broad verification before it is accepted is given in figure 2 for the case of graphite coating.

A matrix of various limited design modifications was inserted in Oskarshamn-1 in 1974 and ramp tested in 1978 at a burn-up of 15 MWd/kg U. All concepts showed the same behaviour in that one or several rods failed at a power level of ~50 kW/m. The exception, however, was graphite coating, where all rods survived the ramp up to 65 kW/m. Yet this can only be regarded as a positive indication justifying further work but quite insufficient to make any quantitative statement as to the amount of improvement.

REFERENCES

1. H Mogard, S Aas, S Junkrans
Power Increases and Fuel Defection
Paper S-431 to the Geneva Conference, 1971

2. H Mogard, U Bergenlid, R Bodh, G Lysell
Experimental Investigations of the Power Ramp Failure Propensity of LWR Fuel
Paper to the International Conference on Nuclear Power and its Fuel Cycle, Salzburg, 2-13 May, 1977

3. S Junkrans, O Värnild
ASEA-ATOM Research on PCI
Paper presented at the ANS Topical Meeting on Water Reactor Fuel Performance, May 9-11, 1977, St Charles, Illinois

4. S Junkrans
ASEA-ATOM BWR Fuel Performance and Fuel Development
Paper presented at Nudex 78

5. S Junkrans, H Nerman
ASEA-ATOM Results on PCI Experiments on Fuel Rods, A Review
Paper presented at the Meeting on Ramping and Load Following Behaviour of Reactor Fuel, Petten, Netherlands, Nov 30 - Dec 1, 1979

6. O Värnild
Ramp testing of BWR fuel rods base irradiated in the Kahl reactor
Paper presented to the enlarged Halden Programme Group Meeting, Sanderstölen, 1977

OSKARSHAMN 1 IN-CORE RAMP EXPERIMENT

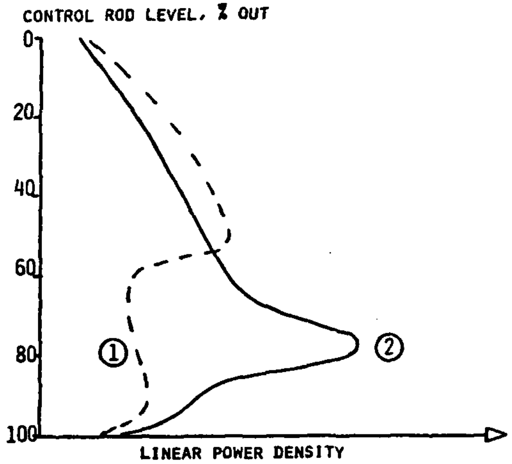

Fig 1a

R2 REACTOR

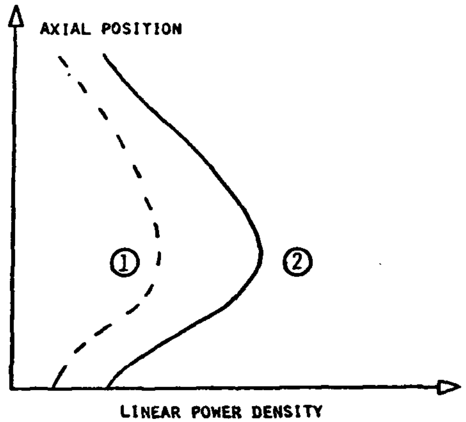

Fig 1b

Results of R2 ramp tests of Oskarshamn - 1 segments at burn-up of 15 MWd/kg U

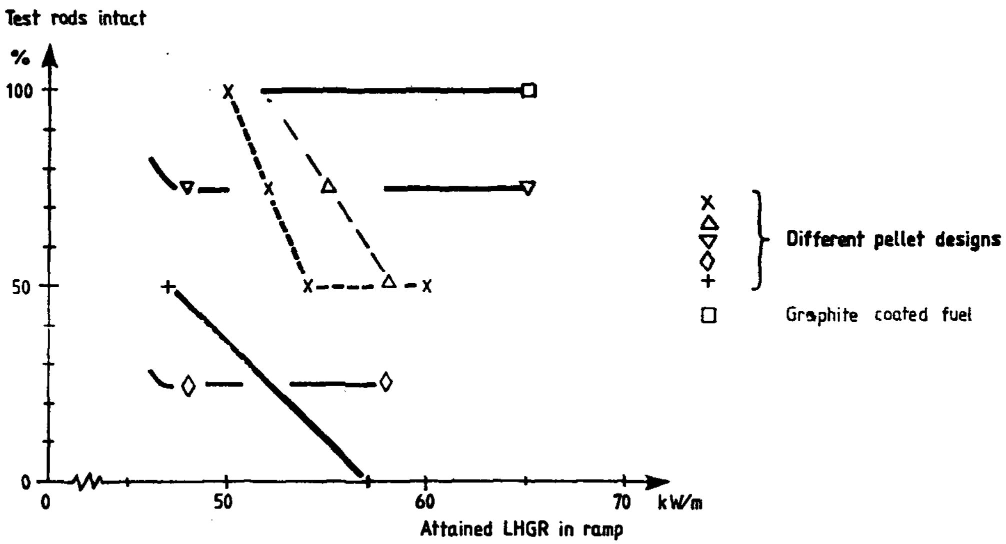

Fig 2

Session IV
(Part 1)

AVAILABLE RESULTS FROM THE EXPERIMENTAL PROGRAMME

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