Page

LIST OF ABBREVIATIONS AND SYMBOLS ix

EXECUTIVE SUMMARY 1

A OBJECTIVES AND SCOPE 3

B WORK PROGRAM 7

- B.l Natural Convection Cooling in the Reactor Cooling System 7
- B.2 Passive Decay Heat Removal from the Core Region 7
- B.3 Steam Jet pumps for Decay Heat Removal 8
- **B.4 Passive Initiators 8**
- B.5 Passive Decay Heat Removal from the Containment 9

C WORK PERFORMED AND RESULTS 11

- C.1 Natural Convection Cooling in the Reactor Cooling System 11
- C.l.l Introduction 11
- C.1.2 Dodewaard Plant Description 12
- C.1.3 RELAP5, TRAC and ATHLET Code Description 16
- C.1.3.1 Overview of the RELAP5 Code 16
- C.1.3.2 Overview of the TRAC Code 17
- C.1.3.3 Overview of the ATHLET Code 18
- C.1.4 Description of Code Nodalizations 21
- C.1.4.1 Modeling Dodewaard Plant with RELAP5 21
- C.1.4.2 Mode1ing Dodewaard Plant with TRAC 26
- C.1.4.3 Mode1ing Dodewaard Plant with ATHLET 27
- C.1.5 Summary of Analyzed Steady States 30
- C.1.6 Summary of Analyzed Accidents with RELAP5 31
- C.1.7 Summary of Analyzed Transients with TRAC and ATHLET 33
- C.l.7 .1 Pressure Regulator Failure-Open 34
- C.1.7 .2 Pressure Regulator Failure-Closed 35
- C.1.7 .3 Turbine Trip with Bypass 35
- C.l.7 .4 Turbine Trip without Bypass 36
- C.l. 7.5 Closure of Main Steam Valve 37
- C.1.7.6 Loss of AC Power 37
- C.1.7.7 Loss ofFeed Water 38
- C.1.7.8 Feed Water Control1er Failure Maximum Demand 39
- C.l. 7.9 Opening of Safety ReliefValve 39
- C.1.8 BWR Physics and Thermal Hydraulics Complementary Actions (BWRCA) 40
- C.1.8.1 Cross-Section Generation and Calculation of

Steady-State Conditions 41

- C.1.8.2 DESIRE Test Facility 43
- C.1.9 Conclusions and Suggested Possible Improvements 43
- C.2 Passive Decay Heat Removal from the Core Region 45
- C.2.1 Introduction 45
- C.2.2 Operation of Dodewaard Reactor 47
- C.2.2.1 Design of the Isolation Condenser in the Dodewaard Reactor 47
- C.2.2.2 Operational Experience with the Dodewaard Reactor 48
- C.2.3 NOKO Facility and Emergency Condenser Experiments 49
- C.2.3.1 Design of the Emergency Condenser in the NOKO Tests 49
- C.2.3.2 Experimental Work in the NOKO Test Facility 51
- C.2.3.2.1 The NOKO-EC First Bundle 52
- C.2.3.2.2 The NOKO-EC Second Bundle 56
- C.2.3.2.3 Pool Heat-Up Experiments 58
- C.2.4 PANDA Facility and Isolation Condenser Experiments 69
- C.2.4.1 Design of the Isolation Condenser in the PANDA Facility 69
- C.2.4.2 Steady-State Experiments with the PANDA-IC 71
- C.2.4.2.1 Pure Steam Tests 71 C.2.4.2.2 Mixture Tests 72
- C.2.4.2.3 Condenser Shutdown Tests 74
- C.2.4.2.4 Conclusions from Steady-State Experiments 74
- C.2.5 Description of Computer Models 74
- C.2.5.1 The ATIII.ET Code 74
- C.2.5.2 The APROS Code 76
- C.2.5.3 The RELAP5 Code 76
- C.2.5.4 The PHOENICS Code 77
- C.2.5.5 The TRAC Code 78
- C.2.6 Analysis of NOKO-EC, PANDA-IC, and Dodewaard-IC with ATHLET Code 78
- C.2.6.1 ATIII.ET Calculations for the NOKO-1 Bundle 78
- C.2.6.2 ATHLET Calculations for the NOKO-2 Bundle 80
- C.2.6.3 ATHLET Calculations for the PANDA-IC 81
- C.2.6.4 ATHLET Calculations for the Dodewaard-IC 84
- C.2.7 Analysis of NOKO-EC and PANDA-IC with RELAP5 Code 86
- C.2.7 .1 RELAP5 Calculations for the NOKO-EC Tests 86
- C.2.7 .2 RELAP5 Calculations for the PANDA-IC Tests 88
- C.2.8 Analysis of NOKO-EC and PANDA-IC with APROS Code 91
- C.2.8.1 APROS Calculations for the NOKO-EC Tests 91
- C.2.8.2 APROS Calculations for the PANDA-IC Tests 92
- C.2.9 Analysis of NOKO-EC with TRAC-BFI Code 94
- C.2.10 Analysis of NOKO and PANDA Pool Side with PHOENICS Code 96
- C.2.10.1 PHOENICS CFD Calculations for the NOKO Pool Side 96
- C.2.10.2 PHOENICS CFD Calculations for the PANDA Pool Side 101

- C.2.11 Applications 103
- C.2.11.1 Degree of Passivity 103
- C.2.11.2 Operation 103
- C.2.11.3 Design 104
- C.2.11.4 Modeling and Validation 106
- C.2.11.5 FurtherR&D 106
- C.2.12 Conclusions and Recommendations for Future R&D 106
- C.3 Application of Steam Jet Pumps for Passive Safety Systems 107
- C.3.1 Introduction 107
- C.3.2 Steam Jet Pump Fundamenta1s 107
- C.3.3 Possible Applications for the SJP 108
- C.3.4 Classification of the SJP according to Working Conditions 111
- C.3.5 Identification of Typical Problems of the SJP 112
- C.3.6 Proposed Research Activities 113
- C.3.7 Conclusions 113
- C.4 Passive Initiators 115
- C.4.1 Introduction 115
- C.4.2 Test Configuration and Designs for PI Tested 116
- C.4.3 Test Matrix 120
- C.4.4 Test Results 122
- C.4.5 Discussion 122
- C.4.5.1 Construction 122
- C.4.5.2 Performance 134
- C.4.6 Study on the Application Pot~ntial of Passive Initiators 134
- C.4.6.1 Possible Control Cap!tbilities 134
- C.4.6.2 Advantages, Disadvantages, and Limitations 134
- C.4.6.3 Possible Applications 136
- C.4.6.3.1 Nuclear Applications 136
- C.4.6.3.2 Non-Nuclear Applications 136
- C.4.7 Feasibility Study of an Innovative Decay Heat Removal System Based on the Use of a Passive Initiator and a Steam Jet Pump
- System 136
- C.4.7 .1 Description and Behavior of the SJP-HRS 137
- C.4.7 .2 Considerations on the Operating Conditions of the SJP-HRS 140
- C.4.7 .3 Present Limits and Future Goals of the Research 142
- C.4.7.3.1 Numerical Simulation of the SJP-HRS 142
- C.4.7.3.2 Experimental Simulation of the SJP-HRS 142
- C.4.8 Conclusion and Recommendations for Future R&D 143 $\,$
- C.5 Passive Decay Heat Removal from the Containment 145
- C.5.1 Introduction 145
- C.5.2 Description of Investigated Designs 146
- C.5.2.1 Passive Containment Condenser 146
- C.5.2.2 Building Condenser 148
- C.5.2.3 Containment Plate Condenser 152

- C.5.3 Perfonned Work and Achieved Results 152
- C.5.3.1 System Tests in the PANDA Facility 153
- C.5.3.1.1 PANDA Facility 153
- C.5.3.1.2 PANDA-PCC Tests 155
- C.5.3.1.3 PANDA-BC Tests 157
- C.5.3.1.4 PANDA-PCTests 175
- C.5.3.2 NOKO Experiments 183
- C.5.3.2.1 NOKO Facility 183
- C.5.3.2.2 NOKO-BC Tests 183
- C.5.3.2.3 NOKO-PC Tests 191
- C.5.3.3 Analysis on PANDA-PCC Tests 194
- C.5.3.3.1 RELAP5 System Analysis 194
- C.5.3.3.2 MELCOR System Analysis 205
- C.5.3.3.3 Analysis of the Behavior of PCC2 during Test M3 with CFX-4 211
- C.5.3.4 Analysis on PANDA-BC Tests 215
- C.5.3.4.1 Analysis with COCOSYS and CFX-4 215
- C.5.3.4.2 RELAP5 System Analysis 220
- C.5.3.4.3 Analysis of Selected Phases of Test BC4 with GOTHIC 228
- C.5.3.4.4 Analysis of Helium Injection Phase in Test BC4 with CFX-4 235
- C.5.3.4.5 Modeling of Water Mixing / Stratification in the Water Storage Pool with GOTHIC and CFX-4 241
- C.5.3.5 Analysis on PANDA-PC Tests 245
- C.5.3.5.1 Analysis with COCOSYS (RALOC) 245
- C.5.3.5.2 Analysis of Test PCl with GOTHIC 247
- C.5.3.5.3 Analysis of Test PCl with CFX-4 251
- C.5.3.6 RALOC Analysis on NOKO-BC Tests 255
- C.5.3.7 RALOC Analysis on NOKO-PC Tests 262
- C.5.3.8 Exchange of Generic Experience from PANTHERS-PCC Tests 269
- C.5.4 Assessment of Results 269
- C.5.4.1 Experimental Work 269
- C.5.4.2 Analytical Work 270
- C.5.5 Conclusions and Recommendations 273

CONCLUSIONS 277

REFERENCES 281