The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1848-T12 - T13 a

Course on Natural Circulation Phenomena and Modelling in Water-Cooled Nuclear Reactors

25 - 29 June 2007

T12 & T13 - The Boiling Water Reactor Stability (part 1)

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THE BWR STABILITY ISSUE

F. D'Auria, A. Bousbia-Salah, A. Lombardi – Lectures T12 & T13

IAEA & ICTP Course on

NATURAL CIRCULATION IN WATER-COOLED NUCLEAR POWER PLANTS

Trieste, Italy, June 25-29 2007

CONTENT

- ✓ THE BWRS ISSUE
- ✓ A HISTORICAL PERSPECTIVE
- ✓ UNDERSTANDING OF INSTABILITIES
- ✓ BWR NPP PHENOMENOLOGY

  SYSTEM CONFIGURATION
  THE LA SALLE EVENT
  THE INSTABILITY EVENTS (planned & un-planned)
  THE ATWS
  SIGNIFICANT RESULTS
  RECENT FINDING

- ✓ BWRS CODES
- ✓ MONITORING AND LICENSING
- ✓ CONCLUSIONS (Q&A by W. Wulff and USNRC)

THE BWRS ISSUE

BWR MAIN DESIGN FEATURE:

TWO-PHASE MIXTURE IN CORE REGION

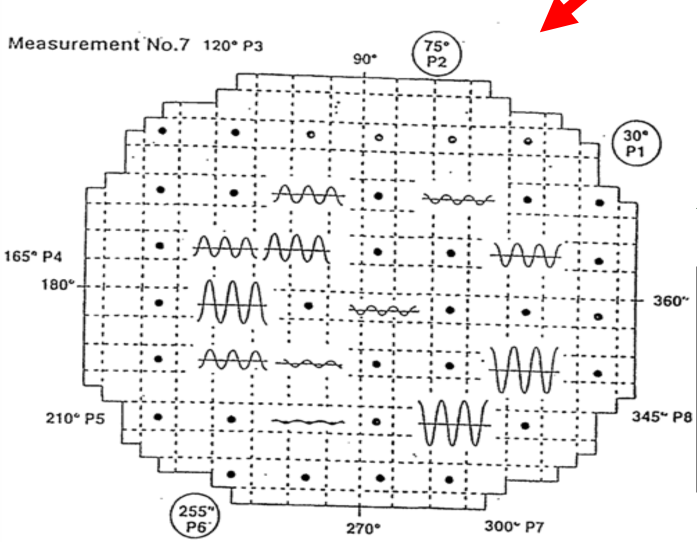
ADVANTAGES

DIRECT TH-DYN CYCLE
OVERALL SYSTEM SIMPLICITY

DRAWBACKS

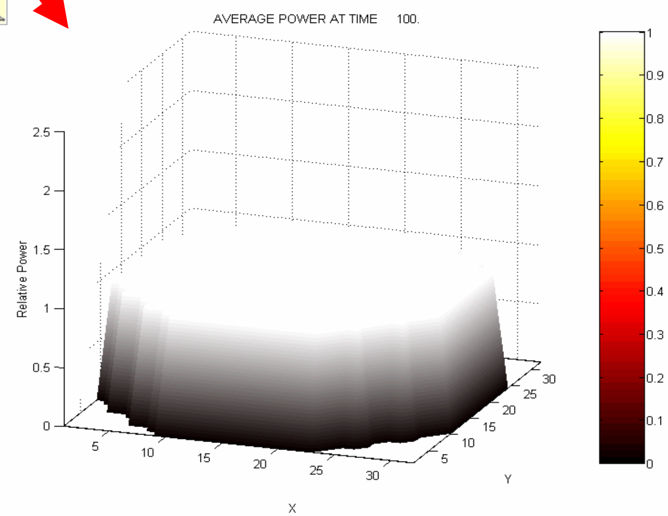
NK FEEDBACK AT VOID COLLAPSE
RADIOACTIVITY OUTSIDE CONT
RPV TH-DYN STABILITY

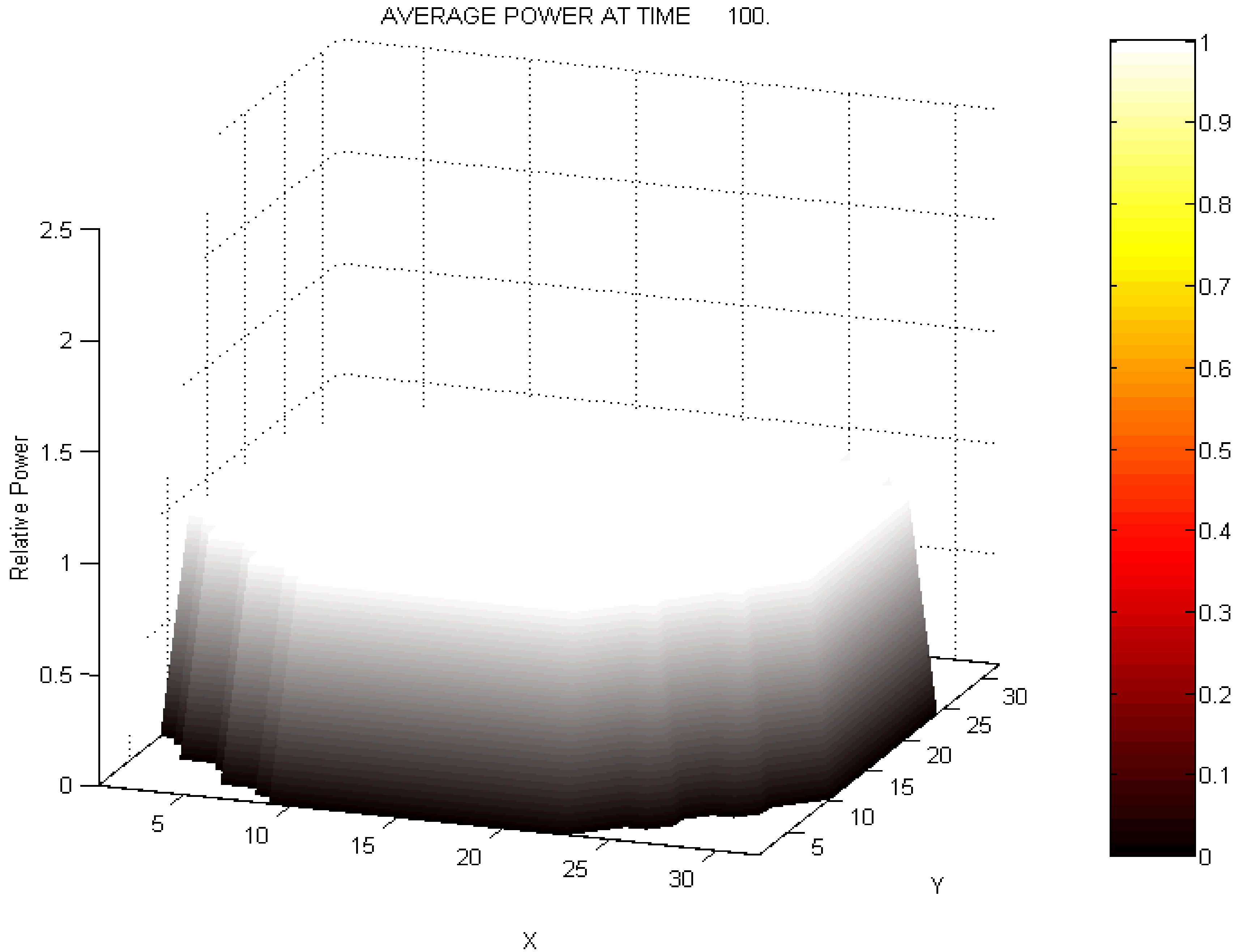
BWR POWER-FLOW MAP



SNAPSHOT

TIME BEHAVIOUR




AVERAGE POWER AT TIME 100.
Relative Power
0
0.5
1
1.5
2
2.5
X
5
10
15
20
25
30
Y
5
10
15
20
25
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

During early years of BWR technology ('50S), there was noticeable concern about nuclear coupled stability (SOAR).

GE proposed Dresden 1, with some questions of design and performance unanswered.

The dual cycle (about half of the turbine steam directly from the core) assured that the plant would be able to make at least half power based on PWR experience.

An electronic engineer recognized the BWR as an analogue of a feedback amplifier (Dresden Project): the feedback would become regenerative, and instability would be the result. At that time (1956), as construction of EBWR was nearing completion, an analysis of BWR dynamics started.

[redacted]

The analysis and the experiments for EBWR were in reasonable agreement (SOAR).

The stability tests at Dresden conducted in March and June 1960 at half power and at full power showed that the power-to-reactivity loop feedback was exceedingly stable, as predicted. The key factor was the oxide pellet fuel, having a long thermal time constant that served to attenuate the void reactivity feedback, preventing it from becoming regenerative.

It was then clear that a larger BWR could be designed without concern about stability eliminating the dual cycle.

No oscillation incident took place for several years of BWR operation.

A number of fuel modifications (& power increase) pose "new" stability problems in the late 70's and during the 80's. Even in the early 90's many of the operating BWR have experienced oscillation events.

[redacted]

[redacted]

Following the pioneering research in the EBWR and at the Vallecitos Laboratories (SOAR, 1957-1960), and an extensive modelling work in the 60's through the 80's (SOAR) the following milestones are identified:

*** An electronic engineer discovered …., 1956,**
*** Operation of the FRIGG loop in Sweden (starting from '60s),**
*** Development and diffusion of the NUFREQ code series (early '70s),**
*** Peach Bottom stability tests in 1977,**
*** Detecting regional oscillations in the Caorso NPP in the early '80s,**
*** Occurrence of the LaSalle event in 1988,**
*** Workshop in Brookhaven, in 1990,**
*** Implementation of safety measures in the operating plants in the '90s,**
*** Issue of the 'SOAR on BWRS' in 1997,**
*** Availability of coupled 3D NK-TH techniques & capability of simulating individual power channels (recent achievement).**

1) OECD/CSNI Report 178 – Proc. of Int. Workshop on BWRS – Brookhaven (US), Oct. 17-19, 1990
2) OECD/CSNI Report – SOAR on BWRS – OECD/GD(97)13, Paris (F), Jan. 1997

[redacted]

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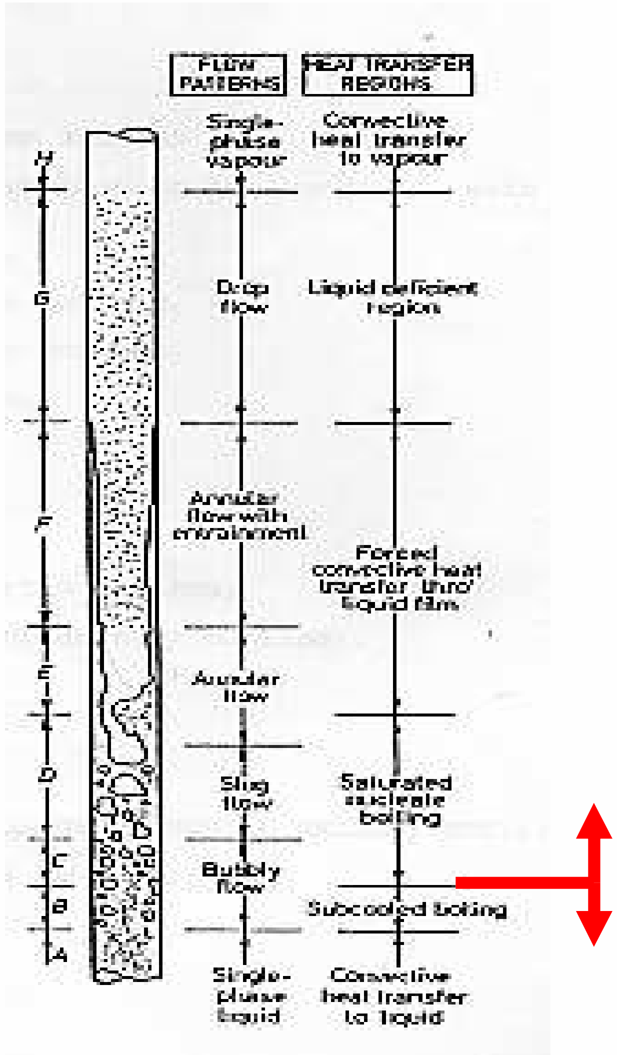
DYNAMIC INSTABILITY IN A BOILING CHANNEL (TH situation)

THE INCREASE IN INLET FLOWRATE CAUSES:

a) Upward movement of the boiling boundary (red line in the figure),
b) Increase of 1-Φ and decrease of 2-Φ length,
c) (Generally) decrease of channel overall DP.
Therefore,
d) Further increase of INLET FLOWRATE i.e. instability & upward propagation of 'high density plug' ➔ DWI



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DYNAMIC INSTABILITY IN A BOILING CHANNEL (TH situation) part 1 of 2

BALANCE EQS (HEM-EVET in this case)

[redacted]

$$\frac{\partial \langle \rho_h \rangle}{\partial t} + \frac{\partial G}{\partial z} = 0 \qquad (2)$$

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z}\left(\frac{G^2}{\langle \rho_h \rangle}\right) = - \frac{\partial P}{\partial z} - \left[\frac{f}{D_H} + \sum_{i=1}^{N} K_i \, \delta (z-z_i) \right] \frac{G^2}{2\langle \rho_h \rangle} + \langle \rho_h \rangle \, g \mathrm{Sin}\, \Theta \qquad (3)$$

$$\frac{\partial (\langle \rho_h \rangle \langle \bar{h} \rangle)}{\partial t} + \frac{\partial (G \langle h \rangle)}{\partial z} = \frac{q'' \, P_H}{A_{x-s}} + \frac{\partial P}{\partial t} \qquad (4)$$

PERTURBED AND LAPLACE TRANSFORMED

[redacted]

$$G(s) = \left[1 + \frac{X_1(s)}{X(s)} \right]^{-1} = \frac{\delta J_{fb}}{\delta J_{in}}$$

[redacted]

[redacted]

DYNAMIC INSTABILITY IN A BOILING CHANNEL (TH situation) part 2 of 2

STABILITY (ANALYSIS) RESULTS
<frequency and phase-space domains>

[redacted]

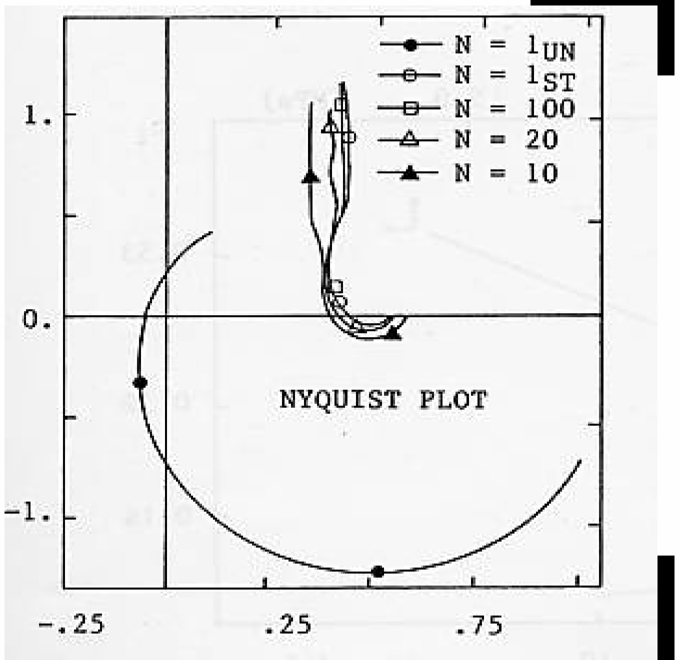


Fig. 10 - Effect on stability of the number of channels.

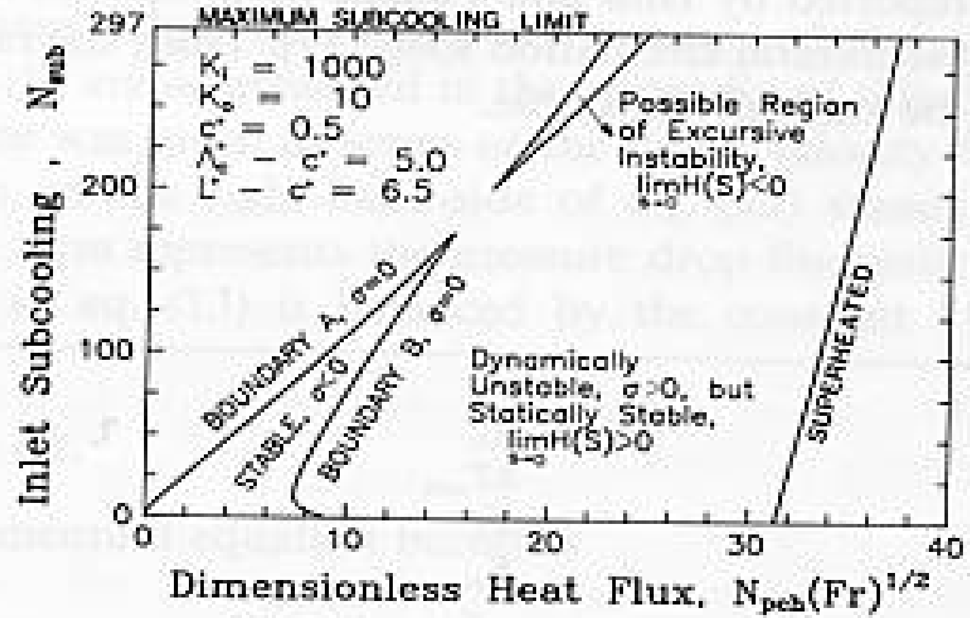


Fig. 3. Typical instability map.

[redacted]

[redacted]

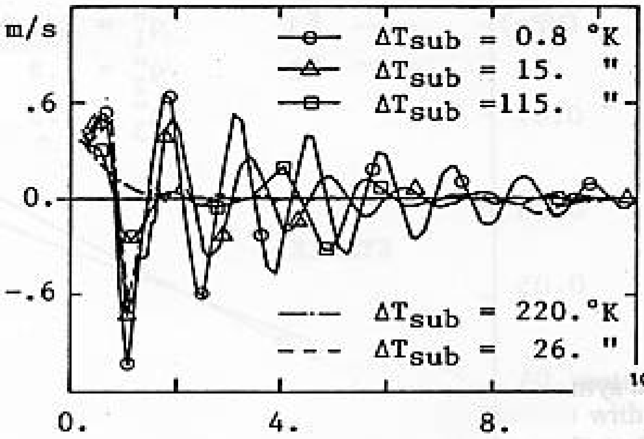
DYNAMIC INSTABILITY IN A BOILING CHANNEL (NK-TH situation) part 1 of 2

In BWR conditions, since the cooling fluid is also a moderator an oscillation in the core void content is reflected as a variation of neutron flux and of generated power that, in turn, affects the void. Coupled neutron-thermal/hydraulic systems may show stable or unstable behaviour or exhibit a self-sustained oscillating conditions called "stable-limit-cycle".

The stability of nominal operating conditions of BWR is ensured. this may not be the case in off-normal situations including ATWS or during start-up or shut-down.

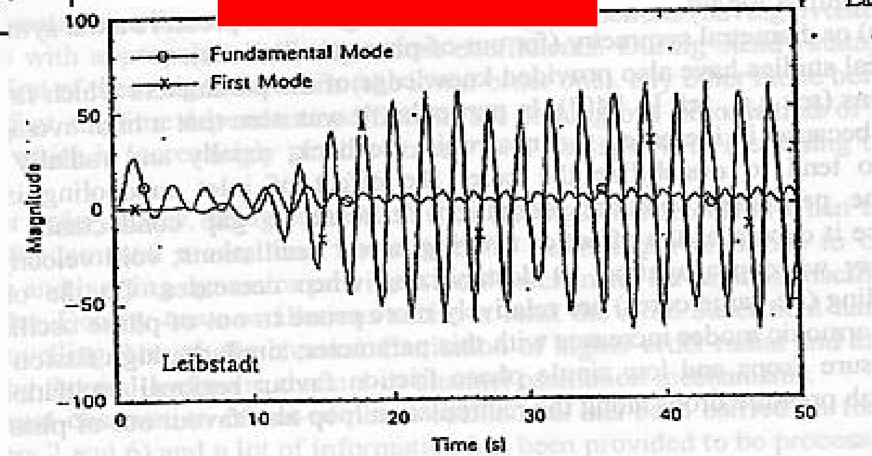
[redacted]

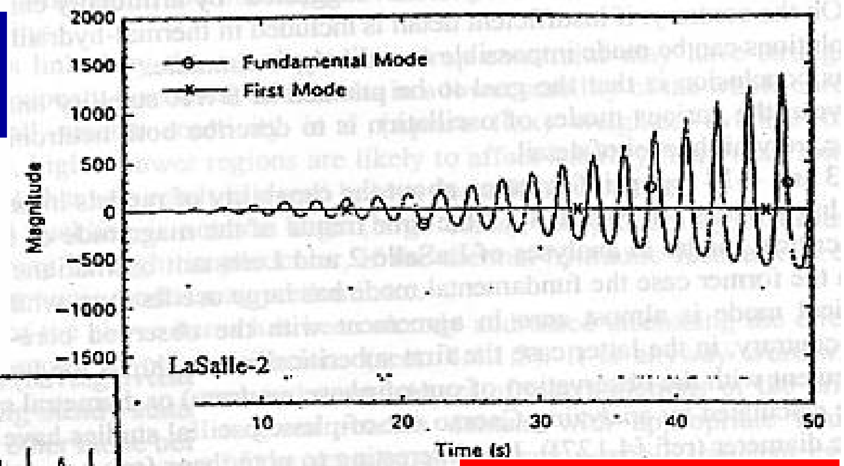
STABILITY RESULTS <time domain>



STABLE

LIMIT CYCLE



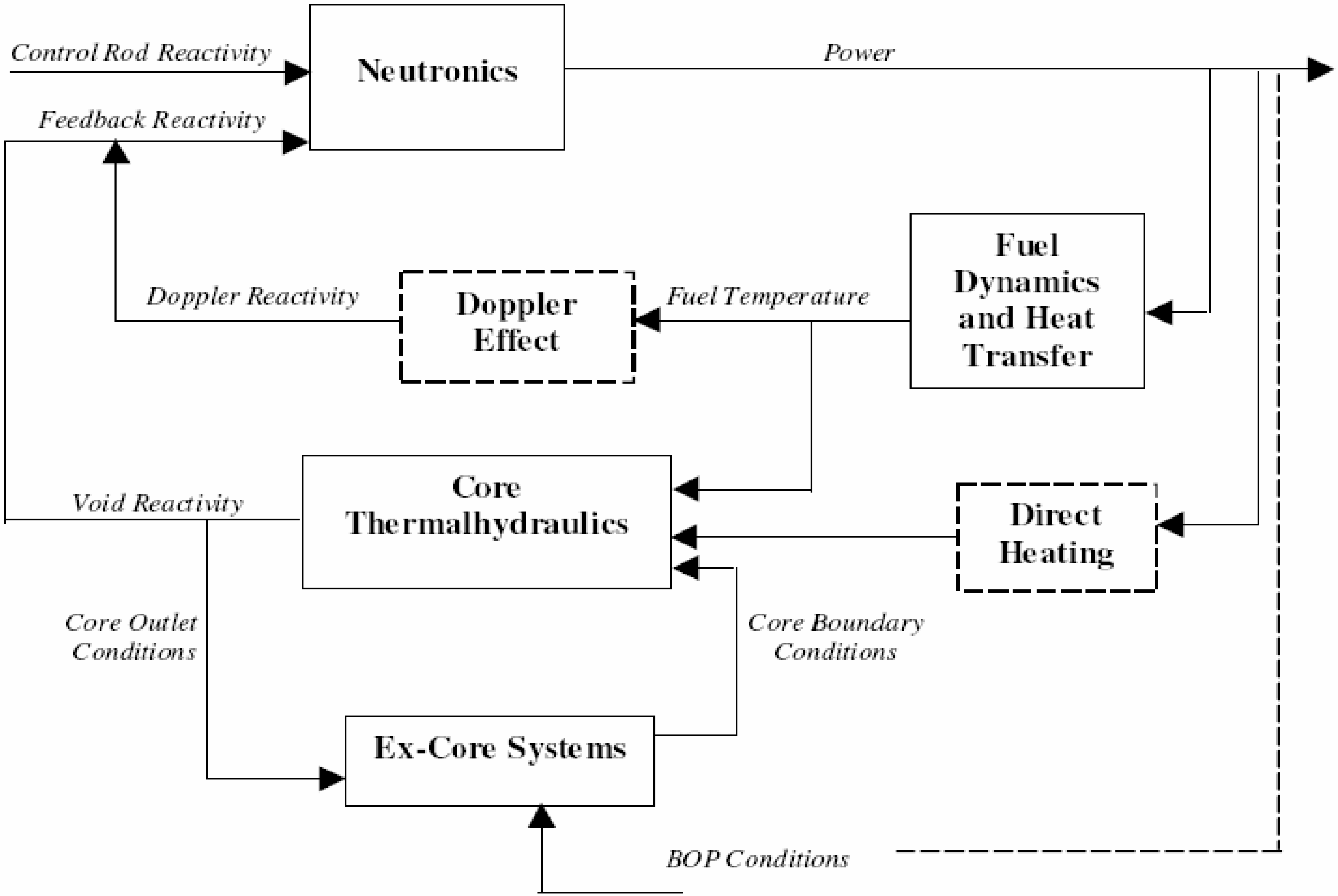


UNSTABLE

[redacted]

[redacted]

DYNAMIC INSTABILITY IN A BOILING CHANNEL (NK-TH situation) part 2 of 2



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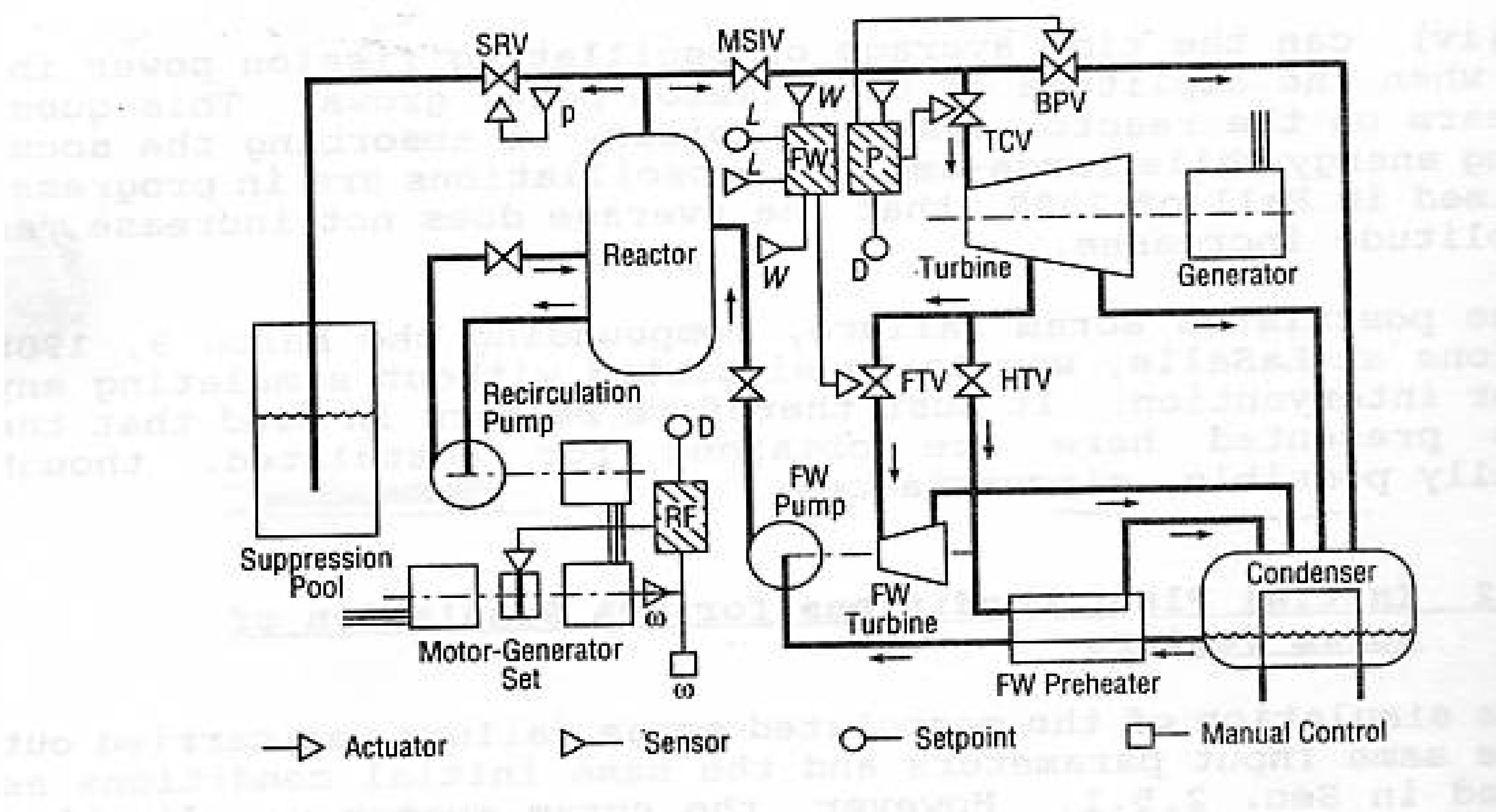
SYSTEM CONFIGURATION (relevant to stability)
THE NPP



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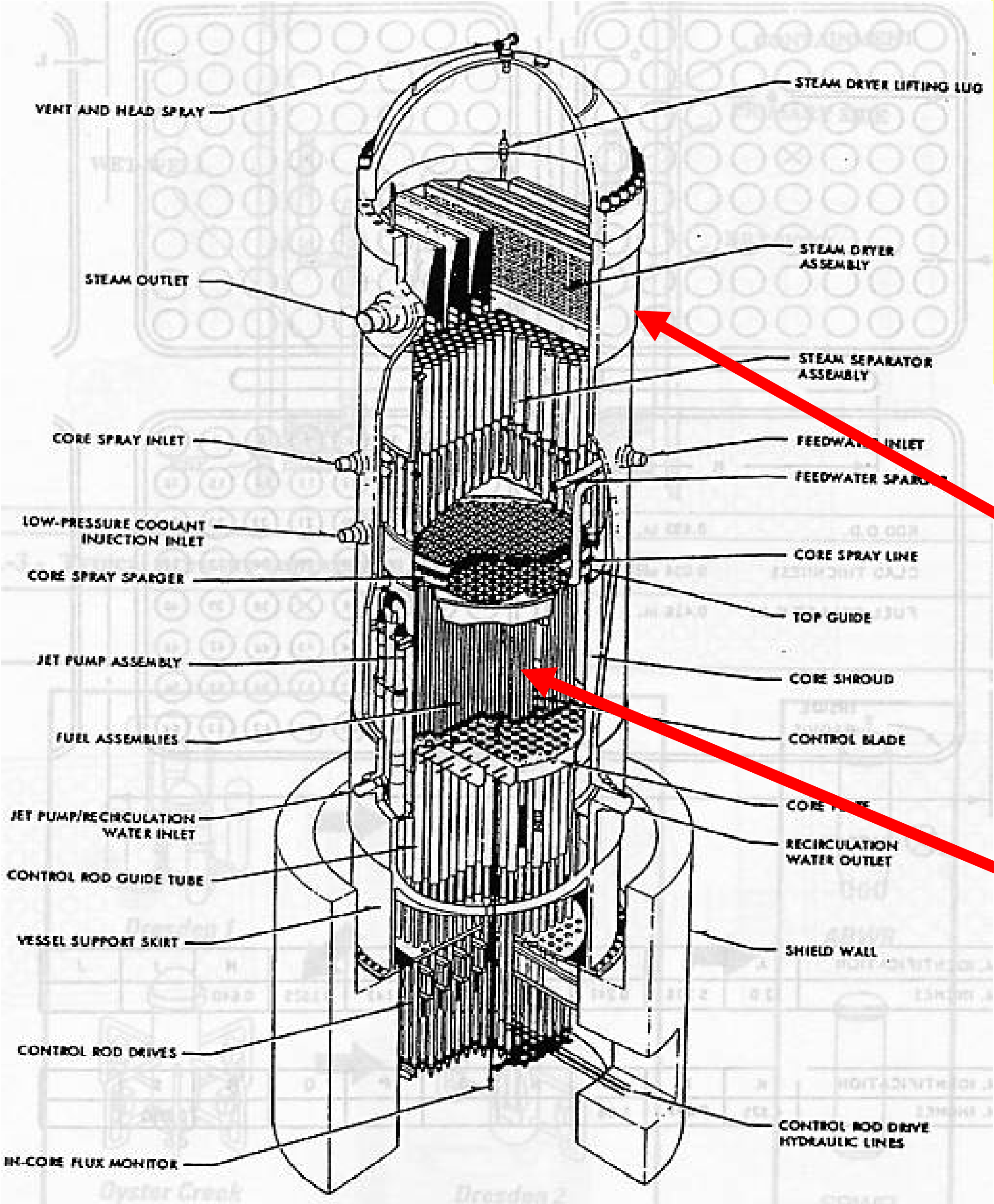
SYSTEM CONFIGURATION (relevant to stability) THE RPV



RPV

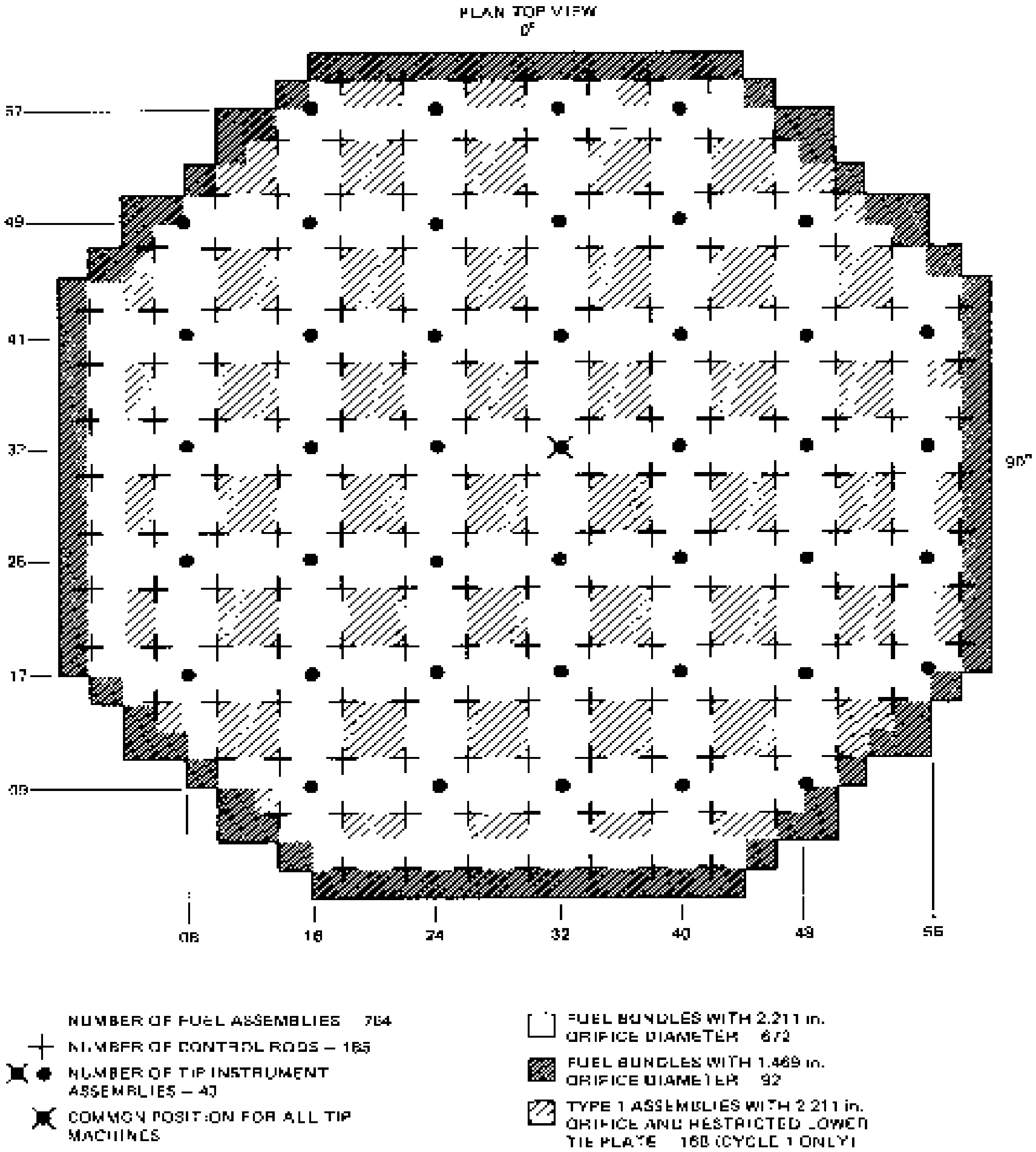
- ~ 23 m height
- ~ 7.5 m diameter
- ~ 7 Mpa op. pressure

CORE

- ~ 800 FA (8x8 to 10x10)
- ~ 4 m height

[redacted]

SYSTEM CONFIGURATION (relevant to stability) THE CORE



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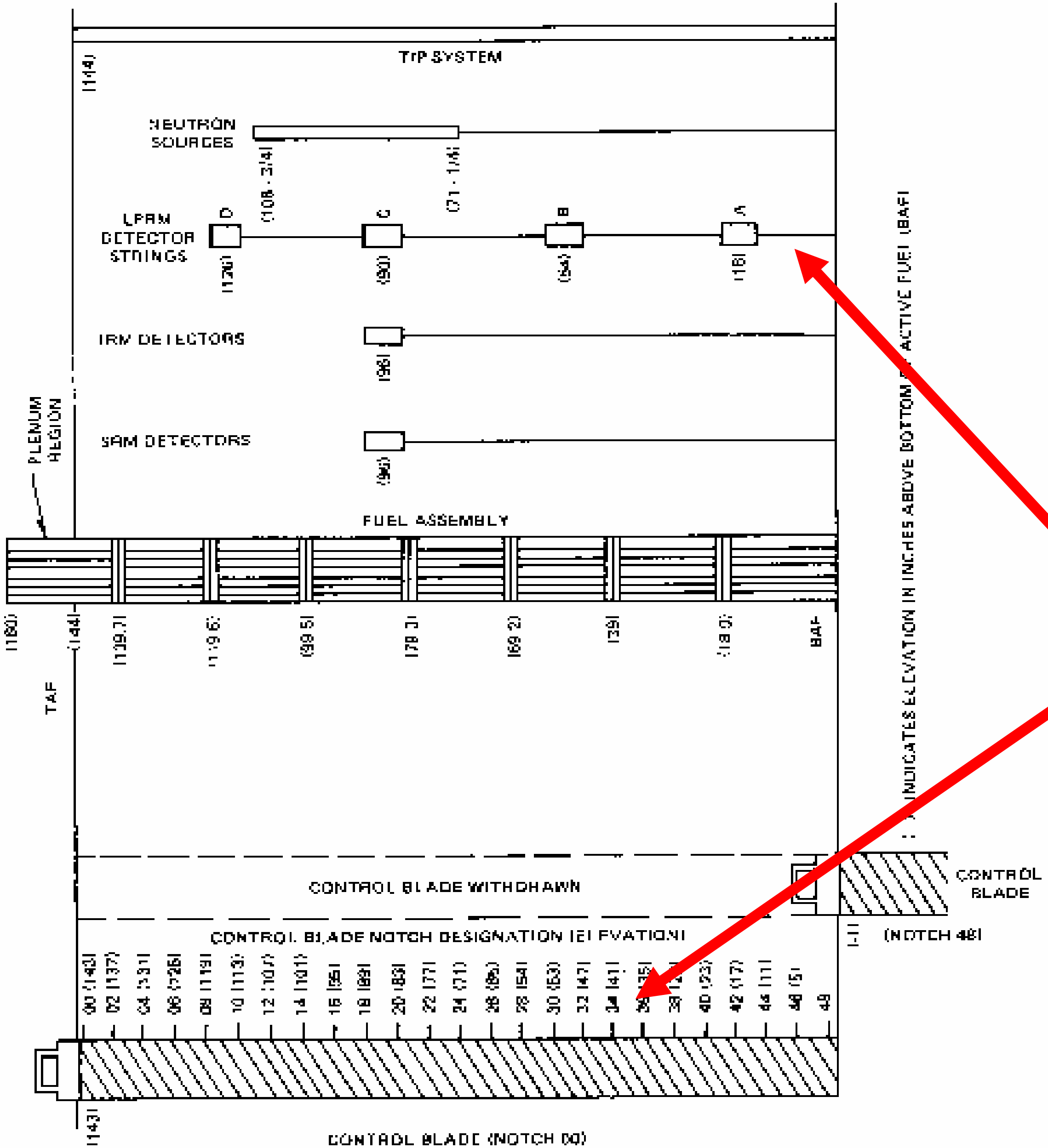


SYSTEM CONFIGURATION (relevant to stability) THE CORE

The LPRM

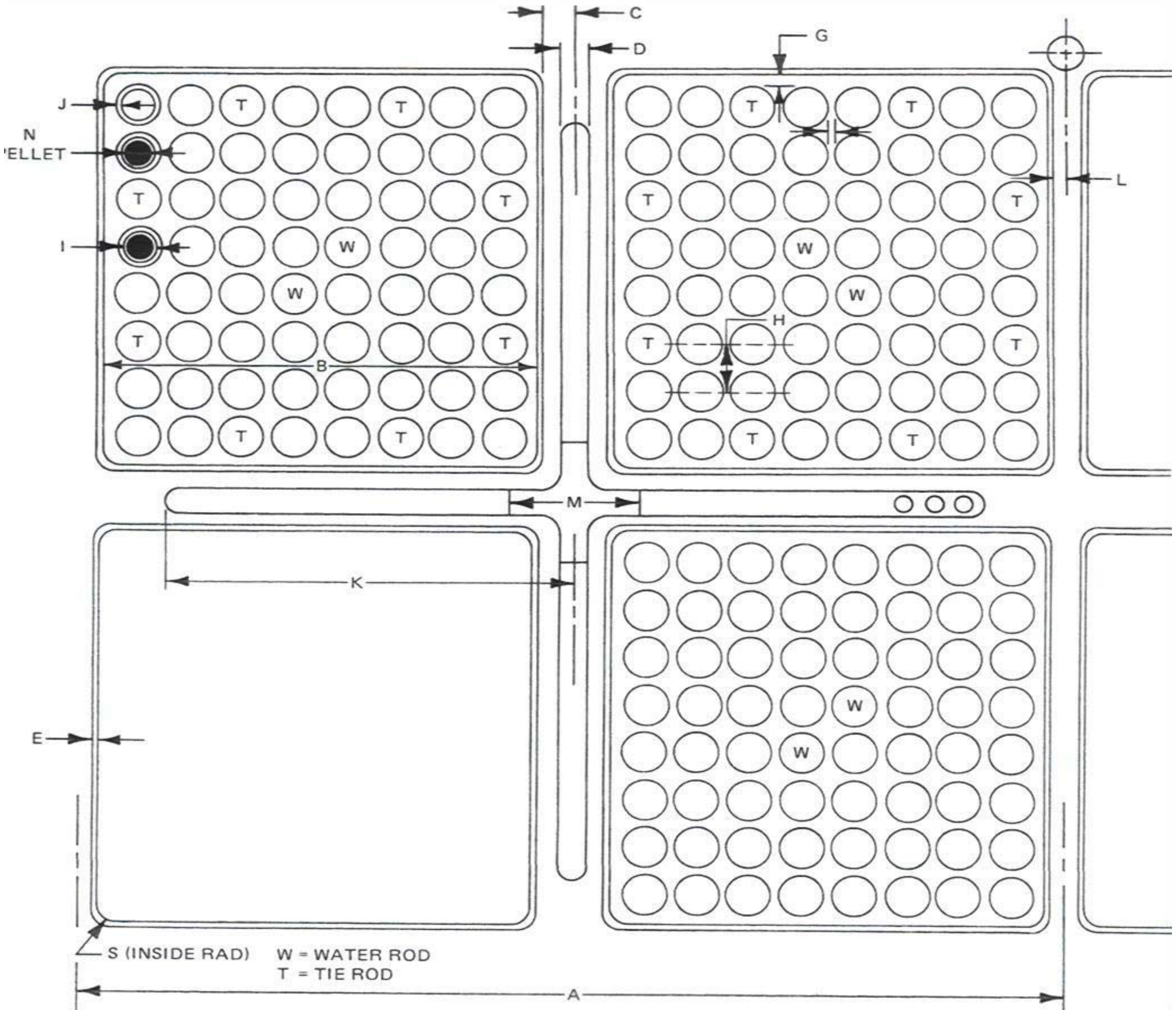
The FA

[redacted]

[redacted]

SYSTEM CONFIGURATION (relevant to stability)

FUEL ASSEMBLY
FUEL ROD
CONTROL ROD



[redacted]

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THE LA SALLE EVENT

(Wulff et al.,NUREG/CR 5816, 1992)

THE INITIAL CONDITIONS AND THE INITIATING EVENT (AOO)

Reactor Power	2,801	MWt	84% of full power
System Pressure	68.78	bar	(997.5 psia)
Core Inlet Flow	10,326	kg/s	(81.95 10^6 lbm/hr)
			76% of full flow
Steam Flow Rate	1,415	kg/s	(11.23 10^6 lbm/hr)
Feedwater Flow Rate	1,427	kg/s	(11.32 10^6 lbm/hr)
Feedwater Temperature	478.9	K	(402.4 °F)

During a routine instrument surveillance, an Instrument Maintenance technician made a valving error* which caused a pressure pulse in the reference leg of the water level instrumentation. This pulse gave a spurious low level signal and thereby actuated the automatic shut-down of both recirculation pumps. The automatic recirculation pump trip is an intended action of the Plant Protection System and occurs to mitigate the consequences of an Anticipated Transient Without Scram (ATWS).

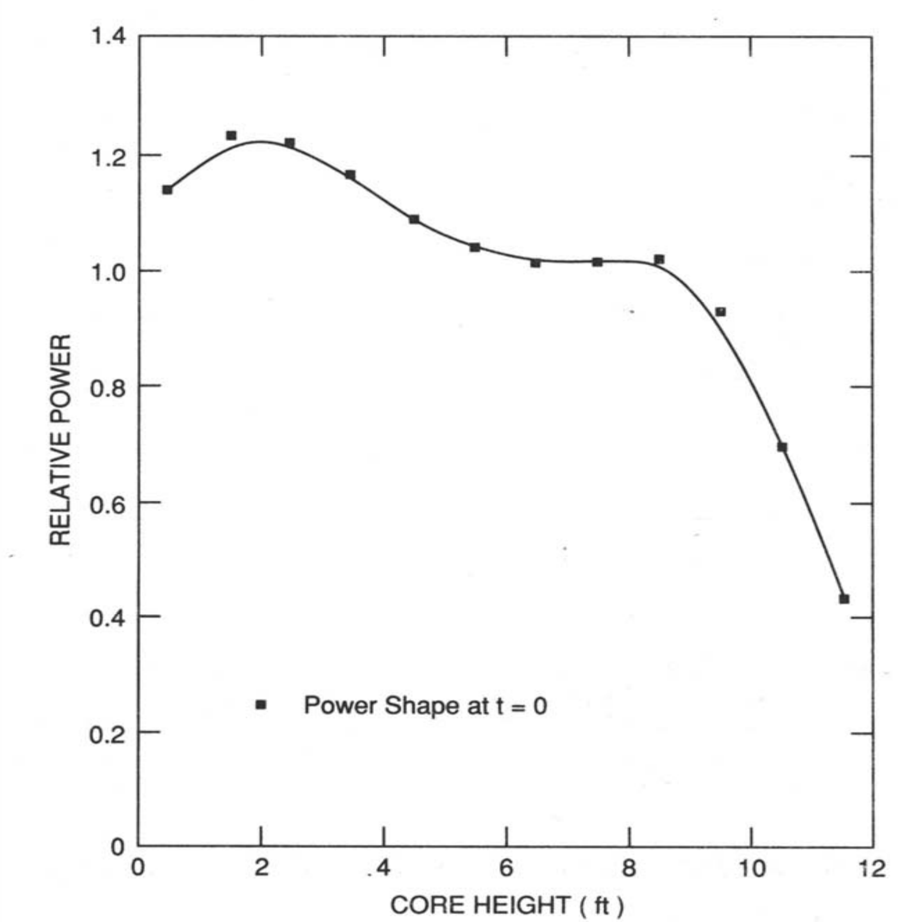
[redacted]

THE LA SALLE EVENT

(Wulff et al.,NUREG/CR 5816, 1992)

THE INITIAL CONDITIONS AND THE INITIATING EVENT (AOO)

[redacted]



BOTTOM PEAKED POWER DISTRIBUTION

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