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신개념원자로 조건에 대한 부수로 해석 코드 기술 개발 및 응용 연구

Development and Application of Subchannel Analysis Code Technology for Advanced Reactor Systems

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제출문

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요약문

다양한 핵연료 및 노심 형태와 냉각재를 사용하는 신개념 원자로에 대한 부수로 해석 코드 기술 개발 및 적용성 평가 연구를 수행하였다. 부수로 해석 코드의 기본 모듈은 기존 경수로 노심 열수력장 해석을 위하여 한국원자력연구소에서 개발중인 MATRA 코드를 바탕으로 개발하였다. 코드 입력 오류를 줄이고 사용자 편이성을 높이기 위하여 입출력 GUI를 개발하였다. 다양한 냉각재에 대한 물성치 계산 모듈을 보완하였으며, 그 결과 액체금속, 개스, 냉매, 그리고 초임계압수 등에 대한 부수로 해석이 가능하다. 부수로 해석 코드를 사용하여 신개념원자로에 적용될 수 있는 다양한 형태의 비정방형 집합체에 대한 CHF 시험자료를 분석하고 예측 성능을 평가하였다. 그리고 고온가스로 및 초임계압 원자로 조건에 대한 부수로 해석 코드의 적용성 평가를 수행하였다. 독일 FZK 연구소와 국제공동 연구를 수행하여 액체 금속을 냉각재로 사용하는 원자로 조건에 대한 부수로 해석을 수행하였다. 그리고 OECD/NRC의 code benchmark에 참여하여 부수로 기포율 분포에 대한 부수로 해석 코드의 예측 성능을 평가하였다.

SUMMARY

A study has been performed for the development and assessment of a subchannel analysis code which is purposed to be used for the analysis of advanced reactor conditions with various configurations of reactor core and several kinds of reactor coolant fluids. The subchannel analysis code was developed on the basis of MATRA code which is being developed at KAERI. A GUI (Graphic User Interface) system was adopted in order to reduce input error and to enhance user convenience. The subchannel code was complemented in the property calculation modules by including various fluids such as heavy liquid metal, gas, refrigerant, and supercritical water. The subchannel code was applied to calculate the local thermal hydraulic conditions inside the non-square test bundles which was employed for the analysis of CHF. The applicability of the subchannel code was evaluated for a high temperature gas cooled reactor condition and supercritical pressure conditions with water and Freon. A subchannel analysis has been conducted for European ADS(Accelerator-Driven subcritical System) with Pb-Bi coolant through the international cooperation work between KAERI and FZK, Germany. In addition, the prediction capability of the subchannel code was evaluated for the subchannel void distribution data by participating an international code benchmark program which was organized by OECD/NRC.

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1. 서론

1.1 연구 개발의 필요성

1.1.1 연구개발의 경제·사회·기술적 중요성

부수로 해석 코드 기술은 핵연료 집합체에서의 CHF(Critical Heat Flux) 및 연료 온도 해석에 필요한 3차원적 열수력장 분포를 계산하고, 이로부터 노심 열출력 성능을 평가하는데 사용되는 핵심적인 코드 기술이다. 현재 국내 가압경수로 설계에 사용되고 있는 부수로 해석 코드로서는 CE사의 TORC 코드나 웨스팅하우스사의 THINC-IV 코드 등이 있다. 신개념 원자로에서는 원자로의 안전성과 경제성의 획기적인 향상, 우라늄 자원의 효율적인 활용 등의 다양한 목표를 충족시키기 위하여 기존 경수로와 달리 새로운 종류의 냉각재나 핵연료 집합체의 적용을 고려하고 있다. 이 경우 핵연료 집합체 설계의 타당성을 열수력적 관점에서 평가하고 신개념 원자로 노심의 열출력 성능을 평가하는 가장 효과적인 방법으로서 부수로 해석 코드 기술이 매우 중요한 역할을 한다. 본 연구에서 고려하고 있는 신개념 원자로에는 다양한 수냉각 원자로와 HLM(Heavy Liquid Metal)을 냉각재로 사용하고 있는 가속기 구동 미임계 핵변환로(ADS: Accelerator-Driven subcritical transmutation System), 연구용 원자로, 그리고 초임계압 원자로(SCWR: Supercritical pressure Water Reactor) 등이 있다. 이들 원자로에 사용되는 냉각재 특성과 비정방형 집합체 기하형태 등으로 인하여 기존의 가압경수로용으로 개발된 부수로 해석 코드 기술을 그대로 적용할 수 없다. 따라서 신개념 원자로 노심에서의 핵연료 집합체 설계 타당성과 열적 여유도 평가를 위하여 부수로 해석 코드 모듈 개발 및 CHF 해석 체계의 구축 등에 대한 연구가 필요하다. 사용후 핵연료 처리 방법의 하나로서 제안된 ADS 노심은 Pb-Bi 냉각재의 밀도와 열전도도 특성, 그리고 핵연료 집합체 채널의 기하 형태에 대한 제약 등으로 인하여 특이한 열수력적 특성을 갖는다. 즉, 냉각재에서의 축방향 및 반경방향 열전도 모델과 유체 특성을 고려한 적절한 난류혼합모델 및 교차류 모델을 부수로 해석 코드에 적용할 필요가 있다. 연구용 원자로의 경우에는 판형(plate-type) 핵연료로 구성되는 채널

해석 모델과, 대기압 근처의 낮은 압력 조건에 적용 가능한 부수로 해석 코드 모델 개발에 대한 연구가 필요하다. 높은 열효율을 얻기 위하여 제안된 초임계압 원자로 노심에서는 냉각재 온도 상승이 200oC 이상 발생하여 노심 상하부 간의 냉각재 밀도 차이가 매우 크며, 효율적인 중성자 감속을 위해 설치하는 water-rod 등으로 인하여 기존 경수로에 비하여 열수력적 비균질도가 상당히 크다. 따라서 안정된 해를 구할 수 있는 수치 해법에 대한 연구를 포함하는 적절한 부수로 해석 코드 기술의 개발이 필요하다. 본 연구를 통하여 시작된 KAERI와 독일 FZK 연구소 간의 국제공동 연구는 KAERI의 부수로 해석 코드 기술과 FZK의 열수력 실험 기술을 효과적으로 활용하여 부수로 해석 코드 개발을 수행하기 위한 것이다. 이를 통하여 KAERI는 부수로 해석 코드 기본 모듈을 제공하고 FZK에서 수행될 열수력 시험 자료를 확보하여 신개념 원자로 적용에 필요한 부수로 해석 코드 기술을 공동 개발할 예정이다.

1.1.2 지금까지의 연구개발 실적

1차년도 연구를 통하여 신개념 원자로 적용을 위한 부수로 해석 코드의 기본 모듈을 정비하였다. 그리고 코드 입출력 체계에 대하여 GUI(Graphic User Interface)를 구현하여 입력 오류를 줄이고 사용자 편의성을 개선하기 위한 기초를 마련하였다. 신개념 원자로에서 고려하고 있는 다양한 냉각재 조건에 대하여 부수로 해석 코드를 적용할 수 있도록 수정하였으며, 여러 가지 형태의 비정방형 집합체에 대하여 코드 예측 성능을 평가하였다. 그리고, 부수로 해석 코드의 기본 모듈을 서울대학교 및 한국과학기술원에서 연구 목적으로 사용할 수 있도록 기술실시 계약을 체결하였다. 독일 FZK 연구소와 국제공동연구 협약을 체결하여 HLM(Heavy Liquid Metal) 및 경수를 냉각재로 사용하는 신개념 원자로에 적용할 수 있는 부수로 해석 코드 모듈을 공동 개발하기로 하였으며, 일차 회의를 통하여 working group을 구성하고 공동연구 항목을 구체화하였다.

1.1.3 현기술상태의 취약성

부수로 해석 코드는 연료봉 단위의 부수로를 기본 제어 체적으로 사용하는 열수력장 해석 코드로서 노심 내의 유량, 온도 및 압력 분포를 3차원 공간에서 계산하며 이로부터 주요 설계 변수인 CHFR이나 연료 온도 등을 계산하는 기능을 가지고 있다. 한국원자력연구소에서는 COBRA-IV-I 코드를 수정/개량하여 지난 수년 동안 부수로 해석 코드 MATRA(Multichannel Analyzer for steady-states and Transients in Rod Arrays)를 개발하고 있으며, 그 결과로서 기존 경수로 조건에 적용 가능한 MATRA-α version을 개발하여 1997년 11월에 한국 컴퓨터 프로그램 보호회에 등록한 바 있다. MATRA 코드는 미래형 핵연료에 대한 열수력적 해석 및 SMART 노심 열수력 설계에 적용한 경험이 있으며, MATRA 코드를 바탕으로 개발된 MATRA-LMR이나 MATRA-h 코드는 KALIMER 노심 해석 및 HANARO 노심 분석 등에 사용된 경험이 있다. 그러나 새로운 개념의 원자로에서는 다양한 종류의 냉각재와 집합체 기하 형태가 고려되고 있으며, 이러한 조건에서 부수로 해석 코드의 적용성은 충분히 확인되지 않은 상태이다.

1.1.4 앞으로의 전망

본 연구를 통하여 신개념 원자로에 적용하기 위한 부수로 해석 코드의 기본 모듈을 개발하고 다양한 원자로 조건에 대한 코드 적용성 평가를 통하여 향후 기술 개발이 필요한 연구 항목들을 도출할 수 있을 것으로 기대된다.

1.2 연구 개발 목표 및 내용

1.2.1 연구개발의 최종목표

신개념 원자로 조건에 적용 가능한 부수로 해석 코드 기본 모듈 개발 및 적용성 평가를 통한 부수로 해석 코드 개발 방향 도출

1.2.2 연차별 연구개발목표 및 내용, 평가기준

➢ 부수로 해석 코드 기본 모듈 개발

- 코드 모듈 및 입출력 체계 정비
- Non-aqueous 냉각재 해석 모듈 개발
- 비정방형 집합체 해석 방법론 정비

➢ 부수로 해석 코드 적용성 평가

- 비정방형 집합체 CHF 해석 체계 특성 평가
- 신개념원자로 노심특성 자료 수집
- 신개념원자로 노심 부수로 해석 모델 개발 및 적용성 평가

1.2.3 추진전략 및 방법

➢ KAERI의 MATRA 코드를 바탕으로 부수로 해석 코드의 기본 모듈을 도출하고 이를 신개념 원자로 적용을 위한 부수로 해석 코드 체계 개발에 활용한다.

➢ 독일 FZK 연구소와의 국제 공동 연구를 통하여 HLM(Heavy Liquid Metal) 및 water를 냉각재로 사용하는 신개념 원자로에 적용 가능한 부수로 해석 코드 체계를 공동 개발한다. 공동 연구는 KAERI의 부수로 해석 코드 기술과 FZK의 모델 개발 및 실험 등에 대한 기술을 바탕으로 KAERI-FZK 간의 Specific Arrangement에 대한 annex를 통하여 추진한다. 본 연구 과제를 통하여 개발된 주요 결과와 FZK의 연구 결과는 부수로 해석 코드 working group을 통하여 서로 교환할 예정이며 이를 통하여 공동으로 부수로 해석 코드 체계를 개발한다.

➢ OECD/NRC가 주관하는 부수로 해석코드 benchmark working group에 참여하여 2상 유동 조건에 대한 부수로 해석 코드 검증 작업을 수행한다.

➢ 국내 부수로 해석 코드 사용자 회의를 추진하고 이를 통하여 여러 가지 원자로 조건에 대한 부수로 해석 코드 적용 연구 정보를 교환한다.

2. 연구 개발 내용 및 결과

2.1 부수로 해석 코드 기본 모듈 개발

2.1.1 코드 모듈 및 입출력 체계 정비

(가) 지배 방정식

MATRA 코드는 COBRA-IV-I 코드[1]로부터 개발된 것으로서 지배방정식 형태는 COBRA-IV-I 코드와 동일하다. 즉, 2상 유동장은 혼합물로 취급하여 HEM (Homogeneous Equilibrium Model) 혹은 SEM(Slip Equilibrium Model)을 적용하고 있다. MATRA 코드의 연속 방정식, 에너지 보존 방정식, 축방향 및 횡방향 운동량 보존식은 아래와 같이 표현된다. 지배 방정식이 유도된 제어 체적은 그림 2.1 ~ 그림 2.4에 제시하였다. 부수로 해석 코드 지배 방정식 유도 과정은 참고 문헌 [2]에 상세히 기술되어 있다.

- 연속방정식:

$$A_i \frac{\partial \langle\langle \rho_m \rangle\rangle_i}{\partial t} + \frac{\partial m_i}{\partial x} + \sum_j \left(w_{ij} + w'_{i\leftrightarrow j} \right) = 0\,. \tag{2.1}$$

- 에너지 보존 방정식:

$$A_i \frac{\partial}{\partial t} \langle\langle \rho_m \rangle\rangle_i \langle\langle h_m \rangle\rangle_i + \frac{\partial}{\partial x}\left(\dot{m}_i \langle \breve{h} \rangle_i \right) + \sum_j w_{ij} \left\langle \breve{h}^* \right\rangle_i = Q \tag{2.2}$$

where,

$$Q = \frac{\partial}{\partial x}\left(\left\langle k \frac{\partial T}{\partial x} \right\rangle_i A_i \right) - \sum_j C_{ij}\left(T_i - T_j \right) - \sum_j w'_{ij}\left(h_i - h_j \right) + \sum_n \xi_n \left\langle q''_n \right\rangle \tag{2.3}$$

- 축방향 운동량 보존식:

$$\frac{\partial \dot{m}_i}{\partial t} + \frac{\partial}{\partial x}\left(\left\langle \sum_k \alpha_k \rho_k u_k^2 \right\rangle_i A_i \right) + \sum_j w_{ij} \left\langle u^* \right\rangle_i = -\bar{A} \frac{\partial P}{\partial x} - F_x \tag{2.4}$$

where,

$$F_x = \frac{1}{2}\left\{\frac{f\phi^2}{d_{hy}\rho_m} + \frac{K}{\rho'\Delta x}\right\}_i \frac{\dot{m}_i^2}{A_i} + f_T\sum_j w'_{ij}\left(u_i - u_j\right) + A_i\left\langle\left\langle\rho_m\right\rangle\right\rangle_i g\cos\theta \qquad (2.5)$$

- 횡방향 운동량 보존식:

$$\frac{\partial w_{ij}}{\partial t} + \frac{\partial}{\partial x}\left(w_{ij}\left\langle\bar{u}\right\rangle_i\right) + \frac{1}{l}\sum_j w_{ij}\left\langle\bar{v}\right\rangle_i = \frac{s_{ij}}{l}\left(P_i - P_j\right) - F_{ij} \qquad (2.6)$$

where,

$$F_{ij} = \frac{1}{2}K_G\frac{w_{ij}\left|w_{ij}\right|}{\rho^* s_{ij} l} + s_{ij}\left\langle\left\langle\rho_m\right\rangle\right\rangle_i g\sin\theta \qquad (2.7)$$

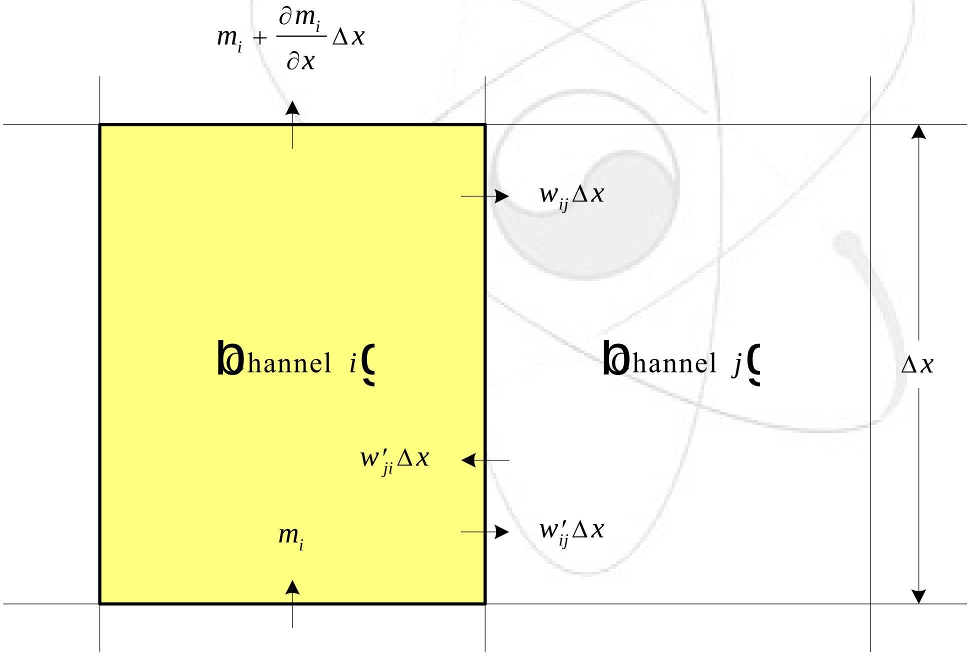


그림 2.1 연속 방정식 유도를 위한 제어 체적표

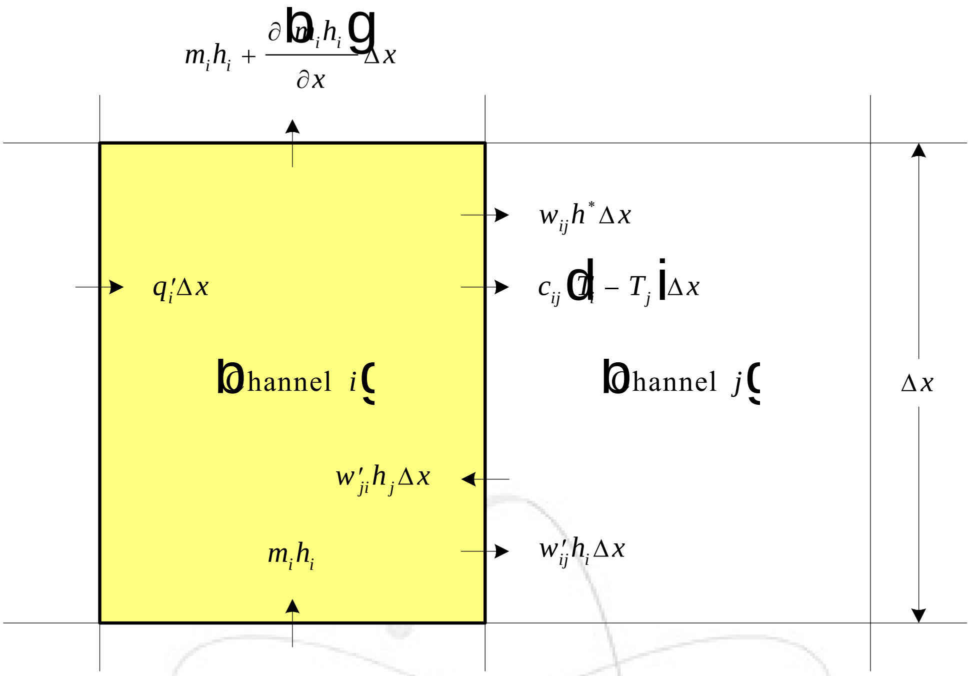


그림 2.2 에너지 보존 방정식 유도를 위한 제어 체적

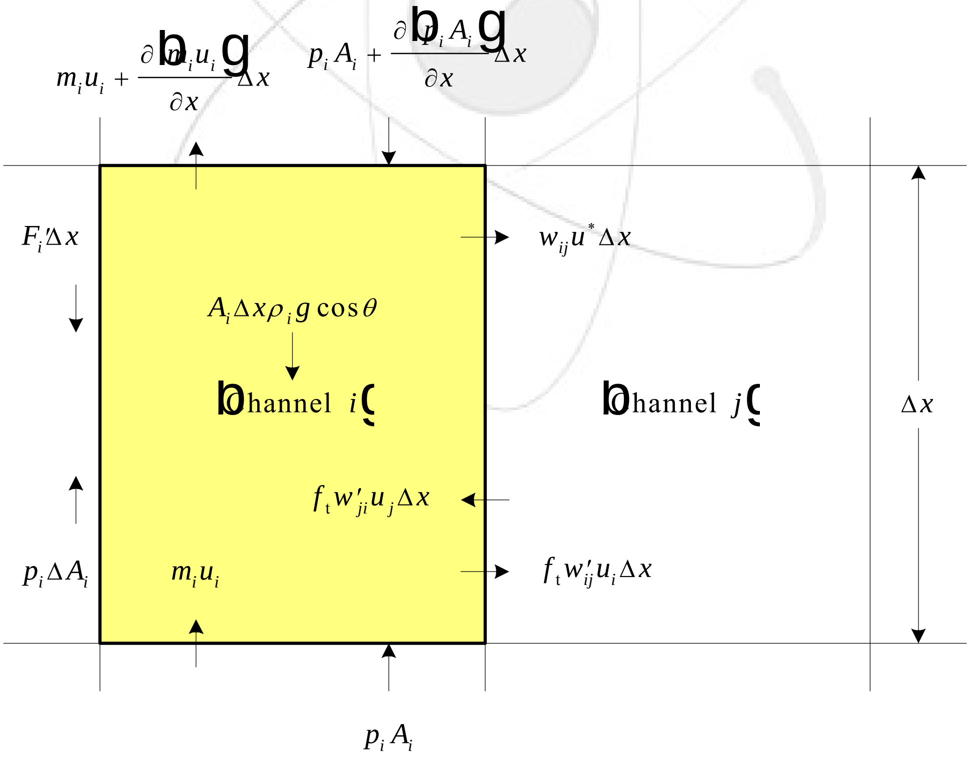


그림 2.3 축방향 운동량 보존 방정식 유도를 위한 제어 체적

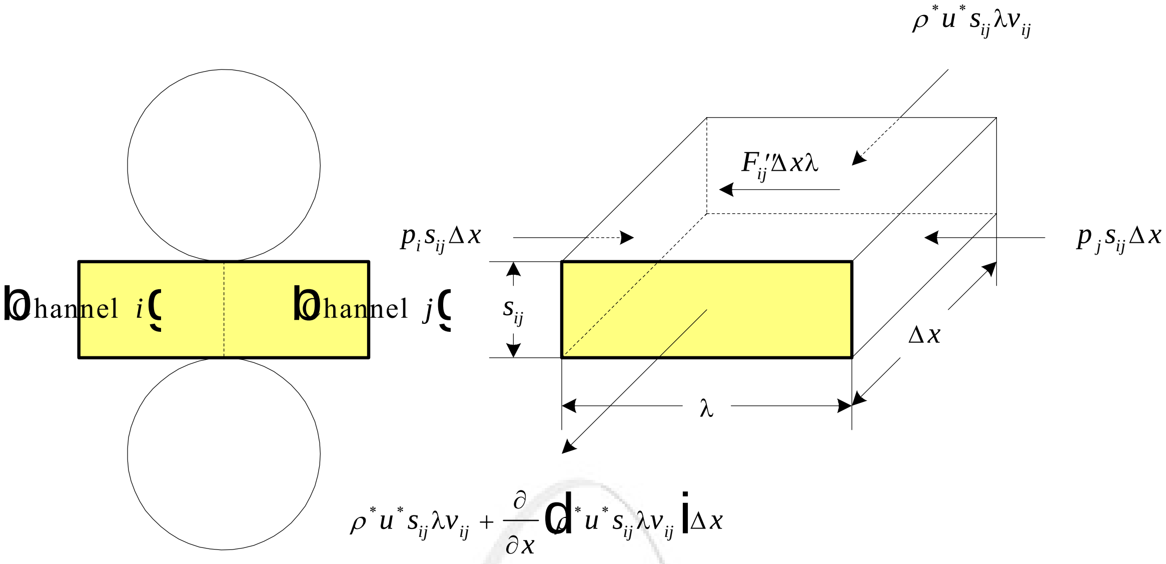


그림 2.4 횡방향 운동량 보존 방정식 유도를 위한 제어 체적

(나) 코드 주요 모형

MATRA는 기존의 CDC CYBER mainframe용 COBRA-IV-I를 토대로 하여 IBM PC 및 HP Workstation에서 사용할 수 있도록 개발된 부수로 해석 코드이다. 그림 2.5는 MATRA 코드의 특징을 기존의 COBRA-IV-I 코드와 비교한 것인데, 본 절에서는 MATRA 코드에서 개선된 주요 코드 기능 및 모델을 기술하였다.

- MATRA 코드의 구조 및 기능

코드의 구조면에서는 먼저 CDC CYBER mainframe version을 IBM PC 및 HP workstation version으로 변환하였다.[3] 그리고 잘못 입력된 코드 입력 자료의 편집을 위해 사용된 방대한 크기의 불필요한 subroutine들을 제거하여 코드 구조를 단순화시켰고, 계산에 자주 사용되는 중요한 상수들의 유효 숫자를 증가시키고 모든 실수들을 2배 정도(double precision)로 그 정밀도를 높여 보다 정확한 계산 결과를 얻을 수 있도록 하였다. 기존의 입·출력 양식을 수정하여 정밀한 정보를 입·출력으로 제공하도록 하였고, 코드 구조를 쉽게 파악할 수 있도록 Fortran 90을 사용하여 코드 내용을 재구성하였다.

코드 기능면에서 보면, COBRA-IV-I에서는 코드의 입·출력 단위 체계로 British 단위 하나만을 사용할 수밖에 없으나, MATRA에서는 SI 와 British 단위를 선택적으로 사용할 수 있도록 입·출력 단위 체계의 전환 기능을 제공하였다. 유체의 물성치에 대한 계산 방법으로 COBRA-IV-I는 포화(saturated) 상태의 물성치로부터 선형 보간법(linear interpolation)에 의하여 과냉(subcooled) 상태의 물성치를 계산함으로써 상당한 오차를 야기했었는데, MATRA에서는 유체의 물성치 계산 routine을 코드 내에 이식하여 과냉 상태의 물성치를 직접 계산함으로써 물성치 계산에 따른 오차를 상당량 줄일 수 있도록 하였다. COBRA-IV-I에서는 계산에 사용되는 축방향 node를 균일하게 분할할 수밖에 없으나, MATRA에서는 flow blockage와 같은 문제 분석 시에 가변적인 축방향 node 생성 기능을 사용하여, 선택적으로 조밀한 node를 사용함으로써 축방향 node 개수를 최적화할 수 있도록 하였다. COBRA-IV-I에서는 유체의 모든 물성치들을 기준 압력인 계통 출구 압력에 대해서 계산하고 있다. 가압 경수로의 정상 상태와 같은 고압의 단상 유동(single-phase flow) 영역에서는 축방향 압력 강하가 유체의 물성치에 미치는 영향이 무시할 수 있을 정도로 작기 때문에, 계통 압력을 이용한 이러한 계산 방법이 어느 정도 타당성을 갖고 있지만, 보다 낮은 압력, 혹은 이상 유동(two-phase flow) 조건에서는 국부 압력이 유체의 물성치에 미치는 영향이 무시할 수 없을 정도가 되는 경우가 종종 있기 때문에, MATRA에서는 유체의 물성치를 계산하는데 있어서, 유동 조건에 따라 사용자가 계통 압력 혹은 국부 압력을 선택적으로 사용할 수 있도록 하였다. 일반적으로 가압 경수로의 열출력을 제한하는 가장 중요한 열수력 인자는 최소 핵비등 이탈율(Minimum Departure from Nucleate Boiling Ratio: MDNBR)이다. MDNBR은 운전 여유도를 결정할 수 있기 때문에, 미리 결정된 한계 DNBR에 대한 운전 가능 영역을 계산할 수 있는 기능이 필요하다. 따라서 MATRA에서는 주어진 MDNBR에 대한 열출력, 봉의 반경 방향 첨두치 및 유량의 값을 찾아내는 MDNBR 추적 계산 기능을 제공하였다. 현재 MATRA는 그림 2.6에서 보인 바와 같이 기본적으로 COBRA-IV-I와 동일한 계산 과정을 사용하고 있다. 즉, 각 축방향 평면에서의 유체의 엔탈피, 밀도, 교차류, 축방향 유량 및 압력을 계산 영역의 입구로부터 출구까지 계산하는 과정을, 교차류와 축방향 유량에 대해 주어진 수렴 조건을 만족할 때까지 반복하게 된다. 이 과정 중에 수행되는 교차류 방정식에 대한 수치 해법으로 COBRA-IV-I는 SOR(Successive Over-Relaxation) 방법을 사용하고

있는데, 저유속 조건과 같은 특정 조건에서 코드의 수렴성을 향상시키기 위하여 가우스 소거법(Gaussian Elimination)을 추가하여 선택적으로 사용할 수 있도록 하였다.

- MATRA 코드의 주요 모형

SMART 노심은 기존 경수로에 비하여 유속 및 건도 조건이 다소 확장되었으며, 신형 원자로 노심에 적용 가능성이 있는 비정방형 집합체에 대해서도 MATRA 코드를 적용할 수 있도록 열수력장 해석 모형을 보완하였다. 이를 위하여 집합체 압력 손실 모형과 기포율 계산 모형, CHF 계산 모형, 그리고 횡방향 전달 모형 등이 개선되었다. 비정방형 집합체에 대한 압력 손실 모형으로서 그리드 형태와 와이어랩 형태의 간격 격자에 적용할 수 있는 Rehme[4,5]의 모형을 적용하였다. 기존의 COBRA-IV-I에서는 이상 유동장에서의 체적(bulk) 기포율을 예측하기 위해 몇 가지 간단한 모형들을 사용하고 있는데, 이들 모형들은 비교적 오래 전에 개발되었고 그 적용 범위가 좁기 때문에 체적 기포율에 대한 새로운 모형이 필요하게 되었다. 따라서 보다 개선되고 적용 범위가 넓은 Chexal-Lellouche[6] 기포율 모형을 MATRA에 구현하게 되었는데, 이 모형은 매우 방대한 영역의 압력과 유량, 기포율 조건에 적용 가능하며, 증기-물, 공기-물, 산소, hydrocarbon등 여러 유형의 유체들에 적용할 수 있다. 난류 혼합에 의한 횡방향 전달 모형은 부수로 해석 코드의 정확도에 큰 영향을 미치는 모형이다. COBRA-IV-I 코드는 인접 수로 간에 난류 혼합으로 인한 질량 교환량이 서로 같다고 가정하는 ‘동일 질량 교환 모형’이 사용되고 있다. 그런데 건도가 높은 조건에서 수행된 실험 결과에 따르면 이러한 모델이 모서리 수로 등에서 잘 맞지 않는 것으로 나타났으며, 이에 따라 ‘동일 체적 교환 모형’이나 기포 이동 모형 등이 제시되고 있다. 이러한 연구 결과를 바탕으로 MATRA 코드에서는 횡방향 전달 모형을 개선하였다[7].

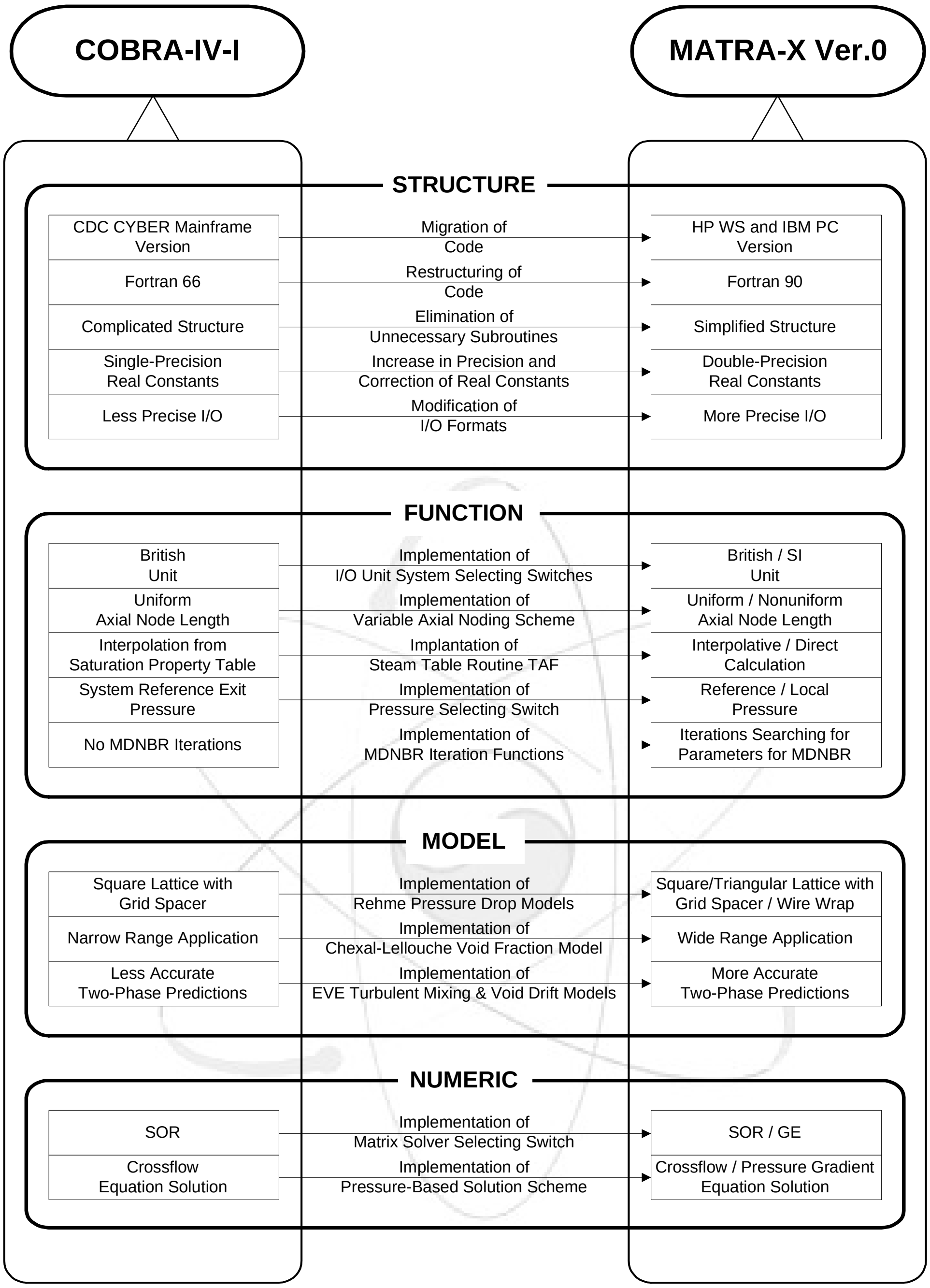


그림 2.5 MATRA 코드와 COBRA-IV-I 코드 특징 비교

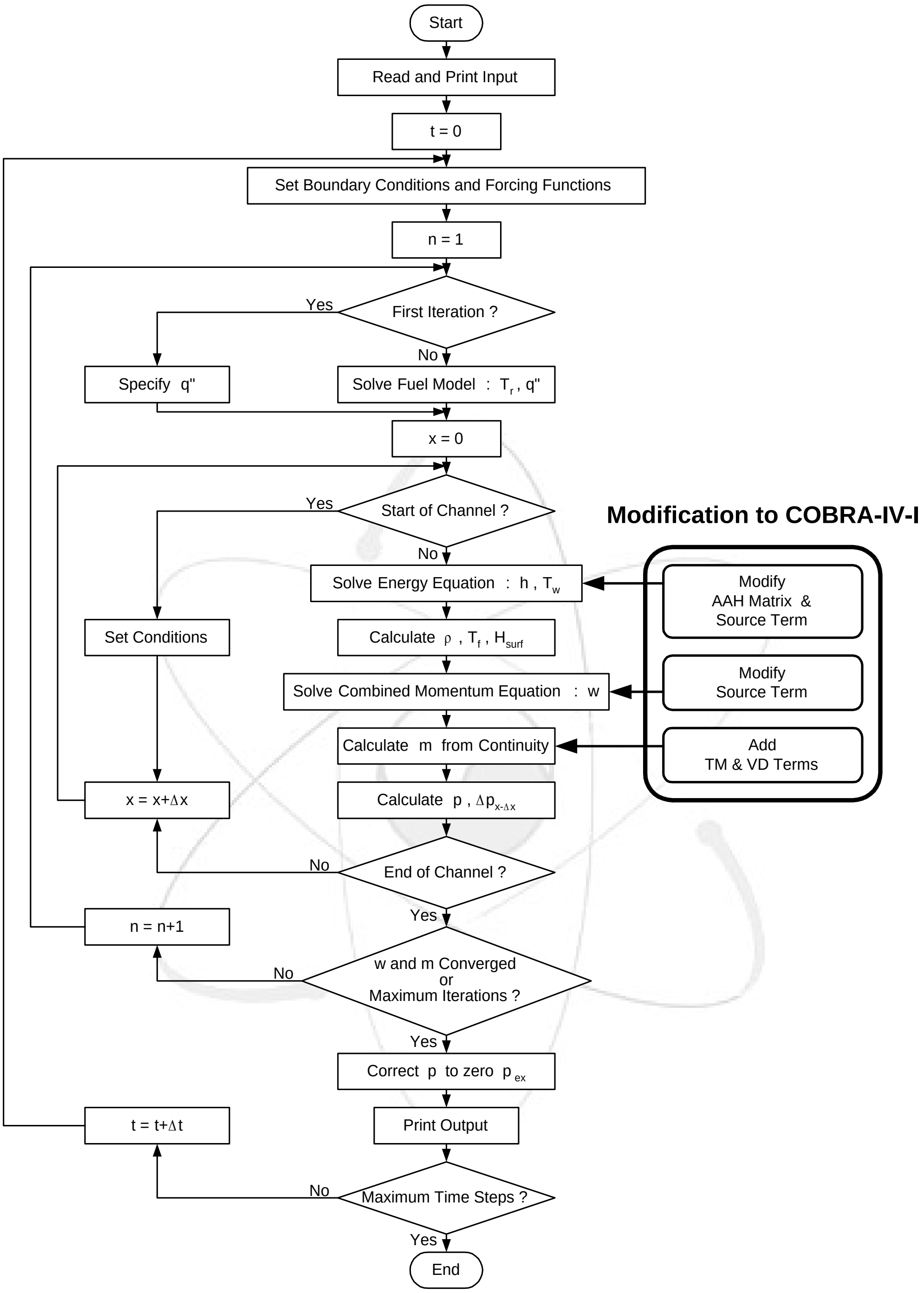


그림 2.6 MATRA-X0 코드의 계산 과정

(다) 코드 입력 체계

MATRA 코드의 입력 자료는 아래 그림과 같이 모두 12개의 입력 카드로 구성된다. 입력 변수에 대한 상세한 설명은 부록-1에 수록하였다.

Group No.	Description	Case	
		First	Subsequent
–	Initial card	Required	Not required
–	Case control card	Required	Required
1	Fluid properties	Required	Optional
2	Friction factor, heat transfer coefficient, and two-phase flow correlations	Required	Optional
3	Axial heat flux distribution	Required	Optional
4	Channel layout and dimensions	Required	Optional
5	Channel area variation	Optional	Optional
6	Gap spacing variation	Optional	Optional
7	Wire wrap and grid spacer information	Optional	Optional
8	Rod layout, dimensions, and properties	Required	Optional
9	Calculation control	Required	Optional
10	Lateral transport models	Required	Optional
11	Operating conditions and transient forcing functions	Required	Optional
12	Output display options	Required	Optional

그림 2.7 MATRA-X0 코드 입력 자료

(라) MATRA 코드 입출력 GUI 체계 개발

MATRA 코드는 텍스트 기반의 콘솔(console) 환경에서 사용하도록 개발되어 왔다. 이번 연구에서는 MATRA 코드 입출력 모듈을 윈도우 기반으로 그래픽화하여 사용자가 MATRA 코드 해석 작업을 쉽게 하도록 했다. 입출력 모듈은 유지보수가 쉬운 Visual Basic 을 이용하여 개발했다. 스프레드 기능을 추가하여 사용자가 입력을 손쉽게 할 수 있도록 하고 차트 기능을 추가하여 출력 파일로부터 원하는 정보를 그래프로 쉽게 알 수 있도록 했다.

- 입력 모듈

MATRA 코드 입출력 GUI 입력 모듈에서 카드입력 4.1을 입력하는 모습을 그림 2.8에 나타냈다.

입력 모듈은 MATRA 코드의 입력 파일을 선택하여 각 카드 입력에 해당하는 입력 양식을 스프레드 형태로 제공한다. 스프레드 기능은 Farpoint사의 Spread ActiveX 콘트롤을 이용했다. 사용자는 MATRA 코드 입력 자료를 스프레드에서 직접 편집, 수정, 저장하고 MATRA 코드를 실행할 수 있다.

MATRA 코드는 formatted 입력을 받으므로, 사용자가 입력 형식에 맞지 않게 잘못 기입하여 에러가 발생하는 경우가 종종 일어났다. 이번에 개발된 입력모듈은 사용자의 입력을 MATRA 코드의 입력 형식에 맞게 파일로 저장함으로써 입력 오류를 획기적으로 줄일 수 있게 되었다.

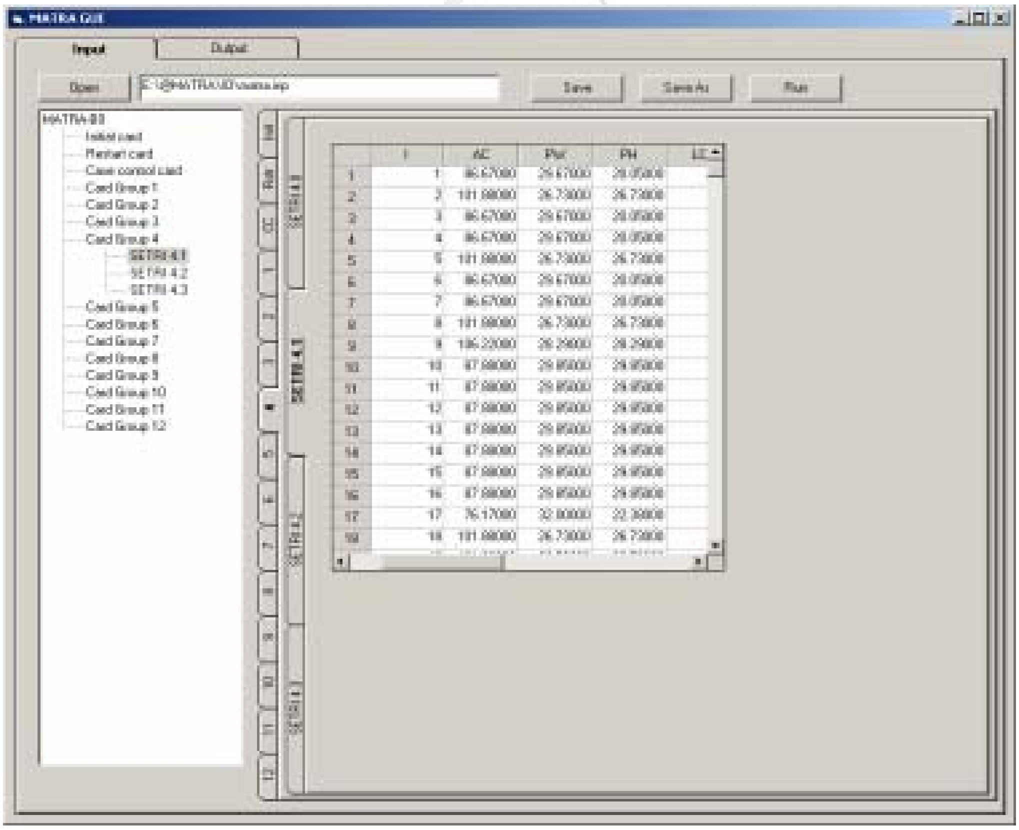


그림 2.8. MATRA 코드 입력 작성 예

- 출력 모듈

MATRA 코드 GUI 출력 모듈은 MATRA 코드 실행 결과 생성된 출력 파일을 불러와서 주요한 출력 결과를 그래프로 보여주는 기능을 제공한다.

MATRA 코드 출력 파일로부터 부수로 출구의 열수력 정보(Channel Exit Summary)를 불러와 스프레드에 나타내고 출구 온도를 그래프에 나타낸 화면을 그림 2.9에 나타냈다. 출력모듈은 오른쪽 위쪽의 스프레드에 출력 파일의 내용을 보여주고, 사용자가 화면 왼쪽에서 원하는 정보를 선택하면, 화면 오른쪽 밑쪽의 차트에 선택된 정보의 그래프를 나타낸다. 출력모듈은 이 차트를 bmp 파일로 저장하거나 프린터에 출력하는 기능을 제공한다.

차트 기능은 윈도우즈에 기본 설치되어 있는 Microsoft Chart ActiveX 콘트롤을 이용했다.

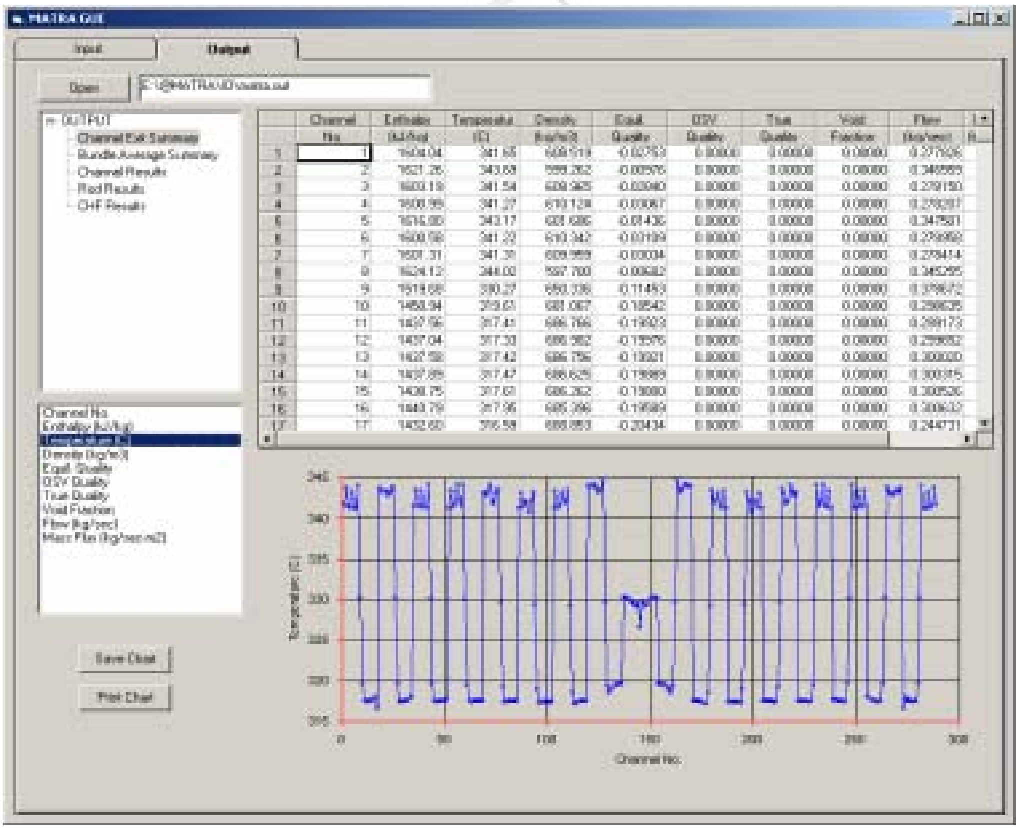


그림 2.9. MATRA 코드 GUI 출력 모듈 사용 예

2.1.2 냉각재 물성치 계산 모듈 개발

(가) 물성치 라이브러리 추가

원자로심을 열수력 설계할 때에는 부수로 해석을 통해 열수력장을 해석하고 MDBNR과 같은 설계조건을 검토하는 것이 필수적이다. 그러나 신개념 원자로심은 기존 경수로 노심과 매우 다른 특징들을 갖고 있어서 기존의 부수로 해석 코드도 이에 맞춰 수정, 개선해야 할 필요성이 대두되었다. 새로운 개념의 노심을 갖는 신형원자로에 대한 부수로 해석을 위해서 MATRA 코드가 갖춰야 할 기능은 다음과 같다.

- 초임계압 경수로 : 기존 PWR 운전조건 보다 높은 초임계 압력에서 물의 물성치 변화와 이로 인한 열전달 현상 등의 변화를 해석할 수 있어야 함.
- 고온가스냉각로 : 냉각재인 헬륨 가스의 물성치와 고온에서 복사열전달 현상 등을 해석할 수 있어야 함.

기존 MATRA 코드는 냉각재 물성치를 계산할 때 입력된 포화 물성치 표를 이용하거나 TAF 함수를 이용하고, 과열 영역에서는 서브루틴 STEM에서 만든 과열 물성치 표를 이용하였다. 함수 TAF는 경수로 운전조건에 해당하는 물의 물성치에 관한 포트란 함수이며, 물 이외의 냉각재에 대해서는 사용자가 따로 포화 물성치 표를 입력해야 했다. 본 연구에서는 MATRA 코드에 SCWR이나 GCR 등의 신개념 원자로심을 해석할 수 있는 기능들을 추가하기 위해 여러 가지 냉매의 물성치 라이브러리를 추가했다. 물성치 계산을 위한 MATRA 코드 수정 내용은 부록-2에 기술하였다.

- NIST/ASME Steam Database v2.2 (NIST Standard Reference Database 10) : 초임계압 영역에서도 사용 가능한 NIST/ASME Steam Database 물성치 라이브러리를 추가했다.
- NIST REFPROP v6.01 (NIST Standard Reference Database 23 - Thermodyanmic and Transport Properties of Refrigerants and Refrigerant

Mixtures) : 고온가스 냉각로 해석을 위해 헬륨의 물성치 뿐만 아니라 초임계압 경수로에서의 물리현상 이해를 위한 각종 실험에서 사용되는 이산화탄소, 프레온 R134a 등 물이 아닌 물질의 물성치를 계산할 수 있는 NIST REFPROP 라이브러리를 추가했다

- 이상기체 상태방정식[8] : 헬륨과 이산화탄소 같은 기체의 물성치는 이상기체 상태방정식의 가정이 유효한 조건에서 계산할 수 있으므로 이상기체 상태방정식에 의한 물성치 계산 기능을 추가했다.

(i) NIST/ASME STEAM은 IAPWS-95 함수에 의해서 물과 증기의 물성치를 계산하며, 물성치의 적용 한계는 다음과 같다.

- Thermodynamic Property Limits:

  $273.15K < T < 1273.15K$

  $P < 1{,}000$ MPa

  Molar Mass = 18.015268 g/mol Vienna Standard Mean Ocean Water (VSMOW)

- Transport Property Limits (IAPWS 1985 + IF97):

  μ

  273.15 K $< T < 1173.15$ K for $P < 300$ MPa

  273.15 K $< T < 873.15$ K for 300 MPa $< P < 350$ MPa

  273.15 K $< T < 423.15$ K for 350 MPa $< P < 500$ MPa

  k

  273.15 K $< T < 1073.15$ K for $P < 100$ MPa

  273.15 K $< T < 673.15$K for 100 MPa $< P < 150$ MPa

  273.15 K $< T < 523.15$ K for 150 MPa $< P < 200$ MPa

  273.15 K $< T < 398.15$ K for 200 MPa $< P < 400$ MPa

- Surface Tension Limits:

  Surface tension is valid from the triple point to the critical point.

  IAPWS-95 : Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use - The International Association for the Properties of Water and Steam

NIST REFPROP는 다음의 냉매들과 그 혼합물들의 물성치를 계산할 수 있다. (Ammonia, Argon, Butane, Co2, Ethane, Helium, Isobutan, Methane, Nitrogen, Oxygen, Propane, Propylen, R11, R113, R114, R115, R116, R12, R123, R124, R125, R13, R134A, R14, R141B, R142B, R143A, R152A, R218, R22, R227Ea, R23, R236Ea, R236Fa, R245Ca, R245Fa, R32, R41, Rc318, Water). 각 물성치들의 계산 한계는 REFPROP 프로그램의 'Info' 메뉴에서 확인할 수 있다.

(ii) R134a 물성치의 적용한계는 다음과 같다.

- Thermodynamic Property Limits:
  $169.9 < T < 453.2$ K
  $P < 70$ MPa
  Molar Mass = 102.03 g/mol

- Transport Property Limits:
  μ
  169.9 K $< T < 500.0$ K
  $P < 100$ MPa
  $\rho < 1740$ kg/m3
  k
  170.0 K $< T < 450.0$ K
  $P < 20.0$ MPa
  $\rho < 1740$ kg/m3

- Surface Tension Limits :
  169.9 K $< T < 374.2$ K

(iii) 헬륨 가스 물성치의 적용 한계는 다음과 같다.

- Thermodynamic Property Limits:
  2.2 K $< T < 1500.0$ K
  Molar Mass = 4.00 g/mol

- Transport Property Limits:

μ
$2.2\ \mathrm{K} < T < 1500.0\ \mathrm{K}$
$P < 100\ \mathrm{MPa}$
$\rho < 355.2\ \mathrm{kg/m3}$
k
$2.2\ \mathrm{K} < T < 1500.0\ \mathrm{K}$
$P < 100\ \mathrm{MPa}$
$\rho < 355.2\ \mathrm{kg/m3}$

- Surface Tension Limits:
  $2.2\ \mathrm{K} < T < 5.2\ \mathrm{K}$

(나) 물성치 라이브러리 검증

MATRA 코드에 추가한 라이브러리가 제대로 작동하는지 확인하기 위해서 MATRA의 물성치 계산값와 독립적인 윈도우즈 프로그램인 NIST STEAM, NIST REFPROP의 물성치를 각각 비교했다. 먼저 MATRA의 물성치와 NIST STEAM의 포화 물성치를 0.1~22 MPa 범위에서 비교하여 표 2.1에 정리했다. 각각의 주요 물성치들의 상대오차는 -4.243e-3 ~ 9.278e-4 %로 나타났다. 주어진 압력과 온도로부터 여러 물성치를 구할 때, MATRA 코드와 윈도우즈 NIST STEAM 프로그램의 물성치를 0.01~40 MPa 의 압력과 300~1250 K 의 온도 범위에서 비교하여 표 2.2에 정리했다. 그 결과 주요 물성치의 상대오차는 -4.8e-5 ~ 4.5e-5 %로 나타났다. 위의 결과로부터 MATRA에 NIST STEAM 라이브러리가 성공적으로 이식되어 잘 작동하고 있는 것으로 나타났다.

MATRA의 물성치와 NIST REFPROP의 포화 물성치를 0.1~22 MPa 범위에서 비교하여 표 2.3에 정리했다. 각각의 주요 물성치들의 상대오차는 -4.243e-3 ~ 9.278e-4 %로 매우 작게 나타났다. MATRA 와 NIST REFPROP 으로부터 주어진 압력과 온도에서의 R134a 물성치를 계산하여 비교했다. 압력은 0.1~4 MPa의 압력과 -60~130 °C 의 온도범위에서 MATRA와 NIST REFPROP 과의 물성치 오차를 표 2.4에 정리했다. 각각의 주요 물성치들의 상대오차는 -4.81e-4 ~ 4.75e-4 %로 매우 작게 나타났다. 위의 결과로부터 MATRA에 NIST REFPROP 라이브러리가 성공적으로

이식되어 잘 작동하고 있는 것으로 나타났다.

헬륨 가스의 물성치를 MATRA 코드의 PROPHE와 NIST REFPROP, 이상기체 상태방정식과 참고문헌에 나타난 자료를 서로 상호 비교하여 표 2.5에 나타냈다. 주어진 압력 0.1~4.0 MPa 과 온도 -60~1230 °C 에서 각 방식의 물성치 값이 매우 일치하는 것으로 나타났다. MATRA 코드의 PROPHE와 NIST REFPROP은 -5.8e-5~3.7e-2 % 의 상대오차가 나타났다. PROPHE와 이상기체 상태방정식의 물성치는 -3~7 %, PROPHE와 참고문헌 자료는 -0.7~3 %의 상대오차를 보였다. MATRA 코드에 NIST REFPROP 라이브러리가 잘 이식되었으며, 빠른 계산을 위해서 이상기체 상태방정식을 사용할 수 있다는 것을 알 수 있다.

표 2.1. 물 포화 물성치 비교 (MATRA와 NIST STEAM)

Saturated Properties	MATRA PROPSTM(a) vs. NIST STEAM(b)	
	Min.	Max.
Pressure Range [MPa]	0.1	22
% Err(Tsat)	-4.243E-03	9.278E-04
% Err(Vf)	-3.904E-05	3.996E-05
% Err(Vg)	-4.157E-05	4.150E-05
% Err(hf)	-4.254E-05	4.108E-05
% Err(hg)	-2.070E-05	1.998E-05
% Err(Cpf)	-3.982E-05	4.015E-05
% Err(Cpg)	-3.762E-05	4.967E-05
% Err(kf)	-1.114E-05	1.119E-05
% Err(kg)	-3.698E-05	4.526E-05
% Err(μf)	-4.482E-05	4.555E-05
% Err(μg)	-2.929E-05	3.801E-05
% Err(σ)	-3.621E-05	4.386E-05

% Err = (a-b)/a × 100 or (a-c)/a × 100

a : PROPSTM = MATRA function for water and steam properties with NIST Steam Database (IAPWS-95) source code.

b : NIST STEAM = NIST/ASME Steam Database with formulation of IAPWS-95.

표 2.2. 주어진 압력과 온도에서의 물 물성치 비교 (MATRA와 NIST STEAM)

Properties with given P & T.	MATRA PROPSTM(a) vs. NIST STEAM(b)	
	Min.	Max.
Pressure Range [MPa]	0.01	40
Temperature Range [K]	300	1250
% Err(V)	-4.765E-05	4.448E-05
% Err(H)	-4.185E-05	3.333E-05
% Err(Cp)	-4.116E-05	4.003E-05
% Err(K)	-4.551E-05	4.106E-05
% Err(μ)	-3.740E-05	4.030E-05

% Err = (a-b)/a × 100 or (a-c)/a × 100

표 2.3. 프레온 포화 물성치 비교 (MATRA와 NIST REFPROP)

Saturated Properties	MATRA PROPREF(a) vs. NIST REFPROP(b)	
	Min.	Max.
Press. [MPa]	0.1	4.0
Temp. [K]	-60.0	130.0
% Err(Vf)	-6.888E-05	5.309E-05
% Err(Vg)	-7.660E-06	1.477E-05
% Err(hf)	-1.331E-05	1.494E-05
% Err(hg)	-1.003E-05	1.218E-05
% Err(sf)	-3.785E-05	4.433E-05
% Err(sf)	-2.884E-05	2.356E-05
% Err(Cpf)	-3.801E-05	3.906E-05
% Err(Cpg)	-4.389E-05	1.807E-05
% Err(muf)	-1.033E-05	2.428E-05
% Err(mug)	-2.633E-05	3.718E-05
% Err(kf)	-5.149E-06	3.845E-05
% Err(kg)	-4.321E-05	1.382E-05
% Err(sig)	-3.489E-05	9.248E-04

% Err = (a-b)/a × 100

a : PROPREF = MATRA function for properties of various refrigerant with source code of the NIST RefProp .

b : NIST REFPROP = NIST RefProp v6

표 2.4. 주어진 압력 온도 조건에서 프레온 물성치 비교 (MATRA와 NIST REFPROP)

Properties with given P & T	MATRA PROPREF(a) vs. NIST REFPROP(b)	
	Min.	Max.
Pressure [MPa]	0.1	4
Temp. [°C]	-60	130
% Err(V)	-4.48E-04	3.13E-04
% Err(h)	-3.74E-04	3.69E-04
% Err(s)	-3.87E-04	4.59E-04
% Err(C_p)	-4.81E-04	4.75E-04
% Err(μ)	-3.70E-04	3.81E-04
% Err(k)	-4.69E-04	4.44E-04
% Err(σ)	-3.17E-01	3.98E-01

표 2.5. 헬륨 가스 물성치 비교

P & T given	MATRA PROPHE(a) vs. NIST REFPROP(b)		MATRA PROPHE(a) vs. IDEAL GAS(c)		MATRA PROPHE(a) vs. HTR-10(d)	
	Min.	Max.	Min.	Max.	Min.	Max.
Pres.[MPa]	0.1	4.0	0.1	4.0	0.1	4.0
Temp.[C]	-60.0	1230.0	-60.0	1230.0	-60.0	1230.0
% Err(V)	0.000E+00	3.659E-02	1.575E-02	2.622E+00	-6.119E-03	8.783E+00
% Err(h)	0.000E+00	3.650E-02	6.902E-02	1.626E+00		
% Err(Cp)	-5.779E-05	0.000E+00	-6.744E-02	2.118E-02	-1.041E-01	-1.540E-02
% Err(μ))			-5.959E-02	4.822E+00	-4.126E-01	2.425E+00
% Err(k)			-3.087E+00	7.026E+00	-7.389E-01	3.095E+00

% Err = (a-b)/a × 100, or (a-c)/c × 100, or (a-d)/d × 100
a : PROPHE = MATRA function for properties of Helium as an ideal gas
b : NIST REFPROP = NIST RefProp v6
c : Irvine, Thomas F. & Liley, P. E., "Steam and gas tables with computer equations," Academic Press, 1984.
d : “Evaluation of High Temperature Gas Cooled Reactor Performance,” IAEA-TECDOC-TBD, Dec., 2004

(다) 물성치 계산 방식 개선

MATRA 코드는 열수력장을 입구부터 출구까지 반복법에 의해 계산하는데, 새로운 물성치 라이브러리는 기존의 TAF 함수보다 계산속도가 훨씬 느리다. 따라서 물성치가 필요할 때마다 라이브러리로부터 물성치를 계산하는 방법은 정밀하지만 계산속도가 매우 늦어진다. 최근에 타분야 코드들간에 연계코드 개발 경향이 나타나고 있는데, 코드 간에 반복 계산이 이뤄지는 경우엔 빠른 계산속도가 요구된다. MATRA 코드에서 새로운 물성치 라이브러리를 사용할 때 계산시간을 단축하기 위해서 기존의 포화 물성치 표에서 보간법으로 물성치를 계산하는 방법을 도입했다. 코드 입력 1번 카드의 J9 옵션값을 0과 1에서 두가지에서 2와 3을 추가 확장하고 IFLUID 옵션과 J9TF 옵션을 추가했다. 표 2.6에 물성치 계산 옵션을

정리했다.

사용자가 J9TF 옵션을 0으로 선택하면 물성치 라이브러리 함수를 그대로 계산하도록 하고, J9TF 옵션을 1로 선택하면, MATRA 코드 계산 초기에 코드 입력으로부터 필요한 압력 및 온도/엔탈피 범위를 판단하고, 충분히 넓은 범위의 포화 물성치 표를 물성치 라이브러리로부터 생성했다. 그리고 이후의 계산에서는 생성된 포화 물성치 표로부터 물성치를 계산하도록 했다. 옵션 J9TF를 2로 선택하면 과냉 영역 뿐만 아니라 과열 영역에서의 물성치 표도 생성하도록 했다.

기존의 Winfrith 실험장치에 운전조건을 과냉 프레온 조건과 초임계압 프레온 조건을 적용하여 물성치 계산 옵션에 따른 계산 속도(표 2.7)와 계산 결과(그림 2.10, 그림 2.11)를 비교했다.

옵션1은 J9을 0으로 선택하고 프레온 R134a의 포화 물성치를 입력 카드 1.1에 입력하여 MATRA 코드 해석한 경우이다. 옵션2와 3은 J9을 2로 선택하여 REFPROP 라이브러리를 사용하여 해석한 경우이다. 옵션2는 J9TF를 0으로 하여 프레온의 물성치를 라이브러리 함수로만 계산한 경우이고, 옵션3은 J9TF를 2로 하여 프레온 R134a의 포화 물성치 표를 REFPROP 라이브러리로부터 생성하여 해석한 경우이다.

옵션2인 라이브러리 함수를 이용할 경우, 옵션1보다 30배 이상 계산 속도가 늘었으나, 라이브러리로부터 물성치 표를 생산하여 해석한 옵션3의 경우는 옵션1과 비슷한 계산 속도를 보였다.

과냉 조건의 프레온 해석 결과를 그림 2.10에 초임계압 조건의 프레온 해석 결과를 그림 4에 나타냈다. 두 경우 모두 부수로 유량 분포와 엔탈피 증가량에 있어서 옵션 2와 옵션 3 사이에 차이가 없는 것으로 나타났다. 그러나 임계에 가까운 조건에서는 물성치의 변화가 매우 크므로 계산 속도가 느리더라도 옵션2를 사용해야 할 것이다.

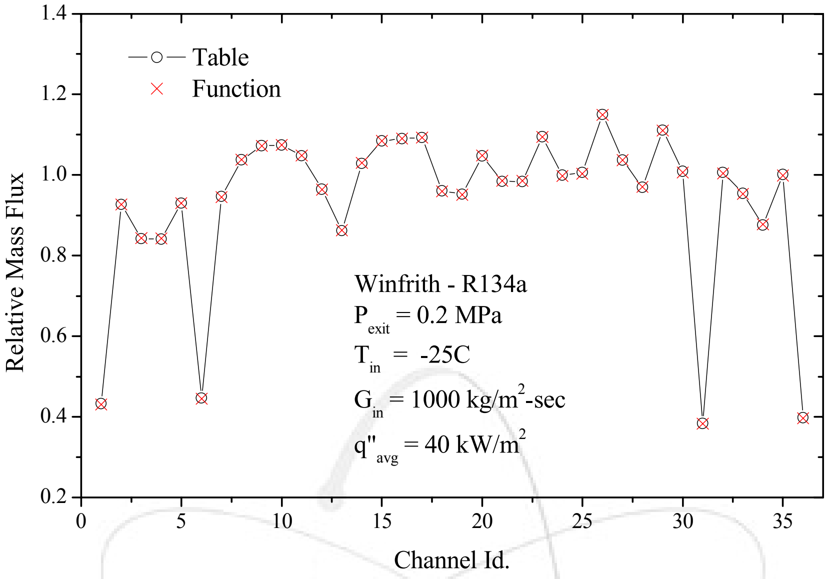
표 2.6. MATRA X 물성치 계산 옵션 및 의미

옵션 변수	J9	IFLUID+	J9TF+
	0 : 과냉 물성치 입력	-	-
	1 : TAF 함수	-	-
	2* : NIST STEAM 라이브러리	-	0 : 함수 이용 1 : 함수 이용, 과열 물성치 표 생성 2 : 과냉 및 과열 물성치 표 생성
	3* : NIST REFPROP 라이브러리	1 : He 2 : R134a 3 : CO2 4 : Air	0 : 함수 이용 1 : 함수 이용, 과열 물성치 표 생성 2 : 과냉 및 과열 물성치 표 생성

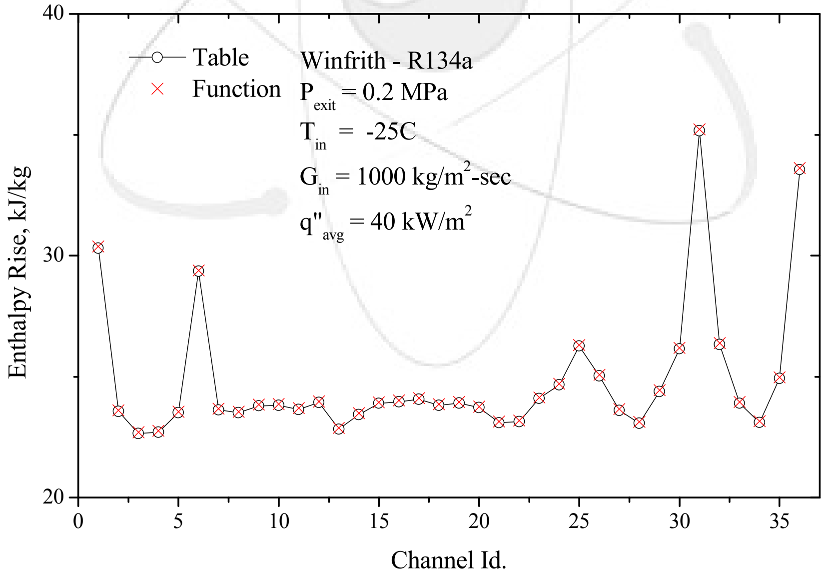
* MATRA X 에서 확장된 옵션
\+ MATRA X 에서 추가된 옵션

표 2.7. 물성치 계산 옵션별 계산 속도 비교

물성치 계산옵션 / CPU time/Outer iteration	옵션 1 1 번 카드 입력에 과냉 물성치 입력	옵션 2 라이브러리 함수 이용	옵션 3 라이브러리 함수로 물성치 표 생성
J9 옵션값	0	3	3
IFLUID 옵션값	-	2	2
J9TF 옵션값	-	0	2
과냉 프레온 문제 해석	0.116	4.892	0.128
초임계압 프레온 문제 해석	0.213	7.513	0.225

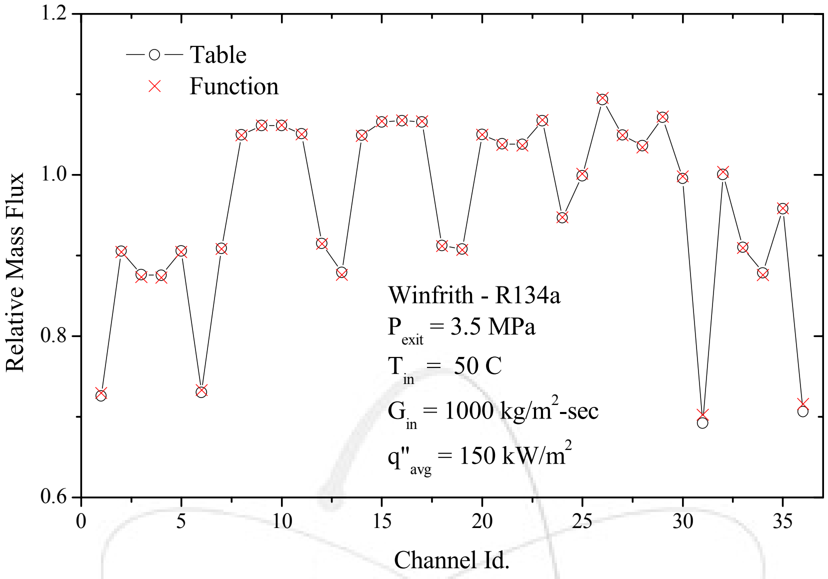


(a) 상대 질량 유속 비교

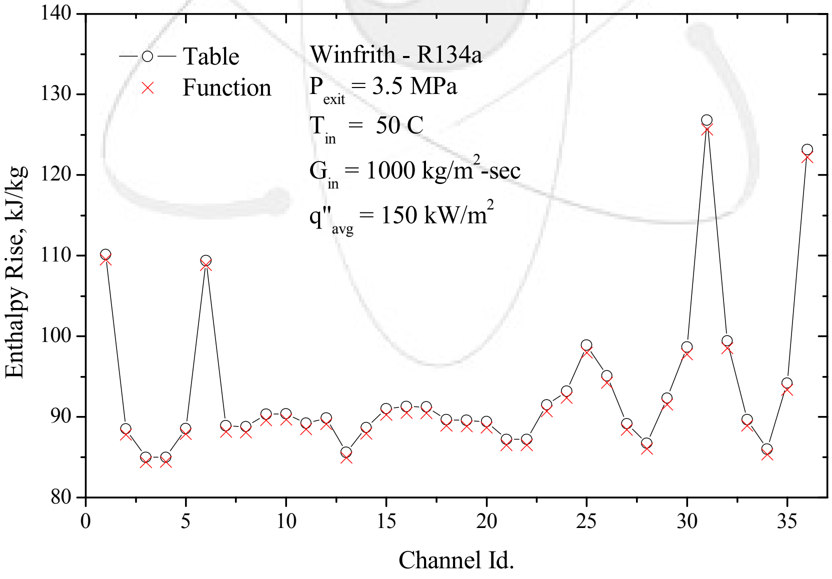


(b) 엔탈피 증가 비교

그림 2.10 물성치 계산 옵션 결과 비교 (과냉 조건 프레온)



(a) 상대 질량 유속 비교



(b) 엔탈피 증가 비교

그림 2.11 물성치 계산 옵션 결과 비교 (초임계압 조건 프레온)

2.2 부수로 해석 코드 적용성 평가

2.2.1 비정방형 집합체 CHF 해석

(가) 비정방형 집합체 특성

비정방형 집합체는 집합체 내의 봉배열 특성에 따라 구분한 것으로서, 직교하지 않는 모든 종류의 봉배열을 갖는 집합체를 의미한다. 신개념 원자로 개발 시 원자로의 안전성을 제고시키기 위하여 저출력 밀도 노심을 구성하는 경우, 혹은 다양한 노심 형태를 구현하고자 하는 경우에 기존 경수로에 사용되는 정방형 집합체를 적용하는데는 한계가 있으므로 여러가지 형태의 비정방형 집합체 적용을 고려할 필요가 있다. 부수로 해석 코드는 주로 정방형 집합체를 사용하는 가압 경수로 노심에 대하여 적용되어 왔으므로, 신개념 원자로 개발에 대비하여 비정방형 집합체에 대한 부수로 해석 코드의 적용성 평가가 필요하다. 본 연구에서는 원자로 노심 열적 여유도 평가시 가장 중요한 설계 인자인 CHF (Critical Heat Flux)에 대하여 부수로 해석 코드의 적용성을 평가하였다. 이를 위하여 비정방형 집합체에 대한 CHF 시험 자료를 수집하였으며, 시험 자료에 대한 부수로 해석을 수행하여 국부조건 개념 CHF 예측 모형의 예측 성능을 평가하였다. 평가에 사용된 비정방형 집합체의 기하형태 특성 자료는 표 2.8에 제시하였다. 시험 집합체의 기하 형태는 부록-3에 제시하였다.

(나) 비정방형 집합체 CHF 분석

시험 집합체 기하 형태 자료를 사용하여 부수로 해석 코드 입력 자료를 작성하였으며, 각 시험 집합체에 대한 부수로 해석 입력 자료 특성은 부록-4에 제시하였다. 비정방형 집합체에 대한 CHF 특성 분석은 집합체 단면적 평균 물성치를 사용하여 수행한 바 있다[9]. 본 연구에서는 부수로 해석 코드를 적용하여 시험 집합체 내부의 국부적인 열수력장 해석을 수행하였으며, 이를 국부조건 CHF 예측 모형에 적용하여 CHF 예측 성능을 평가하였다. 이를 위하여 비정방형

집합체의 CHF 예측에 적용 가능한 것으로 판단되는 여러가지 CHF 상관식들을 조사하였으며, 그 결과 집합체 CHF 상관식으로서 EPRI-1 상관식, Bowring mixed flow 상관식, KfK-3 상관식, PI-3P 상관식, 그리고 원형관 CHF 상관식으로서 AECL 1995 CHF Table, Bowring 상관식, Katto 상관식, Shah 상관식 등이 선정되었다. 상관식 형태는 부록-5에 제시하였다.

부수로 해석 코드를 사용하여 분석한 시험집합체 국부 열수력 조건을 사용하여 CHF 예측 성능을 분석한 결과는 표 2.9에 제시하였다. 분석 결과 집합체 CHF 상관식은 CHF를 평균적으로 낮게 예측하고 원형관 상관식들은 높게 예측하는 것으로 나타났다. 그리고 전체적인 예측 성능을 보면 평균값은 Shah 상관식, RMS 오차는 EPRI-1 상관식이 가장 우수한 것으로 나타났다. 각 상관식으로 예측한 P/M의 분포는 그림 2.12 ~ 2.15에 제시하였다.

표 2.8 비정방형 CHF 시험 집합체 기하형태 특성 자료 (1/3)

	EPRI TS-601	EPRI TS-602	EPRI TS-603	EPRI TS-604	EPRI TS-605	EPRI TS-606	EPRI TS-607	EPRI TS-609	EPRI TS-610	EPRI TS-613
TS barrel shape	Circular	Circular	Circular	Circular	Circular	Circular	Circular	Circular	Circular	Circular
Total No. of rods	19	19	19	19	19	19	19	19	28	37
No. of heated rods	19	19	19	19	19	18	18	18	28	36
Rod pitch (m)	-	-	-	-	-	-	-	-	-	-
Rod diameter (m)	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0152	0.0138
GT diameter (m)	0	0	0	0	0	0.0195	0.0195	0.0195	0	0.0138
Heated length (m)	1.8288	0.889	1.8288	0.4572	2.7432	2.7432	2.667	2.667	1.8288	1.8288
Rod-wall gap (m)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0014	0.0016
Flow tube dia. (m)	0.1033	0.1033	0.1033	0.1033	0.1033	0.1033	0.1033	0.1033	0.1033	0.1033
Flow area (m^2)	0.002528	0.002528	0.002528	0.002528	0.002528	0.002538	0.002538	0.002538	0.003312	0.002878
Central cell d_{hy} (m)	0.0067	0.0067	0.0067	0.0067	0.0067	0.0069	0.0069	0.0069	0.0122	0.0044
Central cell d_{he} (m)	0.0067	0.0067	0.0067	0.0067	0.0067	0.0103	0.0103	0.0103	0.0122	0.0066
Assembly d_{hy} (m)	0.0067	0.0067	0.0067	0.0067	0.0067	0.0067	0.0067	0.0067	0.0080	0.0061
Assembly d_{he} (m)	0.0086	0.0086	0.0086	0.0086	0.0086	0.0091	0.0091	0.0091	0.0099	0.0074
F_{xy}	1.117	1.125	1.120	1.117	1.149	1.135	1.125	1.125	1.101	1.160
APS	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform
Spacer type	Grid	Grid	Grid	Grid	Grid	Grid	Grid	Grid	Grid	Grid
Gsp or Hwire (m)	0.2286	0.2286	0.2286	0.2286	0.2286	0.2286	0.4572	0.4572	0.4572	0.2286
No. of grids	7	3	7	2	11	11	5	5	3	7

표 2.8 비정방형 CHF 시험 집합체 기하형태 특성 자료 (2/3)

Test section ID	EPRI TS-801	EPRI TS-802	EPRI TS-805	EPRI TS-806	EPRI TS-807	EPRI TS-808	EPRI TS-809	EPRI TS-810	EPRI TS-103	EPRI TS-104
TS barrel shape	Circular	Circular	Circular	Circular	Circular	Circular	Circular	Circular	Hexagonal	Hexagonal
Total number of rods	19	19	19	19	19	19	19	19	19	19
Number of heated rods	19	18	18	19	18	19	18	18	19	19
Rod pitch (m)	-	-	-	-	-	-	-	-	0.0151	0.0151
Rod diameter (m)	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0159	0.0107	0.0107
GT diameter (m)	0	0.0151	0.0151	0	0.0151	0	0.0174	0.0174	0	0
Heated length (m)	1.2192	1.2192	1.2192	1.2192	1.2192	1.2192	1.2192	1.2192	1.524	1.524
Rod-wall gap (m)	0.0022	0.0017	0.0017	0.0021	0.0017	0.0021	0.0017	0.0017	0.0028	0.0028
Flow tube diameter (m)	0.0915	0.0915	0.0915	0.0915	0.0915	0.0915	0.0915	0.0915	-	-
Flow area (m^2)	0.002821	0.002839	0.002839	0.002821	0.002839	0.002821	0.002780	0.002780	0.00192	0.00192
Central cell d_{hy} (m)	0.0089	0.0115	0.0115	0.0089	0.0115	0.0089	0.0094	0.0094	0.0128	0.0128
Central cell d_{he} (m)	0.0089	0.0169	0.0169	0.0089	0.0169	0.0089	0.0145	0.0145	0.0128	0.0128
Assembly d_{hy} (m)	0.0091	0.0092	0.0092	0.0091	0.0092	0.0091	0.0090	0.0090	0.0084	0.0084
Assembly d_{he} (m)	0.0119	0.0126	0.0126	0.0119	0.0126	0.0119	0.0124	0.0124	0.0120	0.0120
F_{xy}	1.164	1.141	1.105	1.149	1.112	1.155	1.105	1.174	1.100	1.091
APS	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform
Spacer type	Wire wrap	Grid	Grid	Wire wrap	Grid	Wire wrap	Grid	Grid	Wire-wrap	Grid
Gsp or Hwire (m)	0.2286	0.254	0.254	0.2286	0.254	0.2286	0.254	0.254	0.381	0.381
No. of grids	-	5	5	-	5	-	5	5	-	4

표 2.8 비정방형 CHF 시험 집합체 기하형태 특성 자료 (3/3)

TS ID	Rod Support system	Heat Flux Dist'n	Rod Support location	Rod dia. & p/d	rod-wall & rod-rod gap	A_{flow} (in^2)	A_{heat} (ft^2)
1	A1	B1	C1	D1	E1	1.388	5.890
2	A1	B1	C2	D1	E1	1.388	5.890
3	A2	B1	C1	D1	E1	1.388	5.890
4	A2	B1	C3	D1	E1	1.388	5.890
5	A2	B2	C2	D1	E1	1.388	5.890
6	A2	B2	C1	D1	E1	1.388	5.890
7	A2	B2	C3	D1	E1	1.388	5.890
8	A3	B1	C3	D1	E1	1.388	5.890
9	A3	B1	C3	D1	E2	1.388	5.890
10	A3	B2	C3	D1	E1	1.388	5.890
11	A4	B2	C3	D1	E1	1.388	5.890
12	A2	B3	C3	D1	E1	1.388	5.890
13	A5	B2	C3	D2	E3	1.138	6.597
14	A5	B2	C1	D2	E3	1.138	6.597

A1: single window spring collars, A2: double window spring collars, A3: No. 6 grid, A4: No. 7 grid, A5: No. 8 grid

B1: linear transverse radial, uniform axial, B2: uniform radial, uniform axial, B3: uniform radial, two-step hot inlet axial

C1: 3, 15, 27, 39, 51 (inches from exit end of heated length), g_sp = 12 in., C2: 0, 3, 15, 27, 39, 51, C3: 9, 21, 33, 45

D1: 0.25 in. o.d., p/d=1.36 (pitch=0.34 in.), D2: 0.28 in. o.d., p/d=1.214 (pitch=0.34 in.)

E1: (rod-to-wall gap)/(rod-to-rod gap) = 0.09 / 0.09 in., E2: 0.06 / 0.09 in., E3: 0.045/ 0.06 in.

표 2.9 부수로 해석 결과를 사용한 CHF 예측 성능 분석 결과

CHF 상관식		(P/M)평균	표준편차	RMS 오차	자료수
집합체 CHF 상관식	EPRI-1	0.896	0.170	0.199	1079
	KfK-3	0.876	0.243	0.272	
	PI-3	0.907	0.333	0.346	
	Bowring (Mixed)	0.906	0.418	0.428	
원형관 CHF 상관식	Bowring (Tube)	1.061	0.252	0.259	
	Katto	1.125	0.286	0.312	
	Shah	1.046	0.299	0.302	
	1995 CHF Table (HBM)	1.151	0.203	0.253	
	1995 CHF Table (DSM)	1.747	1.131	1.355	

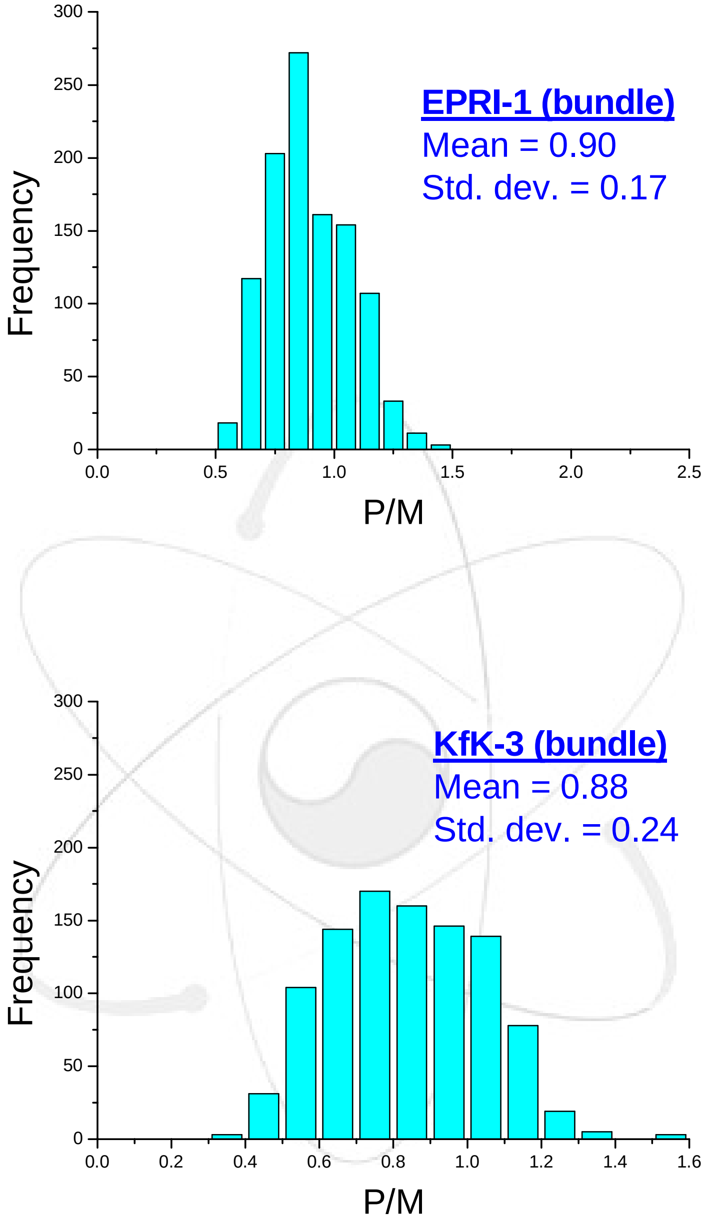


그림 2.12 비정방형 집합체 CHF 예측 성능 (EPRI-1, KfK-3 상관식)

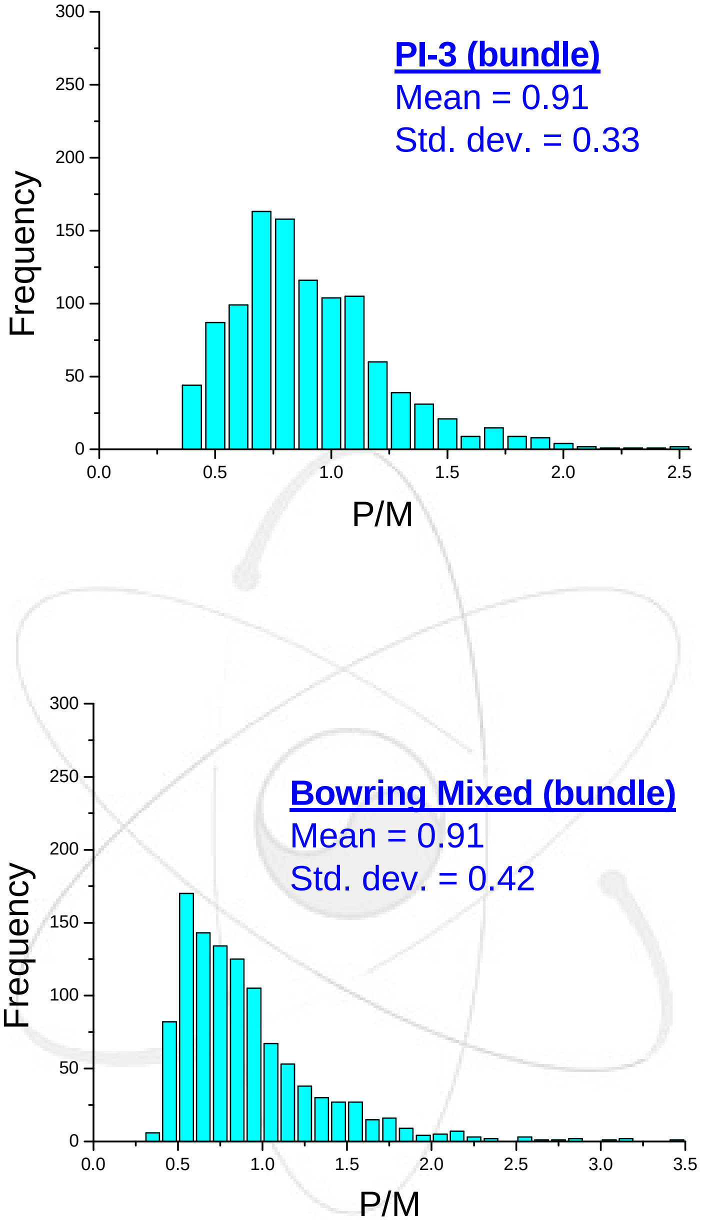


그림 2.13 비정방형 집합체 CHF 예측 성능 (PI-3, Bowring mixed 상관식)

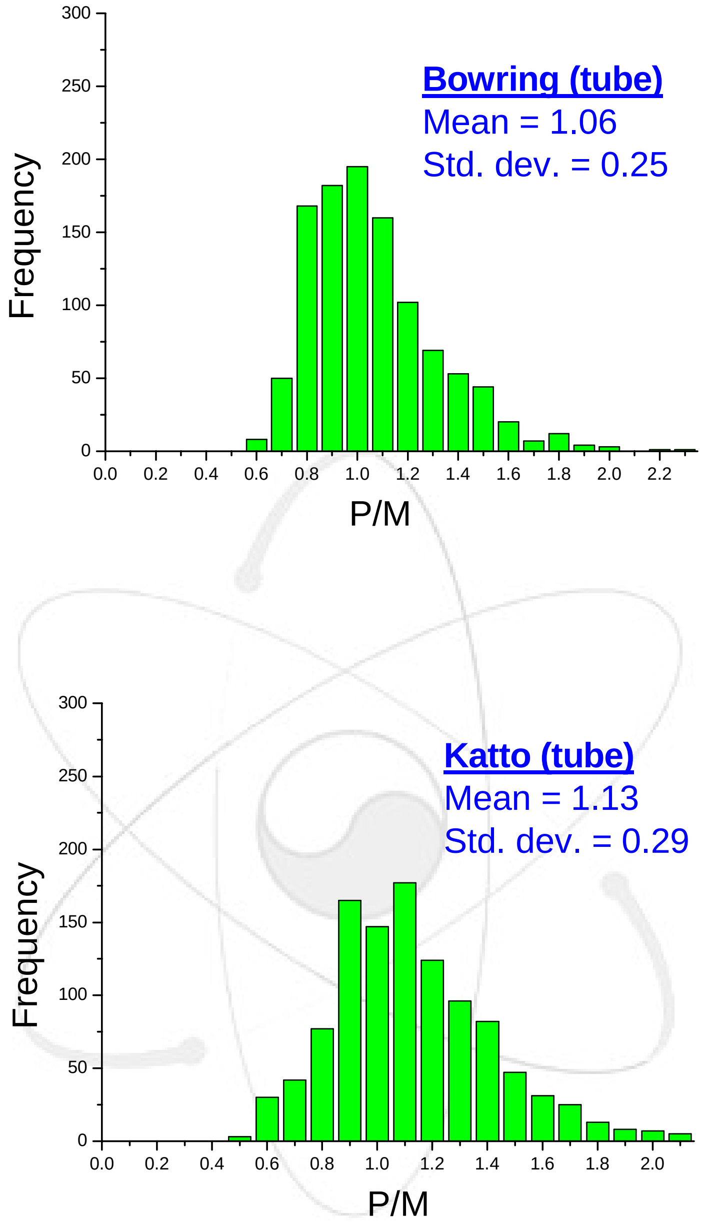


그림 2.14 비정방형 집합체 CHF 예측 성능 (Bowring tube, Katto 상관식)

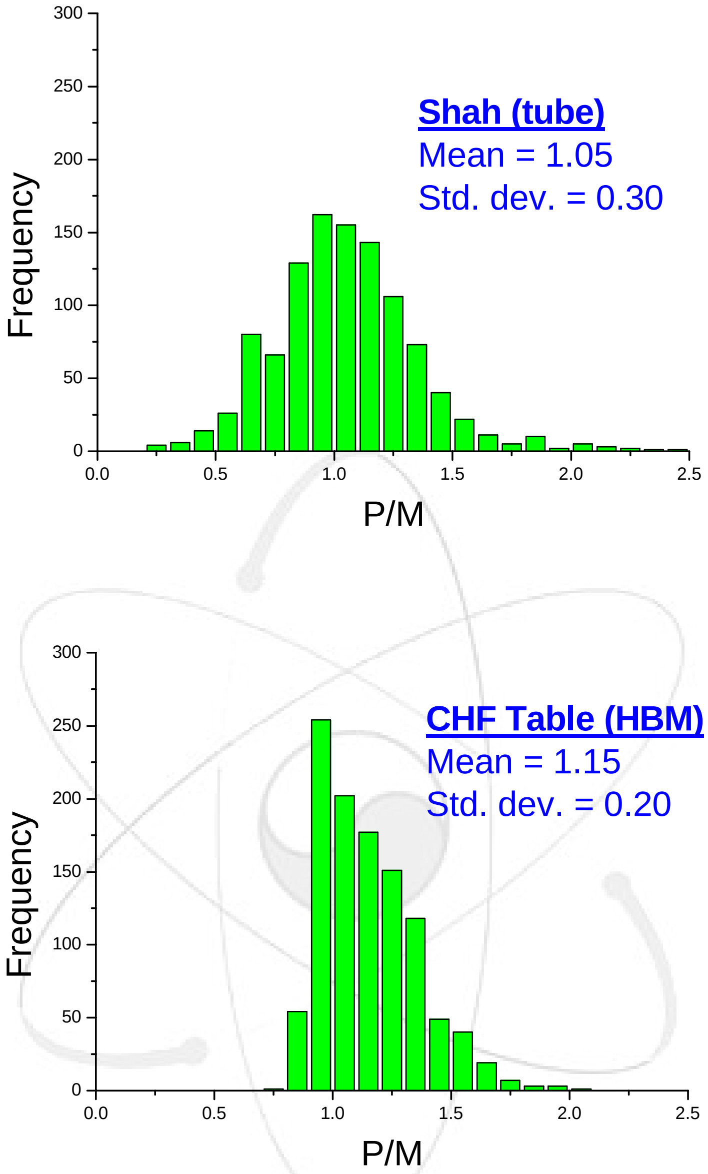


그림 2.15 비정방형 집합체 CHF 예측 성능 (Shah, 1995 CHF table 상관식)

2.2.2 신개념 원자로 조건 적용

(가) 초임계압 조건 부수로 해석 적용

MATRA의 초임계압 노심 해석 능력을 평가하기 위해서 초임계압 5x5 봉다발 프레온 루프 실험을 해석하고, 가상의 초임계압 5x5 봉다발 물 루프 실험을 해석했다. 초임계압 프레온 루프 실험은 KAERI의 열유동 실험실에서 수행한 것으로 5x5 봉다발 루프의 출구 압력을 3.6에서 4.2 MPa로 증가시키며 열전달 현상을 관찰한 실험이다. 유량과 봉 벽면 온도와 입출구 온도 및 압력이 측정되었고, 부수로에서의 온도 측정이 이뤄지지 않았기 때문에 MATRA 코드로 1차원 해석을 수행하여 입출구 온도를 비교했다 (그림 2.16). MATRA 코드 해석 결과, 임계압보다 낮은 압력에서 임계압보다 높은 압력으로의 천이 계산시에도 입구 및 출구 온도를 잘 예측하는 것으로 나타났다.

Winfrith 5x5 봉다발 CHF 실험 장치에 초임계압 물 운전조건을 적용하여 가상의 실험을 MATRA 코드로 해석했다. 시험 집합체 형태는 그림 2.17에 제시하였다. Winfrith CHF 실험은 subcritical 압력 조건에서 수행되었으므로 그림 2.18에서 보듯이 단상 유동 조건 (low heat flux)과 2상 유동 조건 (high heat flux)에서 서로 다른 부수로 유동 분포 특성을 나타낸다. 즉 집합체 모서리 수로의 수력직경은 중심부에 비하여 작으므로 단상 유동 조건에서는 집합체 중심부에 있는 부수로의 유량이 크게 나타난다. 그러나 열속이 큰 경우에는 집합체 중심부에서 2상 유동이 발생하여 압력 손실이 증가하므로 중심부 부수로 유량은 모서리 수로에 비하여 작아지는 경향을 나타낸다. 한편 초임계압 조건에서는 상변화가 일어나지 않으므로 열속의 크기에 관계없이 단상 유동 조건과 유사한 부수로 유량분포 특성을 나타내는 것을 알 수 있다.

초임계압 프레온 실험 HTDET-G250-Q27_PSUDO

Number of Rods	25 (5 x 5)
Average power (kW)	26.86
Flow rate (kg/s)	0.68
Inlet temp. (C)	90.74
Exit Pressure (MPa)	3.6~4.2

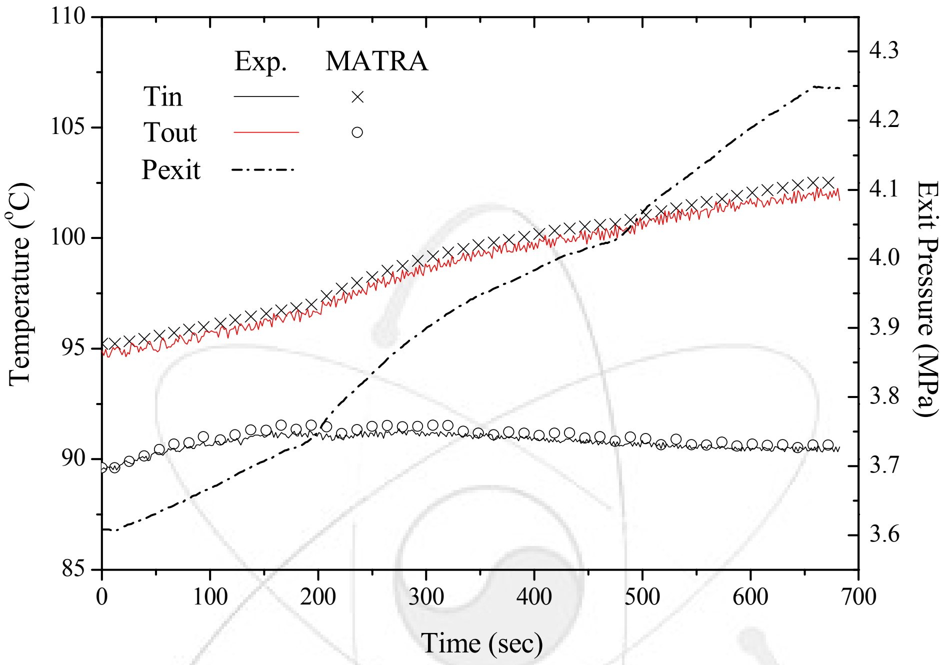


그림 2.16 초임계압 프레온 CHF 실험 해석 결과

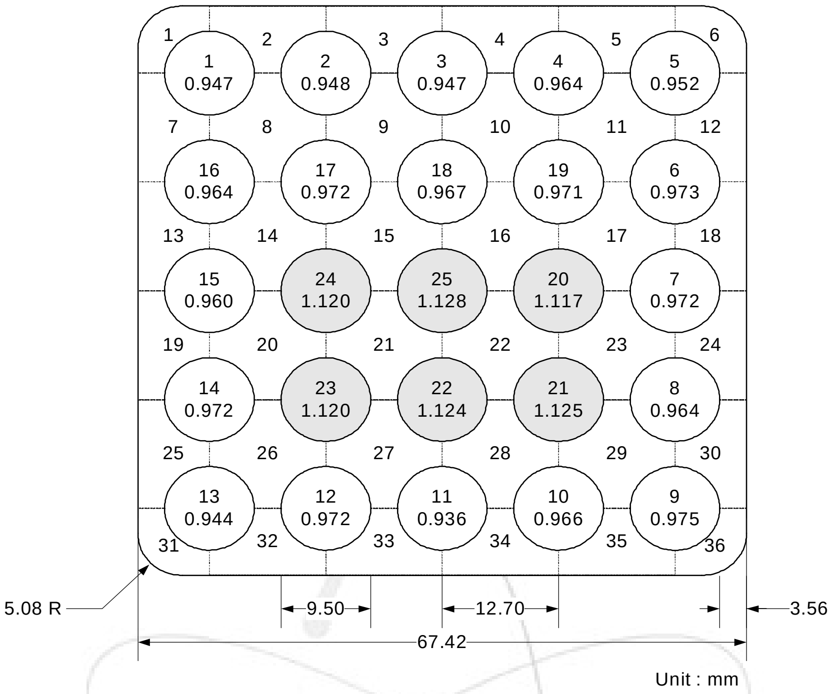


그림 2.17 Winfrith CHF 실험 장치

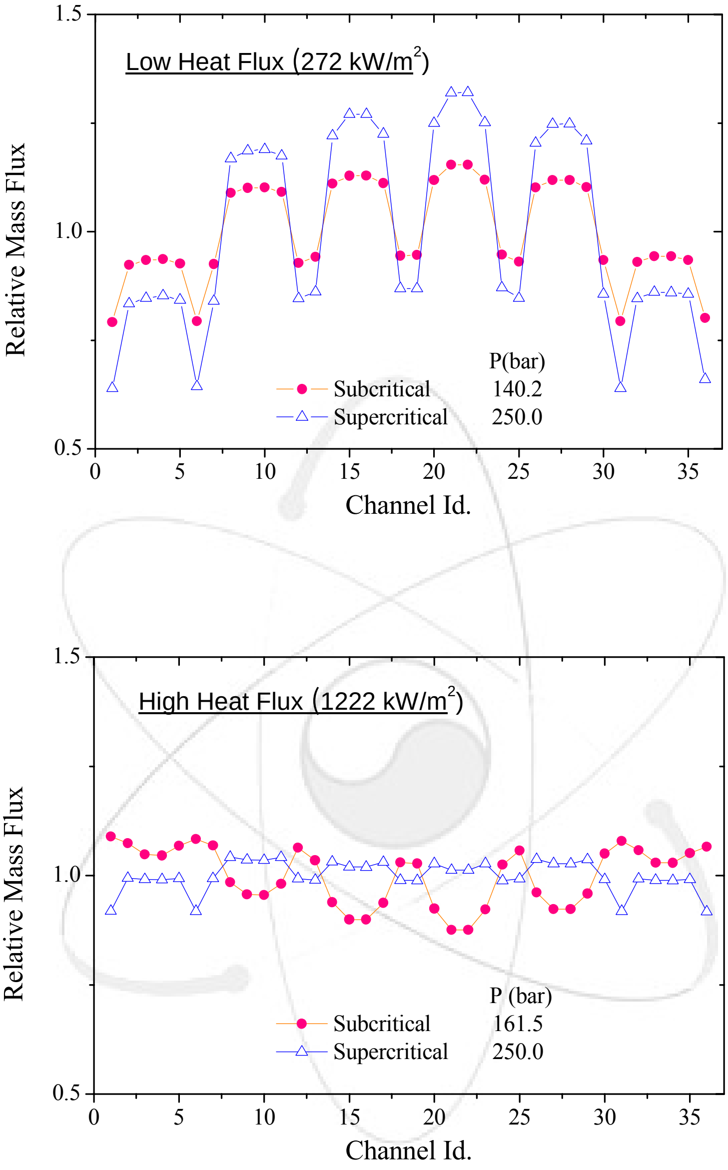


그림 2.18 초임계압 물 실험 해석

(나) 고온 가스로 조건 부수로 해석 적용

(i) 열전달 모형 확장

프리즘형 고온가스냉각로 노심 부수로 해석을 위해 기존의 ‘conducting wall’ 모형을 확장하여 흑연 블록간의 전도, 대류, 복사 열전달 모형을 추가했다. 기존의 conducting wall 모형은 그림 2.19와 같이 wall 내부에 열원이 없고 wall을 가로지르는 횡방향 전도 열전달만을 모사하는 1차원 열전도 모형이다.

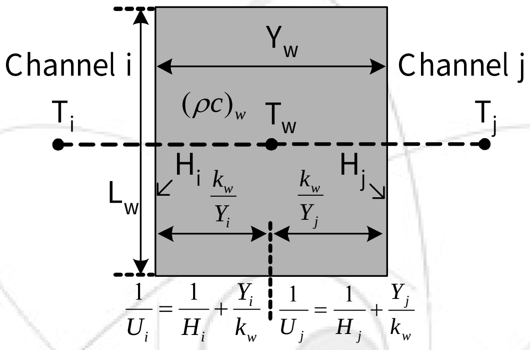
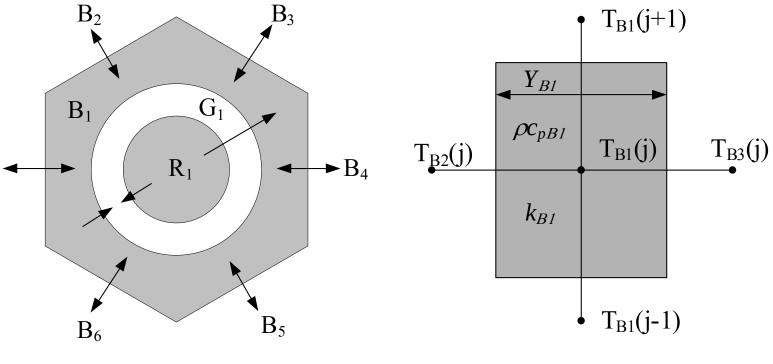


그림 2.19 MATRA 코드의 conducting wall 모형

프리즘형 고온가스냉각로 노심 부수로 해석을 위해서 기존의 1차원 conducting wall 모형을 확장하여 인접한 블록 사이의 전도 열전달과 블록의 축방향 열전달 모형을 추가했다. 그리고 블록 내부의 열원을 추가하고, 봉과 블록 간의 전도 및 복사 열전달 모형, 봉주위 헬륨 가스와 블록 간의 전도 및 대류 열전달 모형 등을 추가했다. 프리즘형 고온가스냉각로 노심 부수로 모형을 그림 2.20에 나타냈다.



Top-View Side-View

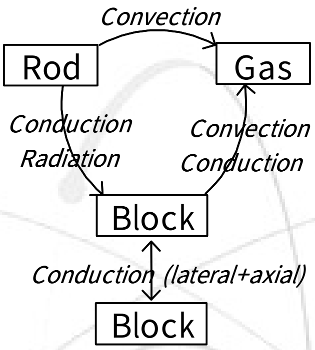


그림 2.20 프리즘형 고온가스냉각로 열전달 모형

위 그림에서 블록의 단면이 육각형이고 내부에 냉각재와 연료봉을 위한 구멍이 있는 형상이므로 전도 열전달에서 유효 전도 두께를 다음과 같이 정의했다:

$$Y_{equiv} = \frac{A_{Block}^{cross-sectional}}{P_{heated}}. \tag{2.8}$$

확장된 열전달 모형은 다음과 같다 :

$$-\left(\cdots_{B1,j} \quad \Delta x_{j+1} + \Delta x_{j} \quad \cdots_{B1,j-1} \quad \Delta x_{j} + \Delta x_{j-1} \right)$$

. (2.9)

여기서,

첫 번째 항 : 봉 -> 블록 간 전도 및 복사 열전달,

두 번째 항 : 블록 -> 헬륨 가스 간 대류 및 전도 열전달,

세 번째 항 : 블록 내부 시간에 따른 변이,

네 번째 항 : 인접 블록 간 횡방향 전도 열전달,

다섯 번째 항 : 블록 내부 축방향 전도 열전달을 나타낸다.

(ii) 열전달 모형 검증

일본의 HENDEL 실험루프 실험을 통해 MATRA 코드의 프리즘형 고온가스냉각로 노심 해석 성능을 평가했다. HENDEL 실험장치는 고온 헬륨 가스로의 열수력적 성능을 실험하기 위한 장치로서 시험부는 그림 2.21에서 보듯이 12개의 연료봉으로 구성된 집합체이며, 12개의 연료봉은 각각 12개의 독립된 채널을 형성한다. 흑연블록에 드릴로 가공된 채널의 내경은 53mm이고 연료봉의 외경은 46mm이다. 하나의 집합체는 단면이 육각형인 570mm 높이의 집합체 7개가 수직으로 쌓인 형태이다.

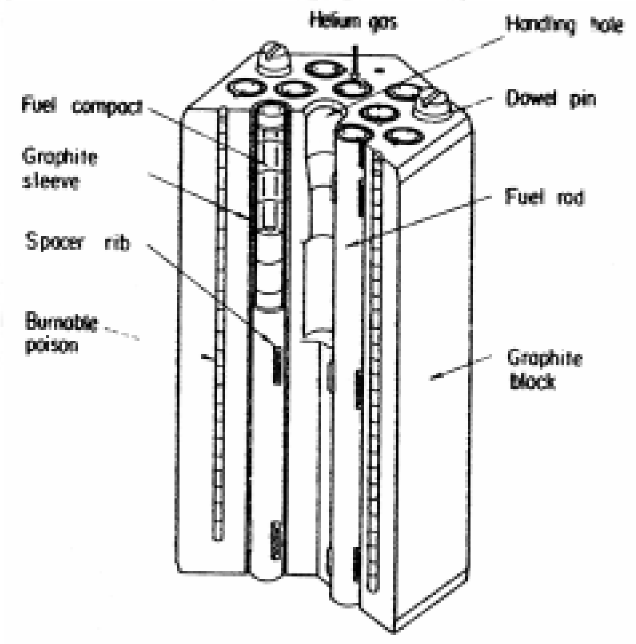
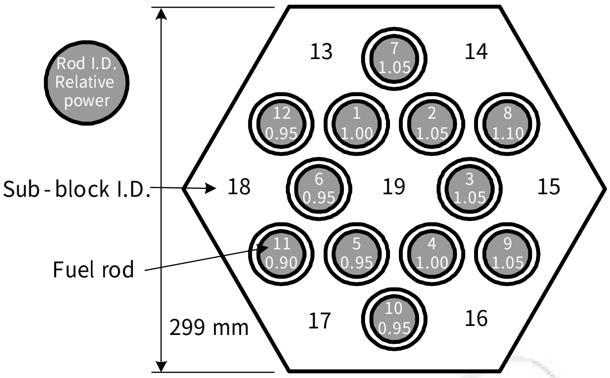
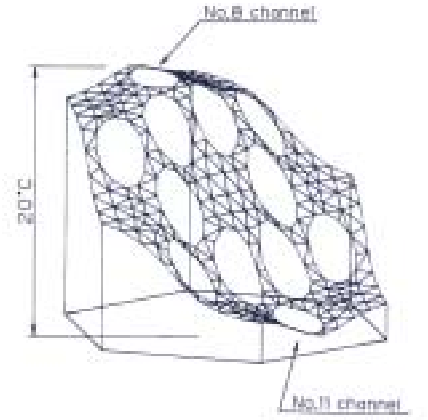


그림 2.21 HENDEL 실험장치 연료 블록

검증용 시험 자료는 XX로 평균 출력은 25.7 kW이며, 봉별 상대 열출력 분포를 11번 봉이 0.8, 8번 봉이 1.1이 되도록 설정한 실험이다(그림 2.22). 이 실험 자료에 대하여 MATRA 코드로 분석한 결과를 그림 2.23에 나타냈다.





Average power (kW)	25.7
Helium flow rate (g/s)	124.3
Inlet temp. (C)	280
Inlet pressure (MPa)	2.0

그림 2.22 고온가스냉각로 노심해석 검증 실험 자료

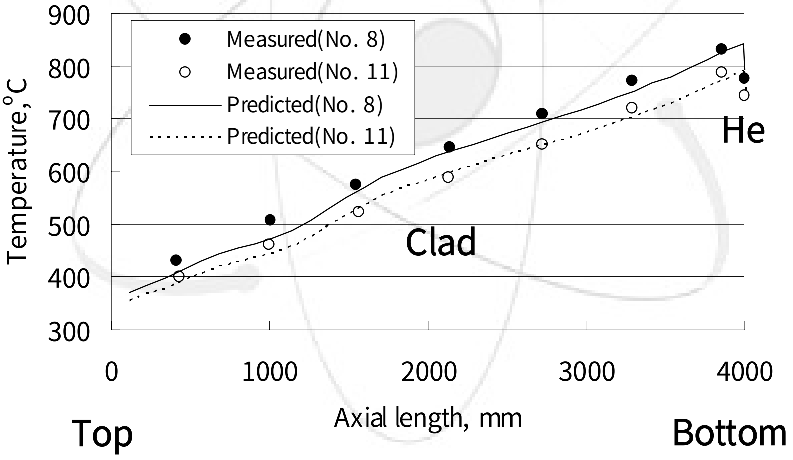


그림 2.23 실험과 MATRA 코드 해석 결과 비교

MATRA 코드는 축방향 온도를 실험 결과와 14 °C 의 오차 범위 이내로 예측하고 있는 것으로 나타났다. 채널 출구에서 8번 부수로와 11번 부수로의 온도차가 실험 결과 20 °C 로 나타났는데, MATRA 코드 해석결과 24 °C 로 비교적 잘 예측하는 것으로 나타났다. 이로써 MATRA 코드에 추가된 블록 열전달 모형이 프리즘형 고온가스냉각로의 노심을 적절히 해석할 수 있는

것으로 나타났다.

(iii) 평행 다수로 모형 개발

각 집합체가 독립된 채널을 이루고 있는 신형 원자로나 고온가스 냉각 원자로(HTGR), 또는 초임계압 원자로(SCR)의 노심은 기존 경수로의 노심과 확연히 구분되는 특징들을 가지고 있다. 기존의 경수로 노심의 집합체들이 서로 개방되어 있어서 집합체와 집합체 또는 부수로와 부수로간에 냉각재의 유동혼합이 발생하는 것과 달리 독립된 평행 다수로 노심에서는 각 집합체가 독립적인 채널을 형성하며 채널간에 교차류나 유동혼합이 발생하지 않는다. 이러한 독립된 평행 다수로 노심에서의 채널별 유량 분포는 각 채널에서 발생하는 압력강하에 의해 결정된다. 독립된 평행 다수로 노심에서 입구 유량과 출구 압력을 알지만 노심 압력 강하량을 알 수 없을 때, 계산된 압력 강하를 기준으로 각 채널별 유량이 재분배되도록 하는 기능을 MATRA 코드에 구현했다. 새로운 MATRA 코드의 기능을 고온가스로의 출력분포에 따른 채널별 유량분포 실험 자료 분석에 적용하였다.

MATRA 코드의 부프로그램 SCHEME에서 축방향으로의 지배방정식 계산이 끝나면 압력강하 경계조건 처리 부프로그램인 PBOUND를 호출한다. PBOUND에 각 채널의 압력강하량으로부터 채널별 유량을 재배분하는 기능을 추가하였다. 노심 평균 압력강하량을 계산하여 평균 압력 강하 보다 큰 압력강하가 발생한 채널의 유량은 감소시키고 반대인 경우엔 증가시키되 축방향에 대해서 반복계산시에 유량이 진동 발산할 수 있으므로 적절한 보정인자를 사용하였다.

MATRA 코드의 압력강하에 따른 유량분배 계산 성능을 검증하기 위해서 HENDEL 실험루프의 채널별 유량분포 실험결과와 비교하였다. 해석 대상 실험은 입구 레이놀즈수 10,000, 유량은 275g/s, 입구 온도 270℃, 입구 압력 3.9MPa, 평균 열입력 47.7kW 조건에서 수행된 #725~#731 실험으로 6번 연료봉의 출력을 평균 열출력의 0~1.5배로 바꾸면서 수행한 것이다. 그림 2.24에 HENDEL 에서 수행된 유량분포 실험 결과와 MATRA 해석 결과를

나타냈다.

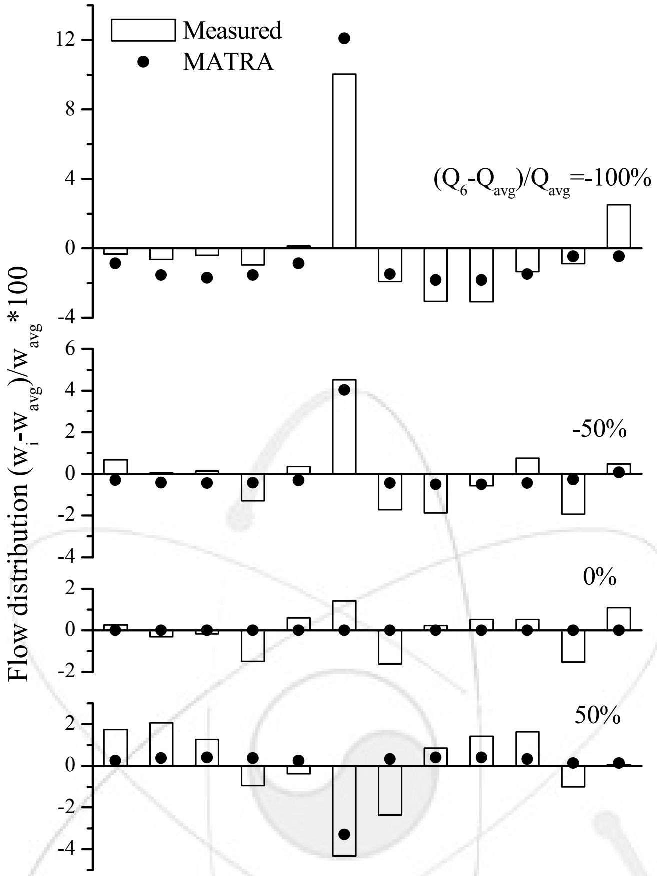


그림 2.24 HENDEL 실험루프 부수로별 유량분포

연료봉 6번의 출력을 0kW로 하였을 때, 6번 채널의 온도가 다른 채널들에 비해서 낮으므로 압력 강하가 작게 발생하므로 6번 채널의 유량이 10% 이상 증가하고 다른 채널들의 유량은 조금씩 감소한 것을 알 수 있다. 연료봉 6번의 출력을 평균 출력의 50%로 하였을 때도 6번 채널의 유량이 4% 가량 증가하고 다른 채널의 유량은 감소하는 추세를 보여주고 있다. 반대로 연료봉 6번의 출력을 평균 출력의 150%로 하였을 때에는 6번 채널의 헬륨 온도가 증가하면서 6번 채널의 유량이 평균 유량에 비해 4% 가량 적고 다른 채널들의 유량이 증가하는 추세를 보이고 있다. 마지막으로 모든 연료봉의 출력을 평균 출력으로 하면 MATRA 코드의 해석은 모든 채널의 유량이 동일한 것으로 나타나지만, 실험 결과는 채널별로 ±1.5% 정도의 차이를 보이는 것으로 나타났다.

고온가스로 12채널 유량분포 실험에 적용한 MATRA 코드 해석결과는 실험의 유량분포 경향을 잘 예측하였고 MATRA 코드의 유량재분배 기능이 잘 작동하는 것으로 나타났다.

2.3 국제 공동 연구

2.3.1 독일 FZK 연구소 공동 연구

본 과제를 통하여 KAEREI와 독일 FZK 연구소는 부수로 해석 코드 개발과 관련한 국제 공동 연구 협약을 체결하였다 (부록-6 참조). 공동 연구의 목적은 경수 혹은 HLM(Heavy Liquid Metal)을 사용하는 신개념 원자로 조건에 적용할 수 있는 부수로 해석 코드 기술을 개발하는 것이다. 공동 연구 체계는 그림 2.25에 제시한 바와 같다. 공동 연구 협약에 따라 부수로 해석 코드 개발을 위한 working group을 구성하였다. 국제공동 연구를 통하여 부수로 해석 코드 MATRA를 유럽의 참조 ADS (Accelerator driven sub-critical system) 모형으로서 LBE(Lead-Bismuth Eutectic)을 냉각재로 사용하는 PDS-XADS의 노심 개념 연구에 적용하였다. 연구 결과로서 발표된 논문은 부록-6에 수록하였다.

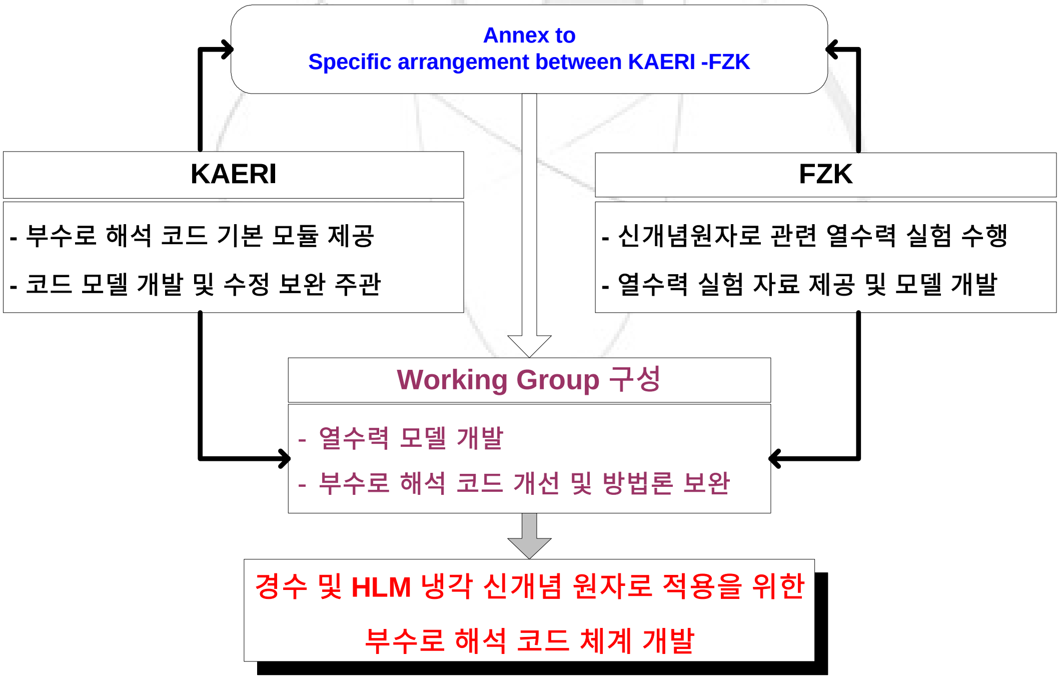


그림 2.25. KAERI-FZK 국제공동 연구 체계

2.3.2 OECD/NRC code benchmark

2상 유동장 조건의 부수로 열수력장 최적 해석 모델 개발에 사용될 수 있는 상세한 부수로 열수력장 측정 자료를 바탕으로 코드 benchmark 국제 회의가 구성되었으며[10], 본 연구에서는 MATRA 코드를 사용하여 benchmark에 참여하였다. 본 benchmark의 목적은 일차적으로 기존의 부수로 열수력장 해석 모델의 예측 성능을 평가하는 것이며, 나아가서 차세대 부수로 열수력장 최적 예측 모델의 개발에 기여하고자 하는 것이다. MATRA와 같이 mixture equation을 사용하여 2상 유동장을 해석하는 부수로 해석 코드는 일반적으로 건도가 높은 조건에서 예측 성능이 나빠지는 경향을 보인다. 이러한 경향은 부수로 간의 기포율 분포 예측시 현저하게 나타나는데, 이러한 문제점을 해결하기 위하여 부수로 간의 난류혼합 모델을 개선하여 예측 성능을 향상시킨 바 있다[7]. 본 연구에서는 MATRA 코드의 개선된 난류혼합 모델을 사용하여 8x8 집합체 내부의 부수로 기포율 분포를 예측하고 실험 자료와 비교하였다.

(가) MATRA 코드의 2상 유동장 난류혼합 모델

부수로 해석 모형에서 부수로 간의 횡방향 질량, 에너지 및 운동량 전달 현상은 기본적으로 아래와 같은 네 가지 모형을 통하여 예측하고 있다.

- Diversion crossflow
- Turbulent mixing
- Void drift
- Viscous transfer

이 때, 연료봉 주위의 원주방향 압력 구배가 없다고 가정하면 원주방향의 회전 유동은 없다. 위의 4가지 모형들 중에서 diversion crossflow는 인접 부수로 간의 압력 차이로 인해 발생되는 것으로서 횡방향 운동량 보존식을 통하여 평가할 수 있다. Turbulent mixing과 viscous transfer 항은 난류 에디의 요동에 의한 영향과 분자 단위의 전달(conduction 혹은 viscous momentum transfer)을 모사하는 것이며, void drift 항은 이상 유동 상태에서 기포의 횡방향 분포가 평형 상태를 이루려고 하는 경향을 모사하기 위한 것이다. 실제로

가압 경수로 노심 분석에 사용되고 있는 부수로 해석 코드 모형들을 검토해 보면 일반적으로 운동량에 대한 viscous transfer는 거의 무시되고 있으며, 에너지에 대한 영향, 즉 부수로 간의 conduction은 몇 가지 코드에서 사용되고 있다. 그리고 void drift 현상이 모형화된 코드는 거의 없는데 이는 가압 경수로 노심의 정상 운전 조건에서는 2상 유동 현상이 크게 나타나지 않기 때문이다. 그러나 사고 상태나 CHF 조건에서는 부수로 내에 상당한 양의 기포가 존재하게 되므로 void drift 모형은 코드 예측의 정확성에 큰 영향을 준다. Turbulent mixing 모형도 기존의 COBRA 계열 부수로 해석 코드에서 사용하는 동일 질량 교환 모형은 단상 유동 조건에서는 타당하지만 이상 유동 조건에서는 동일 체적 교환 모형이 더 잘 맞는 것으로 알려져 있다.

(i) 동일 질량 교환 모델

2.1.1절에 기술한 부수로 해석 지배 방정식의 좌변 마지막 항은 난류 혼합으로 인하여 **i** 부수로와 인접한 부수로 간에 교환되는 질량, 에너지 및 축방향 운동량을 나타내고 있다. 부수로 **i** 와 **j** 사이에서 단위 축방향 길이 당 갭(s_{ij})을 통해 전달되는 난류 유동의 크기는 아래와 같이 정의된다.

$$w'_{ij} \equiv \rho_i s_{ij} v'_{ij} . \tag{2.10}$$

'Mixing length' 이론에 의하면 단상 유동 조건에서 부수로 i 와 j 사이의 요동 속도, v'_{ij} 는 eddy diffusivity에 비례하며, 유효 혼합 길이에 역비례한다. COBRA-IV-I 코드에서 질량에 대한 eddy diffusuvuty는 에너지에 대한 eddy diffusivity와 동일하게 취급하며, 횡방향 요동 속도와 축방향 유속 간의 비율로 정의되는 난류 혼합 인자를 도입하여 난류 유동을 아래와 같이 표현하고 있다.

$$w'_{ij} = \beta \cdot s_{ij} \cdot G_{avg} . \tag{2.11}$$

축방향 운동량에 대한 eddy viscosity는 에너지에 대한 eddy diffusivity에 난류 Prandtl 수와 같은 의미를 갖는 난류 운동량 인자, f_T를 곱하여 평가한다. 난류 혼합 인자는 일반적으로 단상 유동 조건에서 수행되는 열혼합 실험 자료로부터 구하며, COBRA-IV-I 코드에서는 이를 2상 유동 조건에도 그대로 적용하고 있다. COBRA-IV-I 코드의 난류 혼합 모형은 동일 질량 교환(EM) 개념에 근거하고 있다. 즉, 인접한 두 채널 간의 난류 유동 크기는 서로 동일하다는 가정($\rho_i v'_{ij} = \rho_j v'_{ji}$)으로부터 채널 간의 질량 이동이 발생하지

않는다. ($w'_{i\leftrightarrow j} \equiv w'_{ij} - w'_{ji} = 0$)

(ii) 동일 체적 교환 모델

2상 유동 조건에서 수행된 실험 결과에 따르면 인접한 수로 간에 에너지와 운동량 이동 뿐만 아니라 상당한 양의 질량 이동이 발견된 바 있다[11]. 이 현상을 설명하기 위하여 수로 간에 동일한 체적이 교환되는 개념($v'_{ij} = v'_{ji}$)이 도입되었으며, 이 때 난류 혼합은 비평형 기포율 구배에 비례하는 것으로 가정하였다[12]. 즉, 횡방향 혼합은 두 수로 경계면에서의 난류 요동과 수로 간의 기포 이동에 의해 발생하게 된다. 기포 이동은 기포가 평형 분포 상태를 이루는 방향으로 이동하는 경향에 의해 발생하는데, 실험에 의하면 기포는 유로 면적이 넓고 유속이 빠른 영역으로 이동하는 경향을 보인다. Levy의 연구에 따르면 기포의 평형 분포는 유속 분포와 관련이 있다[13]. Levy는 채널 내에서 평형 밀도 분포는 평형 유속 분포와 선형적 비례 관계에 있다고 가정하였다. 그러나 Sadatomi 등의 2 채널에 대한 실험적 연구 결과에서는 이러한 선형적 관계가 발견되지 않았다[14]. 따라서 MATRA 코드에서는 실험 자료 평가를 통하여 기포 이동 계수 K$_{\mathrm{VD}}$를 실험적으로 결정하였다. 이에 따라 난류 혼합으로 인한 질량 교환은 아래와 같이 표현하였다.

$$w'_{i\leftrightarrow j} = \left(v'_{ij}\right)_{SP} \cdot \theta \cdot \left[\left(\alpha_j - \alpha_i\right) - K_{VD} \frac{\left(G_j - G_i\right)}{G_{avg}}\right], \tag{2.12}$$

여기서,

$$\theta \equiv \left(\beta_{TP}/\beta_{SP}\right)\left(\Delta\rho/\rho_f\right). \tag{2.13}$$

2상 유동 난류 혼합에 대한 Beus의 연구[15]에 따르면 위식에 나타나는 보정 인자 θ 는 bubbly-slug 영역에서 아래와 같이 표현된다.

$$\theta = 1 + \left(\theta_M - 1\right)\frac{\chi}{\chi_C}, \tag{2.14}$$

그리고 annular 영역에서는

$$\theta = 1 + \left(\theta_M - 1\right)\frac{1 - \chi_0/\chi_C}{\chi/\chi_C - \chi_0/\chi_C}, \tag{2.15}$$

이며, 여기서

$$\chi_0/\chi_C = 0.57\cdot\mathrm{Re}^{0.0417}, \tag{2.16}$$

그리고 $\theta_M = 5$ 이다[16]. Slug-annular 천이 조건에 해당하는 건도는 아래와 같이 평가된다.

$$\chi_C = \frac{0.4\sqrt{gD_{hy}\rho_f\Delta\rho}/G + 0.6}{\sqrt{\rho_f/\rho_g} + 0.6}. \tag{2.17}$$

이와 유사하게 난류 혼합 및 기포 이동에 의한 에너지 전달량은 아래와 같이 표현된다.

$$w'_{ij}h_i - w'_{ji}h_j = \left(w'_{ij}\right)_{SP}\cdot\theta\cdot\left[\left(\alpha_j-\alpha_i\right) - K_{VD}\frac{\left(G_j-G_i\right)}{G_{avg}}\right]\left(\frac{\rho_f h_f-\rho_g h_g}{\rho_f-\rho_g}\right). \tag{2.18}$$

MATRA 코드에 도입된 난류 혼합 모형은 실험 집합체에 대한 2상 유동 분포 실험 자료 평가를 통하여 최적화 하였다[17]. 최적 K_{VD} 는 아래와 같이 계산된다.

$$K_{VD,OPT} = K_{VD,L} + \frac{\chi_{1,M} - \chi_{1,L}}{S_\chi}, \tag{2.19}$$

여기서 선형 비례 상수는 아래와 같이 정의된다.

$$S_\chi \equiv \frac{\chi_{1,U} - \chi_{1,L}}{K_{VD,U} - K_{VD,L}}. \tag{2.20}$$

실험 자료 평가 결과 K_{VD} 가 증가하면 corner 수로 출구 건도는 감소하며, 선형 비례 상수의 절대값은 국부 건도가 증가함에 따라 커지는 것으로 나타났다. Beus 모델을 사용한 동일 체적 교환 모형을 적용하여 평가한 결과 slug-annular 경계 조건 근처에서 S_χ 의 최소값이 나타났다. 이는 2상 유동 혼합이 이 조건에서 최대값을 갖기 때문에 나타난 결과이다. 시험 자료 분석을 통하여 K_{VD} 에 대한 단순 선형 모델은 아래와 같이 도출되었다.

bubbly-slug flow 영역($\chi < \chi_C$),

$$K_{VD} = a_1\cdot\left(\frac{\chi-\chi_{osv}}{\chi_C-\chi_{osv}}\right). \tag{2.21}$$

$$a_1 = 0.72 \cdot \left(\frac{1 - P_r}{P_r} \right)^{1.33} \quad . \tag{2.22}$$

annular flow 영역($\chi \geq \chi_C$),

$$K_{VD} = a_1 + a_2 \cdot \left(\frac{\chi - \chi_{osv}}{\chi_C - \chi_{osv}} - 1 \right), \tag{2.23}$$

$$a_2 = 10$$

(나) 정상상태 부수로 기포율 분포 해석

부수로 해석이 수행된 8x8 집합체의 부수로 형태는 그림 2.26에 제시하였으며, 주요 기하 형태 자료는 표 2.10과 같다. 부수로 기포율은 X-ray CT scanner 장치를 사용하여 NUPEC에서 측정되었다. 분석 대상 운전 조건은 표 2.11에 제시한 바와 같이 5 종류의 시험 집합체에 대하여 각각 3 가지 서로 다른 출구 건도 (5%, 12%, 25%)를 갖는다. 각각의 조건에 대하여 부수로 해석을 수행한 결과는 그림 2.27 – 그림 2.31에 제시하였다. Grid-type spacer와 반경방향 균일 출력 분포를 갖는 시험집합체에 대하여 MATRA 코드로 계산된 부수로 기포율 분포 예측 성능을 기존의 COBRA/BWR 코드와 THERMIT 코드로 계산된 결과와 비교 하였다. 두 코드의 계산 결과는 참고문헌 [18]에 기술되어 있다. 그 결과 표 2.12에서 보듯이 MATRA 코드의 예측 성능(K_{VD}=1.4 적용)은 기존의 BWR용 부수로 해석 코드나 two-fluid 모델을 사용하는 코드와 비슷한 것으로 나타났다.

표 2.10 시험 집합체 주요 기하 형태 자료

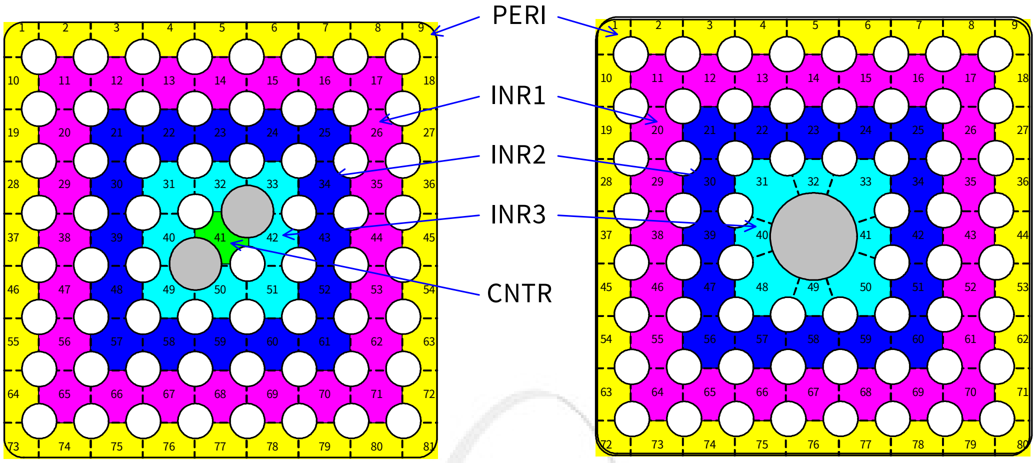
	TS 0-1	TS 4
Number of heater rods	62	60
OD of heater rods (mm)	12.3	12.3
Heated length (mm)	3708	3708
Number of water rods	2	1
OD of water rods	15.0	34.0
Rod pitch (mm)	16.2	16.2
Channel box width (mm)	132.5	132.5
Number of spacers	7	7
Spacer type	Grid	Ferrule

표 2.11 부수로 해석 수행 조건

SN	TS ID	Heater rods	Radial power distribution	Axial power distribution	Spacer type	Exit quality	Exit void
1	0-1	62	Uniform	Uniform	Grid	0.05	0.41
2	0-1	62	Uniform	Uniform	Grid	0.12	0.63
3	0-1	62	Uniform	Uniform	Grid	0.25	0.79
4	0-2	60	Uniform	Uniform	Grid	0.05	0.39
5	0-2	60	Uniform	Uniform	Grid	0.12	0.63
6	0-2	60	Uniform	Uniform	Grid	0.25	0.78
7	0-3	55	Uniform	Uniform	Grid	0.05	0.39
8	0-3	55	Uniform	Uniform	Grid	0.12	0.62
9	0-3	55	Uniform	Uniform	Grid	0.25	0.78
10	1	62	Non-uniform	Cosine	Grid	0.05	0.43
11	1	62	Non-uniform	Cosine	Grid	0.12	0.64
12	1	62	Non-uniform	Cosine	Grid	0.25	0.79
13	4	60	Non-uniform	Uniform	Ferrule	0.05	0.44
14	4	60	Non-uniform	Uniform	Ferrule	0.12	0.65
15	4	60	Non-uniform	Uniform	Ferrule	0.25	0.81

표 2.12 부수로 기포율 분포 예측 성능 비교

TS 0-1, 0-2, 0-3	MATRA	COBRA/BWR	THERMIT-2
Mean (P-M), %	-0.4	-1.1	-2.2
Std. deviation, %	6.0	5.3	6.3



TS 0-1, 0-2, 0-3, 1

TS 4

그림 2.26. 8x8 집합체 부수로 해석 모형

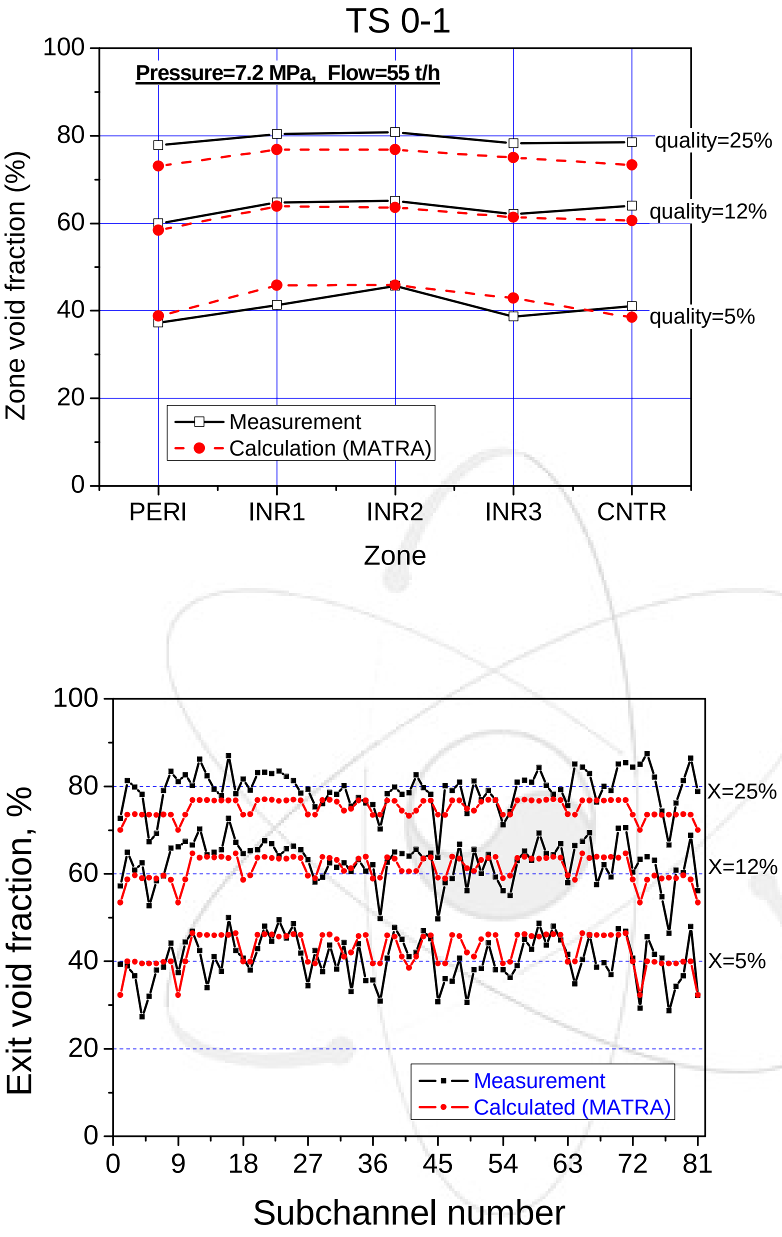


그림 2.27 부수로 기포율 분포 예측치와 실측치 비교 (TS 0-1)

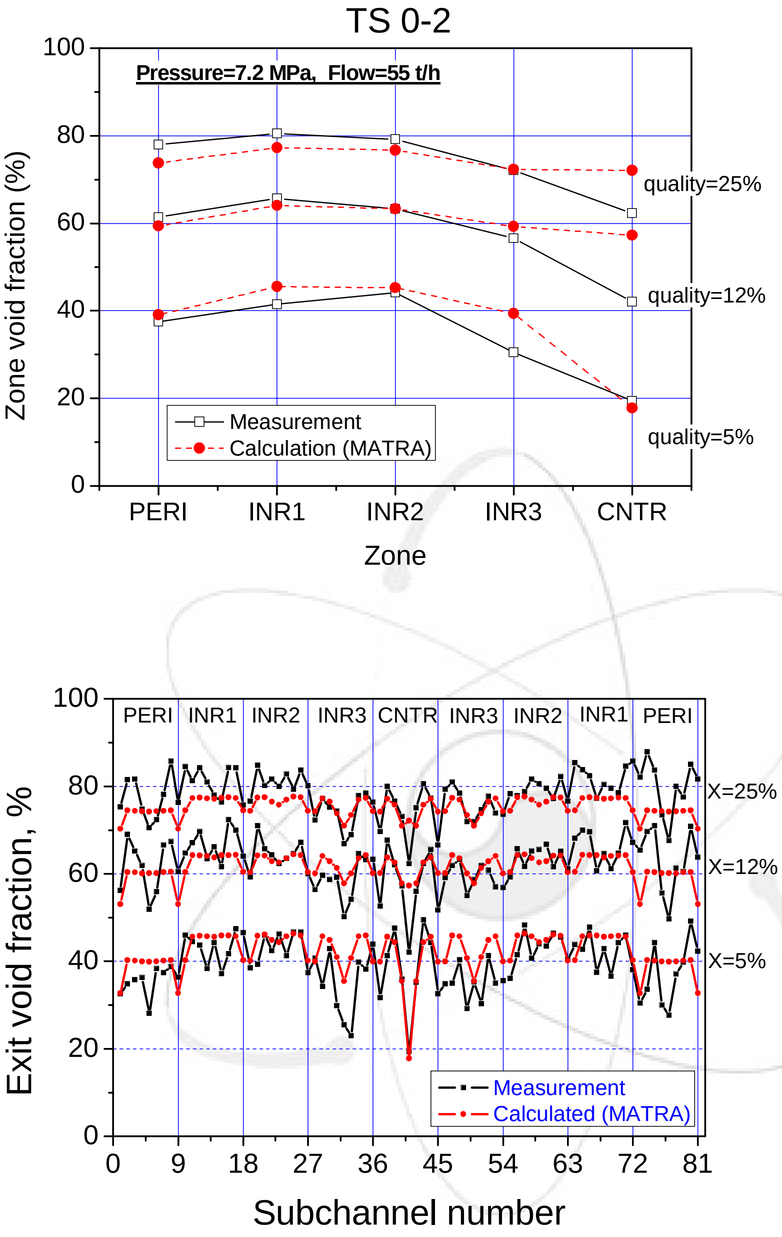


그림 2.28 부수로 기포율 분포 예측치와 실측치 비교 (TS 0-2)

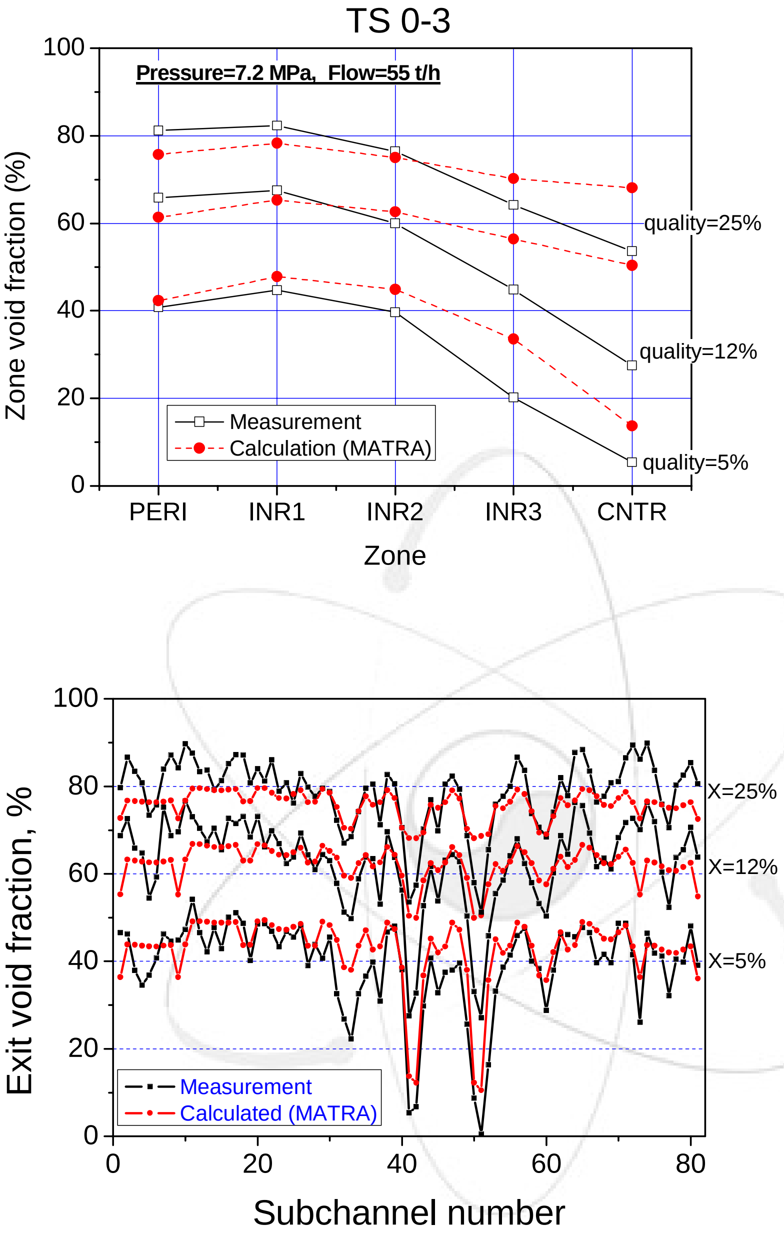


그림 2.29 부수로 기포율 분포 예측치와 실측치 비교 (TS 0-3)

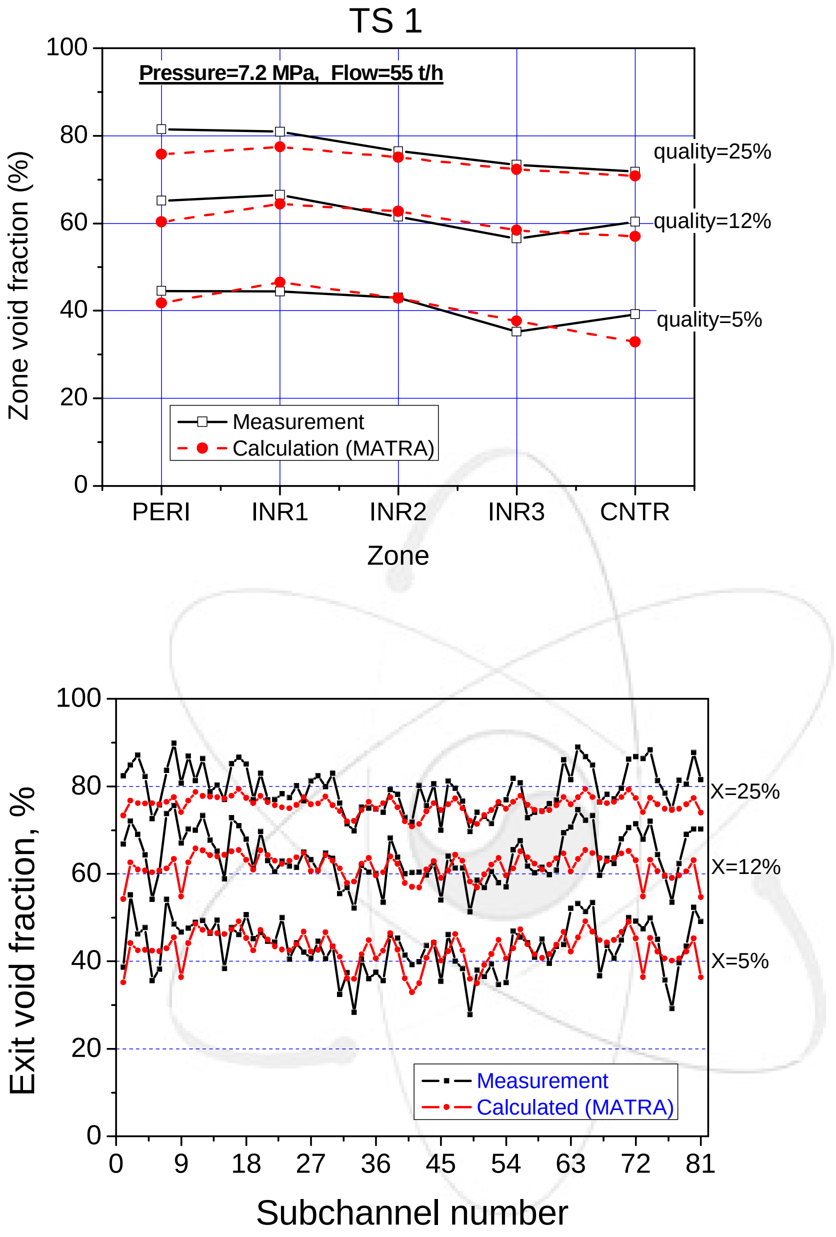


그림 2.30 부수로 기포율 분포 예측치와 실측치 비교 (TS 1)

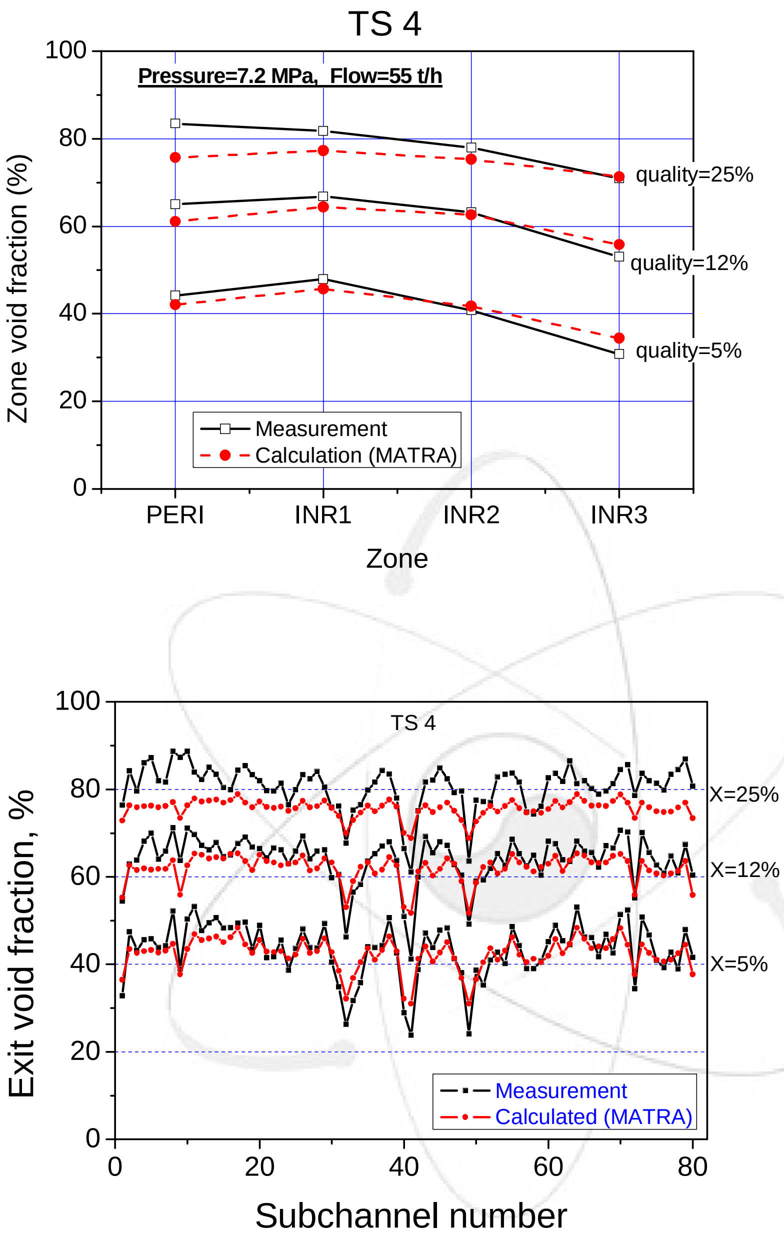


그림 2.31 부수로 기포율 분포 예측치와 실측치 비교 (TS 4)

3. 결론

3.1 연구 개발 목표 달성도 및 대외 기여도

본 연구를 통하여 신개념 원자로에 적용 가능한 부수로 해석 코드의 기본 모듈을 개발하고 여러가지 신개념 원자로 조건에 대하여 부수로 해석 코드의 적용성을 평가하였다. 본 연구는 그림 3.1에 제시한 바와 같이 부수로 해석 코드 체계 개발을 위한 연구의 첫번째 단계에 해당한다. 본 연구를 통하여 신개념 원자로 조건에 대한 부수로 해석 코드의 적용성이 입증되면 향후 GEN-IV 원자로 등의 노심 열수력장 해석 체계를 구성하는 기본 모듈로서 활용이 가능하다. 본 연구의 기대 효과로서 기술적 측면에서는 다양한 냉각재 및 핵연료 형태를 채택하는 신개념 원자로의 설계에 적용 가능한 부수로 해석 코드 기본 모듈을 확보할 수 있으며, 경제·산업적 측면에서는 KAERI가 원천기술을 갖는 부수로 해석 코드의 수출 효과를 기대할 수 있다.

3.2 연구 개발 결과의 활용 계획 및 추가 연구의 필요성

본 연구를 통하여 서울대학교 및 KAIST와 부수로 해석 코드 사용에 관한 기술실시 계약을 체결하였으며, 향후 연구 결과에 대한 정보 교환 등을 통하여 지속적인 부수로 해석 코드 기술 개발 추진할 예정이다. 본 연구 결과는 향후 아래와 같이 신개념 원자로 적용을 위한 열수력장 해석 코드의 개발 방향 도출에 활용 될 수 있다.

- 핵연료와 block, 냉각재 간의 열전달 해석 모델 (conduction - convection 문제)
- 초임계-미임계 압력 과도 조건 해석 모델
- 양방향 채널 유동장 해석 모델
- 코드 연계 모델 (노물리 해석 코드, 과도 해석 코드 등)

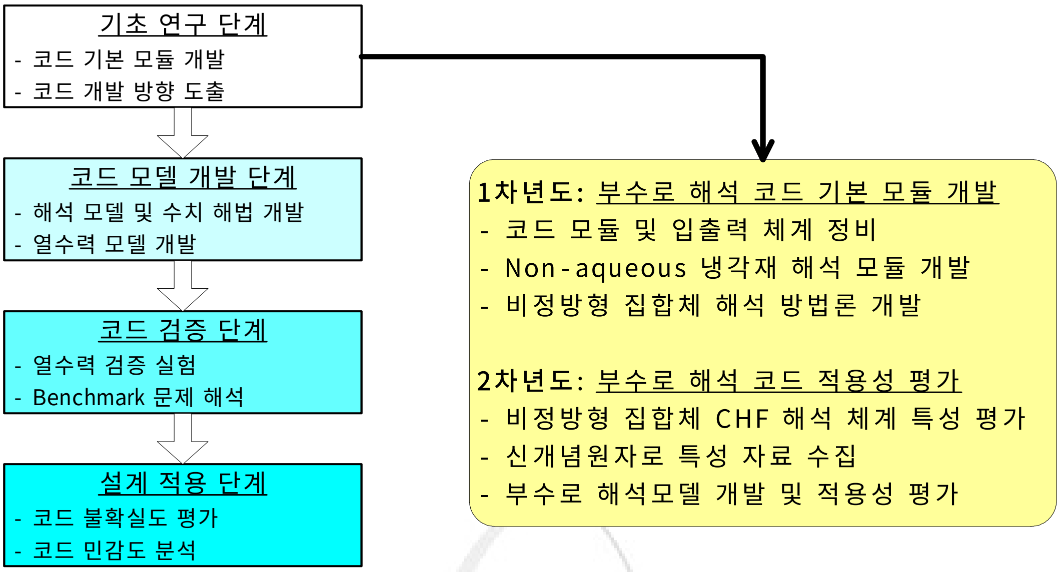


그림 3.1 부수로 해석 코드 개발 연구 체계

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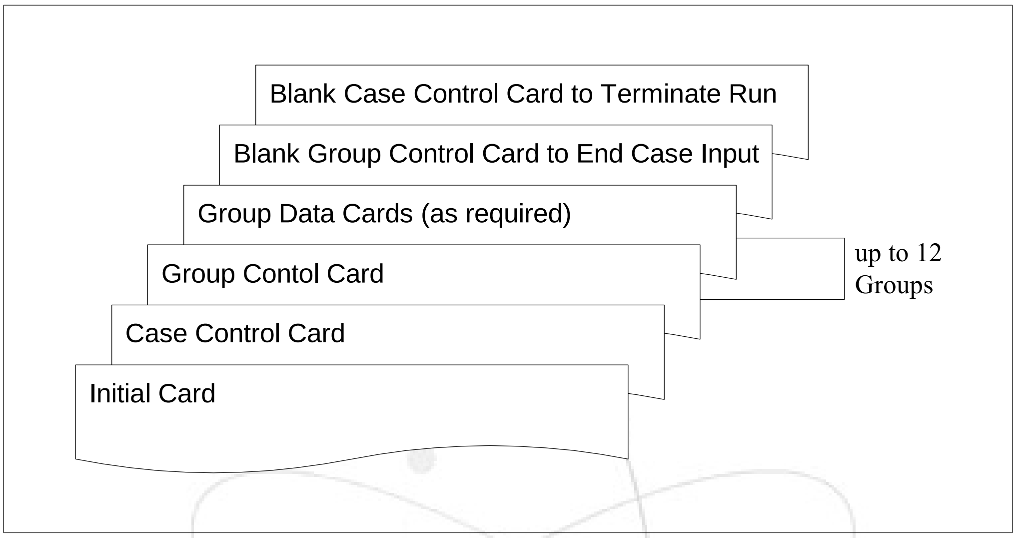
부록-1. MATRA-X0 입력 지침서

Structure of the MATRA Input Deck



Requirements of the MATRA Input Cards and Card Groups

Group No.	Description	Case	
		First	Subsequent
–	Initial card	required	not required
–	Case control card	required	required
1	Fluid properties	required	optional
2	Friction factor, heat transfer coefficient, and two-phase flow correlations	required	optional
3	Axial heat flux distribution	required	optional
4	Channel layout and dimensions	required	optional
5	Channel area variation	optional	optional
6	Gap spacing variation	optional	optional
7	Wire wrap and grid spacer information	optional	optional
8	Rod layout, dimensions, and properties	required	optional
9	Calculation control	required	optional
10	Lateral transport models	required	optional
11	Operating conditions and transient forcing functions	required	optional
12	Output display options	required	optional

Description of Dimensioning Parameters

MC : Maximum number of channels (200)
MG : Maximum number of gaps (400)
MX : Maximum number of axial nodes plus one (1001)
MN : Maximum order of collocation used in fuel model plus three (6)
MR : Maximum number of rods (200)
ME : ***MX*** if no storage on peripherals ; 3 for storage on peripherals
(This implies that axial values will be rolled.) (1001)
MP : Maximum number of cards in property table, axial heat flux table,
and forcing function vs. time tables (1500)
ML : Maximum number of axial locations
for channel area and gap spacing variations (50)
MZ : Maximum number of axial locations for grid spacers (20)
MW : Maximum number of wall-channel thermal connections (50)
MY : Maximum number of axial fuel type divisions (20)
MI : Maximum number of connections to a channel (thermal+flow) (20)
MO : Maximum number of gaps coupled to any one gap via a channel plus one :
Maximum width of ***AAA*** array : (7 for square, 5 for triangular rod array) (20)
MK : Maximum number of grid spacer types (10)
MA : Maximum number of channels that can have channel area variations (50)
MT : Maximum number of fuel types (10)
MS : Maximum number of gaps that can have gap spacing variations (100)

MATRA 1.0		Initial card: Must be the 1st data card of the input deck; Read only once: ***MAXT***, ***IIUNIT***, ***JIUNIT***, ***JOUNIT***, ***IMAST***: (5I10)
I10	***MAXT***	Computer time limit allowed for problem calculations [sec]: ***MAXT*** ≥ 0: Normal calculation ***MAXT*** < 0: Restart calculation from a previously stored solution (**Not checked**) * Requires Card RESTRT 1.0
I10	***IIUNIT***	Input unit system: ***IIUNIT*** $= 0$: British ***IIUNIT*** $= 1$: SI
I10	***JIUNIT***	Input printout unit system: ***JIUNIT*** $= 0$: British ***JIUNIT*** $= 1$: SI
I10	***JOUNIT***	Output printout unit system: ***JOUNIT*** $= 0$: British ***JOUNIT*** $= 1$: SI
I10	***IMAST***	Option for coupling with the neutronics code MASTER (**Not used** for the stand-alone calculation of MATRA): ***IMAST*** $= 0$: No ***IMAST*** $= 1$: Yes

RESTRT 1.0		Restart card (**Not checked**): Optional (***MAXT*** < 0 in MATRA 1.0): ***NJUMP***, ***NA***, ***IT***, ***NTT***, ***TTT***: (4I10, F10)
I10	***NJUMP***	Restart flag: ***NJUMP*** = 0: Direct restart with no input: Continue calculations on a previous steady-state solution (***IT*** ≠ 1 and ***NTT*** = 0); Continue calculations on a previous transient solution (***IT*** ≠ 1 and ***NTT*** ≠ 0) ***NJUMP*** = 1: Restart with additional input: Begin a transient at time zero from a previous steady-state solution (***IT*** = 1 and ***NDT*** = 0 in SETRI 9.2); Calculate a new steady-state solution with a previous solution as the 1st guess (***IT*** ≠ 1 and ***NDT*** = 0 in SETRI 9.2); Continue calculations on a previous transient solution (***NDT*** ≠ 0 in SETRI 9.2) ***NJUMP*** = 2: No restart: Read dump file, print input and output, and then stop ***NJUMP*** = 3: Same as ***NJUMP*** = 0, but print all input
I10	***NA***	Number of additional iterations for implicit solution scheme regardless of ***NJUMP***: The old value of ***NTRIES*** in SETRI 9.2 is increased by ***NA*** in a steady-state solution or is set to ***NA*** in a transient solution; ***NTRIES*** may be reset directly in SETRI 9.2 if ***NJUMP*** = 1
I10	***IT***	Flag to begin a transient solution at time zero from a previous steady-state solution: Must read in transient data (***NJUMP*** = 1) from SETRI (***IT*** = 1); For other restart cases, the value of ***IT*** is ignored (***IT*** = 0): ***IT*** = 0: Continue time steps ***IT*** = 1: Start from time zero
I10	***NTT***	Number of additional time steps allowed regardless of ***IT***: Used to increase the value of ***NDT*** in SETRI 9.2 to continue or start a transient solution
F10	***TTT***	Total additional transient time regardless of ***IT*** [sec]: The time step size is ***TTT***/***NTT*** unless a time step size forcing function has been or will be supplied (***NJUMP*** = 1) in SETRI 9.5

SETUP 1.0

Case control card:
KASE, ***J1***, ***TEXT***: (2I10, 17A4)

I10	***KASE***	Problem case number: $\boldsymbol{KASE} > 0$: Begin case with core initialized to zero $\boldsymbol{KASE} < 0$: Use previous case solution as the 1st guess $\boldsymbol{KASE} = 0$: Stop
I10	***J1***	Print option for input data: $\boldsymbol{J1} = 0$: Print only new input $\boldsymbol{J1} = 1$: Print all input $\boldsymbol{J1} = 2$: Print only operating conditions $\boldsymbol{J1} = 10$: Print all input, then stop
17A4	***TEXT***	Output text for problem identification: Maximum 68 characters

Card Group 1 Fluid Properties

SETRI 1.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***: (6I10)
I10	***NGROUP***	Card group number: Must be 1
I10	***N1***	Number of (saturation and/or superheated) fluid property cards to be read: $(0 \leq \boldsymbol{N1} \leq \boldsymbol{MP})$: $\boldsymbol{N1} = 0$: $\boldsymbol{N4} = 1$ and $\boldsymbol{N2} = 0$ $\boldsymbol{N1} > 0$: $\boldsymbol{N4} = 0$
I10	***N2***	Option for calculation of superheated vapor (H_2O) properties: $(0 \leq \boldsymbol{N2} \leq 1)$: $\boldsymbol{N2} = 0$: No calculation $\boldsymbol{N2} = 1$: ***N1*** superheated vapor properties are calculated
I10	***N3***	Upper limit for temperature range of superheated vapor (H_2O) properties (Applicable only if $\boldsymbol{N2} = 1$): $(0 \leq \boldsymbol{N3} \leq 1)$: $\boldsymbol{N3} = 0$: Calculate ***N1*** superheated vapor properties from saturation temperature at system pressure to 1500 °F (815.6 °C) $\boldsymbol{N3} = 1$: Calculate ***N1*** superheated vapor properties from saturation temperature at system pressure to a temperature specified by ***TMAX*** * Requires Card SETRI 1.2
I10	***N4***	Method for calculation of fluid properties: $(0 \leq \boldsymbol{N4} \leq 1)$: $\boldsymbol{N4} = 0$: Interpolative calculation of fluid properties from saturation property table: Property table inputs are necessary * Requires Card SETRI 1.1 $\boldsymbol{N4} = 1$: Direct calculation of fluid (H_2O) properties from Function TAF: Property table inputs are not necessary
I10	***N5***	Switch for selecting pressure used in calculation of fluid properties: $(0 \leq \boldsymbol{N5} \leq 1)$: $\boldsymbol{N5} = 0$: System reference (exit) pressure $\boldsymbol{N5} = 1$: Local pressure
SETRI 1.1		Saturation fluid property table: Optional ($\boldsymbol{N4} = 0$); Read in ***N1*** cards for saturated liquid and vapor properties: ***PP***(*J*), ***TT***(*J*), ***VVF***(*J*), ***VVG***(*J*), ***HHF***(*J*), ***HHG***(*J*), ***UUF***(*J*), ***KKF***(*J*), ***SSIGMA***(*J*), $J = 1$ to ***N1***: (9F10)
F10	***PP***(*J*)	Pressure [psia; MPa]
F10	***TT***(*J*)	Saturation temperature [°F; °C]
F10	***VVF***(*J*)	Specific volume of saturated liquid [ft^3/lb_m; m^3/kg]

F10	***VVG***(*J*)	Specific volume of saturated vapor [$\mathrm{ft^3/lb_m}$; $\mathrm{m^3/kg}$]
F10	***HHF***(*J*)	Specific enthalpy of saturated liquid [$\mathrm{Btu/lb_m}$; kJ/kg]
F10	***HHG***(*J*)	Specific enthalpy of saturated vapor [$\mathrm{Btu/lb_m}$; kJ/kg]
F10	***UUF***(*J*)	Viscosity of saturated liquid [$\mathrm{lb_m}$/ft-hr; kg/m-sec]
F10	***KKF***(*J*)	Thermal conductivity of saturated liquid [Btu/hr-ft- °F ; kW/m- °C]
F10	***SSIGMA***(*J*)	Surface tension of saturated liquid [$\mathrm{lb_f}$/ft; N/m]

SETRI 1.2

Maximum temperature of superheated vapor (H_2O):
Optional (***N2*** = 1 and ***N3*** = 1):
TMAX: (F10)

F10	***TMAX***	Upper limit for temperature range of superheated vapor properties [°F ; °C]: Default for ***N3*** = 0 is ***TMAX*** = 1500 °F (815.6 °C)

Card Group 2 — Friction Factor, Heat Transfer Coefficient, and Two-Phase Flow Correlations

SETRI 2.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***: (8I10)
I10	***NGROUP***	Card group number: Must be 2
I10	***N1***	Subcooled void fraction: For $\boldsymbol{N3} > 0$ in SETRI 9.0, ***N1*** will be reset as $\boldsymbol{N1} = 0$; $(0 \le \boldsymbol{N1} \le 1)$: $\boldsymbol{N1} = 0$: No model $\boldsymbol{N1} = 1$: Levy model
I10	***N2***	Bulk void fraction: For $\boldsymbol{N3} > 0$ in SETRI 9.0, ***N2*** will be reset as $\boldsymbol{N2} = 0$; $(0 \le \boldsymbol{N2} \le 6)$: $\boldsymbol{N2} = 0$: Homogeneous model $\boldsymbol{N2} = 1$: Modified Armand model $\boldsymbol{N2} = 3$: Chexal-Lellouche model $\boldsymbol{N2} = 5$: Slip model: Read in a slip ratio * Requires Card SETRI 2.4 $\boldsymbol{N2} = 6$: Polynomial function of quality: Read in number of terms and coefficients for up to a 6th-order polynomial * Requires Card SETRI 2.4
I10	***N3***	Two-phase friction multiplier: For $\boldsymbol{N3} > 0$ in SETRI 9.0, ***N3*** will be reset as $\boldsymbol{N3} = 0$; $(0 \le \boldsymbol{N3} \le 5)$: $\boldsymbol{N3} = 0$: Homogeneous model $\boldsymbol{N3} = 1$: Armand model $\boldsymbol{N3} = 5$: Polynomial function of quality: Read in number of terms and coefficients for up to a 6th-order polynomial * Requires Card SETRI 2.5
I10	***N4***	Heated wall viscosity correction in friction factor: $(0 \le \boldsymbol{N4} \le 1)$: $\boldsymbol{N4} = 0$: No $\boldsymbol{N4} = 1$: Yes
I10	***N5***	Single-phase laminar friction factor: $(0 \le \boldsymbol{N5} \le 1)$: $\boldsymbol{N5} = 0$: No $\boldsymbol{N5} = 1$: Yes: Read in up to 4 sets of laminar friction factor correlation constants * Requires Card SETRI 2.2
I10	***N6***	Single-phase rod-to-coolant heat transfer coefficient: $(0 \le \boldsymbol{N6} \le 1)$: $\boldsymbol{N6} = 0$: Dittus-Boelter correlation $\boldsymbol{N6} = 1$: Read in a user-supplied correlation * Requires Card SETRI 2.3
I10	***N7***	Single-phase turbulent friction factor: $(0 \le \boldsymbol{N7} \le 2)$:

N7 = 0: Square rod array
N7 = 1: Rehme correlation for triangular rod array
with wire wrap:
* Requires Card SETRI 2.6:
Ref: K. Rehme,
"Pressure Drop Correlations
for Fuel Element Spacers,"
Nuclear Technology,
Vol. 17, pp. 15-23,
January 1973
N7 = 2: Rehme correlation for triangular rod array
with/without grid spacer:
* Requires Card SETRI 2.7:
Equivalent annular zone;
Ref: K. Rehme,
"Pressure Drop Performance of Rod
Bundles in Hexagonal Arrangements,"
Int. J. Heat Mass Transfer,
Vol. 15, pp. 2499-2517,
1972

SETRI 2.1

Single-phase turbulent friction factor –
Square rod array:
Required; Not optional (Dummy read for ***N7*** = 1 or 2);
Read in up to 4 sets corresponding to 4 channel types:
AA(*I*), ***BB***(*I*), ***CC***(*I*), *I* = 1 to 4: (12F10)

F10	***AA***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AA} \times \mathrm{Re}^{\boldsymbol{BB}} + \boldsymbol{CC}$ (Recommended: 0.316 for 5000 < Re < 30000; 0.184 for 30000 < Re < 1000000)
F10	***BB***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AA} \times \mathrm{Re}^{\boldsymbol{BB}} + \boldsymbol{CC}$ (Recommended: -0.25 for 5000 < Re < 30000; -0.20 for 30000 < Re < 1000000)
F10	***CC***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AA} \times \mathrm{Re}^{\boldsymbol{BB}} + \boldsymbol{CC}$ (Recommended: 0. for 5000 < Re < 30000; 0. for 30000 < Re < 1000000)

SETRI 2.2

Single-phase laminar friction factor:
Optional (***N5*** = 1);
Read in up to 4 sets corresponding to 4 channel types:
AAL(*I*), ***BBL***(*I*), ***CCL***(*I*), *I* = 1 to 4: (12F10)

F10	***AAL***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AAL} \times \mathrm{Re}^{\boldsymbol{BBL}} + \boldsymbol{CCL}$ (Recommended: 64.)
F10	***BBL***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AAL} \times \mathrm{Re}^{\boldsymbol{BBL}} + \boldsymbol{CCL}$ (Recommended: -1.)
F10	***CCL***(*I*)	Constant of the correlation in the form as $f = \boldsymbol{AAL} \times \mathrm{Re}^{\boldsymbol{BBL}} + \boldsymbol{CCL}$ (Recommended: 0.)

SETRI 2.3			Single-phase rod-to-coolant heat transfer coefficient: Optional (***N6*** = 1): ***AH***(*I*), *I* = 1 to 4: (4F10)
	F10	***AH***(*I*)	Constant of the correlation in the form as $h = (k/D)\times(\boldsymbol{AH}(1)\times \mathrm{Re}^{\boldsymbol{AH}(2)}\times \mathrm{Pr}^{\boldsymbol{AH}(3)}+\boldsymbol{AH}(4))$: Defaults for ***N6*** = 0 are 0.023, 0.8, 0.4, and 0. for ***AH***(1) through ***AH***(4), respectively (Dittus-Boelter correlation)
SETRI 2.4			Bulk void fraction model – slip or polynomial: Optional (***N2*** = 5 or 6): ***NV***, (***AV***(*I*), *I* = 1 to 7): (I10, 7F10)
	I10	***NV***	Number of terms for up to a 6th-order polynomial if ***N2*** = 6 (**Not used** if ***N2*** = 5)
	F10	***AV***(*I*)	A single term slip ratio ***AV***(1) if ***N2*** = 5; Constants for up to a 6th-order polynomial function of void fraction (α) vs. quality (χ) if ***N2*** = 6 (*I* = 1 to 7) in the form as $\alpha = \boldsymbol{AV}(1)+\boldsymbol{AV}(2)\times\chi+\cdots+\boldsymbol{AV}(7)\times\chi^{6}$
SETRI 2.5			Two-phase friction multiplier model – polynomial: Optional (***N3*** = 5): ***NF***, (***AF***(*I*), *I* = 1 to 7): (I10, 7F10)
	I10	***NF***	Number of terms for up to a 6th-order polynomial
	F10	***AF***(*I*)	Constants for up to a 6th-order polynomial function of two-phase friction multiplier (ϕ) vs. quality (χ) (*I* = 1 to 7) in the form as $\phi = \boldsymbol{AF}(1)+\boldsymbol{AF}(2)\times\chi+\cdots+\boldsymbol{AF}(7)\times\chi^{6}$
SETRI 2.6			Single-phase turbulent friction factor – Rehme correlation for triangular rod array with wire wrap: Optional (***N7*** = 1): ***PITCHR***, ***DIAR***, ***PITCHW***, ***DIAW***, ***NOR***, ***NOW***, ***IGL***: (4F10, 3I10)
	F10	***PITCHR***	Rod pitch [in; mm]
	F10	***DIAR***	Rod diameter [in; mm]
	F10	***PITCHW***	Wire wrap pitch [in; mm]
	F10	***DIAW***	Wire wrap diameter [in; mm]
	I10	***NOR***	Number of rods
	I10	***NOW***	Number of wire wraps

I10	***IGL***	Switch for selecting global or local Reynolds number: ***IGL*** = 0: Bundle average Reynolds number (Recommended) ***IGL*** = 1: Channel average Reynolds number (**Not used**)

SETRI 2.7

Single-phase turbulent friction factor –
Rehme correlation for triangular rod array
with/without grid spacer:
Optional (***N7*** = 2):
PITCHR, ***DIAR***, ***X1R***, ***X2R***, ***TOLXR***, ***TOLFR***,
IMAXR, ***MTDR***, ***IGL***: (6F10, 3I10)

F10	***PITCHR***	Rod pitch [in; mm]
F10	***DIAR***	Rod diameter [in; mm]
F10	***X1R***	Initial lower bound of the root of the nonlinear equation: the Rehme correlation for single-phase turbulent friction factor for the "equivalent annular zone" of triangular rod array (Recommended: 0.001: dependent on Re and P/D)
F10	***X2R***	Initial upper bound of the root of the nonlinear equation: the Rehme correlation for single-phase turbulent friction factor for the "equivalent annular zone" of triangular rod array (Recommended: 0.049: dependent on Re and P/D)
F10	***TOLXR***	Convergence factor for the root (Recommended: 2.5E-7)
F10	***TOLFR***	Convergence factor for the function value at the root (Recommended: 1.E-5)
I10	***IMAXR***	Maximum allowed number of iterations for finding the root (Recommended: 100)
I10	***MTDR***	Flag to designate a particular root finding method: ***MTDR*** = 1: Bisection method ***MTDR*** = 2: Newton-Raphson method ***MTDR*** = 3: Newton-Raphson / Bisection method (Recommended)
I10	***IGL***	Switch for selecting global or local Reynolds number: ***IGL*** = 0: Bundle average Reynolds number (Recommended) ***IGL*** = 1: Channel average Reynolds number (**Not used**)

Card Group 3 Axial Heat Flux Distribution

SETRI 3.0		Group control card: ***NGROUP***, ***N1***: (2I10)
I10	***NGROUP***	Card group number: Must be 3
I10	***N1***	Number of entries in axial heat flux table: Must read in at least two points; $(2 \le \boldsymbol{N1} \le \boldsymbol{MP})$
SETRI 3.1		Axial heat flux table: Read in ***N1*** pairs of data: ***Y***(*L*), ***AXIAL***(*L*), $L = 1$ to ***N1***: (10F10)
F10	***Y***(*L*)	Relative axial location (***X***/***Z***) at which heat flux is given, where ***Z*** is the total axial length in SETRI 9.1: Must include 0. and 1. as end points
F10	***AXIAL***(*L*)	Relative heat flux at ***X***/***Z***: Local-to-average heat flux ratio

Card Group 4 Channel Layout and Dimensions

SETRI 4.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***: (7I10)
I10	***NGROUP***	Card group number: Must be 4
I10	***N1***	Number of channels for which informations are to be read: One data card for each channel, unless already assigned (e.g., restart cases); $(N1 \geq 1)$
I10	***N2***	Total number of channels, regardless of ***N1***: $(1 \leq N2 \leq MC)$
I10	***N3***	Number of gaps for which relative direction angles for crossflows are to be read: $(0 \leq N3 \leq MG)$ * Requires Card SETRI 4.3 if $N3 > 0$
I10	***N4***	Number of wall-channel thermal connections: $(0 \leq N4 \leq MW)$ * Requires Card SETRI 4.2 if $N4 > 0$
I10	***N5***	Logical unit from which card set SETRI 4.1 is to be read: $(N5 \geq 0)$: $N5 = 0$: Read from input deck $(LU = I2 = 5)$ $N5 > 0$: Read from logical unit ***N5*** $(LU = N5 = 9)$ (**Not used**)
I10	***N6***	Logical unit from which card set SETRI 4.3 is to be read: $(N6 \geq 0)$: $N6 = 0$: Read from input deck $(LU = I2 = 5)$ $N6 > 0$: Read from logical unit ***N6*** $(LU = N6 = 9)$ (**Not used**)
SETRI 4.1		Channel geometry data: Read in ***N1*** cards: ***N***, ***I***, ***AC***(*I*), ***PW***(*I*), ***PH***(*I*), (***LC***(*I*,*L*), ***GAPS***(*I*,*L*), ***DIST***(*I*,*L*), $L = 1$ to 4), $J = 1$ to ***N1***: (I2, I8, 3F10, 4(I10, 2F10))
I2	***N***	Channel type for friction factors in SETRI 2.1 and 2.2: Default for $N = 0$ is $N = 1$; $(1 \leq N \leq 4)$
I8	***I***	Channel identification number: $(1 \leq I \leq N2)$
F10	***AC***(*I*)	Nominal channel flow area [in^2; mm^2]
F10	***PW***(*I*)	Nominal channel wetted perimeter [in; mm]
F10	***PH***(*I*)	Nominal channel heated perimeter [in; mm]

I10	***LC***(*I*,*L*)	Adjacent channel identification number for up to 4 channels adjacent to channel ***I***: If the channels are input with ascending identification numbers, only connections $\boldsymbol{LC}(I,L) > \boldsymbol{I}$ need to be read in; If a line of symmetry splits a gap at a boundary, ***LC***(*I*,*L*) must be negative; $-\boldsymbol{N2} \le \boldsymbol{LC}(I,L) \le \boldsymbol{N2}$
F10	***GAPS***(*I*,*L*)	Nominal gap spacing [in; mm] between channel ***I*** and the adjacent channel specified by ***LC***(*I*,*L*)
F10	***DIST***(*I*,*L*)	Centroid-to-centroid distance [in; mm] between channel ***I*** and the adjacent channel specified by ***LC***(*I*,*L*): Required if $\boldsymbol{N1} = 3$ in SETRI 10.0 or $\boldsymbol{N3} = 1$ in SETRI 10.0
SETRI 4.2		Wall-channel thermal connection data: Optional ($\boldsymbol{N4} > 0$); Read in ***N4*** cards: ***KW***, ***RHOLCP***(*KW*), ***WIDTH***(*KW*), ***IKW***(*KW*), ***RWALL***(1,*KW*), ***JKW***(*KW*), ***RWALL***(2,*KW*), $K = 1$ to ***N4***: (I10, 2F10, 2(I10, F10))
I10	***KW***	Wall-channel thermal connection identification number: ($1 \le \boldsymbol{KW} \le \boldsymbol{N4}$)
F10	***RHOLCP***(*KW*)	Wall heat capacity parameter [Btu/ft^2- °F ; kJ/m^2- °C]
F10	***WIDTH***(*KW*)	Width of wall [in; mm]: Heat conduction area = $\boldsymbol{WIDTH}(KW) \times \boldsymbol{DX}$, where ***DX*** is axial node length
I10	***IKW***(*KW*)	Channel identification number adjacent to wall
F10	***RWALL***(1,*KW*)	Conductive resistance of the wall associated with the ***IKW***(*KW*) channel [sec-ft^2- °F /Btu; m^2- °C /kW]
I10	***JKW***(*KW*)	Channel identification number adjacent to wall
F10	***RWALL***(2,*KW*)	Conductive resistance of the wall associated with the ***JKW***(*KW*) channel [sec-ft^2- °F /Btu; m^2- °C /kW]
SETRI 4.3		Gap orientation data: Optional ($\boldsymbol{N3} > 0$): ***K***, ***ANGLE***(*K*), $L = 1$ to ***N3***: (5(I10, F10))
I10	***K***	Gap identification number for which the relative direction angle for crossflow is specified: ($1 \le \boldsymbol{K} \le \boldsymbol{N3}$)
F10	***ANGLE***(*K*)	Relative direction angle for positive crossflow

through gap ***K*** [positive degrees]

Card Group 5 — Channel Area Variation

(Optional Card Group)

SETRI 5.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***: (4I10)
I10	***NGROUP***	Card group number: Must be 5
I10	***N1***	Number of channels for which area variation tables are to be read: $(0 \leq \boldsymbol{N1} \leq \boldsymbol{MA})$
I10	***N2***	Number of axial locations for channel area variation: Must read in at least two points; $(0 \leq \boldsymbol{N2} \leq \boldsymbol{ML})$ * Requires Cards SETRI 5.1 and 5.2 if $\boldsymbol{N2} > 0$
I10	***N3***	Number of iterations for gradual insertion of channel area variations: Default for $\boldsymbol{N3} = 0$ is $\boldsymbol{N3} = 1$; For a restart case, ***N3*** must be reread if desired; $(\boldsymbol{N3} \geq 1)$
SETRI 5.1		Table of axial locations for channel area variation: Optional ($\boldsymbol{N2} > 0$): ***AXL***(*L*), $L = 1$ to ***N2***: (10F10)
F10	***AXL***(*L*)	Relative axial locations (***X***/***Z***) at which channel area variations will be specified; Must include 0. and 1. as end points
SETRI 5.2		Table of channel area variation factors: Optional ($\boldsymbol{N2} > 0$); For ***N1*** channels, read channel area variation factors at ***N2*** relative axial locations corresponding to ***AXL***(*L*): ***I***, (***AFACT***(*L*,*J*), $L = 1$ to ***N2***), $J = 1$ to ***N1***: (I10/10F10)
I10	***I***	Channel identification number for which channel area variations are being specified: Read according to (I10) format, then skip to the next card and read a complete set of factors ***AFACT***(*L*,*J*) corresponding to ***AXL***(*L*) locations; Repeat until factors for ***N1*** channels are read; $(1 \leq \boldsymbol{I} \leq \boldsymbol{N2}$ in SETRI 4.0)
F10	***AFACT***(*L*,*J*)	Relative channel area at ***X***/***Z***: Varied-to-nominal channel area ratio

Card Group 6 Gap Spacing Variation

(Optional Card Group)

SETRI 6.0

Group control card:
NGROUP, ***N1***, ***N2***: (3I10)

I10	***NGROUP***	Card group number: Must be 6
I10	***N1***	Number of gaps for which gap spacing variation tables are to be read: $(0 \le N1 \le MS)$
I10	***N2***	Number of axial locations for gap spacing variation: Must read in at least two points; $(0 \le N2 \le ML)$ * Requires Cards SETRI 6.1 and 6.2 if $N2 > 0$

SETRI 6.1

Table of axial locations for gap spacing variation:
Optional ($N2 > 0$):
GAPXL(*L*), $L = 1$ to ***N2***: (10F10)

F10	***GAPXL***(*L*)	Relative axial locations (X/Z) at which gap spacing variations will be specified: Must include 0. and 1. as end points

SETRI 6.2

Table of gap spacing variation factors:
Optional ($N2 > 0$);
For ***N1*** gaps, read gap spacing variation factors
at ***N2*** relative axial locations
corresponding to ***GAPXL***(*L*):
K, (***GFACT***(*L*,*J*), $L = 1$ to ***N2***), $J = 1$ to ***N1***:
(I10/10F10)

I10	***K***	Gap identification number for which gap spacing variations are being specified: Read according to (I10) format, then skip to the next card and read a complete set of factors ***GFACT***(*L*,*J*) corresponding to ***GAPXL***(*L*) locations; Repeat until factors for ***N1*** gaps are read; $(1 \le K \le NK)$, where ***NK*** is the number of gaps
F10	***GFACT***(*L*,*J*)	Relative gap spacing at X/Z: Varied-to-nominal gap spacing ratio

Card Group 7 Wire Wrap and Grid Spacer Information

(Optional Card Group)

SETRI 7.0

Group control card:
NGROUP, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***: (7I10)

I10	***NGROUP***	Card group number: Must be 7
I10	***N1***	Option for wire wrap / grid spacer input data: $(1 \leq \boldsymbol{N1} \leq 3)$: $\boldsymbol{N1} = 1$: Wire wrap input only * Requires Cards SETRI 7.1, 7.2, and 7.3 $\boldsymbol{N1} = 2$: Grid spacer input only * Requires Cards SETRI 7.4 and 7.5 $\boldsymbol{N1} = 3$: Both wire wrap and grid spacer input * Requires Cards SETRI 7.1 through 7.5
I10	***N2***	Number of gaps for which wire wrap crossing data are to be read: $(\boldsymbol{N2} \geq 0)$
I10	***N3***	Number of axial locations for grid spacers: $(0 \leq \boldsymbol{N3} \leq \boldsymbol{MZ})$
I10	***N4***	Number of grid spacer types: $(0 \leq \boldsymbol{N4} \leq \boldsymbol{MK})$
I10	***N5***	Number of iterations for gradual insertion of grid loss terms: Default for $\boldsymbol{N5} = 0$ is $\boldsymbol{N5} = 1$; For a restart case, ***N5*** must be reread if desired; $(\boldsymbol{N5} \geq 1)$
I10	***N6***	Logical unit from which card sets SETRI 7.2 and 7.3 are to be read: $(\boldsymbol{N6} \geq 0)$: $\boldsymbol{N6} = 0$: Read from input deck $(\boldsymbol{LU} = \boldsymbol{I2} = 5)$ $\boldsymbol{N6} > 0$: Read from logical unit ***N6*** $(\boldsymbol{LU} = \boldsymbol{N6} = 9)$ (**Not used**)

SETRI 7.1

Wire wrap specifications:
Optional $(\boldsymbol{N1} = 1$ or $3)$:
PITCH, ***DIA***, ***THICK***: (3F10)

F10	***PITCH***	Wire wrap pitch [in; mm]
F10	***DIA***	Rod outer diameter [in; mm]
F10	***THICK***	Wire wrap thickness [in; mm]

SETRI 7.2

Wire wrap crossing data:
Optional $(\boldsymbol{N1} = 1$ or $3)$:
K, ***DUR***(*K*), (***XCROSS***(*K*,*L*), $L = 1$ to 2), $M = 1$ to ***N2***:
(I10, 3F10)

I10	***K***	Gap identification number for which wire wrap crossing data are being specified:

		(1 ≤ ***K*** ≤ ***MG***)
F10	***DUR***(*K*)	Effective fraction of a wire wrap pitch length for forced crossflow (Recommended: ***DUR***(*K*) = ***DX***/***PITCH***, where ***PITCH*** is wire wrap pitch)
F10	***XCROSS***(*K*,*L*)	Wire wrap crossing angle [dimensionless]: Calculated by dividing the angle between the gap and wire (at the bundle inlet) by 360 deg; Positive if the wire wrap is moving from a smaller- to a larger-number channel and negative if otherwise; If the wire wrap is on a gap boundary at the bundle inlet, ***XCROSS***(*K*,*L*) = +1. or -1. not zero

SETRI 7.3

Wire wrap inventory:
Optional (***N1*** = 1 or 3):
NWRAP(*I*), *I* = 1 to ***N2*** in SETRI 4.0: (10I10)

I10	***NWRAP***(*I*)	Number of wire wraps in each channel at the bundle inlet: If the wire wrap is on a gap boundary at the bundle inlet, the wire wrap is assumed to be in the channel into which it is proceeding

SETRI 7.4

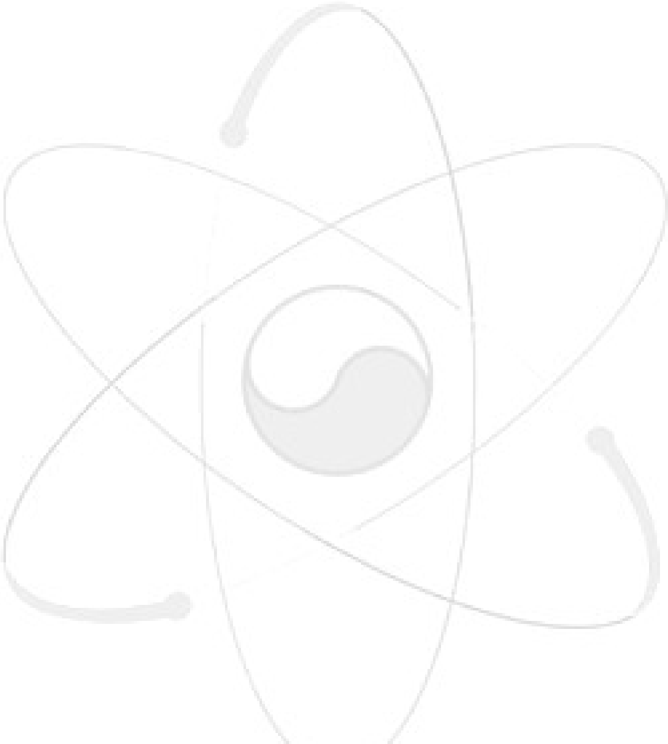
Table of axial locations and types for grid spacers:
Optional (***N1*** = 2 or 3):
GRIDXL(*L*), ***IGRID***(*L*), *L* = 1 to ***N3***: (5(F10, I10))

F10	***GRIDXL***(*L*)	Relative axial locations (***X***/***Z***) of grid spacers
I10	***IGRID***(*L*)	Grid spacer type at ***X***/***Z***

SETRI 7.5

Loss coefficient and forced crossflow (if desired)
in each channel for each grid spacer type:
Optional (***N1*** = 2 or 3):
(***J***, ***CD***(*J*,*I*), ***K***, ***FXFLOW***(*K*,*I*),
II = 1 to ***N2*** in SETRI 4.0), *I* = 1 to ***N4***:
(I10, F10, I10, F10)

I10	***J***	Channel identification number for which grid spacer data are being supplied: (1 ≤ ***J*** ≤ ***N2*** in SETRI 4.0)
F10	***CD***(*J*,*I*)	Loss coefficient in channel ***J*** for grid spacer type ***I***
I10	***K***	Gap associated with channel ***J***, through which forced crossflow is specified: If blank, no forced crossflow; (1 ≤ ***K*** ≤ ***NK***), where ***NK*** is the number of gaps
F10	***FXFLOW***(*K*,*I*)	Fraction of axial flow which is diverted through gap ***K*** for grid spacer type ***I***



Card Group 8 Rod Layout, Dimensions, and Properties

SETRI 8.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***, ***N8***, ***N9***: (10I10)
I10	***NGROUP***	Card group number: Must be 8
I10	***N1***	Number of rods for which informations are to be read: One data card for each rod; For restart cases or multiple case runs, it is only necessary to read new rod input; $(N1 \geq 1)$
I10	***N2***	Total number of rods, regardless of ***N1***: $(1 \leq N2 \leq MR)$
I10	***N3***	Order of approximation used in fuel model: Number of fuel collocation points minus one; $(0 \leq N3 \leq MN-3)$: $N3 = 0$: No fuel model ($N3 < 2$: If $N3 = 1$, then $N3 = 0$: reset) $N3 = 2$: 2nd-order collocation (3 collocation points) * Requires Card SETRI 8.2 $N3 = 3$: 3rd-order collocation (4 collocation points) * Requires Card SETRI 8.2
I10	***N4***	Number of fuel material types for which thermal properties are to be specified (Applicable only if $N3 > 1$): $(1 \leq N4 \leq MT)$
I10	***N5***	Critical heat flux: $(N5 \geq 0)$: $N5 = 0$: No CHF calculations $N5 = 1$: B&W-2 correlation $N5 = 2$: W-3 correlation * Requires Card SETRI 8.5 if $N5 > 0$
I10	***N6***	Additional fuel model options (Applicable only if $N3 > 1$): $(0 \leq N6 \leq 3)$: $N6 = 0$: No additional fuel model $N6 = 1$: Variable thermal conductivity only * Requires Card SETRI 8.3 $N6 = 2$: Axial conduction only $N6 = 3$: Both variable thermal conductivity and axial conduction * Requires Card SETRI 8.3 ($N6 = 2$ or 3 also specifies fluid axial conduction; No additional input required)
I10	***N7***	Heat transfer coefficient: $(0 \leq N7 \leq 1)$: $N7 = 0$: Dittus-Boelter or other correlation specified in SETRI 2.3 $N7 = 1$: Complete boiling and nonboiling correlation package similar to that of RELAP-4

I10	***N8***	Option for axially varying fuel material (Applicable only if ***N3*** > 1): (0 ≤ ***N8*** ≤ ***MT***): ***N8*** = 0: No axially varying fuel material: Each fuel rod is constructed of a single material ***N8*** > 0: Number of fuel material configuration types for axially varying fuel material: Read in fuel zone information * Requires Card SETRI 8.4
I10	***N9***	Logical unit from which card set SETRI 8.1 is to be read: (***N9*** ≥ 0): ***N9*** = 0: Read from input deck (***LU*** = ***I2*** = 5) ***N9*** > 0: Read from logical unit ***N9*** (***LU*** = ***N9*** = 9) (**Not used**)
SETRI 8.1		Rod data: Read in ***N1*** cards: ***N***, ***I***, ***DR***(*I*), ***RADIAL***(*I*), (***LR***(*I*,*L*), ***PHI***(*I*,*L*), *L* = 1 to 6), *J* = 1 to ***N1***: (I2, I8, 2F10, 6(I10, F10))
I2	***N***	Fuel shape and fuel material option: Absolute value of ***N*** determines the material property configuration of fuel ***I***: For ***N8*** = 0 (axially uniform fuel material), ABS(***N***) corresponds to one of ***N4*** fuel materials in SETRI 8.2 of which rod ***I*** is made; For ***N8*** > 0 (axially varying fuel material), ABS(***N***) corresponds to one of ***N8*** fuel material configurations in SETRI 8.4 specifying the fuel material vs. axial height; If any rod is specified to have axially varying properties (***N8*** > 0), all rods (including axially uniform rods) must have an axial configuration specified in SETRI 8.4: ***N*** ≥ 0: Cylindrical fuel ***N*** < 0: Plate fuel
I8	***I***	Rod identification number: (1 ≤ ***I*** ≤ ***N2***)
F10	***DR***(*I*)	Rod outer diameter [in; mm]: If cladding is around the rod, ***DR***(*I*) is the cladding outer diameter
F10	***RADIAL***(*I*)	Radial power factor for rod ***I*** as a fraction of the average heat flux specified in SETRI 11.1
I10	***LR***(*I*,*L*)	Adjacent channel identification number for up to 6 channels surrounding rod ***I***
F10	***PHI***(*I*,*L*)	Fraction of the total rod power input to adjacent channel: Fraction of the outer rod perimeter

facing the channel identified by ***LR***(*I*,*L*)

SETRI 8.2

Fuel material properties:
Optional (***N3*** > 1);
Read in ***N4*** cards corresponding to ***N4*** materials
for which thermal properties are specified;
Each fuel rod consists of one or more of these materials:
KFUEL(*I*), ***CFUEL***(*I*), ***RFUEL***(*I*), ***DFUEL***(*I*),
KCLAD(*I*), ***CCLAD***(*I*), ***RCLAD***(*I*), ***TCLAD***(*I*),
HGAP(*I*), *I* = 1 to ***N4***: (9F10)

F10	***KFUEL***(*I*)	Thermal conductivity of fuel [Btu/hr-ft- °F ; kW/m- °C]
F10	***CFUEL***(*I*)	Specific heat of fuel [Btu/lb_m- °F ; kJ/kg- °C]
F10	***RFUEL***(*I*)	Density of fuel [lb_m/ft^3; kg/m^3]
F10	***DFUEL***(*I*)	Fuel pellet diameter [in; mm]
F10	***KCLAD***(*I*)	Thermal conductivity of cladding [Btu/hr-ft- °F ; kW/m- °C]
F10	***CCLAD***(*I*)	Specific heat of cladding [Btu/lb_m- °F ; kJ/kg- °C]
F10	***RCLAD***(*I*)	Density of cladding [lb_m/ft^3; kg/m^3]
F10	***TCLAD***(*I*)	Cladding thickness [in; mm]
F10	***HGAP***(*I*)	Fuel-cladding gap conductance [Btu/hr-ft^2- °F ; kW/m^2- °C]

SETRI 8.3

Variable thermal conductivity:
Optional (***N3*** > 1 and (***N6*** = 1 or 3));
Only applies to the material
specified by the 1st card of SETRI 8.2:
TREF, (***BK***(*I*), *I* = 2 to 4): (4F10)

F10	***TREF***	Reference temperature where k = ***KFUEL***(1) [°F ; °C]
F10	***BK***(*I*)	Coefficients for up to 3rd-order polynomial approximation for thermal conductivity vs. temperature of the form as k = ***KFUEL***(1)×(1 +***BK***(2)×(T-***TREF***) +***BK***(3)×(T-***TREF***)^2 +***BK***(4)×(T-***TREF***)^3)

SETRI 8.4

Specification of axially varying fuel materials:
Optional (***N3*** > 1 and ***N8*** > 0);
Must read in a fuel zone configuration table
for each fuel type ***N*** in SETRI 8.1:
KNZ, (***ZEND***(*I*,*L*), ***IZTYP***(*I*,*L*), *L* = 1 to ***KNZ***),
I = 1 to ***N8***: (I10/5(F10, I10))

I10	***KNZ***	Number of axial zones to be read for a table of fuel material vs. axial distance for fuel type ***I***: Read according to (I10) format, then skip to the next card

			and read a complete set of factors ***ZEND***(*I*,*L*) and ***IZTYP***(*I*,*L*); Repeat until factors for ***N8*** fuel material configuration types are read; (1 ≤ ***KNZ*** ≤ ***MY***)
	F10	***ZEND***(*I*,*L*)	Relative axial location (***X***/***Z***) of the end of a fuel zone: If fuel type ***I*** is axially uniform, ***ZEND***(*I*,1) = 1.
	I10	***IZTYP***(*I*,*L*)	Type of fuel material in the fuel zone ending at ***ZEND***(*I*,*L*): Each ***IZTYP***(*I*,*L*) corresponds to a fuel material specified in SETRI 8.2; Only fuel material type 1 can have variable thermal conductivity
SETRI 8.5			Miscellaneous CHF-related information: Optional (***N5*** > 0): ***ICCRIT***, ***DEMATX, ISMV, FEDH, FEQ***: (I10, F10, I10, F10, F10)
	I10	***ICCRIT***	Identification number of the channel of MDNBR occurrence used in the coarse-mesh analysis: ***ICCRIT*** = 0: Critical channel determined by calculation; ***ICCRIT*** > 0: Critical channel determined by ***ICCRIT***
	F10	***DEMATX***	Not used.
	I10	***ISMV***	Not used.
	F10	***FEDH***	Not used
	F10	***FEQ***	Not used

Card Group 9 Calculation Control

SETRI 9.0
Group control card:
NGROUP, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***, ***N8***, ***N9***:
(10I10)

I10 ***NGROUP*** Card group number: Must be 9

I10 ***N1*** Output print option for axial levels:
$(\boldsymbol{N1} \geq 1)$:
$\boldsymbol{N1} = 1$: Print all axial levels
$\boldsymbol{N1} > 1$: Print every ***N1*** axial levels

I10 ***N2*** Output print option for time steps:
$(\boldsymbol{N2} \geq 1)$:
$\boldsymbol{N2} = 1$: Print all time steps
$\boldsymbol{N2} > 1$: Print every ***N2*** time steps

I10 ***N3*** Solution algorithm to solve the problem:
$(0 \leq \boldsymbol{N3} \leq 4)$:
$\boldsymbol{N3} = 0$: Implicit solution
(multi-pass marching scheme)
with inlet flow boundary condition:
Implicit steady-state
and implicit transient calculations
$\boldsymbol{N3} = 1$: Explicit solution
with pressure drop boundary condition:
Running start
from implicit solution as initial condition
(**Not checked**)
$\boldsymbol{N3} = 2$: Explicit solution
with pressure drop boundary condition:
Standing start
from zero flow initial condition
(**Not checked**)
$\boldsymbol{N3} = 3$: Explicit solution
with inlet flow boundary condition:
Running start
from implicit solution as initial condition
(**Not checked**)
$\boldsymbol{N3} = 4$: Explicit solution
with inlet flow boundary condition:
Standing start
from zero flow initial condition
(**Not checked**)
* Requires Cards SETRI 9.3 and 9.4 if $\boldsymbol{N3} > 0$

I10 ***N4*** Problem roll option:
$(0 \leq \boldsymbol{N4} \leq 1)$:
$\boldsymbol{N4} = 0$: No roll option:
All variables reside in core at all times
$\boldsymbol{N4} = 1$: Roll option:
Only 3 axial levels of information
($\boldsymbol{J}$-1, $\boldsymbol{J}$, and $\boldsymbol{J}$+1)
are stored in core at one time
(**Not checked**)

I10 ***N5*** Maximum time step table option
(Applicable only if $\boldsymbol{N3} > 0$):

		(0 ≤ ***N5*** ≤ ***MP***): ***N5*** = 0 or 1: Maximum transient time step is ***FDT*** in SETRI 9.3 for all time ***N5*** > 1: Read in ***N5*** pairs of information (time, maximum time step) for variable maximum time steps (**Not checked**) * Requires Card SETRI 9.5
I10	***N6***	Number of axial zones for variable axial node length: (0 ≤ ***N6*** ≤ ***MX***): ***N6*** = 0 or 1: Uniform axial node length ***N6*** > 1: Nonuniform axial node length: Read in ***N6*** pairs of information (no. of axial nodes, frac. of axial node length) for variable axial node length for each zone * Requires Card SETRI 9.6
I10	***N7***	Combined momentum equation solver: (0 ≤ ***N7*** ≤ 3): ***N7*** = 0: Diversion crossflow solved by SOR (Successive Over-Relaxation: Gauss-Seidel iteration modified to include over-relaxation) ***N7*** = 1: Diversion crossflow solved by GE (Gauss Elimination) ***N7*** = 2: Axial pressure gradient solved by SOR ***N7*** = 3: Axial pressure gradient solved by GE
I10	***N8***	Iteration on power, rod radial peaking factor, or flow: (0 ≤ ***N8*** ≤ 3): ***N8*** = 0: No iteration ***N8*** = 1: Iterate on power ***N8*** = 2: Iterate on rod radial peaking factor * Requires Card SETRI 9.9 ***N8*** = 3: Iterate on flow * Requires Cards SETRI 9.7 and 9.8 if ***N8*** > 0
I10	***N9***	Debugging option for numerical stability: (0 ≤ ***N9*** ≤ 1): ***N9*** = 0: No printout ***N9*** = 1: Print out the numerical stability results for coefficient matrix and source vector
SETRI 9.1		Calculation parameters: ***Z***, ***TTIME***, ***WERRX***, ***WERRY***, ***FERROR***, ***KIJ***, ***SL***, ***FTM***, ***THETA***, ***USDON***, ***DAMPNG***, ***ACCELY***, ***ACCELF***, ***ZH***: (14F10)
F10	***Z***	Total axial length [in; mm]
F10	***TTIME***	Total transient time [sec]
F10	***WERRX***	External convergence limit for crossflow: Defined for implicit crossflow solution as the maximum allowable error in iterative crossflows at any axial level; If any error is greater than ***WERRX***,

		the solution proceeds through another iterative axial sweep over the entire bundle; Default for ***WERRX*** ≤ 0. is 0.1
F10	***WERRY***	Internal convergence limit for crossflow or axial pressure gradient (Applicable only if ***N7*** = 0 or 2): Defined for implicit crossflow or axial pressure gradient solution as the convergence limit for the SOR method at any axial level; In the code, the internal convergence limits are modified as follows: ***WERRYT*** = MAX(***WERRY***,MIN(0.01,***QOM***×0.01)) for ***N7*** = 0 (Diversion crossflow solved by SOR), where ***QOM*** is the maximum error in iterative crossflows at the upstream axial levels; ***WERRYT*** = ***WERRY***×0.001 for ***N7*** = 2 (Axial pressure gradient solved by SOR); Default for ***WERRY*** ≤ 0. is 0.001
F10	***FERROR***	External convergence limit for axial flow: Defined for implicit axial flow solution as the maximum allowable error in iterative axial flows at any axial level; If any error is greater than ***FERROR***, the solution proceeds through another iterative axial sweep over the entire bundle; Default for ***FERROR*** ≤ 0. is 0.01
F10	***KIJ***	Diversion crossflow resistance coefficient: Default for ***KIJ*** ≤ 0. is 0.5
F10	***SL***	Lateral momentum parameter: No default; (Recommended: 0.5)
F10	***FTM***	Turbulent momentum factor: Default for ***FTM*** < 0. is 0.
F10	***THETA***	Channel orientation (from vertical) [degrees]: Default for ***THETA*** = 0. is vertical; Otherwise, read in the nearest angle away from the vertical
F10	***USDON***	Contribution of velocities from the donor and receiver channels in u* calculation: Default for ***USDON*** < 0. is 0.; If ***USDON*** = 0., then u* = 0.5×(u(*I*)+u(*J*)), and if ***USDON*** = 1., then u* = u(*I*), where ***I*** and ***J*** are donor and receiver channels, respectively; Any value between 0. and 1. is acceptable
F10	***DAMPNG***	Acceleration factor for iterative pressure difference between adjacent channels: ***SP***(*K*,*J*,*N*) = ***DAMPNG***×***SP***(*K*,*J*,*N*) +(1.-***DAMPNG***)×***SP***(*K*,*J*,*N*-1), where ***N*** and ***N***-1

		are the present and previous iterations, respectively; Defined for implicit solution for pressure difference between adjacent channels; Default for ***DAMPNG*** ≤ 0. is 0.8
F10	***ACCELY***	Acceleration factor for iterative crossflow or axial pressure gradient (Applicable only if ***N7*** = 0 or 2): $\boldsymbol{W}(K,J,N) = \boldsymbol{ACCELY} \times \boldsymbol{W}(K,J,N) + (1.-\boldsymbol{ACCELY}) \times \boldsymbol{W}(K,J,N-1)$; Defined for implicit crossflow or axial pressure gradient solution by SOR; Default for ***ACCELY*** ≤ 0. is 1.6
F10	***ACCELF***	Acceleration factor for iterative axial flow: $\boldsymbol{F}(I,J,N) = \boldsymbol{ACCELF} \times \boldsymbol{F}(I,J,N) + (1.-\boldsymbol{ACCELF}) \times \boldsymbol{F}(I,J,N-1)$; Defined for implicit axial flow solution; Default for ***ACCELF*** ≤ 0. is 0.7
F10	***ZH***	Heated axial length [in; mm]: Default for ***ZH*** ≤ 0. is ***Z***

SETRI 9.2 Additional calculation parameters:
NDX, ***NDT***, ***NTRIES***, ***ITRY***, ***ITRYM***: (5I10)

I10	***NDX***	Number of axial nodes
I10	***NDT***	Number of time steps: For implicit transients, the time step size is ***TTIME***/***NDT***; For explicit transients, the time step size is problem-dependent with ***NDT*** and ***TTIME*** being the limits on the total number of time steps and length of the transient
I10	***NTRIES***	Maximum number of external iterations allowed in implicit solution scheme, regardless of ***WERRX*** and ***FERROR***: Default for ***NTRIES*** ≤ 0 is 20
I10	***ITRY***	Maximum number of internal iterations allowed in implicit solution scheme, regardless of ***WERRY*** (Applicable only if ***N7*** = 0 or 2): Default for ***ITRY*** ≤ 0 is MAX(2×***NK***,20), where ***NK*** is the number of gaps
I10	***ITRYM***	Minimum number of iterations in the internal crossflow solution for implicit solution scheme, regardless of convergence (Applicable only if ***N7*** = 0): Default for ***ITRYM*** ≤ 0 is 5

SETRI 9.3 Calculation parameters for explicit solution scheme (**Not checked**):

		Optional (***N3*** > 0): ***FCOUR***, ***FDT***, ***XZERR***, ***YZERR***, ***THX***, ***THD***, ***ACCEL1***, ***ACCEL2***: (8F10)
F10	***FCOUR***	Courant time step limitation parameter: ***FCOUR*** = velocity×***DT***/***DX***, where ***DT*** is time step size; Default for ***FCOUR*** ≤ 0. or ***FCOUR*** > 1. is 0.2
F10	***FDT***	Maximum time step regardless of ***FCOUR*** [sec]: No default
F10	***XZERR***	Iterative flow field convergence limit for explicit solution scheme: Default for ***XZERR*** ≤ 0. is 0.001
F10	***YZERR***	Iterative energy field convergence limit for explicit solution scheme (**Not used**): Default for ***YZERR*** ≤ 0. is 0.0001
F10	***THX***	For ***THX*** = 1., the integrated liquid level is printed for each channel at each time step; For ***THX*** = 0., No liquid level printout
F10	***THD***	For ***THD*** = 1., optional interface sharpening parameter, equivalent to the downward liquid velocity
F10	***ACCEL1***	Acceleration factor for iterative current pressure change: Defined for explicit solution; Default for ***ACCEL1*** ≤ 0. is 1.
F10	***ACCEL2***	Acceleration factor for pressure change from last iteration (**Not used**): Defined for explicit solution; Default for ***ACCEL2*** ≤ 0. is 0.
SETRI 9.4		Additional calculation parameters for explicit solution scheme (**Not checked**): Optional (***N3*** > 0): ***NTRYX***, ***NTRYY***, ***KNOFLO***, ***JNOFLO***: (4I10)
I10	***NTRYX***	Maximum number of allowable iterations in the flow solution for explicit solution scheme, regardless of ***XZERR***: Default for ***NTRYX*** ≤ 0 is 100
I10	***NTRYY***	Maximum number of allowable iterations in the energy solution for explicit solution scheme, regardless of ***YZERR*** (**Not used**): Default for ***NTRYY*** ≤ 0 is 20
I10	***KNOFLO***	No crossflow permitted through gap identification number ***KNOFLO*** or less, at and above the axial node ***JNOFLO***

I10	***JNOFLO***	No crossflow permitted through gap identification number ***KNOFLO*** or less, at and above the axial node ***JNOFLO***
SETRI 9.5		Table of maximum time step size for explicit solution scheme (**Not checked**): Optional (***N3*** > 0 and ***N5*** > 1): ***YT***(*L*), ***FT***(*L*), *L* = 1 to ***N5***: (10F10)
F10	***YT***(*L*)	Time for maximum time step [sec]: Must include 0.
F10	***FT***(*L*)	Maximum time step size allowed at this time [sec]
SETRI 9.6		Table of variable axial node length: Optional (***N6*** > 1): ***NVDX***(*I*), ***VDX***(*I*), *I* = 1 to ***N6***: (5(I10, F10))
I10	***NVDX***(*I*)	Number of axial nodes in ***I***-th axial zone
F10	***VDX***(*I*)	Fractional axial node length (***DX***/***Z***) for ***I***-th axial zone
SETRI 9.7		Calculation parameters for power, rod radial peaking factor, or flow iteration: Optional (***N8*** > 0): ***LIMTYP***, ***ITMAX***, ***NRODAD***: (3I10)
I10	***LIMTYP***	Limits to be used in the iterative solution: For ***LIMTYP*** = 0, limits are on DNBR and coolant quality at the MDNBR location, and core average exit enthalpy may not exceed saturation; For ***LIMTYP*** = 1, limits are on DNBR and coolant quality at the MDNBR location
I10	***ITMAX***	Maximum number of iterations: Default for ***ITMAX*** ≤ 0 is 20
I10	***NRODAD***	Number of rods to be adjusted: Optional (***N8*** = 2)
SETRI 9.8		Calculation parameters for power, rod radial peaking factor, or flow iteration: Optional (***N8*** > 0): ***DDNBR***, ***DNBRCO***, ***DNBRTOL***, ***QUALMX***, ***QUALCO***, ***QUALTOL***, ***TOLQ***, ***TOLG***: (8F10)
F10	***DDNBR***	Desired MDNBR
F10	***DNBRCO***	DNBR adjustment coefficient: Default for ***DNBRCO*** = 0. is -0.4 if ***N8*** = 1 or 2 Default for ***DNBRCO*** = 0. is 0.3 if ***N8*** = 3
F10	***DNBRTOL***	DNBR tolerance: Default for ***DNBRTOL*** ≤ 0. is 0.005

F10	***QUALMX***	Maximum coolant quality at the MDNBR location
F10	***QUALCO***	Coolant quality adjustment coefficient: Default for ***QUALCO*** = 0. is 5.0 if ***N8*** = 1 or 2 Default for ***QUALCO*** = 0. is - 1.4 if ***N8*** = 3
F10	***QUALTOL***	Maximum local coolant quality tolerance: Default for ***QUALTOL*** ≤ 0. is 0.005
F10	***TOLQ***	Tolerance on adjustment of power or rod radial peaking factor: Default for ***TOLQ*** ≤ 0. is 0.0025
F10	***TOLG***	Tolerance on adjustment of flow: Default for ***TOLG*** ≤ 0. is 0.0025

SETRI 9.9

Identification numbers of the rods to be adjusted in ascending order:
Optional (***N8*** = 2):
IRODAD(*L*), *L* = 1 to ***NRODAD***: (10I10)

I10	***IRODAD***(*L*)	Identification numbers of the rods to be adjusted

Card Group 10 Lateral Transport Models

SETRI 10.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***, ***N8***, ***N9***: (10I10)
I10	***NGROUP***	Card group number: Must be 10
I10	***N1***	Single-phase turbulent mixing correlation: $(0 \le \boldsymbol{N1} \le 3)$: $\boldsymbol{N1} = 0$: $w' = \boldsymbol{ABETA} \times (G \times s)$ $\boldsymbol{N1} = 1$: $w' = \boldsymbol{ABETA} \times Re^{\boldsymbol{BBETA}} \times (G \times s)$ $\boldsymbol{N1} = 2$: $w' = \boldsymbol{ABETA} \times Re^{\boldsymbol{BBETA}} \times (G \times D)$ $\boldsymbol{N1} = 3$: $w' = \boldsymbol{ABETA} \times Re^{\boldsymbol{BBETA}} \times (G \times D) \times (s/z)$
I10	***N2***	Two-phase turbulent mixing correlation for equal mass exchange model (Applicable only if $\boldsymbol{N5} = 0$): $(0 \le \boldsymbol{N2} \le \boldsymbol{MP})$: $\boldsymbol{N2} = 0$ or 1: Assumed to be the same as single-phase $\boldsymbol{N2} > 1$: Turbulent mixing parameter is a function of quality or void fraction: Read in ***N2*** pairs of data for a table of two-phase turbulent mixing parameter vs. quality or void fraction * Requires Card SETRI 10.2
I10	***N3***	Radial thermal conduction mixing: $(0 \le \boldsymbol{N3} \le 1)$: $\boldsymbol{N3} = 0$: No thermal conduction $\boldsymbol{N3} = 1$: Read in geometry factor for radial thermal conduction mixing * Requires Card SETRI 10.3
I10	***N4***	Independent variable of two-phase turbulent mixing correlation for equal mass exchange model (Applicable only if $\boldsymbol{N5} = 0$ and $\boldsymbol{N2} > 1$): $(0 \le \boldsymbol{N4} \le 1)$: $\boldsymbol{N4} = 0$: Quality $\boldsymbol{N4} = 1$: Void fraction
I10	***N5***	Turbulent mixing model: $(0 \le \boldsymbol{N5} \le 1)$: $\boldsymbol{N5} = 0$: Equal mass exchange turbulent mixing model $\boldsymbol{N5} = 1$: Equal volume exchange turbulent mixing model
I10	***N6***	Void drift model (Applicable only if $\boldsymbol{N5} = 1$): $(0 \le \boldsymbol{N6} \le 1)$: $\boldsymbol{N6} = 0$: No void drift model $\boldsymbol{N6} = 1$: Read in void drift correction factor * Requires Card SETRI 10.4
I10	***N7***	Type of void drift correction factor (Applicable only if $\boldsymbol{N5} = 1$ and $\boldsymbol{N6} = 1$): $(0 \le \boldsymbol{N7} \le 3)$:

		N7 = 0: Independent of flow regime (KAERI) ***N7*** = 1: Independent of flow regime (MIT) ***N7*** = 2: Dependent on flow regime (KAERI) ***N7*** = 3: Dependent on flow regime and pressure (KAERI): (Recommended)
I10	***N8***	Two-phase turbulent mixing multiplier model: (0 ≤ ***N8*** ≤ 1): ***N8*** = 0: No model ***N8*** = 1: Beus model: (Recommended)
I10	***N9***	Debugging option for lateral exchange: (0 ≤ ***N9*** ≤ 1): ***N9*** = 0: No printout ***N9*** = 1: Print out the lateral exchange results for the key channels 1, 2, and 3
SETRI 10.1		Single-phase turbulent mixing correlation constants: ***ABETA***, ***BBETA***: (2F10)
F10	***ABETA***	Constant of the correlations specified in the ***N1*** option
F10	***BBETA***	Constant of the correlations specified in the ***N1*** option
SETRI 10.2		Table of two-phase turbulent mixing parameter vs. quality or void fraction for equal mass exchange model: Optional (***N5*** = 0 and ***N2*** > 1): ***XQUAL***(*L*), ***BX***(*L*), *L* = 1 to ***N2***: (10F10)
F10	***XQUAL***(*L*)	Quality (***N4*** = 0) or void fraction (***N4*** = 1)
F10	***BX***(*L*)	Two-phase turbulent mixing parameter
SETRI 10.3		Geometry factor for radial thermal conduction mixing: Optional (***N3*** = 1): ***GK***: (F10)
F10	***GK***	Geometry factor for radial thermal conduction mixing: Normally greater than 1.
SETRI 10.4		Void drift correction factor (***CVD***): Optional (***N5*** = 1 and ***N6*** = 1): ***CVDB***, ***CVDA***, ***CVDB1***, ***CVDB2***: (4F10)
F10	***CVDB***	Void drift correction factor for bubbly-slug flow regime: Required for ***N7*** = 0, 1, 2; If ***N7*** = 0, ***CVD*** is independent of flow regime (KAERI) (Recommended: ***CVDB*** = 3. at BWR pressure (about 1000 psia)); If ***N7*** = 1, ***CVD*** is independent of flow regime (MIT: Kelly et al.: THERMIT-2), ***CVD***(MIT) = ***CVD***(KAERI)

		×(average void fraction at gap) (Recommended: ***CVDB*** = 1.4 at BWR pressure (about 1000 psia)); If ***N7*** = 2, ***CVD*** is dependent on flow regime (KAERI) (Recommended: ***CVDB*** = 1.5 at BWR pressure (about 1000 psia) for bubbly-slug flow regime; At PWR pressure (about 2250 psia), ***CVDB*** = 0. is temporarily recommended); If ***N7*** = 3, ***CVD*** is dependent on flow regime and pressure (KAERI) (Recommended: ***CVDB*** = 0.; ***CVDB*** is re-calculated using ***CVDB1*** and ***CVDB2*** in the code)
F10	***CVDA***	Void drift correction factor for annular flow regime: Required for ***N7*** = 2, 3; If ***N7*** = 0, ***CVDA*** = ***CVDB*** (Default); If ***N7*** = 1, ***CVDA*** = ***CVDB*** (Default); If ***N7*** = 2, ***CVD*** is dependent on flow regime (KAERI) (Recommended: ***CVDA*** = 5. at BWR pressure (about 1000 psia) for annular flow regime; At PWR pressure (about 2250 psia), ***CVDA*** = 0. is temporarily recommended); If ***N7*** = 3, ***CVDA*** = 10. (Recommended)
F10	***CVDB1***	Void drift correction factor for bubbly-slug flow regime: Required for ***N7*** = 3 ***CVDB1*** = 0.72 (Recommended)
F10	***CVDB2***	Void drift correction factor for bubbly-slug flow regime: Required for ***N7*** = 3 ***CVDB2*** = 1.33 (Recommended)

Card Group 11 Operating Conditions and Transient Forcing Functions

SETRI 11.0

Group control card:
NGROUP, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***, ***N8***, ***N9***, ***N10***:
(11I10)

I10 ***NGROUP***

Card group number: Must be 11

I10 ***N1***

Option for specified inlet enthalpy or temperature:
(0 ≤ ***N1*** ≤ 3):
N1 = 0: Uniform inlet enthalpy ***HIN***
specified in SETRI 11.1
N1 = 1: Uniform inlet temperature ***HIN***
specified in SETRI 11.1
N1 = 2: Individual channel inlet enthalpy
* Requires Card SETRI 11.2
N1 = 3: Individual channel inlet temperature
* Requires Card SETRI 11.2

I10 ***N2***

Option for specified inlet mass velocity:
(0 ≤ ***N2*** ≤ 3):
N2 = 0: Uniform inlet mass velocity ***GIN***
specified in SETRI 11.1
N2 = 1: Average bundle mass velocity ***GIN***
specified in SETRI 11.1
but channel inlet flows split
for equal pressure gradient
across the 1st axial node
N2 = 2: Average bundle mass velocity ***GIN***
specified in SETRI 11.1
but channel inlet flows split
by individual channel inlet flow fraction
* Requires Card SETRI 11.3
N2 = 3: Average bundle mass velocity ***GIN***
specified in SETRI 11.1
but channel inlet flows split
by individual channel inlet mass velocity
fraction
* Requires Card SETRI 11.3

I10 ***N3***

Transient forcing function for system (exit) pressure:
(0 ≤ ***N3*** ≤ ***MP***):
N3 = 0 or 1: No
N3 > 1: Read in ***N3*** pairs of values
for a table of system pressure factor vs. time
* Requires Card SETRI 11.4

I10 ***N4***

Transient forcing function for inlet enthalpy
or temperature:
(-***MP*** ≤ ***N4*** ≤ ***MP***):
N4 = -1, 0, or 1: No
N4 > 1: Read in ***N4*** pairs of values
for a table of inlet enthalpy
or temperature factor vs. time
* Requires Card SETRI 11.5
N4 < -1: Read in ABS(***N4***) sets of values
for a table of inlet enthalpy
or temperature factors vs. time;

		For ABS(***N4***) transient times, read in inlet enthalpy or temperature factor at each channel * Requires Card SETRI 11.5a
I10	***N5***	Transient forcing function for inlet mass velocity or pressure drop: (0 ≤ ***N5*** ≤ ***MP***): ***N5*** = 0 or 1: No ***N5*** > 1: Read in ***N5*** pairs of values for a table of inlet mass velocity factor, pressure drop, or pressure drop factor vs. time * Requires Card SETRI 11.6
I10	***N6***	Transient forcing function for average heat flux: (0 ≤ ***N6*** ≤ ***MP***): ***N6*** = 0 or 1: No ***N6*** > 1: Read in ***N6*** pairs of values for a table of average heat flux factor vs. time * Requires Card SETRI 11.7
I10	***N7***	Option for pressure drop boundary condition transients (Applicable only if ***N3*** = 1 or 2 in SETRI 9.0, and ***N5*** > 1): (0 ≤ ***N7*** ≤ 1): ***N7*** = 0: Read in ***N5*** pairs of values for a table of pressure drop (psi) vs. time ***N7*** = 1: Read in ***N5*** pairs of values for a table of pressure drop factor vs. time
I10	***N8***	Transient forcing function for exit enthalpy: (0 ≤ ***N8*** ≤ ***MP***): ***N8*** = 0 or 1: No ***N8*** > 1: Read in ***N8*** pairs of values for a table of exit enthalpy factor vs. time * Requires Card SETRI 11.8
I10	***N9***	Transient forcing function for axial power distribution: (0 ≤ ***N9*** ≤ ***MP***): ***N9*** = 0 or 1: No ***N9*** > 1: Read in ***N9*** sets of values for a table of axial peaking factors vs. time; For ***N9*** transient times, read in axial peaking factor at each axial location corresponding to ***Y***(*L*) specified in SETRI 3.1 * Requires Card SETRI 11.9
I10	***N10***	Transient forcing function for radial power distribution: (0 ≤ ***N10*** ≤ ***MP***): ***N10*** = 0 or 1: No ***N10*** > 1: Read in ***N10*** sets of values for a table of radial peaking factors vs. time; For ***N10*** transient times, read in radial peaking factor at each rod corresponding to ***I*** specified in SETRI 8.1 * Requires Card SETRI 11.10

SETRI 11.1		Operating conditions: ***PEXIT***, ***HIN***, ***GIN***, ***AFLUX***, ***HOUT***, ***DPS***, ***QMOD***: (7F10)
F10	***PEXIT***	System reference (exit) pressure [psia; MPa]
F10	***HIN***	Inlet enthalpy or temperature depending on ***N1***: If ***HIN*** is negative, the inlet enthalpy will be either the absolute value of ***HIN*** or the last calculated 1st node enthalpy if the flow has reversed; If ***N1*** = 0 or 2, ***HIN*** is inlet enthalpy [Btu/lb_m; kJ/kg]; If ***N1*** = 1 or 3, ***HIN*** is inlet temperature [°F ; °C]
F10	***GIN***	Inlet mass velocity to be distributed by the ***N2*** option [Mlb_m/hr-ft^2; kg/sec-m^2]
F10	***AFLUX***	Average heat flux [MBtu/hr-ft^2; kW/m^2]
F10	***HOUT***	Exit enthalpy [Btu/lb_m; kJ/kg]: If ***HOUT*** is specified, and the flow reverses, the new exit enthalpy will be ***HOUT***; Otherwise, for ***HOUT*** blank, the new exit enthalpy will be the calculated exit enthalpy before reversal
F10	***DPS***	Pressure drop [psi; MPa]: Option to specify a pressure drop rather than a flow boundary condition in the steady-state implicit solution scheme; The code iterates on the total inlet flow rate until the calculated pressure drop is close to ***DPS***
F10	***QMOD***	Fraction of heat generated in the moderator
SETRI 11.2		Individual channel inlet enthalpy or temperature: Optional (***N1*** = 2 or 3): ***HINLET***(*I*), *I* = 1 to ***N2*** in SETRI 4.0: (10F10)
F10	***HINLET***(*I*)	Inlet enthalpy or temperature of each channel: If ***N1*** = 2, ***HINLET***(*I*) is inlet enthalpy [Btu/lb_m; kJ/kg] If ***N1*** = 3, ***HINLET***(*I*) is inlet temperature [°F ; °C]
SETRI 11.3		Individual channel inlet flow fraction or mass velocity fraction: Optional (***N2*** = 2 or 3): ***FINLET***(*I*), *I* = 1 to ***N2*** in SETRI 4.0: (10F10)
F10	***FINLET***(*I*)	Inlet flow fraction or mass velocity fraction of each channel: If ***N2*** = 2, ***FINLET***(*I*) is inlet flow fraction (Ratio of mass flow rate of each channel to that of total channels) If ***N2*** = 3, ***FINLET***(*I*) is inlet mass velocity fraction
SETRI 11.4		Transient forcing function for system (exit) pressure: Optional (***N3*** > 1): ***YP***(*L*), ***FP***(*L*), *L* = 1 to ***N3***: (10F10)

F10	***YP***(*L*)	Transient time [sec]: Must include 0.
F10	***FP***(*L*)	Fraction of steady-state system (exit) pressure
SETRI 11.5		Transient forcing function for inlet enthalpy or temperature (global): Optional (***N4*** > 1): ***YH***(*L*), ***FH***(*L*), *L* = 1 to ***N4***: (10F10)
F10	***YH***(*L*)	Transient time [sec]: Must include 0.
F10	***FH***(*L*)	Fraction of steady-state inlet enthalpy (***N1*** = 0 or 2) or temperature (***N1*** = 1 or 3)
SETRI 11.5a		Transient forcing function for inlet enthalpy or temperature (local): Optional (***N4*** < -1): ***YH***(*L*), (***FHC***(*I*,*L*), *I* = 1 to ***N2*** in SETRI 4.0), *L* = 1 to ABS(***N4***): (F10/10F10)
F10	***YH***(*L*)	Transient time [sec]: Must include 0.
F10	***FHC***(*I*,*L*)	Fraction of steady-state inlet enthalpy (***N1*** = 0 or 2) or temperature (***N1*** = 1 or 3) at each channel
SETRI 11.6		Transient forcing function for inlet mass velocity or pressure drop: Optional (***N5*** > 1): ***YG***(*L*), ***FG***(*L*), *L* = 1 to ***N5***: (10F10)
F10	***YG***(*L*)	Transient time [sec]: Must include 0.
F10	***FG***(*L*)	Fraction of steady-state inlet mass velocity (***N3*** = 0, 3, or 4 in SETRI 9.0); Pressure drop (psi) ((***N3*** = 1 or 2 in SETRI 9.0) and ***N7*** = 0); Fraction of steady-state pressure drop ((***N3*** = 1 or 2 in SETRI 9.0) and ***N7*** = 1)
SETRI 11.7		Transient forcing function for average heat flux: Optional (***N6*** > 1): ***YQ***(*L*), ***FQ***(*L*), *L* = 1 to ***N6***: (10F10)
F10	***YQ***(*L*)	Transient time [sec]: Must include 0.
F10	***FQ***(*L*)	Fraction of steady-state average heat flux
SETRI 11.8		Transient forcing function for exit enthalpy: Optional (***N8*** > 1):

		YHX(*L*), ***FHX***(*L*), *L* = 1 to ***N8***: (10F10)
F10	***YHX***(*L*)	Transient time [sec]: Must include 0.
F10	***FHX***(*L*)	Fraction of steady-state exit enthalpy, ***HOUT*** in SETRI 11.1
SETRI 11.9		Transient forcing function for axial power distribution: Optional (***N9*** > 1): ***YQX***(*L*), (***FQX***(*I*,*L*), *I* = 1 to ***N1*** in SETRI 3.0), *L* = 1 to ***N9***: (F10/10F10)
F10	***YQX***(*L*)	Transient time [sec]: Must include 0.
F10	***FQX***(*I*,*L*)	Axial peaking factor at each axial location corresponding to ***Y***(*L*) specified in SETRI 3.1
SETRI 11.10		Transient forcing function for radial power distribution: Optional (***N10*** > 1): ***YQR***(*L*), (***FQR***(*I*,*L*), *I* = 1 to ***N1*** in SETRI 8.0), *L* = 1 to ***N10***: (F10/10F10)
F10	***YQR***(*L*)	Transient time [sec]: Must include 0.
F10	***FQR***(*I*,*L*)	Radial peaking factor at each rod corresponding to ***I*** specified in SETRI 8.1

Card Group 12 Output Display Options

SETRI 12.0		Group control card: ***NGROUP***, ***N1***, ***N2***, ***N3***, ***N4***, ***N5***, ***N6***, ***N7***, ***N8***: (9I10)
I10	***NGROUP***	Card group number: Must be 12
I10	***N1***	Output print option: (0 ≤ ***N1*** ≤ 3): ***N1*** = 0: Print channel results only ***N1*** = 1: Print channel and gap crossflow results only ***N1*** = 2: Print channel and rod results only ***N1*** = 3: Print channel, gap crossflow, and rod results
I10	***N2***	Output print option for channel results: (0 ≤ ***N2*** ≤ ***MC***): ***N2*** = 0: Print all channel results ***N2*** > 0: Read in ***N2*** channel identification numbers of channels to be printed * Requires Card SETRI 12.1
I10	***N3***	Output print option for rod results: If ***N5*** > 0 in SETRI 8.0, CHF data are also printed along with the rod results; (0 ≤ ***N3*** ≤ ***MR***): ***N3*** = 0: Print all rod results ***N3*** > 0: Read in ***N3*** rod identification numbers of rods to be printed * Requires Card SETRI 12.2
I10	***N4***	Output print option for fuel (pellet) node temperatures for all rods specified by ***N3*** (Applicable only if ***N3*** > 1 in SETRI 8.0): (2 ≤ ***N4*** ≤ 7): ***N4*** = 2: Print rod centerline and surface temperatures along with cladding surface and fluid temperatures (If ***N4*** ≤ 2, then ***N4*** = 2: reset) ***N4*** > 2: Print ***N4*** equally spaced interior rod temperatures (including rod centerline and surface temperatures) along with cladding surface and fluid temperatures
I10	***N5***	Output print option for gap crossflow results: (0 ≤ ***N5*** ≤ ***MG***): ***N5*** = 0: Print all gap crossflows ***N5*** > 0: Read in ***N5*** gap identification numbers of gaps to be printed * Requires Card SETRI 12.3
I10	***N6***	Output plotting option for transients: (***N6*** ≥ 0): ***N6*** = 0: No ***N6*** > 0: Plot every ***N6*** time steps: Read in 4 sets of maximum and minimum coordinates

		for the 4 variables plotted * Requires Card SETRI 12.6
I10	***N7***	Output plotting option for channel transients (Applicable only if ***N6*** > 0): (0 ≤ ***N7*** ≤ ***MC***): ***N7*** = 0: Plot all channel results ***N7*** > 0: Read in ***N7*** channel identification numbers of channels to be plotted * Requires Card SETRI 12.4
I10	***N8***	Output plotting option for gap crossflow transients (Applicable only if ***N6*** > 0): (0 ≤ ***N8*** ≤ ***MG***): ***N8*** = 0: Plot all gap crossflows ***N8*** > 0: Read in ***N8*** gap identification numbers of gaps to be plotted * Requires Card SETRI 12.5
SETRI 12.1		Identification numbers of channels to be printed: Optional (***N2*** > 0): ***PRINTC***(*L*), *L* = 1 to ***N2***: (10I10)
I10	***PRINTC***(*L*)	Identification numbers of channels for which results to be printed
SETRI 12.2		Identification numbers of rods to be printed: Optional (***N3*** > 0): ***PRINTR***(*L*), *L* = 1 to ***N3***: (10I10)
I10	***PRINTR***(*L*)	Identification numbers of rods for which results to be printed
SETRI 12.3		Identification numbers of gaps to be printed: Optional (***N5*** > 0): ***PRINTG***(*L*), *L* = 1 to ***N5***: (10I10)
I10	***PRINTG***(*L*)	Identification numbers of gaps for which results to be printed
SETRI 12.4		Identification numbers of channels to be plotted: Optional (***N7*** > 0): ***IPLTCH***(*L*), *L* = 1 to ***N7***: (10I10)
I10	***IPLTCH***(*L*)	Identification numbers of channels for which results to be plotted
SETRI 12.5		Identification numbers of gaps to be plotted: Optional (***N8*** > 0): ***IPLTGP***(*L*), *L* = 1 to ***N8***: (10I10)
I10	***IPLTGP***(*L*)	Identification numbers of gaps for which results to be plotted
SETRI 12.6		Maximum and minimum coordinates for the 4 variables plotted:

Optional (***N6*** > 0);
Mass velocity, enthalpy, and pressure drop are plotted for each channel specified,
and crossflow is plotted for each gap specified;
If ***HIP***(*I*) = 0., that quantity is not plotted:
HIP(*I*), ***ZPT***(*I*), *I* = 1 to 4: (8F10)

F10	***HIP***(*I*)	Maximum coordinates for the 4 variables plotted: ***HIP***(1): Mass velocity [Mlb$_m$/hr-ft^2; kg/sec-m^2] ***HIP***(2): Enthalpy [kBtu/lb$_m$; kJ/kg] ***HIP***(3): Pressure drop [psi; MPa] ***HIP***(4): Crossflow [lb$_m$/sec-ft; kg/sec-m]
F10	***ZPT***(*I*)	Minimum coordinates for the 4 variables plotted: ***ZPT***(1): Mass velocity [Mlb$_m$/hr-ft^2; kg/sec-m^2] ***ZPT***(2): Enthalpy [kBtu/lb$_m$; kJ/kg] ***ZPT***(3): Pressure drop [psi; MPa] ***ZPT***(4): Crossflow [lb$_m$/sec-ft; kg/sec-m]

부록-2. 물성치 관련 MATRA 코드 수정 내용

Each modifications can be found by comment '!v1.03' in source FORTRAN files.

APROP.F was added for interface of selecting the proper property function.

```
[APROP.F]

      FUNCTION APROP (I1,P1,P2)

      INCLUDE 'spec/spec35'

      SELECT CASE (J9)
      CASE (1)
         ! J9=1, TAF
         APROP = TAF(I1, P1, P2)
      CASE (2)
         ! J9=2, NIST Steam Database
         APROP = PROPSTM(I1, P1, P2)
      CASE (3)
         ! J9=2, IF97 Steam Table by Kim Soo Hyung (KAERI)
         ! TAF = TAF_IF97(I1, P1, P2)
      CASE (4)
         ! J9=4, NIST RefProp v.7, Refrigerant Properties.
         APROP = PROPREF(I1, P1, P2)
      CASE (5)
         ! J9=5, Helium for Ideal Gas
         APROP = PROPHE(I1, P1, P2)
      END SELECT

      RETURN
      END
```

These three function files were added for property calculation;

[PROPSTM.F] NIST ASME Steam Database for Water and Steam's Properties
[PROPREF.F] NIST RefProp for Refrigerant's Properties
[PROPHE.F] Ideal Gas Function for He Properties

[PSA.F] and [TSA.F] were modified to consider new coolants and supercritical conditions.

```
[PSA.F] & [TSA.F]

      INCLUDE 'spec/spec35'

      SELECT CASE (J9)
      CASE (2)
          …
      CASE (3)
          …
      CASE (4)
          …

      CASE (5)
          …
      END SELECT
```

J9 option was extended to 5 and all related codes were modified as follows:

```
All [SELECT CASE (J9)]

        SELECT CASE (J9)
        CASE (0)
        CASE (1:)  <--- (1)
        END SELECT
```

Supercritical features were considered and implemented in [PROP.F].
And then [VOID.F], [RESULT.F] and [SETRI.F] were modified to consider supercritical feature.

```
[PROP.F]
      SELECT CASE (IPART)   ! Case for calculation of properties
      CASE (1)   ! Calculates saturated fluid properties
         SELECT CASE (J9)   ! Method for calculation of fluid properties
         CASE (1:)          ! Direct calculation of saturated fluid properties
                            ! from Function TAF
            ...
            IF (ISINGLE .EQ. 1) THEN   ! Always single phase
               HFG = 1.D+10
               TF  = 1.D+10
               HF  = 1.D+10
               HG  = 1.D+10 + 1.D0
               HFG = 1.D+10
            ENDIF
            ...
         END SELECT
         ...
      CASE (2)   ! Calculates subcooled or superheated fluid properties
!                  and calculates miscellaneous parameters
         SELECT CASE (J9)   ! Method for calculation of fluid properties
         CASE (1:)          ! Direct calculation of saturated fluid properties
                            ! from Function TAF
            ...
            DO JP=1,NDXP1
               DO I=1,NCHANL
                  ...
                     IF (ISINGLE .EQ. 0) THEN
                        TFL(I,J) =TFLS(I,J)*1.8D0+32.D0
                        HFL(I,J) =APROP(102,PLS(I,J),TFLS(I,J))*CFH
                        HGL(I,J) =APROP(-102,PLS(I,J),TFLS(I,J))*CFH
                        HFGL(I,J)=HGL(I,J)-HFL(I,J)
                     ELSE
                        TFL(I,J)  = 1.D10
                        HFL(I,J)  = 1.D10
                        HGL(I,J)  = 1.D10 + 1.D0
                        HFGL(I,J) = 1.D10
                     ENDIF
               END DO
            END DO
         END SELECT
      END SELECT
```

```
[VOID.F]

       DO I=1,NCHANL
          ...
          IF (J3.NE.0) THEN   ! No homogeneous model for bulk void fraction
             ...
             IF (HFGL(I,J) .LE. 0.99D10) THEN
```

```
                QUAL(I)=DMIN1(DMAX1(QUAL(I),0.D0),1.D0)
             ELSE
                QUAL(I)=0.D0
             ENDIF
             …
          ENDIF
          …
          QUAL(I)=(HU-HFL(I,J))/HFGL(I,J)
          IF (HFGL(I,J) .LE. 0.99D10) THEN
             QUAL(I)=DMIN1(DMAX1(QUAL(I),0.D0),1.D0)
          ELSE
             QUAL(I)=0.D0
          ENDIF
          …
       END DO
```

```
[RESULT.F]

!---- Channel exit summary
               IF (HFGL(I,NDXP1) .GT. 0.99D10) THEN
                  OUTPUT(2)=0.D0
               ELSE
                  OUTPUT(2)=(H(I,NDXP1)-HFL(I,NDXP1))/HFGL(I,NDXP1)
                                                                ! [Dimensionless]
               ENDIF
               …
!---- Bundle averaged results
               IF (HFGAVG .LT. 0.99D10) THEN
                  OUTPUT(6)=(OUTPUT(3)-HFAVG)/HFGAVG   ! [Dimensionless]
               ELSE
                  OUTPUT(6)=0.D0
               ENDIF
               …
!---- Channel results (no roll option)
                  IF(HFGL(I,J) .GT. 0.99D10) THEN
                     OUTPUT(6)=0.D0
                  ELSE
                     OUTPUT(6)=(H(I,J)-HFL(I,J))/HFGL(I,J)   ! [Dimensionless]
                  ENDIF
               …
```

```
[SETRI.F]
      ! SETRI 11.3
      …
      IF (HFG.GT.0.99D10) THEN
         XIN=0.D0
      ELSE
         XIN=(HIN-HF)/HFG
      ENDIF
      …
```

[READBUF.F] was added and [LOAD.F] and [SETRI.F] were modified to read input and process input comments.

[MATRA.F] was modified to enhance the user interface.

This is the screen message of normal MATRA program execution.

```
E:\MATRA.X\Run>matra
```

```
MATRA.X v1.03 (2005.08.03)

 INPUT (w/o extension) : winfrith.freon      ← user input
 INPUT  FILE : winfrith.freon.inp
 OUTPUT FILE : winfrith.freon.out

E:\MATRA.X\Run>
```

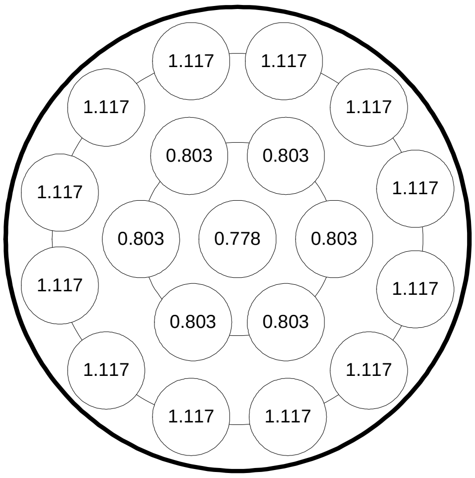
Console batch job is now supported by program argument :

```
E:\MATRA.X\Run>matra CASE-1
E:\MATRA.X\Run>matra CASE-2
      …
```

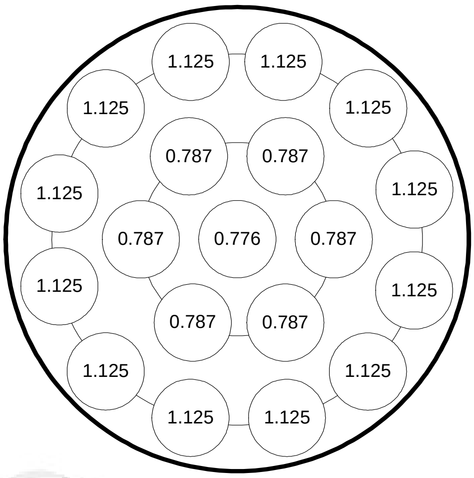
MATRA program will stop without abnormal error message if user enter wrong input file name :

```
E:\MATRA.X\Run>matra fff

MATRA.X v1.03 (2005.08.03)

 INPUT  FILE : fff.inp
 OUTPUT FILE : fff.out
 *ERROR* CANNOT OPEN INPUT fff.inp
```

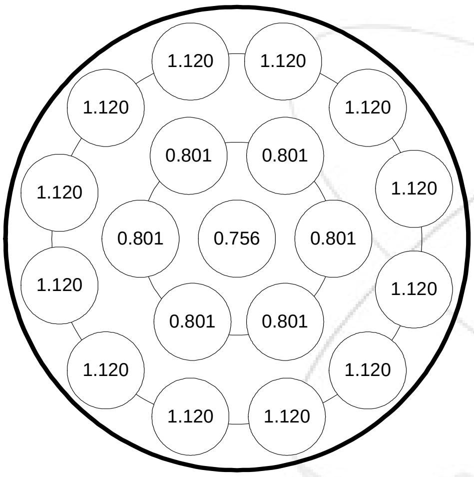
부록-3. 비정방형 CHF 시험 집합체 기하 형태 및 봉별 출력 분포



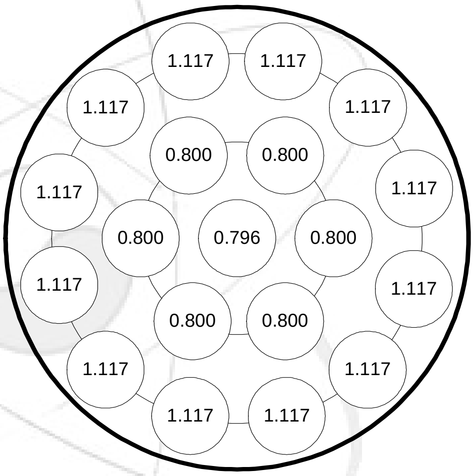
TS-601 (grid)



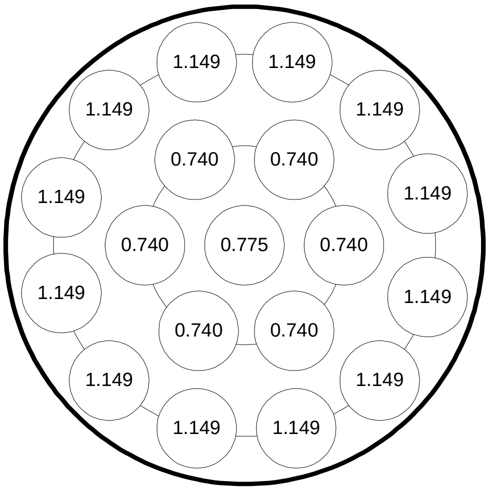
TS-602 (grid)



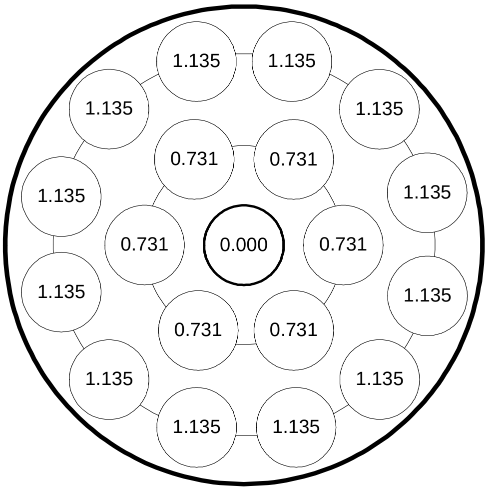
TS-603 (grid)



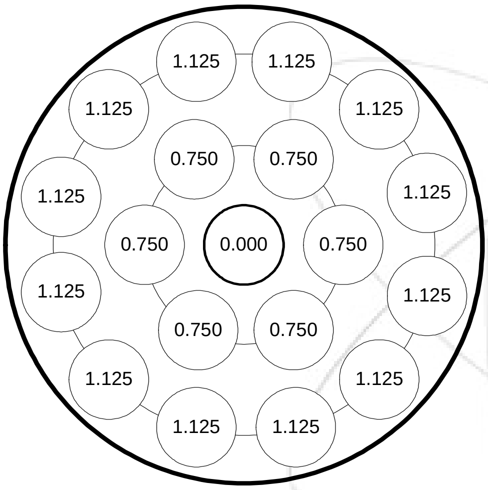
TS-604 (grid)



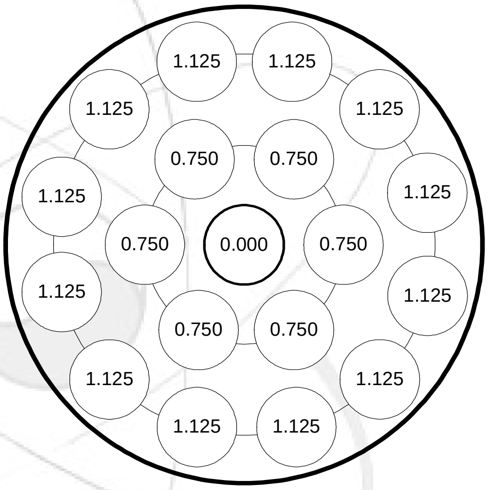
TS-605 (grid)



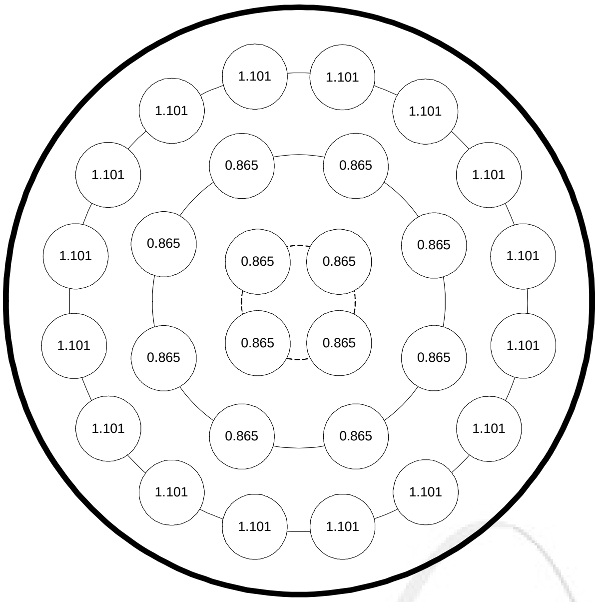
TS-606 (grid)



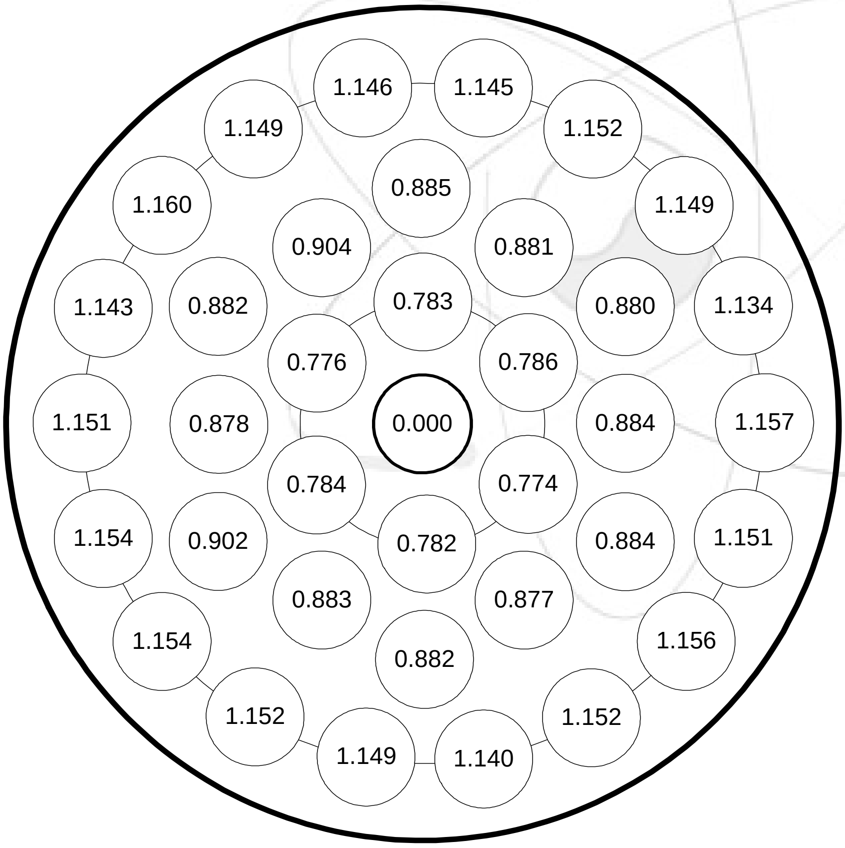
TS-607 (grid)



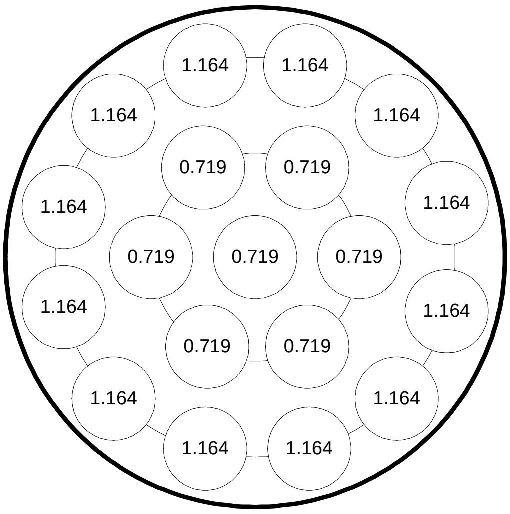
TS-609 (grid)



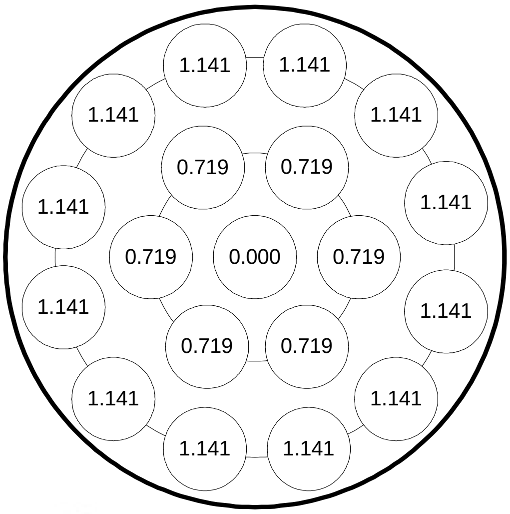
TS-610 (grid)



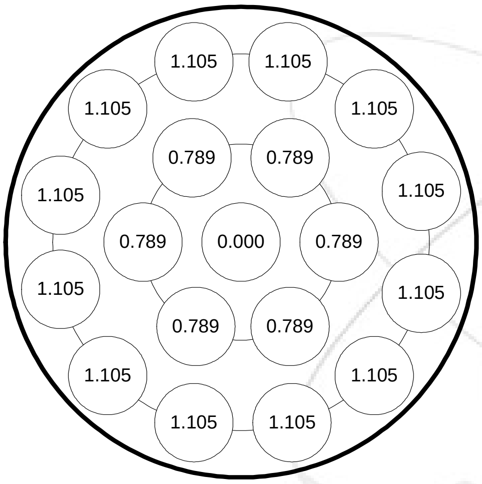
TS-613 (grid)



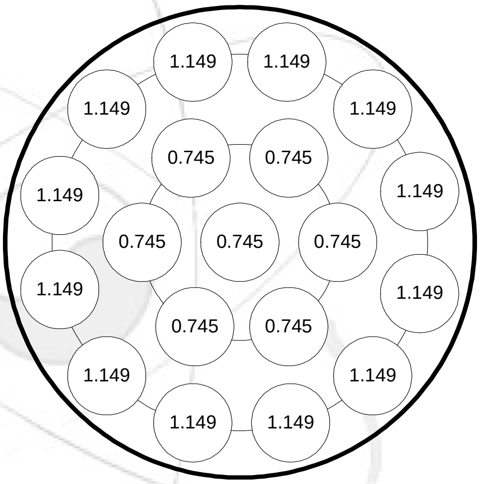
TS-801 (wire-wrap)



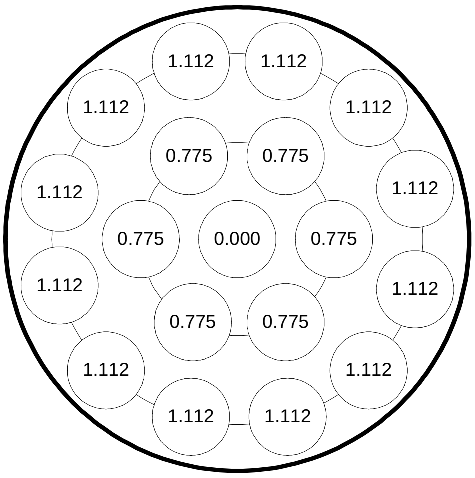
TS-802 (grid)



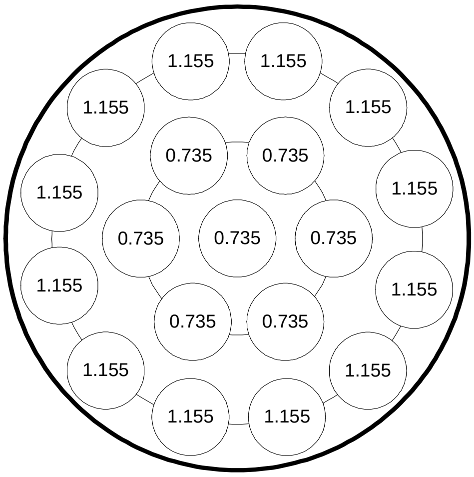
TS-805 (grid)



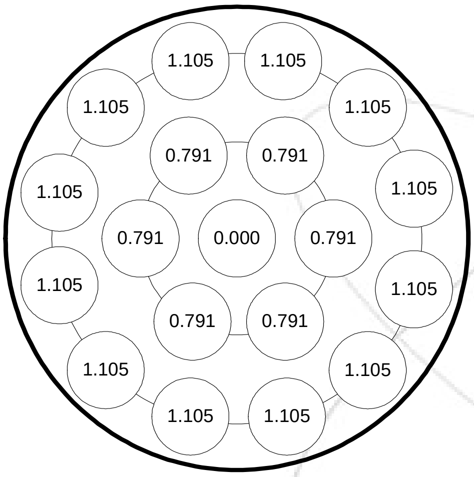
TS-806 (wire-wrap)



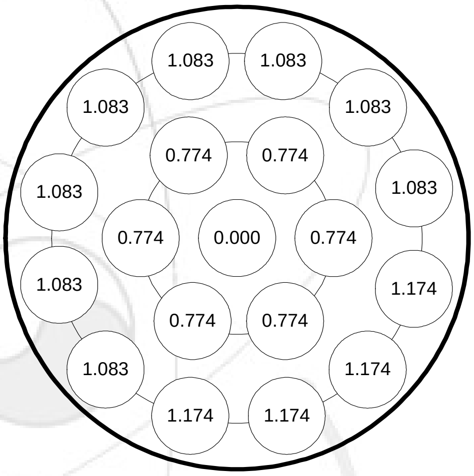
TS-807 (grid)



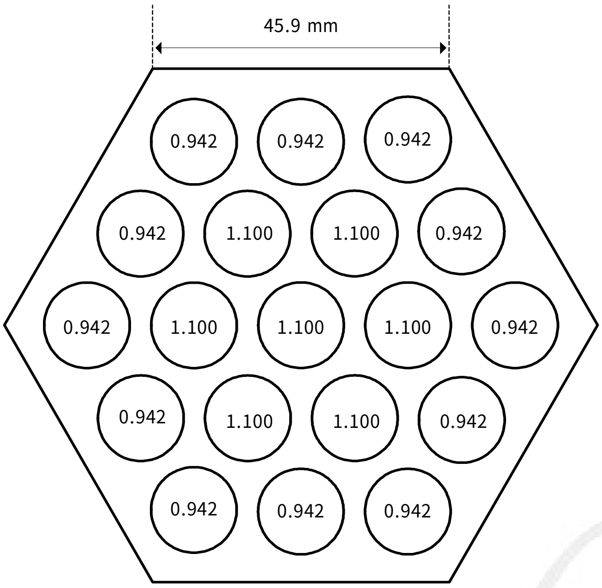
TS-808 (wire-wrap)



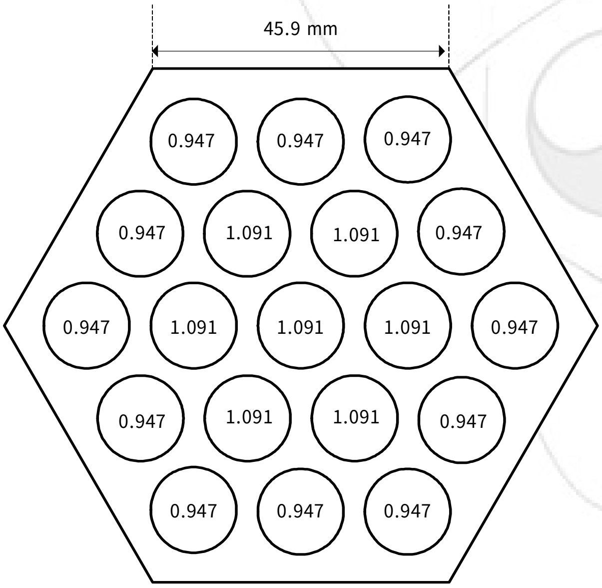
TS-809 (grid)



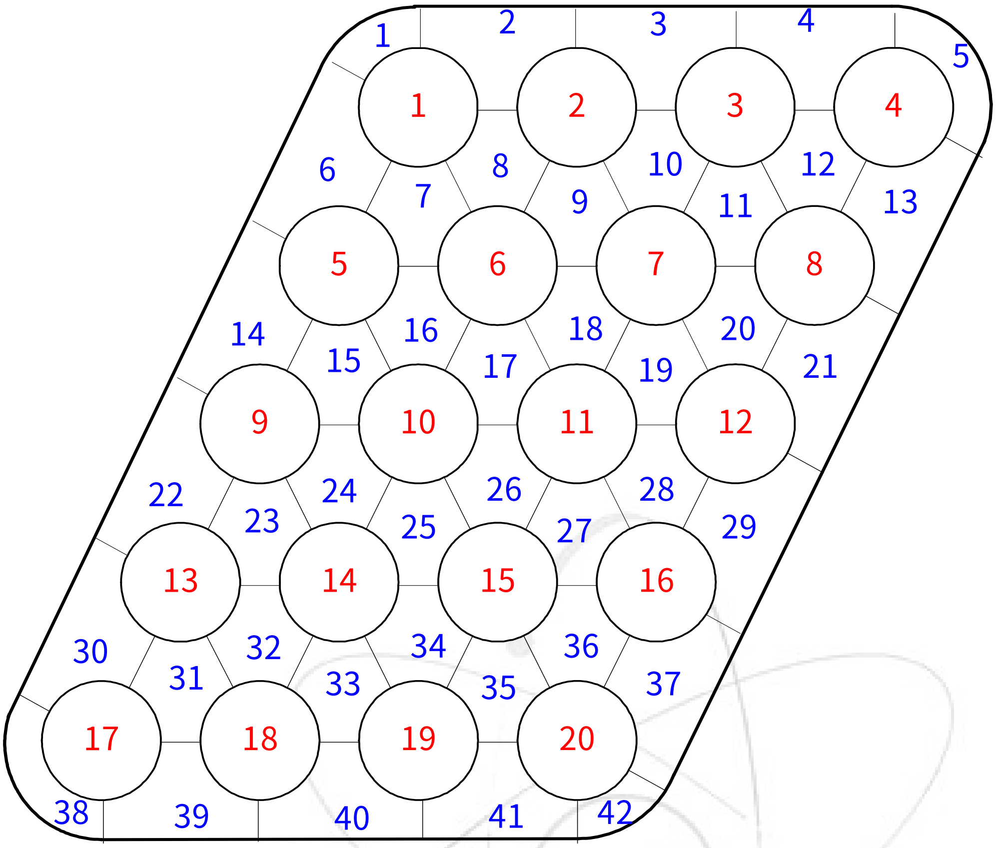
TS-810 (grid)



TS 103 (wire-wrap)



TS 104 (grid)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부록-4. 비정방형 CHF 시험집합체 부수로 해석을 위한 기본 자료

(가) 자료 설명

```
- Card 01.00 : Required --------------------------------------------------
   KEY,ITS : (A10,A10)
   KEY = 'ITS       '
   ITS = Test section identification

- Card 02.00 : Required --------------------------------------------------
   KEY,BRL,BRLH : (A10,A10,A10)
   KEY = 'BRL       '
   BRL = Barrel type
         : BRL='Hexagonal ' : Hexagonal barrel
         : BRL='Circular  ' : Circular barrel
         : BRL='Parallel  ' : Parallelogrammatic barrel
   BRLH = Barrel heating
          : BRLH='Heated    ' : Heated barrel wall
          : BRLH='Unheated  ' : Unheated barrel wall

- Card 03.00 : Required --------------------------------------------------
   KEY,LTC : (A10,A10)
   KEY = 'LTC       '
   LTC = Lattice type
         : LTC='Triangular' : Triangular lattice
         : LTC='Mixed1    ' : Mixed1 lattice
         : LTC='Mixed2    ' : Mixed2 lattice
         : LTC='Mixed3    ' : Mixed3 lattice
         : LTC='Mixed4    ' : Mixed4 lattice

- Card 04.00 : Required --------------------------------------------------
   KEY,UNT : (A10,A10)
   KEY = 'UNT       '
   UNT = Unit system
         : UNT='British   ' : British unit system
         : UNT='SI        ' : SI unit system

- Card 05.00 : Required --------------------------------------------------
   KEY : (A10)
   KEY = 'GMT       '
         : Geometrical input
- Card 05.01 : Required --------------------------------------------------
   KEY,NRT : (10X,A10,I10)
   KEY = 'NRT       '
   NRT = Total number of rods
- Card 05.02 : Required --------------------------------------------------
   KEY,NRH : (10X,A10,I10)
   KEY = 'NRH       '
   NRH = Number of heated rods
- Card 05.03 : Required --------------------------------------------------
   KEY,PRP : (10X,A10,F10)
   KEY = 'PRP       '
   PRP = Rod pitch (primary) [in ; mm]
- Card 05.04 : Required --------------------------------------------------
   KEY,DRH : (10X,A10,F10)
   KEY = 'DRH       '
   DRH = Heated rod diameter [in ; mm]
- Card 05.05 : Required --------------------------------------------------
   KEY,DRU : (10X,A10,F10)
   KEY = 'DRU       '
   DRU = Unheated rod diameter [in ; mm]
- Card 05.06 : Required --------------------------------------------------
   KEY,SRW : (10X,A10,F10)
   KEY = 'SRW       '
   SRW = Rod-to-wall gap [in ; mm]
- Card 05.07 : Required --------------------------------------------------
   KEY,ZHT : (10X,A10,F10)
   KEY = 'ZHT       '
   ZHT = Heated length [in ; mm]
- Card 05.08 : Required --------------------------------------------------
   KEY,AFT : (10X,A10,F10)
   KEY = 'AFT       '
```

```
   AFT = Total flow area [in2 ; mm2]
- Card 05.09 : Required --------------------------------------------------
   KEY,RCC : (10X,A10,F10)
   KEY = 'RCC       '
   RCC = Corner radius or corner secant [in ; mm]
         : RCC>0. : Corner radius
         : RCC<0. : Corner secant (Except for parallelogrammatic barrel)
         : RCC=0. : Neither corner radius nor corner secant
- Card 05.10 : Optional --------------------------------------------------
   * Required for circular barrel only
   KEY,DTF : (10X,A10,F10)
   KEY = 'DTF       '
   DTF = Flow tube diameter [in ; mm]
- Card 05.11 : Optional --------------------------------------------------
   * Required for parallelogrammatic barrel & triangular lattice only
   KEY,NRR,NCR : (10X,A10,I10,I10)
   KEY = 'NRC       '
   NRR = Number of rod rows
   NCR = Number of rod columns
- Card 05.12 : Required --------------------------------------------------
   KEY : (10X,A10)
   KEY = 'EOD       '
         : End of data

- Card 06.00 : Required --------------------------------------------------
   KEY,APS : (A10,A10)
   KEY = 'APS       '
   APS = Axial power shape
         : APS='Uniform    ' : Uniform
         : APS='Nonuniform' : Nonuniform

- Card 07.00 : Required --------------------------------------------------
   KEY,NAP : (A10,I10)
   KEY = 'NAP       '
   NAP = Number of axial power distribution points
         : NAP=0 : Uniform
         : NAP>0 : Nonuniform : Requires Card 08.01

- Card 08.00 : Required --------------------------------------------------
   KEY : (A10)
   KEY = 'APF       '
         : Axial power factors

- Card 08.01 : Optional --------------------------------------------------
   * Required for NAP>0
   (YAP(J),APF(J)),J=1,NAP : (10X,F10,F10) : NAP cards
   YAP(J) = Relative axial locations at which axial power factors are given
*            : Must include 0. and 1. as end points
   APF(J) = Axial power factors
   NAP : Number of axial power distribution points (Card 07.00)

- Card 09.00 : Required --------------------------------------------------
   KEY,NTC : (A10,I10)
   KEY = 'NTC       '
   NTC = Number of axial locations for thermocouples

- Card 10.00 : Required --------------------------------------------------
   KEY,(ZTC(J),J=1,NTC) : (A10,12F10)
   KEY = 'ZTC       '
   ZTC(J) = Axial locations for thermocouples [in ; mm]
   NTC : Number of axial locations for thermocouples (Card 09.00)

- Card 11.00 : Required --------------------------------------------------
   KEY,NZG : (A10,I10)
   KEY = 'NZG       '
   NZG = Number of axial locations for grid spacers
         : NZG=0 : No grid spacers
         : NZG>0 : Requires Card 14.01

- Card 12.00 : Required --------------------------------------------------
   KEY,NKG : (A10,I10)
   KEY = 'NKG       '
   NKG = Number of grid spacer types

- Card 13.00 : Required --------------------------------------------------
   KEY,(CKG(L),L=1,NKG) : (A10,12F10)
```

KEY = 'CKG   '
CKG(L) = Loss coefficients for grid spacer types
NKG : Number of grid spacer types (Card 12.00)

- Card 14.00 : Required --
KEY : (A10)
KEY = 'ZGS   '
: Axial locations for grid spacers

- Card 14.01 : Optional --
* Required for NZG>0
(IKG(J),ZGS(J)),J=1,NZG : (10X,I10,F10) : NZG cards
IKG(J) = Grid spacer type identification numbers
ZGS(J) = Axial locations for grid spacers [in ; mm]
NZG : Number of axial locations for grid spacers (Card 11.00)

- Card 15.00 : Required --
KEY,NWW,THWW,RDWW : (A10,I10,F10,A10)
KEY = 'NWW   '
NWW = Number of wire wraps for one rod
THWW = Wire wrap starting angle [degrees]
increasing in a counterclockwise-rotation direction
* : Should be greater than or equal to 0. and less than 360.
: THWW= 0. : Right
* : THWW= 90. : Top (default)
: THWW=180. : Left
: THWW=270. : Bottom
RDWW = Wire wrap rotation direction
: RDWW='Clockwise ' : Clockwise rotation
* : RDWW='Counterclo' : Counterclockwise rotation (default)

- Card 16.00 : Required --
KEY,PWW : (A10,F10)
KEY = 'PWW   '
PWW = Wire wrap pitch [in ; mm]

- Card 17.00 : Required --
KEY,DWW : (A10,F10)
KEY = 'DWW   '
DWW = Wire wrap diameter [in ; mm]

- Card 18.00 : Required --
KEY : (A10)
KEY = 'RNS   '
: Rod numbering scheme

- Card 18.01 : Required --
(IR(L,M),M=1,NRS-1+L),L=1,NRS : (*I*) : NRS cards
(IR(L,M),M=1,3*NRS-1-L),L=NRS+1,2*NRS-1 : (*I*) : NRS-1 cards
* For hexagonal barrel
(LR,DRING(LR),PRRING(LR),(IRRING(LR,MR),MR=1,NRRING(LR))),
L=1,NRINGR : (I*,2F*,*I*) : NRINGR cards
* For circular barrel
(IR(L,M),M=1,NCR),L=1,NRR : (*I*) : NRR cards
* For parallelogrammatic barrel
IR(L,M) = Rod identification numbers
NRS : Number of rods along a side of a square or a hexagon
LR = Ring identification number
DRING(LR) = Ring Diameter [in ; mm]
PRRING(LR) = Rod pitch for the ring numbered as LR [in ; mm]
IRRING(LR,MR) = Rod identification numbers
NRRING(LR) : Number of rods for the ring numbered as LR
NRINGR : Total number of rings for rods including center rod
NRR : Number of rod rows
NCR : Number of rod columns

For hexagonal barrel :
NRS=(1+SQRT(1+4/3*(NRT-1)))/2
* The small unheated rod (occupying 1-heated-rod space) should be represented by a positive integer (not zero).
For circular barrel :
* The small unheated rod (occupying 1-heated-rod space)
should be represented by a positive integer (not zero).
For parallelogrammatic barrel :
* The small unheated rod (occupying 1-heated-rod space)
should be represented by a positive integer (not zero).

- Card 19.00 : Required --
KEY : (A10)
KEY = 'RPF '
: Radial power factors

- Card 19.01 : Required --
(RPF(IR(L,M)),M=1,NRS-1+L),L=1,NRS : (*F*) : NRS cards
(RPF(IR(L,M)),M=1,3*NRS-1-L),L=NRS+1,2*NRS-1 : (*F*) : NRS-1 cards
* For hexagonal barrel
(RPF(IRRING(LR,MR)),MR=1,NRRING(LR)),LR=1,NRINGR : (*F*) : NRINGR cards
* For circular barrel
(RPF(IR(L,M)),M=1,NCR),L=1,NRR : (*F*) : NRR cards
* For parallelogrammatic barrel
RPF(IR(L,M)) = Radial power factors
IR(L,M) : Rod identification numbers (Card 18.01)
NRS : Number of rods along a side of a square or a hexagon (Card 18.01)
RPF(IRRING(LR,MR)) = Radial power factors
IRRING(LR,MR) : Rod identification numbers (Card 18.01)
NRRING(LR) : Number of rods for the ring numbered as LR (Card 18.01)
NRINGR : Total number of rings for rods including center rod (Card 18.01)
NRR : Number of rod rows (Card 18.01)
NCR : Number of rod columns (Card 18.01)

For hexagonal barrel :
* RPF for the small unheated rod (occupying 1-heated-rod space)
should be represented by zero.
For circular barrel :
* RPF for the small unheated rod (occupying 1-heated-rod space)
should be represented by zero.
For parallelogrammatic barrel :
* RPF for the small unheated rod (occupying 1-heated-rod space)
should be represented by zero.

- Card 20.00 : Required --
KEY,TMP : (A10,F10)
KEY = 'TMP '
TMP = Turbulent mixing parameter

- Card 21.00 : Required --
KEY,IRCHF : (A10,I10)
KEY = 'IRC '
IRCHF = Identification number of the rod where CHF occurred

- Card 22.00 : Required --
KEY,ICCHF : (A10,I10)
KEY = 'ICC '
ICCHF = Identification number of the channel where CHF occurred

- Card 23.00 : Required --
KEY : (A10)
KEY = 'EOD '
: End of data

- Card 24.00 : Required --
ITS,NOC : (A10,10X,I10)
ITS = Test section identification
* : Must be the same as ITS in Card 01.00
NOC = Total number of operating conditions

- Card 25.00 : Required --
* 2 dummy cards should be given for legends of data.

- Card 26.00 : Required --
(ISN(I),IRN(I),PE(I),TI(I),GI(I),QA(I)),I=1,NOC : (2I*,4F*) : NOC cards
ISN(I) = Serial Number
IRN(I) = Run Number
PE (I) = System pressure [psi ; bar]
TI (I) = Inlet temperature [F ; C]
GI (I) = Inlet mass velocity [Mlbm/hr-ft2 ; kg/sec-m2]
QA (I) = Average heat flux [MBtu/hr-ft2 ; kW/m2]

(나) 시험집합체 특성 자료

(TS-103)

```
REF         Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 1, Sep. 1982.
ITS         EPRI-103
BRL         Hexagonal Unheated
LTC         Triangular
UNT         British
GMT
            NRT        19
            NRH        19
            PRP         0.596
            DRH         0.422
            DRU
            SRW         0.112
            ZHT        60.000
            AFT         3.7055    (2.977     Report)
            RCC
            EOD
APS         Uniform
NAP
APF         (Z/Zh)     (Q/Qa)
NTC          1
ZTC         59.500
NZG
NKG
CKG
ZGS         (Type)     (Z)
NWW            1         90.          Counterclockwise
PWW          15.000
DWW            0.112     (Minimum: SRW)
RNS
                 1     2     3
              12    13    14     4
            11    18    19    15     5
              10    17    16     6
                 9     8     7
RPF
                      0.942     0.942     0.942
                 0.942     1.100     1.100     0.942
            0.942     1.100     1.100     1.100     0.942
                 0.942     1.100     1.100     0.942
                      0.942     0.942     0.942
TMP          0.050
IRC          0
ICC          0
EOD

EPRI-103   (WH)           8
( SN    RN      PE        TI       GI        QA       N1)
(                psi          F Ml/hf2 MB/hf2              )
    1    61   1500.   538.0   1.004   0.534   19.0
    2    62   1500.   521.0   1.003   0.546   19.0
    3    63   1500.   502.0   1.000   0.564   17.0
    4    64   1500.   482.0   1.000   0.572   14.0
    5    65   1500.   540.0   1.995   0.617   19.0
    6    66   1500.   520.0   2.000   0.666   19.0
    7    67   1500.   497.0   2.012   0.695   19.0
    8    68   1500.   481.0   1.990   0.755   19.0
```

(TS-104)

```
REF         Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 1, Sep. 1982.
ITS         EPRI-104
BRL         Hexagonal Unheated
LTC         Triangular
UNT         British
GMT
            NRT        19
            NRH        19
            PRP         0.596
            DRH         0.422
            DRU
            SRW         0.112
            ZHT        60.000
            AFT         3.7055    (2.976      Report)
            RCC
            EOD
APS         Uniform
NAP
APF         (Z/Zh)      (Q/Qa)
NTC           1
ZTC         59.500
NZG           4
NKG           1
CKG           1.000
ZGS         (Type)      (Z)
             1            3.00
             1           18.00
             1           33.00
             1           48.00
NWW
PWW
DWW
RNS
                  1    2    3
              12   13   14    4
            11   18   19   15    5
              10   17   16    6
                  9    8    7
RPF
                       0.947    0.947    0.947
                  0.947    1.091    1.091    0.947
             0.947    1.091    1.091    1.091    0.947
                  0.947    1.091    1.091    0.947
                       0.947    0.947    0.947
TMP          0.005
IRC         0
ICC         0
EOD

EPRI-104   (WH)          12
( SN    RN      PE       TI       GI       QA       N1)
(              psi        F Ml/hf2 MB/hf2          )
    1   74   1500.   542.0   1.009   0.470   19.0
    2   75   1500.   541.0   2.002   0.534   19.0
    3   76   1500.   540.0   2.987   0.654   13.0
    4   77   1500.   521.0   1.009   0.500   19.0
    5   78   1500.   499.0   0.996   0.523   14.0
    6   79   1500.   476.0   0.994   0.559   13.0
    7   80   1500.   521.0   1.999   0.588   13.0
    8   81   1500.   500.0   1.990   0.654   13.0
    9   82   1500.   481.0   2.019   0.717   13.0
   10   83   1500.   520.0   3.007   0.731   13.0
   11   84   1500.   500.0   3.002   0.816   13.0
   12   85   1500.   481.0   2.979   0.901   13.0
```

```
(TS-601)
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
             EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS          EPRI-601
BRL           Circular   Unheated
LTC           Mixed1
UNT           British
GMT
             NRT         19
             NRH         19
             PRP
             DRH           0.780
             DRU
             SRW           0.060
             ZHT         72.000
             AFT           3.9184    (3.918      Report)
             RCC
             DTF           4.068
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             1
ZTC           71.250
NZG             7
NKG             1
CKG             1.000     (0.000      Report)
ZGS           (Type)      (Z)
              1            9.00
              1           18.00
              1           27.00
              1           36.00
              1           45.00
              1           54.00
              1           63.00
NWW
PWW
DWW
RNS           (NRing DRing PRod)                                                 (NRing DRing PRod)
              1   3.1680   0.81994      1    2    3    4    5    6    7    8    9   10   11   12     (1   3.1680   0.8294   Report)
              2   1.63988 0.81994     13   14   15   16   17   18                                    (2   1.6400   0.8587   Report)
              3   0.0000   0.0000      19                                                           (3   0.0000   0.0000   Report)
RPF
              1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117
              0.803   0.803   0.803   0.803   0.803   0.803
              0.778
TMP             0.005
IRC           0
ICC           0
EOD

EPRI-601    (AE)          34
( SN     RN       PE        TI       GI       QA      N1)
(                 psi        F Ml/hf2 MB/hf2            )
   601     1   1000.   526.0   0.505   0.207   19.0
   601     2   1000.   495.0   0.504   0.216   19.0
   601     3   1000.   449.0   0.506   0.227   19.0
   601     4   1000.   412.0   0.500   0.233   19.0
   601     5   1000.   363.0   0.507   0.257   19.0
   601     6   1000.   526.0   0.996   0.314   19.0
   601     7   1000.   490.0   0.996   0.322   19.0
   601     8   1000.   452.0   0.996   0.333   19.0
   601     9   1000.   410.0   0.993   0.349   19.0
   601    10   1000.   365.0   1.002   0.368   19.0
   601    11   1000.   526.0   2.006   0.403   19.0
   601    12   1000.   490.0   1.991   0.419   19.0
   601    13   1000.   452.0   1.992   0.439   19.0
   601    18    750.   491.0   0.496   0.227   19.0
   601    19    750.   441.0   0.503   0.242   19.0
   601    20    750.   377.0   0.500   0.254   19.0
   601    21    750.   493.0   0.995   0.363   19.0
   601    22    750.   443.0   0.994   0.384   19.0
   601    23    750.   372.0   0.996   0.403   19.0
   601    24    750.   492.0   2.024   0.461   19.0
   601    27   1200.   544.0   0.497   0.190   19.0
```

```
   601    28   1200.   491.5   0.510   0.206   19.0
   601    29   1200.   423.0   0.500   0.218   19.0
   601    30   1200.   543.0   1.008   0.284   19.0
   601    31   1200.   421.0   1.002   0.313   19.0
   601    32   1200.   487.5   0.993   0.289   19.0
   601    33   1200.   543.0   1.989   0.373   19.0
   601    34   1200.   492.0   2.005   0.402   19.0
   601    35   1200.   431.0   2.018   0.449   19.0
   601    36   1200.   543.0   3.004   0.457    2.0
   601    38    500.   452.0   0.499   0.245   19.0
   601    39    500.   441.0   0.996   0.395   19.0
   601    40    500.   368.0   0.990   0.425   19.0
   601    41    500.   359.0   0.508   0.260   19.0
```

(TS-602)

```
REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
           EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS        EPRI-602
BRL         Circular   Unheated
LTC         Mixed1
UNT          British
GMT
           NRT          19
           NRH          19
           PRP
           DRH            0.780
           DRU
           SRW            0.060
           ZHT          35.000
           AFT            3.9184     (3.918       Report)
           RCC
           DTF            4.068
           EOD
APS        Uniform
NAP
APF        (Z/Zh)      (Q/Qa)
NTC          1
ZTC        34.250
NZG          3
NKG          1
CKG          1.000      (0.000       Report)
ZGS        (Type)       (Z)
            1            9.00
            1           18.00
            1           27.00
NWW
PWW
DWW
RNS        (NRing DRing PRod)                                                              (NRing DRing PRod)
           1   3.1680   0.81994      1    2    3    4    5    6    7    8    9   10   11   12    (1   3.1680   0.8294   Report)
           2   1.63988 0.81994     13   14   15   16   17   18                                  (2   1.6400   0.8587   Report)
           3   0.0000   0.0000      19                                                         (3   0.0000   0.0000   Report)
RPF
           1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125
           0.787   0.787   0.787   0.787   0.787   0.787
           0.776
TMP          0.005
IRC         0
ICC         0
EOD

EPRI-602    (AE)            46
( SN      RN         PE          TI          GI          QA         N1)
(                   psi           F Ml/hf2 MB/hf2             )
       602          42      1000.0       529.0       0.503       0.300         19.0
       602          43      1000.0       493.0       0.493       0.306         19.0
       602          44      1000.0       452.0       0.500       0.321         19.0
       602          45      1000.0       412.0       0.505       0.335         19.0
       602          46      1000.0       356.0       0.505       0.357         19.0
       602          47      1000.0       526.0       0.996       0.425         11.0
       602          48      1000.0       493.0       0.992       0.444          2.0
       602          49      1000.0       456.0       0.985       0.469          2.0
       602          50      1000.0       412.0       0.984       0.502          2.0
       602          51      1000.0       358.0       1.003       0.522         18.0
```

602	52	1000.0	523.0	2.043	0.496	2.0
602	53	1000.0	490.0	1.991	0.526	2.0
602	54	1000.0	451.5	1.995	0.562	2.0
602	55	1000.0	410.0	2.002	0.629	2.0
602	56	1000.0	368.0	1.999	0.717	2.0
602	65	1000.0	522.5	3.017	0.551	2.0
602	66	1000.0	490.0	3.031	0.595	2.0
602	67	1000.0	452.5	2.979	0.686	2.0
602	75	1000.0	520.0	0.506	0.284	19.0
602	78	1000.0	505.0	0.993	0.414	2.0
602	79	1000.0	507.0	2.011	0.507	2.0
602	80	1000.0	366.0	1.003	0.545	18.0
602	81	1000.0	418.0	0.987	0.479	2.0
602	91	1000.0	492.0	1.023	0.427	2.0
602	57	750.0	497.0	0.500	0.341	19.0
602	58	750.0	434.0	0.498	0.358	19.0
602	59	750.0	372.0	0.501	0.380	19.0
602	60	750.0	492.0	0.983	0.505	2.0
602	61	750.0	441.5	0.988	0.546	2.0
602	62	750.0	382.0	0.994	0.595	19.0
602	63	750.0	493.5	1.978	0.572	11.0
602	64	750.0	442.0	2.020	0.664	2.0
602	68	750.0	487.0	3.000	0.652	2.0
602	95	750.0	448.0	2.999	0.725	2.0
602	85	500.0	449.0	0.510	0.384	19.0
602	86	500.0	399.0	0.512	0.396	19.0
602	87	500.0	444.0	1.008	0.549	2.0
602	88	500.0	388.0	0.991	0.607	2.0
602	89	500.0	449.0	1.994	0.628	2.0
602	74	1200.0	545.5	0.503	0.255	19.0
602	76	1200.0	489.0	0.499	0.268	19.0
602	77	1200.0	543.0	1.008	0.363	11.0
602	82	1200.0	423.0	1.000	0.430	2.0
602	83	1200.0	486.5	1.009	0.377	2.0
602	84	1200.0	541.5	1.994	0.418	2.0
602	92	1200.0	421.0	0.489	0.315	19.0

(TS-603)

REF Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data, EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS EPRI-603
BRL Circular Unheated
LTC Mixed1
UNT British
GMT
    NRT 19
    NRH 19
    PRP
    DRH 0.780
    DRU
    SRW 0.060
    ZHT 72.000
    AFT 3.9184 (3.918 Report)
    RCC
    DTF 4.068
    EOD
APS Uniform
NAP
APF (Z/Zh) (Q/Qa)
NTC 1
ZTC 71.250
NZG 7
NKG 1
CKG 1.000 (0.000 Report)
ZGS (Type) (Z)
    1 9.00
    1 18.00
    1 27.00
    1 36.00
    1 45.00
    1 54.00
    1 63.00
NWW
PWW
DWW

```
RNS        (NRing DRing PRod)                                                        (NRing DRing PRod)
           1   3.1680   0.81994     1    2    3    4    5    6    7    8    9   10   11   12   (1   3.1680   0.8294   Report)
           2   1.63988 0.81994    13   14   15   16   17   18                                (2   1.6400   0.8587   Report)
           3   0.0000   0.0000     19                                                          (3   0.0000   0.0000   Report)
RPF
           1.120   1.120   1.120   1.120   1.120   1.120   1.120   1.120   1.120   1.120   1.120   1.120
           0.801   0.801   0.801   0.801   0.801   0.801
           0.756
TMP         0.005
IRC        0
ICC        0
EOD

EPRI-603   (AE)          19
( SN     RN        PE         TI        GI        QA       N1)
(                psi         F Ml/hf2 MB/hf2          )
       603         96    1000.0    527.0    0.504     0.214      19.0
       603         97    1000.0    493.5    0.493     0.218      19.0
       603         98    1000.0    450.0    0.506     0.232      19.0
       603         99    1000.0    412.0    0.504     0.238      19.0
       603        100    1000.0    358.0    0.504     0.252      19.0
       603        101    1000.0    523.0    1.000     0.308      19.0
       603        102    1000.0    450.0    1.002     0.331      19.0
       603        103    1000.0    393.5    0.994     0.351      19.0
       603        104    1000.0    527.5    2.016     0.414      19.0
       603        105    1000.0    471.0    2.001     0.453      19.0
       603        106    1200.0    542.0    0.993     0.271      19.0
       603        109    1200.0    541.0    1.996     0.369      19.0
       603        111    1200.0    541.0    0.508     0.195      19.0
       603        115    1200.0    543.0    2.977     0.466      19.0
       603        107     750.0    492.0    0.993     0.346      19.0
       603        110     750.0    492.0    1.995     0.455      19.0
       603        112     750.0    488.5    0.504     0.236      19.0
       603        108     500.0    446.0    0.999     0.378      19.0
       603        113     500.0    450.0    0.502     0.250      19.0
```

(TS-604)

```
REF         Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-604
BRL          Circular   Unheated
LTC          Mixed1
UNT           British
GMT
            NRT          19
            NRH          19
            PRP
            DRH            0.780
            DRU
            SRW            0.060
            ZHT          18.000
            AFT            3.9184     (3.918       Report)
            RCC
            DTF            4.068
            EOD
APS          Uniform
NAP
APF          (Z/Zh)      (Q/Qa)
NTC            1
ZTC          17.250
NZG            2
NKG            1
CKG            1.000       (0.000       Report)
ZGS          (Type)      (Z)
             1              0.00
             1              9.00
NWW
PWW
DWW
RNS        (NRing DRing PRod)                                                        (NRing DRing PRod)
           1   3.1680   0.81994     1    2    3    4    5    6    7    8    9   10   11   12   (1   3.1680   0.8294   Report)
           2   1.63988 0.81994    13   14   15   16   17   18                                (2   1.6400   0.8587   Report)
           3   0.0000   0.0000     19                                                          (3   0.0000   0.0000   Report)
RPF
```

```
            1.117  1.117  1.117  1.117  1.117  1.117  1.117  1.117  1.117  1.117  1.117  1.117
            0.800  0.800  0.800  0.800  0.800  0.800
            0.796
TMP          0.005
IRC         0
ICC         0
EOD

EPRI-604   (AE)          12
( SN    RN       PE        TI        GI        QA        N1)
(                psi        F Ml/hf2 MB/hf2          )
      604       125   1000.0     530.0     0.502     0.384      6.0
      604       126   1000.0     519.0     1.012     0.485      6.0
      604       127   1000.0     529.0     1.984     0.693      3.0
      604       128   1000.0     441.0     0.998     0.512      6.0
      604       129   1000.0     363.0     1.008     0.581      3.0
      604       130   1000.0     356.0     0.511     0.508      6.0
      604       131   1000.0     442.0     0.506     0.479      6.0
      604       132   1000.0     489.0     0.501     0.430      6.0
      604       133   1000.0     485.0     0.998     0.488      6.0
      604       134   1200.0     532.0     0.513     0.357      6.0
      604       135   1200.0     538.0     1.009     0.469      6.0
      604       136   1200.0     484.0     1.004     0.469      3.0
```

(TS-605)

```
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-605
BRL          Circular   Unheated
LTC          Mixed1
UNT          British
GMT
            NRT          19
            NRH          19
            PRP
            DRH            0.780
            DRU
            SRW            0.060
            ZHT          108.000
            AFT            3.9184    (3.918       Report)
            RCC
            DTF            4.068
            EOD
APS          Uniform
NAP
APF          (Z/Zh)     (Q/Qa)
NTC            1
ZTC          107.250
NZG            11
NKG            1
CKG            1.000      (0.000       Report)
ZGS          (Type)      (Z)
             1             9.00
             1            18.00
             1            27.00
             1            36.00
             1            45.00
             1            54.00
             1            63.00
             1            72.00
             1            81.00
             1            90.00
             1            99.00
NWW
PWW
DWW
RNS          (NRing DRing PRod)                                                          (NRing DRing PRod)
             1   3.1680   0.81994     1    2    3    4    5    6    7    8    9   10   11   12    (1    3.1680    0.8294    Report)
             2   1.63988 0.81994     13   14   15   16   17   18                                   (2    1.6400    0.8587    Report)
             3   0.0000   0.0000      19                                                            (3    0.0000    0.0000    Report)
RPF
             1.149   1.149   1.149   1.149   1.149   1.149   1.149   1.149   1.149   1.149   1.149   1.149
             0.740   0.740   0.740   0.740   0.740   0.740
             0.775
```

```
TMP            0.005
IRC          0
ICC          0
EOD

EPRI-605    (AE)          26
( SN    RN        PE        TI        GI        QA       N1)
(                psi         F Ml/hf2 MB/hf2          )
        605        137   1000.0      525.5     0.498      0.159        19.0
        605        138   1000.0      488.0     0.499      0.169        19.0
        605        139   1000.0      450.0     0.503      0.179        19.0
        605        140   1000.0      524.0     0.985      0.249        19.0
        605        141   1000.0      491.0     1.002      0.263        19.0
        605        142   1000.0      450.5     1.005      0.274        19.0
        605        143   1000.0      528.0     2.001      0.333        19.0
        605        146   1000.0      356.0     0.505      0.197        19.0
        605        147   1000.0      365.0     0.998      0.285        19.0
        605        148   1000.0      410.0     0.998      0.278        19.0
        605        160   1000.0      411.0     0.501      0.182        19.0
        605        149   1200.0      542.0     1.979      0.308        19.0
        605        150   1200.0      537.0     1.016      0.225        19.0
        605        151   1200.0      541.0     0.495      0.147        19.0
        605        156   1200.0      442.5     0.988      0.244        19.0
        605        157   1200.0      433.0     0.511      0.175        19.0
        605        155    500.0      447.0     0.983      0.281         5.0
        605        159    500.0      446.0     0.496      0.180        19.0
        605        162    500.0      355.5     0.507      0.199        19.0
        605        167    500.0      395.5     0.989      0.315         5.0
        605        152    750.0      493.0     0.492      0.170        19.0
        605        153    750.0      490.5     0.992      0.275         5.0
        605        154    750.0      450.0     0.980      0.292        19.0
        605        158    750.0      420.5     0.491      0.184        19.0
        605        161    750.0      353.0     0.505      0.198        19.0
        605        168    750.0      389.5     1.007      0.310        19.0
```

(TS-606)

```
REF           Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
             EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS          EPRI-606
BRL           Circular    Unheated
LTC           Mixed1
UNT            British
GMT
             NRT          19
             NRH          18
             PRP
             DRH            0.780
             DRU            0.767
             SRW            0.060
             ZHT          108.000
             AFT            3.9184     (3.918        Report)
             RCC
             DTF            4.068
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             1
ZTC           107.250
NZG             11
NKG             1
CKG             1.000       (0.000        Report)
ZGS           (Type)       (Z)
              1              9.00
              1             18.00
              1             27.00
              1             36.00
              1             45.00
              1             54.00
              1             63.00
              1             72.00
              1             81.00
              1             90.00
              1             99.00
```

```
NWW
PWW
DWW
RNS        (NRing DRing PRod)                                                          (NRing DRing PRod)
           1  3.1680  0.81994    1   2   3   4   5   6   7   8   9  10  11  12    (1   3.1680   0.8294   Report)
           2  1.63988 0.81994   13  14  15  16  17  18                            (2   1.6400   0.8587   Report)
           3  0.0000  0.0000    19                                                (3   0.0000   0.0000   Report)
RPF
           1.135  1.135  1.135  1.135  1.135  1.135  1.135  1.135  1.135  1.135  1.135  1.135
           0.731  0.731  0.731  0.731  0.731  0.731
           0.000
TMP         0.005
IRC        0
ICC        0
EOD
```

EPRI-606 (AE) 20

(SN	RN	PE	TI	GI	QA	N1)
(		psi	F	Ml/hf2	MB/hf2	)
606	173	500.0	452.0	0.494	0.193	9.0
606	176	500.0	372.0	0.500	0.205	9.0
606	183	500.0	452.0	0.998	0.281	7.0
606	190	500.0	403.0	0.980	0.313	7.0
606	172	750.0	496.0	0.491	0.184	9.0
606	175	750.0	412.0	0.498	0.214	9.0
606	181	750.0	495.0	1.010	0.273	7.0
606	189	750.0	413.0	0.970	0.316	7.0
606	171	1000.0	525.0	0.512	0.176	9.0
606	174	1000.0	441.0	0.490	0.203	9.0
606	177	1000.0	358.0	0.502	0.233	7.0
606	179	1000.0	526.0	1.005	0.250	9.0
606	182	1000.0	475.0	0.993	0.278	7.0
606	186	1000.0	529.0	1.974	0.352	9.0
606	188	1000.0	417.0	0.981	0.312	7.0
606	178	1200.0	431.0	0.500	0.204	9.0
606	180	1200.0	506.0	1.003	0.256	7.0
606	184	1200.0	446.0	0.991	0.290	7.0
606	185	1200.0	536.0	2.003	0.331	9.0
606	191	1200.0	531.0	0.512	0.170	9.0

(TS-607)

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REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
           EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS        EPRI-607
BRL         Circular   Unheated
LTC         Mixed1
UNT         British
GMT
           NRT        19
           NRH        18
           PRP
           DRH          0.780
           DRU          0.767
           SRW          0.060
           ZHT        105.000
           AFT          3.9184    (3.918      Report)
           RCC
           DTF          4.068
           EOD
APS         Uniform
NAP
APF         (Z/Zh)     (Q/Qa)
NTC           1
ZTC         104.250
NZG           18
NKG           2
CKG           1.000      1.000          (0.000      Report)
ZGS         (Type)      (Z)
            2           13.75
            1           15.00
            2           24.00
            2           31.75
            1           33.00
            2           42.00
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            2          49.75
            1          51.00
            2          52.50
            2          60.00
            2          67.50
            1          69.00
            2          70.50
            2          78.00
            2          85.50
            1          87.00
            2          96.00
            2          103.50
NWW
PWW
DWW
RNS         (NRing DRing PRod)                                                   (NRing DRing PRod)
            1  3.1680   0.81994     1   2   3   4   5   6   7   8   9  10  11  12   (1  3.1680  0.8294  Report)
            2  1.63988 0.81994     13  14  15  16  17  18                          (2  1.6400  0.8587  Report)
            3  0.0000   0.0000     19                                              (3  0.0000  0.0000  Report)
RPF
            1.125  1.125  1.125  1.125  1.125  1.125  1.125  1.125  1.125  1.125  1.125  1.125
            0.750  0.750  0.750  0.750  0.750  0.750
            0.000
TMP          0.005
IRC         0
ICC         0
EOD

EPRI-607   (AE)         23
( SN    RN        PE        TI        GI       QA       N1)
(                psi       F Ml/hf2 MB/hf2           )
     607       198     500.0     454.0     0.503     0.198      11.0
     607       202     500.0     374.0     0.503     0.219      11.0
     607       210     500.0     392.0     1.009     0.329      11.0
     607       220     500.0     450.0     1.010     0.276       8.0
     607       262     500.0     368.0     0.500     0.217       7.0
     607       197     750.0     498.0     0.510     0.191      11.0
     607       201     750.0     414.0     0.500     0.221      11.0
     607       206     750.0     497.0     1.010     0.275       8.0
     607       209     750.0     412.0     1.010     0.341      11.0
     607       196    1000.0     528.0     0.501     0.180      11.0
     607       199    1000.0     443.0     0.509     0.215       7.0
     607       203    1000.0     357.0     0.510     0.244      13.0
     607       204    1000.0     524.0     1.036     0.260       8.0
     607       207    1000.0     476.0     1.020     0.301      11.0
     607       208    1000.0     415.0     1.010     0.343      11.0
     607       218    1000.0     527.0     2.050     0.366       8.0
     607       200    1200.0     430.5     0.501     0.212      13.0
     607       205    1200.0     508.0     1.014     0.269       8.0
     607       217    1200.0     540.0     2.060     0.354       8.0
     607       219    1200.0     552.0     2.040     0.374       8.0
     607       221    1200.0     445.0     1.010     0.308       8.0
     607       222    1200.0     445.5     1.000     0.306       8.0
     607       223    1200.0     540.0     0.500     0.172       7.0
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(TS-609)

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REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-609
BRL          Circular   Unheated
LTC          Mixed1
UNT          British
GMT
            NRT         19
            NRH         18
            PRP
            DRH           0.780
            DRU           0.767
            SRW           0.060
            ZHT         105.000
            AFT           3.9184     (3.918       Report)
            RCC
            DTF           4.068
            EOD
```

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APS         Uniform
NAP
APF         (Z/Zh)      (Q/Qa)
NTC           1
ZTC         104.250
NZG           18
NKG           2
CKG           1.000       1.000          (0.000       Report)
ZGS         (Type)      (Z)
            2           13.75
            1           15.00
            2           24.00
            2           31.75
            1           33.00
            2           42.00
            2           49.75
            1           51.00
            2           52.50
            2           60.00
            2           67.50
            1           69.00
            2           70.50
            2           78.00
            2           85.50
            1           87.00
            2           96.00
            2           103.50
NWW
PWW
DWW
RNS         (NRing DRing PRod)                                                            (NRing DRing PRod)
            1   3.1680   0.81994     1    2    3    4    5    6    7    8    9   10   11   12    (1   3.1680   0.8294   Report)
            2   1.63988 0.81994     13   14   15   16   17   18                                (2   1.6400   0.8587   Report)
            3   0.0000   0.0000      19                                                         (3   0.0000   0.0000   Report)
RPF
            1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125   1.125
            0.750   0.750   0.750   0.750   0.750   0.750
            0.000
TMP           0.005
IRC          0
ICC          0
EOD

EPRI-609   (AE)          30
( SN     RN        PE        TI        GI        QA       N1)
(                 psi        F Ml/hf2 MB/hf2             )
       609        293     500.0     463.0     0.506     0.201      12.0
       609        296     500.0     370.0     0.504     0.218       9.0
       609        310     500.0     458.0     1.017     0.265      10.0
       609        313     500.0     379.0     1.035     0.312      10.0
       609        327     500.0     418.0     1.021     0.291      12.0
       609        328     500.0     380.0     1.018     0.334       9.0
       609        332     500.0     455.0     0.525     0.197      11.0
       609        292     750.0     503.0     0.522     0.200      12.0
       609        295     750.0     368.0     0.506     0.232       9.0
       609        311     750.0     412.0     1.011     0.311      10.0
       609        322     750.0     496.0     1.038     0.265      12.0
       609        323     750.0     502.0     1.525     0.336      12.0
       609        324     750.0     461.5     1.028     0.289      12.0
       609        326     750.0     410.0     1.005     0.329       9.0
       609        329     750.0     376.0     0.990     0.347      11.0
       609        331     750.0     495.0     0.512     0.209      11.0
       609        335     750.0     356.0     0.501     0.224      11.0
       609        297    1000.0     371.0     0.497     0.240      11.0
       609        306    1000.0     518.5     1.036     0.262      10.0
       609        309    1000.0     532.0     2.020     0.348      10.0
       609        312    1000.0     416.0     0.994     0.315      11.0
       609        320    1000.0     522.0     1.031     0.247      12.0
       609        325    1000.0     418.0     1.016     0.331      12.0
       609        330    1000.0     504.0     0.523     0.226      11.0
       609        334    1000.0     374.0     0.512     0.222      11.0
       609        294    1200.0     432.0     0.499     0.228      11.0
       609        307    1200.0     514.0     1.007     0.260      10.0
       609        308    1200.0     553.0     2.030     0.335      10.0
       609        321    1200.0     514.0     1.036     0.255      10.0
       609        333    1200.0     424.0     0.518     0.209      12.0
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(TS-610)
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
             EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS          EPRI-610
BRL           Circular   Unheated
LTC           Mixed3
UNT           British
GMT
             NRT          28
             NRH          28
             PRP                          (PR11=0.65472; PR12=0.66841; PR22=0.81358; PR23=0.66660; PR33=0.64205)
             DRH            0.598
             DRU
             SRW            0.057
             ZHT          72.000
             AFT            5.1331    (5.147       Report)
             RCC
             DTF            4.068
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             1
ZTC           71.000
NZG            12
NKG             2
CKG             1.000       1.000     (0.000       0.000        Report)
ZGS           (Type)      (Z)
              2             9.00
              2            16.75
              1            18.00
              2            27.00
              2            34.75
              1            36.00
              2            37.50
              2            45.00
              1            54.00
              2            55.50
              2            63.00
              2            70.50
NWW
PWW
DWW
RNS           (NRing  DRing  PRod)                                                                       (NRing  DRing
PRod)
              1   3.3560   0.65472     1    2    3    4    5    6    7    8    9   10   11   12   13   14   15   16    (1    3.3500   0.6578
Report)
              2   2.1260   0.81358    17   18   19   20   21   22   23   24                                            (2    2.1260   0.8349
Report)
              3   0.9080   0.64205    25   26   27   28                                                                (3    0.9080   0.7131
Report)
RPF
              1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101   1.101
              0.865   0.865   0.865   0.865   0.865   0.865   0.865   0.865
              0.865   0.865   0.865   0.865
TMP             0.005
IRC           0
ICC           0
EOD

EPRI-610    (AE)          39
( SN     RN       PE        TI        GI        QA       N1)
(                psi         F Ml/hf2 MB/hf2            )
   610      1    750.   370.0   0.503   0.378    4.0
   610      4    750.   495.0   0.497   0.314    4.0
   610      8    750.   496.0   0.988   0.393   14.6
   610     12    750.   473.0   0.985   0.426   14.0
   610      2   1000.   371.5   0.506   0.381    4.1
   610      5   1000.   531.0   0.496   0.291    4.0
   610      7   1000.   531.0   0.982   0.358    6.1
   610     11   1000.   472.5   0.990   0.420   14.0
   610     15   1000.   533.0   1.476   0.423    4.0
   610     21   1000.   528.5   1.557   0.434   14.0
```

610	39	1000.	534.0	1.472	0.429	4.0
610	44	1000.	532.0	0.491	0.280	14.0
610	6	1250.	558.5	0.991	0.320	4.0
610	9	1250.	463.0	1.022	0.414	4.0
610	14	1250.	564.0	1.473	0.367	2.0
610	16	1250.	518.0	1.516	0.417	4.0
610	19	1250.	560.0	1.994	0.396	2.0
610	22	1250.	549.5	1.954	0.430	4.0
610	26	1250.	560.0	2.233	0.435	2.0
610	30	1250.	561.0	2.328	0.434	2.0
610	31	1250.	564.5	1.967	0.402	2.0
610	37	1250.	565.0	1.477	0.374	2.0
610	41	1250.	561.0	1.486	0.374	4.0
610	43	1250.	560.0	1.001	0.329	14.0
610	46	1250.	552.0	1.975	0.431	4.0
610	47	1250.	518.0	1.501	0.423	4.0
610	48	1250.	463.0	1.033	0.420	4.0
610	3	1500.	358.0	0.511	0.360	4.0
610	10	1500.	455.0	1.002	0.389	4.0
610	13	1500.	570.0	1.489	0.335	4.0
610	17	1500.	513.0	1.501	0.405	4.0
610	18	1500.	574.0	1.984	0.367	2.0
610	23	1500.	537.0	1.975	0.416	4.0
610	24	1500.	577.0	2.479	0.411	2.0
610	27	1500.	560.0	2.476	0.431	4.0
610	28	1500.	581.5	2.965	0.438	2.0
610	33	1500.	576.5	2.494	0.417	2.0
610	35	1500.	580.0	1.996	0.370	2.0
610	42	1500.	578.0	1.917	0.383	2.0

(TS-613)

REF Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS EPRI-613
BRL Circular Unheated
LTC Mixed4
UNT British
GMT
NRT 37
NRH 36
PRP (PR11=0.59075; PR12=0.58506; PR1F=0.68764)
DRH 0.542
DRU 0.542
SRW 0.062
ZHT 72.000
AFT 4.4606 (4.433 Report)
RCC
DTF 4.068
EOD
APS Uniform
NAP
APF (Z/Zh) (Q/Qa)
NTC 1
ZTC 71.500
NZG 7
NKG 1
CKG 1.000 (0.000 Report)
ZGS (Type) (Z)
1 9.00
1 18.00
1 27.00
1 36.00
1 45.00
1 54.00
1 63.00
NWW
PWW
DWW
RNS (NRing DRing PRod) (NRing DRing PRod)
1 3.4020 0.59075 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 (1 0.0000 0.0000 Report)
2 2.34026 0.58506 19 20 21 22 23 24 25 26 27 28 29 30 (2 0.0000 0.0000 Report)

```
              3   1.17013  0.58506     31    32    33    34    35    36                                                      (3    0.0000
0.0000    Report)
              4   0.0000    0.0000      37                                                                                   (4    0.0000
0.0000    Report)
RPF
              1.145    1.152    1.149    1.134    1.157    1.151    1.156    1.152    1.140    1.149    1.152    1.154    1.154    1.151    1.143    1.160
1.149    1.146
              0.885    0.881    0.880    0.884    0.884    0.877    0.882    0.883    0.902    0.878    0.882    0.904
              0.783    0.786    0.774    0.782    0.784    0.776
              0.000
TMP            0.005
IRC           0
ICC           0
EOD

EPRI-613    (AE)           38
( SN     RN        PE         TI         GI          QA        N1)
(                  psi          F Ml/hf2 MB/hf2             )
   613    42    1005.   536.0   1.210   0.250   34.0
   613    43    1250.   565.0   0.990   0.218   34.0
   613    44    1250.   555.0   0.990   0.222   34.0
   613    45    1250.   542.0   0.990   0.228   34.0
   613    46    1250.   522.0   0.990   0.234   31.0
   613    47    1250.   504.0   0.990   0.241   36.0
   613    48    1250.   486.0   1.000   0.247   36.0
   613    49    1480.   594.0   0.960   0.188   34.0
   613    50    1505.   562.0   1.000   0.201   36.0
   613    51    1490.   542.0   0.990   0.208   36.0
   613    52    1490.   517.5   0.990   0.218   36.0
   613    53    1490.   487.5   1.000   0.229   36.0
   613    54    1505.   455.0   0.990   0.241   36.0
   613    55    1495.   412.0   1.010   0.264   32.0
   613    73    1000.   539.0   0.490   0.172   34.0
   613    74    1000.   514.0   0.500   0.180   34.0
   613    75    1000.   490.0   0.500   0.189   34.0
   613    76    1000.   488.0   0.520   0.183   34.0
   613    77    1000.   465.0   0.490   0.191   34.0
   613    78    1000.   435.0   0.490   0.198   36.0
   613    79    1000.   397.0   0.500   0.204   36.0
   613    80    1000.   356.0   0.500   0.213   36.0
   613    81    1515.   528.0   0.520   0.146   36.0
   613    82    1500.   542.0   0.510   0.153   36.0
   613    98    1500.   585.0   1.490   0.218   31.0
   613    99    1500.   548.0   1.430   0.236   31.0
   613   100    1500.   508.0   1.490   0.265   31.0
   613   101    1500.   592.0   1.970   0.235   31.0
   613   102    1500.   569.0   1.970   0.252   31.0
   613   103    1500.   504.0   0.510   0.162   31.0
   613   104    1500.   465.0   0.510   0.174   34.0
   613   105    1500.   430.0   0.500   0.186   35.0
   613   106    1500.   395.0   0.510   0.190   34.0
   613   107    1500.   354.0   0.500   0.207   34.0
   613   108    1500.   296.0   0.480   0.222   34.3
   613   109     750.   502.0   0.490   0.197   36.0
   613   110     750.   470.0   0.430   0.207   31.0
   613   111     750.   419.0   0.510   0.222   31.0
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(TS-801)

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REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
             EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS          EPRI-801
BRL           Circular    Unheated
LTC           Mixed2
UNT           British
GMT
             NRT          19
             NRH          19
             PRP                          (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
             DRH            0.625
             DRU
             SRW            0.085
             ZHT          48.000
             AFT            4.3723     (4.306       Report)
```

```
              RCC
              DTF            3.604
              EOD
APS           Uniform
NAP
APF           (Z/Zh)     (Q/Qa)
NTC             1
ZTC           47.250
NZG
NKG
CKG
ZGS           (Type)     (Z)
NWW              1           90.          Counterclockwise
PWW              9.000
DWW              0.049373 (Minimum: PR23-DRH=0.67437-0.625)
RNS           (NRing DRing PRod)                                      (NRing DRing PRod)
              1   2.8090   0.71237    1    3    5    7    9   11    (1   2.8040   1.4682   Report)
              2   2.6720   0.71237    2    4    6    8   10   12    (2   2.6720   1.3991   Report)
              3   1.4230   0.7115    13   14   15   16   17   18    (3   1.4230   0.7451   Report)
              4   0.0000   0.0000    19                              (4   0.0000   0.0000   Report)
RPF
              1.164   1.164   1.164   1.164   1.164   1.164
              1.164   1.164   1.164   1.164   1.164   1.164
              0.719   0.719   0.719   0.719   0.719   0.719
              0.719
TMP             0.050
IRC           0
ICC           0
EOD

EPRI-801    (UK)          38
( SN     RN        PE         TI        GI        QA       N1)
(                  psi         F Ml/hf2 MB/hf2           )
    801      1   1000.   527.0   0.500   0.320   12.0
    801      2   1000.   488.0   0.500   0.367   12.0
    801      3   1000.   447.0   0.510   0.416   12.0
    801      4   1000.   526.0   0.770   0.371   12.0
    801      5   1000.   487.0   0.760   0.436    2.0
    801      6   1000.   447.0   0.760   0.486    2.0
    801      7   1000.   526.0   1.500   0.414    2.0
    801      8   1000.   486.0   1.490   0.507    2.0
    801      9   1000.   447.0   1.490   0.589    2.0
    801     10   1000.   525.0   2.010   0.442    2.0
    801     11   1000.   486.0   2.020   0.545    2.0
    801     12   1000.   446.0   2.010   0.643    2.0
    801     13   1000.   454.0   0.510   0.418   12.0
    801     14   1000.   408.0   0.490   0.455    2.0
    801     15   1000.   358.0   0.500   0.502    2.0
    801     16   1000.   408.0   0.750   0.552    2.0
    801     17   1000.   361.0   0.780   0.625    2.0
    801     18   1000.   410.0   1.500   0.683    2.0
    801     19   1000.   435.0   2.000   0.707    6.0
    801     20   1000.   464.0   1.980   0.619   10.0
    801     21   1000.   506.0   2.010   0.483    2.0
    801     22   1000.   505.0   1.520   0.493    2.0
    801     23   1000.   507.0   0.770   0.420    2.0
    801     24   1000.   505.0   0.500   0.357   12.0
    801     25   1000.   506.0   0.500   0.327    0.0
    801     26   1000.   528.0   2.530   0.466   10.0
    801     27   1000.   492.0   2.550   0.609    2.0
    801     28   1000.   466.0   2.530   0.624    0.0
    801     29   1000.   471.0   2.480   0.655    6.0
    801     30   1000.   513.0   2.460   0.515   10.0
    801     31   1000.   528.0   1.900   0.451    2.0
    801     32   1000.   529.0   1.940   0.440   10.0
    801     36   1000.   410.0   0.500   0.457    2.0
    801     37   1000.   410.0   0.460   0.435   12.0
    801     38   1000.   501.0   2.000   0.527   10.0
    801     39   1000.   470.0   2.040   0.610   10.0
    801     40   1000.   431.0   2.060   0.690    2.0
    801     41   1000.   432.0   1.520   0.648   10.0
```

(TS-802)

```
REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
           EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS        EPRI-802
BRL         Circular   Unheated
LTC         Mixed1
UNT         British
GMT
           NRT        19
           NRH        18
           PRP                    (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
           DRH          0.625
           DRU          0.596
           SRW          0.065
           ZHT        48.000
           AFT          4.3723    (4.306      Report)
           RCC
           DTF          3.604
           EOD
APS         Uniform
NAP
APF         (Z/Zh)     (Q/Qa)
NTC           1
ZTC         47.250
NZG           5
NKG           1
CKG         1.000
ZGS         (Type)     (Z)
            1            0.00
            1           10.00
            1           20.00
            1           30.00
            1           40.00
NWW
PWW
DWW
RNS         (NRing DRing PRod)                        (NRing DRing PRod)
            1  2.7490  0.7115     1   2   3   4   5   6   7   8   9  10  11  12   (1  2.7490  0.7197  Report)
            2  1.4230  0.7115    13  14  15  16  17  18                           (2  1.4740  0.7718  Report)
            3  0.0000  0.0000    19                                               (3  0.0000  0.0000  Report)
RPF
            1.141  1.141  1.141  1.141  1.141  1.141  1.141  1.141  1.141  1.141  1.141  1.141
            0.719  0.719  0.719  0.719  0.719  0.719
            0.000
TMP           0.005
IRC         0
ICC         0
EOD

EPRI-802  (UK)        9
( SN    RN      PE        TI       GI       QA      N1)
(              psi        F Ml/hf2 MB/hf2          )
     802        42   1000.0    527.0    0.510    0.419    11.0
     802        43   1000.0    489.0    0.520    0.462    11.0
     802        44   1000.0    448.0    0.510    0.488    11.0
     802        45   1000.0    528.0    0.650    0.477    11.0
     802        46   1000.0    489.0    0.740    0.520    11.0
     802        47   1000.0    446.0    0.740    0.570    11.0
     802        48   1000.0    532.0    1.490    0.604     9.0
     802        49   1000.0    492.0    1.490    0.680    11.0
     802        50   1000.0    451.0    1.510    0.741    11.0
```

(TS-805)

```
REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
           EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS        EPRI-805
BRL         Circular   Unheated
LTC         Mixed1
UNT         British
GMT
           NRT        19
           NRH        18
           PRP                    (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
           DRH          0.625
```

```
          DRU          0.596
          SRW          0.065
          ZHT         48.000
          AFT          4.3723    (4.306      Report)
          RCC
          DTF          3.604
          EOD
APS        Uniform
NAP
APF        (Z/Zh)      (Q/Qa)
NTC          1
ZTC        47.250
NZG          5
NKG          1
CKG         1.000
ZGS        (Type)      (Z)
           1             0.00
           1            10.00
           1            20.00
           1            30.00
           1            40.00
NWW
PWW
DWW
RNS        (NRing DRing PRod)                                        (NRing DRing PRod)
           1   2.8440   0.7361     1   2   3   4   5   6   7   8   9  10  11  12   (1   2.8440   0.7446   Report)
           2   1.4722   0.7361    13  14  15  16  17  18                           (2   1.4740   0.7718   Report)
           3   0.0000   0.0000    19                                               (3   0.0000   0.0000   Report)
RPF
           1.105   1.105   1.105   1.105   1.105   1.105   1.105   1.105   1.105   1.105   1.105   1.105
           0.789   0.789   0.789   0.789   0.789   0.789
           0.000
TMP          0.005
IRC        0
ICC        0
EOD

EPRI-805   (UK)          11
```

(SN	RN	PE	TI	GI	QA	N1)
(		psi	F	Ml/hf2	MB/hf2	)
805	76	1000.0	518.0	0.498	0.445	11.0
805	77	1000.0	479.0	0.491	0.477	11.0
805	78	1000.0	442.0	0.495	0.517	11.0
805	79	1000.0	398.0	0.499	0.544	5.0
805	80	1000.0	522.0	0.733	0.541	11.0
805	81	1000.0	480.0	0.736	0.588	11.0
805	82	1000.0	442.0	0.740	0.638	11.0
805	83	1000.0	400.0	0.750	0.685	11.0
805	84	1000.0	522.0	1.479	0.671	4.0
805	85	1000.0	480.0	1.476	0.768	5.0
805	86	1000.0	442.0	1.484	0.844	7.0

(TS-806)

```
REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
          EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS       EPRI-806
BRL        Circular   Unheated
LTC        Mixed2
UNT        British
GMT
          NRT         19
          NRH         19
          PRP                      (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
          DRH          0.625
          DRU
          SRW          0.083
          ZHT         48.000
          AFT          4.3723    (4.306      Report)
          RCC
          DTF          3.604
          EOD
APS        Uniform
NAP
```

```
APF          (Z/Zh)      (Q/Qa)
NTC            1
ZTC          47.250
NZG
NKG
CKG
ZGS          (Type)      (Z)
NWW            1            90.          Counterclockwise
PWW           9.000
DWW            0.049373 (Minimum: PR23-DRH=0.67437-0.625)
RNS          (NRing DRing PRod)                                    (NRing DRing PRod)
             1   2.8090   0.71237      1    3    5    7    9   11    (1   2.8040   1.4682   Report)
             2   2.6720   0.71237      2    4    6    8   10   12    (2   2.6720   1.3991   Report)
             3   1.4230   0.7115      13   14   15   16   17   18    (3   1.4230   0.7451   Report)
             4   0.0000   0.0000      19                             (4   0.0000   0.0000   Report)
RPF
             1.149   1.149   1.149   1.149   1.149   1.149
             1.149   1.149   1.149   1.149   1.149   1.149
             0.745   0.745   0.745   0.745   0.745   0.745
             0.745
TMP            0.050
IRC          0
ICC          0
EOD

EPRI-806    (UK)          15
( SN     RN        PE        TI        GI        QA        N1)
(                  psi        F Ml/hf2 MB/hf2          )
       806        87     1000.0     515.0     0.490     0.318         2.0
       806        88     1000.0     516.0     0.740     0.369         2.0
       806        89     1000.0     520.0     1.460     0.429         2.0
       806        90     1000.0     522.0     1.940     0.442         2.0
       806        91     1000.0     518.0     1.980     0.455         2.0
       806        92     1000.0     480.0     1.950     0.570         2.0
       806        93     1000.0     477.0     1.470     0.541         2.0
       806        94     1000.0     441.0     1.470     0.603         2.0
       806        95     1000.0     443.0     1.910     0.668         2.0
       806        96     1000.0     439.0     0.740     0.457         2.0
       806        97     1000.0     402.0     0.750     0.496         2.0
       806        98     1000.0     477.0     0.740     0.413         2.0
       806        99     1000.0     477.0     0.480     0.340         2.0
       806       100     1000.0     440.0     0.490     0.371         2.0
       806       101     1000.0     400.0     0.500     0.403         2.0
```

(TS-807)

```
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
             EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS          EPRI-807
BRL           Circular   Unheated
LTC           Mixed1
UNT           British
GMT
             NRT          19
             NRH          18
             PRP                       (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
             DRH            0.625
             DRU            0.596
             SRW            0.065
             ZHT          48.000
             AFT            4.3723     (4.306       Report)
             RCC
             DTF            3.604
             EOD
APS           Uniform
NAP
APF          (Z/Zh)      (Q/Qa)
NTC            1
ZTC          47.250
NZG            5
NKG            1
CKG           1.000
ZGS          (Type)      (Z)
             1             0.00
```

```
             1          10.00
             1          20.00
             1          30.00
             1          40.00
NWW
PWW
DWW
RNS          (NRing DRing PRod)                                    (NRing DRing PRod)
             1  2.8440  0.7361     1   2   3   4   5   6   7   8   9  10  11  12   (1  2.8440  0.7446  Report)
             2  1.4722  0.7361    13  14  15  16  17  18                            (2  1.4740  0.7718  Report)
             3  0.0000  0.0000    19                                                (3  0.0000  0.0000  Report)
RPF
             1.112  1.112  1.112  1.112  1.112  1.112  1.112  1.112  1.112  1.112  1.112  1.112
             0.775  0.775  0.775  0.775  0.775  0.775
             0.000
TMP           0.005
IRC          0
ICC          0
EOD

EPRI-807   (UK)         12
( SN    RN       PE       TI       GI       QA      N1)
(              psi       F Ml/hf2 MB/hf2          )
      807       102    1000.0    521.0    0.506    0.443    11.0
      807       103    1000.0    525.0    0.730    0.551    12.0
      807       104    1000.0    522.0    1.365    0.658    11.0
      807       105    1000.0    522.0    1.953    0.768    11.0
      807       106    1000.0    518.0    1.487    0.718    11.0
      807       107    1000.0    488.0    1.473    0.776    11.0
      807       108    1000.0    479.0    0.743    0.602    11.0
      807       109    1000.0    438.0    0.752    0.650    11.0
      807       110    1000.0    400.0    0.747    0.686    11.0
      807       111    1000.0    479.0    0.491    0.478    11.0
      807       112    1000.0    441.0    0.496    0.506    11.0
      807       113    1000.0    400.0    0.498    0.540    11.0
```

(TS-808)

```
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-808
BRL          Circular   Unheated
LTC          Mixed2
UNT          British
GMT
            NRT          19
            NRH          19
            PRP                        (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
            DRH             0.625
            DRU
            SRW             0.083
            ZHT          48.000
            AFT             4.3723     (4.306       Report)
            RCC
            DTF             3.604
            EOD
APS          Uniform
NAP
APF          (Z/Zh)      (Q/Qa)
NTC            1
ZTC          47.250
NZG
NKG
CKG
ZGS          (Type)      (Z)
NWW             1            90.          Counterclockwise
PWW            9.000
DWW            0.049373 (Minimum: PR23-DRH=0.67437-0.625)
RNS          (NRing DRing PRod)                            (NRing DRing PRod)
             1  2.8090  0.71237    1   3   5   7   9  11   (1  2.8040  1.4682  Report)
             2  2.6720  0.71237    2   4   6   8  10  12   (2  2.6720  1.3991  Report)
             3  1.4230  0.7115    13  14  15  16  17  18   (3  1.4230  0.7451  Report)
             4  0.0000  0.0000    19                       (4  0.0000  0.0000  Report)
RPF
```

```
           1.155  1.155  1.155  1.155  1.155  1.155
           1.155  1.155  1.155  1.155  1.155  1.155
           0.735  0.735  0.735  0.735  0.735  0.735
           0.735
TMP         0.050
IRC        0
ICC        0
EOD

EPRI-808   (UK)          16
( SN    RN       PE        TI        GI        QA      N1)
(                psi        F Ml/hf2 MB/hf2          )
     808      114   1000.0    521.0    0.499    0.325      2.0
     808      115   1000.0    521.0    0.742    0.399      4.0
     808      116   1000.0    520.0    1.430    0.517      4.0
     808      117   1000.0    521.0    1.980    0.521      4.0
     808      118   1000.0    520.0    2.370    0.534      4.0
     808      119   1000.0    480.0    1.970    0.648      2.0
     808      120   1000.0    470.0    1.480    0.631      2.0
     808      121   1000.0    480.0    0.490    0.356      2.0
     808      122   1000.0    440.0    0.470    0.382      2.0
     808      123   1000.0    399.0    0.500    0.422      2.0
     808      124   1000.0    485.0    0.740    0.442      4.0
     808      125   1000.0    438.0    0.753    0.499      4.0
     808      126   1000.0    397.0    0.764    0.537      4.0
     808      127   1000.0    442.0    1.490    0.628      2.0
     808      128   1000.0    456.0    1.990    0.729      2.0
     808      129   1000.0    474.0    2.490    0.720      2.0
```

(TS-809)

```
REF        Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
          EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS       EPRI-809
BRL        Circular   Unheated
LTC        Mixed1
UNT        British
GMT
          NRT          19
          NRH          18
          PRP                     (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
          DRH           0.625
          DRU           0.687
          SRW           0.085
          ZHT          48.000
          AFT           4.308     (4.320       Report)
          RCC
          DTF           3.604
          EOD
APS        Uniform
NAP
APF        (Z/Zh)     (Q/Qa)
NTC          1
ZTC        47.250
NZG          5
NKG          1
CKG         1.000
ZGS        (Type)     (Z)
           1            0.00
           1           10.00
           1           20.00
           1           30.00
           1           40.00
NWW
PWW
DWW
RNS        (NRing DRing PRod)                              (NRing DRing PRod)
           1  2.8440  0.7361     1   2   3   4   5   6   7   8   9  10  11  12   (1  2.8440  0.7446  Report)
           2  1.4722  0.7361    13  14  15  16  17  18                           (2  1.4740  0.7718  Report)
           3  0.0000  0.0000    19                                               (3  0.0000  0.0000  Report)
RPF
           1.105  1.105  1.105  1.105  1.105  1.105  1.105  1.105  1.105  1.105  1.105  1.105
           0.791  0.791  0.791  0.791  0.791  0.791
           0.000
```

```
TMP          0.005
IRC          0
ICC          0
EOD

EPRI-809   (UK)        6
( SN    RN       PE       TI       GI       QA      N1)
(               psi       F Ml/hf2 MB/hf2         )
       809       130    1000.0     520.0     0.484     0.377       8.0
       809       131    1000.0     519.0     0.723     0.455       8.0
       809       132    1000.0     519.0     1.453     0.583      10.0
       809       133    1000.0     519.0     1.937     0.635      10.0
       809       134    1000.0     482.0     1.904     0.688       2.0
       809       135    1000.0     436.0     1.962     0.740      10.0
```

(TS-810)

```
REF         Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-810
BRL         Circular   Unheated
LTC         Mixed1
UNT         British
GMT
            NRT        19
            NRH        18
            PRP                  (PR12=0.71237; PR13=0.74051; PR23=0.67437; PR34=0.7115)
            DRH         0.625
            DRU         0.687
            SRW         0.065
            ZHT        48.000
            AFT         4.308    (4.320      Report)
            RCC
            DTF         3.604
            EOD
APS         Uniform
NAP
APF         (Z/Zh)     (Q/Qa)
NTC           1
ZTC         47.250
NZG           5
NKG           1
CKG         1.000
ZGS         (Type)     (Z)
             1           0.00
             1          10.00
             1          20.00
             1          30.00
             1          40.00
NWW
PWW
DWW
RNS         (NRing DRing PRod)                              (NRing DRing PRod)
             1  2.8440  0.7361    1   2   3   4   5   6   7   8   9  10  11  12   (1  2.8440  0.7446  Report)
             2  1.4722  0.7361   13  14  15  16  17  18                           (2  1.4740  0.7718  Report)
             3  0.0000  0.0000   19                                               (3  0.0000  0.0000  Report)
RPF
            1.083  1.083  1.083  1.174  1.174  1.174  1.174  1.083  1.083  1.083  1.083  1.083
            0.774  0.774  0.774  0.774  0.774  0.774
            0.000
TMP          0.005
IRC          0
ICC          0
EOD

EPRI-810   (UK)        12
( SN    RN       PE       TI       GI       QA      N1)
(               psi       F Ml/hf2 MB/hf2         )
       810       136    1000.0     525.0     0.480     0.466       7.0
       810       137    1000.0     528.0     0.718     0.558       9.0
       810       138    1000.0     526.0     1.465     0.707       9.0
       810       139    1000.0     519.0     1.988     0.773      11.0
       810       140    1000.0     484.0     1.454     0.794       9.0
       810       141    1000.0     496.0     1.945     0.817      11.0
       810       142    1000.0     483.0     0.724     0.629       9.0
```

```
     810      143    1000.0     440.0     0.742     0.690        5.0
     810      144    1000.0     402.0     0.751     0.740        5.0
     810      145    1000.0     483.0     0.481     0.507        5.0
     810      146    1000.0     442.0     0.485     0.537        5.0
     810      147    1000.0     400.0     0.488     0.573        5.0


(WAPD-1)
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
             WAPD-TM-1013, Jan. 1975.
ITS          WAPD-01
BRL           Parallel   Unheated
LTC           Triangular
UNT            British
GMT
             NRT           20
             NRH           20
             PRP            0.340
             DRH             0.250
             DRU
             SRW             0.090
             ZHT           54.000
             AFT            0.0001     (?.???        Report)
             RCC            0.215      (.5*DRH+SRW)
             NRC            5               4
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC              2
ZTC           53.750       51.000
NZG              5
NKG              1
CKG             0.0
ZGS           (Type)       (Z)
              1            3.0
              1            15.0
              1            27.0
              1            39.0
              1            51.0
NWW
PWW
DWW
RNS
                     1     2     3     4
                  5     6     7     8
               9    10    11    12
            13    14    15    16
         17    18    19    20
RPF
                                  1.500     1.500     1.500     1.500
                             1.250     1.250     1.250     1.250
                        1.000     1.000     1.000     1.000
                   0.750     0.750     0.750     0.750
              0.500     0.500     0.500     0.500
TMP             0.005
IRC            0
ICC            0
EOD

WAPD-01      (WH)            31
( SN     RN        PE         TI        GI        QA       N1)
(                 psi            F Ml/hf2 MB/hf2            )
      100   5        2000.0   599.6     0.498     0.161     5.1
      100   6        2000.0   499.5     0.499     0.211     5.1
      100   7        2000.0   502.1     0.498     0.223     5.1
      100   8        2000.0   399.8     0.500     0.254     5.1
      100   9        2000.0   601.0     1.001     0.203     5.1
      100 10        2000.0   601.7     0.992     0.228     5.1
      100 11        2000.0   499.5     0.997     0.277     5.1
      100 12        2000.0   498.6     1.008     0.286     5.1
      100 13        2000.0   499.5     0.999     0.307     5.1
      100 14        2000.0   499.5     0.998     0.312     5.1
      100 15        2000.0   399.8     0.998     0.380     5.1
```

```
    100 16        2000.0   601.0    1.492    0.236    5.1
    100 17        2000.0   498.6    1.487    0.366    5.1
    100 18        2000.0   601.0    1.995    0.297    5.1
    100 19        2000.0   497.8    1.990    0.458    5.1
    100 20        2000.0   601.0    2.990    0.395    5.1
    100 21        2000.0   502.1    3.000    0.626    5.1
    100 22        2000.0   601.0    3.500    0.458    5.1
    100 23        2000.0   497.8    4.030    0.792    5.1
    100 25        1600.0   501.2    0.498    0.216    5.1
    100 26        1600.0   497.7    0.999    0.324    5.1
    100 30        1200.0   501.1    0.499    0.222    5.1
    100 31        1200.0   400.7    0.503    0.275    5.1
    100 32        1200.0   298.2    0.496    0.310    5.1
    100 33        1200.0   498.5    0.997    0.320    5.1
    100 34        1200.0   500.2    0.998    0.322    5.1
    100 35        1200.0   400.7    0.999    0.413    5.1
    100 36        1200.0   305.0    0.991    0.490    5.1
    100 37        1200.0   501.1    1.997    0.425    5.1
    100 38        1200.0   501.9    2.990    0.513    5.1
    100 39        1200.0   497.6    3.910    0.639    5.1
```

(WAPD-2)

```
REF         LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
           WAPD-TM-1013, Jan. 1975.
ITS        WAPD-02
BRL         Parallel   Unheated
LTC         Triangular
UNT         British
GMT
           NRT          20
           NRH          20
           PRP           0.340
           DRH            0.250
           DRU
           SRW            0.090
           ZHT          54.000
           AFT           0.0001    (?.???       Report)
           RCC           0.215     (.5*DRH+SRW)
           NRC            5             4
           EOD
APS         Uniform
NAP
APF         (Z/Zh)      (Q/Qa)
NTC          2
ZTC         53.750      50.000
NZG          6
NKG          1
CKG          0.0
ZGS         (Type)      (Z)
            1           3.0
            1           15.0
            1           27.0
            1           39.0
            1           51.0
            1           54.0
NWW
PWW
DWW
RNS
                  1    2    3    4
                5    6    7    8
              9   10   11   12
           13   14   15   16
         17   18   19   20
RPF
                          1.500     1.500     1.500     1.500
                     1.250     1.250     1.250     1.250
                1.000     1.000     1.000     1.000
           0.750     0.750     0.750     0.750
      0.500     0.500     0.500     0.500
TMP          0.005
IRC         0
ICC         0
EOD
```

```
WAPD-02     (WH)            24
( SN     RN        PE         TI         GI         QA       N1)
(                psi          F Ml/hf2 MB/hf2           )
       200 6          2000.0   598.3     0.498     0.158     5.1
       200 7          2000.0   491.7     0.500     0.215     5.1
       200 8          2000.0   399.8     0.498     0.244     5.1
       200 9          2000.0   299.6     0.495     0.292     5.1
       200 10         2000.0   198.4     0.502     0.307     5.1
       200 11         2000.0   599.0     0.994     0.203     5.1
       200 12         2000.0   498.6     0.995     0.291     5.1
       200 13         2000.0   499.5     0.995     0.295     5.1
       200 14         2000.0   497.8     0.954     0.298     5.1
       200 15         2000.0   399.8     0.999     0.354     5.1
       200 16         2000.0   400.7     0.999     0.362     5.1
       200 17         2000.0   298.7     0.989     0.422     5.1
       200 18         2000.0   299.6     0.993     0.423     5.1
       200 19         2000.0   197.4     1.003     0.502     5.1
       200 20         2000.0   499.5     1.495     0.382     5.1
       200 21         2000.0   499.5     2.000     0.447     5.1
       200 22         2000.0   501.2     3.000     0.604     5.1
       200 23         2000.0   501.2     4.000     0.757     5.1
       200 25         1600.0   498.6     0.486     0.218     5.1
       200 26         1600.0   498.6     0.996     0.321     5.1
       200 29         1200.0   499.4     0.499     0.229     5.1
       200 30         1200.0   295.2     0.496     0.340     5.1
       200 31         1200.0   498.5     0.998     0.347     5.1
       200 32         1200.0   307.9     0.990     0.493     5.1
```

(WAPD-3)

```
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
             WAPD-TM-1013, Jan. 1975.
ITS          WAPD-03
BRL           Parallel   Unheated
LTC           Triangular
UNT           British
GMT
             NRT          20
             NRH          20
             PRP           0.340
             DRH            0.250
             DRU
             SRW            0.090
             ZHT          54.000
             AFT           0.0001     (?.???       Report)
             RCC           0.215      (.5*DRH+SRW)
             NRC           5             4
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             2
ZTC           53.750       51.000
NZG             5
NKG             1
CKG            0.0
ZGS           (Type)       (Z)
               1            3.0
               1            15.0
               1            27.0
               1            39.0
               1            51.0
NWW
PWW
DWW
RNS
                         1     2     3     4
                      5     6     7     8
                   9    10    11    12
               13    14    15    16
             17    18    19    20
RPF
                                    1.500      1.500      1.500      1.500
```

```
                              1.250      1.250      1.250      1.250
                         1.000      1.000      1.000      1.000
                    0.750      0.750      0.750      0.750
               0.500      0.500      0.500      0.500
TMP             0.005
IRC            0
ICC            0
EOD

WAPD-03      (WH)              39
( SN     RN          PE          TI          GI          QA        N1)
(                   psi            F Ml/hf2 MB/hf2             )
      300 4            2000.0    599.0     0.500      0.164      5.1
      300 5            2000.0    501.2     0.499      0.188      5.1
      300 6            2000.0    398.8     0.501      0.242      5.1
      300 7            2000.0    599.0     0.997      0.214      5.1
      300 8            2000.0    498.6     1.001      0.312      5.1
      300 9            2000.0    397.0     1.013      0.392      5.1
      300 10           2000.0    401.7     1.000      0.411      5.1
      300 11           2000.0    599.6     1.496      0.230      5.1
      300 12           2000.0    498.6     1.503      0.402      5.1
      300 13           2000.0    397.9     1.512      0.523      5.1
      300 14           2000.0    299.6     1.512      0.621      5.1
      300 15           2000.0    598.3     2.000      0.290      5.1
      300 16           2000.0    499.5     2.000      0.474      5.1
      300 17           2000.0    502.1     2.000      0.486      5.1
      300 18           2000.0    401.7     2.010      0.655      5.1
      300 19           2000.0    299.6     2.020      0.782      5.1
      300 20           2000.0    201.4     2.020      0.951      5.1
      300 21           2000.0    598.3     3.000      0.381      5.1
      300 22           2000.0    501.2     3.000      0.623      5.1
      300 23           2000.0    503.0     3.010      0.662      5.1
      300 24           2000.0    398.8     3.020      0.882      5.1
      300 25           2000.0    498.6     3.880      0.778      5.1
      300 26           2000.0    404.5     4.020      1.043      5.1
      300 27           1600.0    500.3     1.001      0.311      5.1
      300 28           1600.0    400.2     1.005      0.387      5.1
      300 29           1600.0    498.6     2.000      0.437      5.1
      300 30           1600.0    399.3     2.010      0.592      5.1
      300 31           1600.0    501.2     3.000      0.552      5.1
      300 32           1600.0    399.3     3.010      0.786      5.1
      300 33           1200.0    501.1     0.996      0.342      5.1
      300 34           1200.0    397.0     1.005      0.405      5.1
      300 35           1200.0    200.2     1.008      0.576      5.1
      300 36           1200.0    498.5     1.994      0.428      5.1
      300 37           1200.0    402.6     2.010      0.590      5.1
      300 38           1200.0    300.1     2.010      0.746      5.1
      300 39           1200.0    200.2     2.020      0.899      5.1
      300 40           1200.0    501.1     2.990      0.527      5.1
      300 41           1200.0    399.8     3.010      0.789      5.1
      300 42           1200.0    403.5     4.010      0.910      5.1
```

(WAPD-4)

```
REF             LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
                WAPD-TM-1013, Jan. 1975.
ITS             WAPD-04
BRL              Parallel    Unheated
LTC              Triangular
UNT               British
GMT
                NRT            20
                NRH             20
                PRP              0.340
                DRH               0.250
                DRU
                SRW               0.090
                ZHT            54.000
                AFT              0.0001      (?.???        Report)
                RCC              0.215        (.5*DRH+SRW)
                NRC             5               4
                EOD
APS              Uniform
NAP
```

```
APF         (Z/Zh)      (Q/Qa)
NTC           3
ZTC         53.500      52.875      43.500
NZG           4
NKG           1
CKG           0.0
ZGS         (Type)      (Z)
            1           9.0
            1           21.0
            1           33.0
            1           45.0
NWW
PWW
DWW
RNS
                   1    2    3    4
                 5    6    7    8
               9   10   11   12
            13   14   15   16
          17   18   19   20
RPF
                                1.500     1.500     1.500     1.500
                           1.250     1.250     1.250     1.250
                      1.000     1.000     1.000     1.000
                 0.750     0.750     0.750     0.750
            0.500     0.500     0.500     0.500
TMP           0.005
IRC          0
ICC          0
EOD

WAPD-04     (WH)          30
( SN     RN       PE        TI        GI        QA       N1)
(               psi          F Ml/hf2 MB/hf2          )
     400    5          2000.0     598.3     0.498               0.146     5.1
     400    6          2000.0     496.0     0.500               0.191     5.1
     400    7          2000.0     397.0     0.505               0.249     5.1
     400    8          2000.0     200.4     0.503               0.331     5.1
     400    9          2000.0     596.9     0.976               0.153     5.1
     400    10         2000.0     499.5     1.001               0.274     5.1
     400    11         2000.0     497.8     1.001               0.283     5.1
     400    12         2000.0     401.7     1.005               0.370     5.1
     400    13         2000.0     399.8     1.012               0.373     5.1
     400    14         2000.0     200.4     1.002               0.506     5.1
     400    15         2000.0     599.6     1.494               0.242     5.1
     400    16         2000.0     499.5     1.503               0.373     5.1
     400    17         2000.0     601.7     1.997               0.289     5.1
     400    18         2000.0     501.2     2.000               0.463     5.1
     400    19         2000.0     501.2     2.000               0.471     5.1
     400    20         2000.0     400.7     2.020               0.630     5.1
     400    21         2000.0     296.7     2.020               0.791     5.1
     400    22         2000.0     601.0     2.990               0.363     5.1
     400    23         2000.0     497.8     3.020               0.641     5.1
     400    24         2000.0     403.5     3.010               0.849     5.1
     400    25         2000.0     501.2     4.010               0.776     5.1
     400    28         1200.0     497.6     0.497               0.221     5.1
     400    29         1200.0     204.2     0.501               0.362     5.1
     400    30         1200.0     500.2     0.995               0.314     5.1
     400    31         1200.0     200.2     1.002               0.532     5.1
     400    32         1200.0     498.5     2.000               0.433     5.1
     400    33         1200.0     401.6     2.000               0.559     5.1
     400    34         1200.0     501.1     3.000               0.527     5.1
     400    35         1200.0     400.7     3.010               0.731     5.1
     400    36         1200.0     495.9     4.000               0.608     5.1
```

(WAPD-5)

```
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
            WAPD-TM-1013, Jan. 1975.
ITS         WAPD-05
BRL          Parallel    Unheated
LTC          Triangular
UNT          British
GMT
```

```
          NRT        20
          NRH        20
          PRP         0.340
          DRH          0.250
          DRU
          SRW          0.090
          ZHT        54.000
          AFT          0.0001    (?.???      Report)
          RCC          0.215     (.5*DRH+SRW)
          NRC          5           4
          EOD
APS        Uniform
NAP
APF        (Z/Zh)     (Q/Qa)
NTC          2
ZTC        53.750     50.000
NZG          6
NKG          1
CKG          0.0
ZGS        (Type)     (Z)
            1          3.0
            1          15.0
            1          27.0
            1          39.0
            1          51.0
            1          54.0
NWW
PWW
DWW
RNS
                  1    2    3    4
                5    6    7    8
              9   10   11   12
            13   14   15   16
          17   18   19   20
RPF
                              1.000     1.000     1.000     1.000
                          1.000     1.000     1.000     1.000
                      1.000     1.000     1.000     1.000
                  1.000     1.000     1.000     1.000
              1.000     1.000     1.000     1.000
TMP          0.005
IRC         0
ICC         0
EOD

WAPD-05    (WH)           3
( SN     RN       PE       TI       GI       QA       N1)
(                psi       F Ml/hf2 MB/hf2          )
    500 3        2000.0   499.5    0.499    0.279    5.1
    500 4        2000.0   399.8    0.508    0.337    5.1
    500 5        2000.0   397.9    1.002    0.524    5.1
```

(WAPD-6)

```
REF        LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
           WAPD-TM-1013, Jan. 1975.
ITS        WAPD-06
BRL         Parallel   Unheated
LTC         Triangular
UNT         British
GMT
          NRT        20
          NRH        20
          PRP         0.340
          DRH          0.250
          DRU
          SRW          0.090
          ZHT        54.000
          AFT          0.0001    (?.???      Report)
          RCC          0.215     (.5*DRH+SRW)
          NRC          5           4
          EOD
APS        Uniform
NAP
```

APF (Z/Zh) (Q/Qa)
NTC 2
ZTC 53.630 49.000
NZG 5
NKG 1
CKG 0.0
ZGS (Type) (Z)

	(Type)	(Z)
	1	3.0
	1	15.0
	1	27.0
	1	39.0
	1	51.0

NWW
PWW
DWW
RNS

```
                    1     2     3     4
                 5     6     7     8
              9    10    11    12
          13    14    15    16
      17    18    19    20
```

RPF

```
                              1.000     1.000     1.000     1.000
                         1.000     1.000     1.000     1.000
                    1.000     1.000     1.000     1.000
               1.000     1.000     1.000     1.000
          1.000     1.000     1.000     1.000
```

TMP 0.005
IRC 0
ICC 0
EOD

WAPD-06 (WH) 23

(SN	RN	PE	TI	GI	QA	N1)
(		psi	F	Ml/hf2	MB/hf2	)
600	4	2000.0	601.7	0.497	0.211	5.1
600	5	2000.0	498.6	0.501	0.275	5.1
600	6	2000.0	198.4	0.503	0.422	5.1
600	7	2000.0	598.3	0.997	0.266	5.1
600	8	2000.0	501.2	0.998	0.392	5.1
600	9	2000.0	499.5	1.009	0.404	5.1
600	10	2000.0	596.9	1.501	0.332	5.1
600	11	2000.0	501.2	1.499	0.521	5.1
600	12	2000.0	572.1	2.090	0.481	5.1
600	13	2000.0	499.5	2.000	0.635	5.1
600	14	2000.0	572.9	3.070	0.620	5.1
600	15	2000.0	496.9	3.010	0.855	5.1
600	16	2000.0	567.5	3.620	0.713	5.1
600	18	1600.0	497.7	0.500	0.309	5.1
600	19	1600.0	500.3	0.998	0.405	5.1
600	20	1600.0	499.4	2.000	0.579	5.1
600	24	1200.0	501.9	0.498	0.330	5.1
600	25	1200.0	401.6	0.500	0.392	5.1
600	26	1200.0	197.2	0.502	0.496	5.1
600	27	1200.0	500.2	0.998	0.468	5.1
600	28	1200.0	398.8	1.000	0.573	5.1
600	29	1200.0	501.9	1.991	0.591	5.1
600	30	1200.0	500.2	2.990	0.751	5.1

(WAPD-7)

REF LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
WAPD-TM-1013, Jan. 1975.
ITS WAPD-07
BRL Parallel Unheated
LTC Triangular
UNT British
GMT

NRT	20
NRH	20
PRP	0.340
DRH	0.250
DRU	
SRW	0.090
ZHT	54.000

```
           AFT         0.0001    (?.???      Report)
           RCC          0.215     (.5*DRH+SRW)
           NRC          5           4
           EOD
APS         Uniform
NAP
APF         (Z/Zh)     (Q/Qa)
NTC           2
ZTC         53.630      53.000
NZG           4
NKG           1
CKG          0.0
ZGS         (Type)     (Z)
             1          9.0
             1          21.0
             1          33.0
             1          45.0
NWW
PWW
DWW
RNS
                   1    2    3    4
                 5    6    7    8
               9   10   11   12
            13   14   15   16
          17   18   19   20
RPF
                             1.000     1.000     1.000     1.000
                         1.000     1.000     1.000     1.000
                     1.000     1.000     1.000     1.000
                 1.000     1.000     1.000     1.000
             1.000     1.000     1.000     1.000
TMP           0.005
IRC          0
ICC          0
EOD

WAPD-07     (WH)          35
( SN     RN        PE        TI        GI        QA        N1)
(                 psi           F Ml/hf2 MB/hf2           )
    700 4          2000.0   603.1    0.498    0.188    5.1
    700 5          2000.0   498.6    0.501    0.236    5.1
    700 6          2000.0   398.8    0.502    0.272    5.1
    700 7          2000.0   598.3    0.973    0.204    5.1
    700 8          2000.0   598.3    1.001    0.208    5.1
    700 9          2000.0   499.5    1.005    0.345    5.1
    700 10         2000.0   499.5    1.001    0.353    5.1
    700 11         2000.0   499.5    1.013    0.355    5.1
    700 12         2000.0   396.0    1.009    0.447    5.1
    700 13         2000.0   402.6    1.005    0.445    5.1
    700 14         2000.0   399.8    1.003    0.485    5.1
    700 15         2000.0   198.4    1.012    0.630    5.1
    700 16         2000.0   499.5    1.502    0.486    5.1
    700 17         2000.0   396.0    1.518    0.630    5.1
    700 18         2000.0   197.4    1.517    0.816    5.1
    700 19         2000.0   569.1    2.050    0.460    5.1
    700 20         2000.0   499.5    2.010    0.616    5.1
    700 21         2000.0   404.5    2.010    0.806    5.1
    700 22         2000.0   195.4    2.020    0.988    5.1
    700 23         2000.0   398.8    3.020    1.038    5.1
    700 24         1600.0   500.3    1.009    0.326    5.1
    700 25         1600.0   497.7    2.000    0.518    5.1
    700 26         1600.0   500.3    3.010    0.695    5.1
    700 29         1200.0   500.2    0.499    0.297    5.1
    700 30         1200.0   399.8    0.502    0.364    5.1
    700 31         1200.0   198.2    0.503    0.460    5.1
    700 32         1200.0   501.9    1.013    0.389    5.1
    700 33         1200.0   496.8    0.998    0.419    5.1
    700 34         1200.0   400.7    1.009    0.498    5.1
    700 35         1200.0   197.2    1.004    0.632    5.1
    700 36         1200.0   497.6    2.000    0.492    5.1
    700 37         1200.0   400.7    2.010    0.695    5.1
    700 38         1200.0   203.2    2.020    1.014    5.1
    700 39         1200.0   495.9    3.010    0.669    5.1
    700 40         1200.0   400.7    3.010    0.864    5.1
```

```
(WAPD-8)
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
             WAPD-TM-1013, Jan. 1975.
ITS          WAPD-08
BRL           Parallel   Unheated
LTC           Triangular
UNT           British
GMT
             NRT          20
             NRH          20
             PRP           0.340
             DRH            0.250
             DRU
             SRW            0.090
             ZHT          54.000
             AFT           0.0001     (?.???       Report)
             RCC           0.215      (.5*DRH+SRW)
             NRC           5              4
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             3
ZTC           53.500      52.875       43.500
NZG             4
NKG             1
CKG             0.0
ZGS           (Type)      (Z)
              1           9.0
              1           21.0
              1           33.0
              1           45.0
NWW
PWW
DWW
RNS
                        1    2    3    4
                      5    6    7    8
                    9   10   11   12
                 13   14   15   16
             17   18   19   20
RPF
                                 1.500     1.500     1.500     1.500
                             1.250     1.250     1.250     1.250
                         1.000     1.000     1.000     1.000
                     0.750     0.750     0.750     0.750
                 0.500     0.500     0.500     0.500
TMP             0.005
IRC           0
ICC           0
EOD

WAPD-08     (WH)            42
( SN     RN         PE          TI          GI          QA          N1)
(                  psi           F MI/hf2 MB/hf2                  )
      800 5          2000.0    600.3     0.500      0.139      5.1
      800 6          2000.0    497.8     0.440      0.185      5.1
      800 7          2000.0    399.8     0.499      0.254      5.1
      800 8          2000.0    200.4     0.498      0.335      5.1
      800 9          2000.0    599.6     0.965      0.208      5.1
      800 10         2000.0    596.9     1.000      0.194      5.1
      800 11         2000.0    500.4     0.995      0.290      5.1
      800 12         2000.0    500.4     1.000      0.302      5.1
      800 13         2000.0    402.6     0.990      0.384      5.1
      800 14         2000.0    400.7     0.995      0.395      5.1
      800 15         2000.0    399.8     1.000      0.371      5.1
      800 16         2000.0    211.4     0.990      0.561      5.1
      800 17         2000.0    606.4     1.490      0.238      5.1
      800 18         2000.0    500.4     1.500      0.401      5.1
      800 19         2000.0    397.9     1.495      0.535      5.1
      800 20         2000.0    595.5     2.000      0.306      5.1
      800 21         2000.0    499.5     2.000      0.494      5.1
      800 22         2000.0    403.5     2.000      0.660      5.1
      800 23         2000.0    399.8     2.000      0.630      5.1
```

800 24	2000.0	599.0	3.000	0.398	5.1
800 25	2000.0	501.2	2.990	0.645	5.1
800 26	2000.0	500.4	3.880	0.780	5.1
800 28	1600.0	500.3	0.498	0.195	5.1
800 29	1600.0	497.7	1.000	0.294	5.1
800 30	1600.0	497.7	1.000	0.267	5.1
800 31	1600.0	499.4	1.495	0.350	5.1
800 32	1600.0	499.4	2.000	0.422	5.1
800 33	1600.0	500.3	3.000	0.567	5.1
800 37	1200.0	498.5	0.499	0.221	5.1
800 38	1200.0	397.9	0.497	0.252	5.1
800 39	1200.0	198.2	0.497	0.342	5.1
800 40	1200.0	498.5	0.995	0.308	5.1
800 41	1200.0	498.5	1.000	0.299	5.1
800 42	1200.0	397.9	0.993	0.385	5.1
800 43	1200.0	397.0	1.000	0.348	5.1
800 44	1200.0	396.0	1.000	0.345	5.1
800 45	1200.0	499.4	1.495	0.349	5.1
800 46	1200.0	400.7	1.500	0.440	5.1
800 47	1200.0	497.6	1.990	0.403	5.1
800 48	1200.0	397.0	2.000	0.533	5.1
800 49	1200.0	498.5	3.000	0.530	5.1
800 50	1200.0	498.5	3.680	0.605	5.1

(WAPD-9)

```
REF       LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
          WAPD-TM-1013, Jan. 1975.
ITS       WAPD-09
BRL        Parallel   Unheated
LTC        Triangular
UNT        British
GMT
          NRT         20
          NRH         20
          PRP          0.340
          DRH           0.250
          DRU
          SRW           0.060
          ZHT         54.000
          AFT          0.0001    (?.???      Report)
          RCC          0.175     (.5*DRH+SRW)
          NRC          5           4
          EOD
APS        Uniform
NAP
APF        (Z/Zh)     (Q/Qa)
NTC          3
ZTC        53.500     52.875      43.500
NZG          4
NKG          1
CKG          0.0
ZGS        (Type)     (Z)
            1          9.0
            1          21.0
            1          33.0
            1          45.0
NWW
PWW
DWW
RNS
                  1    2    3    4
                5    6    7    8
              9   10   11   12
           13   14   15   16
         17   18   19   20
RPF
                                 1.500     1.500     1.500     1.500
                             1.250     1.250     1.250     1.250
                         1.000     1.000     1.000     1.000
                     0.750     0.750     0.750     0.750
                 0.500     0.500     0.500     0.500
TMP          0.005
IRC         0
ICC         0
```

```
EOD

WAPD-09     (WH)           45
( SN     RN        PE         TI        GI        QA       N1)
(                 psi          F Ml/hf2 MB/hf2           )
      900 7          2005.0   599.0    0.574    0.128     5.1
      900 8          2000.0   499.5    0.572    0.205     5.1
      900 9          1990.0   497.8    0.574    0.189     5.1
      900 10         2002.0   497.8    0.572    0.190     5.1
      900 11         2005.0   404.5    0.572    0.242     5.1
      900 12         2000.0   398.8    0.571    0.258     5.1
      900 13         1998.0   398.8    0.571    0.249     5.1
      900 14         2005.0   199.4    0.575    0.356     5.1
      900 15         2000.0   597.6    1.109    0.187     5.1
      900 16         1995.0   500.4    1.145    0.314     5.1
      900 17         2000.0   498.6    1.145    0.309     5.1
      900 18         2005.0   498.6    1.148    0.306     5.1
      900 19         2000.0   401.7    1.142    0.406     5.1
      900 20         2000.0   401.7    1.151    0.404     5.1
      900 21         1990.0   398.9    1.143    0.423     5.1
      900 22         2000.0   197.4    1.152    0.603     5.1
      900 23         2000.0   598.3    1.719    0.251     5.1
      900 24         2005.0   504.7    1.720    0.409     5.1
      900 25         2000.0   501.2    1.717    0.424     5.1
      900 26         2000.0   399.8    1.727    0.499     5.1
      900 27         2000.0   199.4    1.725    0.833     5.1
      900 28         1995.0   598.2    2.297    0.301     5.1
      900 29         2000.0   499.5    2.297    0.524     5.1
      900 30         2000.0   403.5    2.301    0.632     5.1
      900 31         2000.0   397.9    2.306    0.700     5.1
      900 32         2000.0   200.4    2.303    1.027     5.1
      900 33         2002.0   599.7    3.153    0.379     5.1
      900 34         1995.0   501.2    3.444    0.707     5.1
      900 35         2000.0   501.2    3.425    0.680     5.1
      900 36         2000.0   397.9    3.459    0.967     5.1
      900 38         1595.0   499.4    0.572    0.184     5.1
      900 39         1605.0   497.7    1.145    0.291     5.1
      900 40         1605.0   396.5    1.142    0.367     5.1
      900 41         1605.0   500.3    2.298    0.462     5.1
      900 42         1600.0   499.4    3.441    0.605     5.1
      900 46         1200.0   499.4    0.571    0.202     5.1
      900 47         1195.0   400.7    0.569    0.235     5.1
      900 48         1198.0   500.2    1.142    0.291     5.1
      900 49         1200.0   402.6    1.153    0.375     5.1
      900 50         1205.0   397.9    1.141    0.382     5.1
      900 51         1200.0   198.2    1.151    0.581     5.1
      900 52         1207.0   498.5    2.286    0.393     5.1
      900 53         1195.0   406.3    2.291    0.615     5.1
      900 54         1204.0   499.4    3.433    0.537     5.1
      900 55         1210.0   399.8    3.448    0.807     5.1
```

(WAPD-10)

```
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
             WAPD-TM-1013, Jan. 1975.
ITS          WAPD-10
BRL           Parallel   Unheated
LTC           Triangular
UNT           British
GMT
             NRT           20
             NRH           20
             PRP            0.340
             DRH             0.250
             DRU
             SRW             0.090
             ZHT           54.000
             AFT            0.0001     (?.???       Report)
             RCC            0.215      (.5*DRH+SRW)
             NRC            5             4
             EOD
APS           Uniform
NAP
APF           (Z/Zh)      (Q/Qa)
NTC             3
```

```
ZTC         53.500    52.875    43.500
NZG           4
NKG           1
CKG           0.0
ZGS         (Type)     (Z)
            1          9.0
            1          21.0
            1          33.0
            1          45.0
NWW
PWW
DWW
RNS
                  1    2    3    4
                5    6    7    8
              9   10   11   12
            13   14   15   16
          17   18   19   20
RPF
                          1.000    1.000    1.000    1.000
                       1.000    1.000    1.000    1.000
                    1.000    1.000    1.000    1.000
                 1.000    1.000    1.000    1.000
              1.000    1.000    1.000    1.000
TMP           0.005
IRC          0
ICC          0
EOD

WAPD-10    (WH)          17
( SN    RN       PE        TI       GI       QA      N1)
(               psi        F Ml/hf2 MB/hf2        )
   1000   5        2000.0    599.0    0.499             0.196     5.1
   1000   6        2000.0    498.6    0.499             0.241     5.1
   1000   7        2000.0    399.8    0.500             0.295     5.1
   1000   8        2000.0    200.4    0.500             0.402     5.1
   1000   9        2000.0    600.3    0.966             0.245     5.1
   1000   10       2000.0    500.4    0.995             0.368     5.1
   1000   11       2000.0    499.5    0.998             0.357     5.1
   1000   12       2000.0    400.7    1.000             0.492     5.1
   1000   13       1995.0    498.6    1.497             0.519     5.1
   1000   14       2000.0    496.9    2.003             0.633     5.1
   1000   16       1595.0    500.3    0.498             0.283     5.1
   1000   17       1603.0    500.3    0.996             0.385     5.1
   1000   21       1195.0    496.8    0.495             0.323     5.1
   1000   22       1200.0    397.0    0.499             0.378     5.1
   1000   23       1200.0    198.2    0.500             0.468     5.1
   1000   24       1195.0    500.2    0.992             0.437     5.1
   1000   25       1205.0    398.8    0.998             0.522     5.1
```

(WAPD-11)

```
REF         LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
            WAPD-TM-1013, Jan. 1975.
ITS         WAPD-11
BRL          Parallel   Unheated
LTC          Triangular
UNT          British
GMT
            NRT         20
            NRH         20
            PRP          0.340
            DRH           0.250
            DRU
            SRW           0.090
            ZHT         54.000
            AFT          0.0001    (?.???      Report)
            RCC          0.215     (.5*DRH+SRW)
            NRC          5            4
            EOD
APS          Uniform
NAP
APF          (Z/Zh)     (Q/Qa)
NTC            1
```

```
ZTC          53.630
NZG            4
NKG            1
CKG            0.0
ZGS          (Type)      (Z)
              1           9.0
              1          21.0
              1          33.0
              1          45.0
NWW
PWW
DWW
RNS
                    1    2    3    4
                  5    6    7    8
                9   10   11   12
             13   14   15   16
           17   18   19   20
RPF
                             1.000     1.000     1.000     1.000
                         1.000     1.000     1.000     1.000
                     1.000     1.000     1.000     1.000
                 1.000     1.000     1.000     1.000
             1.000     1.000     1.000     1.000
TMP            0.005
IRC           0
ICC           0
EOD

WAPD-11     (WH)           26
( SN      RN        PE         TI         GI        QA       N1)
(                   psi         F Ml/hf2 MB/hf2           )
    1100          5        2000.0   599.0    0.498     0.183     5.1
    1100          6        2000.0   499.5    0.497     0.239     5.1
    1100          7        2000.0   397.9    0.498     0.276     5.1
    1100          8        2000.0   200.4    0.502     0.368     5.1
    1100          9        2000.0   600.3    1.006     0.230     5.1
    1100         10        2000.0   498.6    1.007     0.303     5.1
    1100         11        2000.0   498.6    0.996     0.297     5.1
    1100         12        2000.0   400.7    0.996     0.394     5.1
    1100         13        2000.0   400.7    0.999     0.396     5.1
    1100         14        2000.0   200.4    0.995     0.555     5.1
    1100         15        2000.0   599.6    1.508     0.304     5.1
    1100         16        2000.0   498.6    1.502     0.410     5.1
    1100         17        2000.0   397.9    1.501     0.560     5.1
    1100         18        2000.0   569.8    2.008     0.376     5.1
    1100         19        2000.0   500.4    2.003     0.520     5.1
    1100         20        2000.0   401.7    2.002     0.672     5.1
    1100         24        1200.0   499.4    0.497     0.322     5.1
    1100         25        1200.0   399.8    0.498     0.367     5.1
    1100         26        1200.0   199.2    0.500     0.452     5.1
    1100         27        1200.0   499.4    1.003     0.423     5.1
    1100         28        1200.0   496.8    0.995     0.431     5.1
    1100         29        1200.0   397.9    0.996     0.526     5.1
    1100         30        1200.0   199.2    0.999     0.629     5.1
    1100         31        1200.0   498.5    1.502     0.491     5.1
    1100         32        1200.0   399.8    1.500     0.570     5.1
    1100         33        1200.0   498.5    2.005     0.570     5.1
```

(WAPD-13)

```
REF          LeTourneau, B.W., et. al., CHF and Pressure Drop Tests with ...
             WAPD-TM-1013, Jan. 1975.
ITS          WAPD-13
BRL           Parallel   Unheated
LTC           Triangular
UNT           British
GMT
             NRT          20
             NRH          20
             PRP           0.340
             DRH            0.280
             DRU
             SRW            0.045
             ZHT          54.000
```

```
          AFT        0.0001    (?.???    Report)
          RCC        0.185     (.5*DRH+SRW)
          NRC        5            4
          EOD
APS        Uniform
NAP
APF        (Z/Zh)     (Q/Qa)
NTC          1
ZTC        53.500
NZG          4
NKG          1
CKG          0.0
ZGS        (Type)     (Z)
           1          9.0
           1          21.0
           1          33.0
           1          45.0
NWW
PWW
DWW
RNS
                     1    2    3    4
                   5    6    7    8
                 9   10   11   12
              13   14   15   16
          17   18   19   20
RPF
                              1.000    1.000    1.000    1.000
                          1.000    1.000    1.000    1.000
                      1.000    1.000    1.000    1.000
                  1.000    1.000    1.000    1.000
              1.000    1.000    1.000    1.000
TMP          0.005
IRC        0
ICC        0
EOD

WAPD-13    (WH)         37
( SN    RN      PE       TI      GI       QA      N1)
(              psi       F Ml/hf2 MB/hf2           )
    1300        5      2000.0   198.7   0.503   0.301   5.1
    1300        6      2000.0   401.8   0.503   0.222   5.1
    1300        7      2000.0   500.4   0.503   0.189   5.1
    1300        8      2000.0   599.7   0.504   0.153   5.1
    1300        9      2000.0   199.2   1.006   0.481   5.1
    1300       10      2000.0   397.5   1.008   0.332   5.1
    1300       11      2000.0   400.3   1.015   0.330   5.1
    1300       12      2000.0   501.0   1.008   0.253   5.1
    1300       13      2000.0   501.0   1.001   0.284   5.1
    1300       14      2000.0   499.7   1.001   0.248   5.1
    1300       15      2000.0   598.4   1.014   0.187   5.1
    1300       16      2000.0   599.5   1.004   0.192   5.1
    1300       17      2000.0   500.5   1.512   0.336   5.1
    1300       18      2000.0   600.1   1.520   0.225   5.1
    1300       19      2000.0   216.6   1.992   0.808   5.1
    1300       20      2000.0   403.4   2.002   0.596   5.1
    1300       21      2000.0   498.4   2.005   0.436   5.1
    1300       22      2000.0   600.4   2.015   0.261   5.1
    1300       23      2000.0   402.0   2.991   0.800   5.1
    1300       24      2000.0   500.5   3.014   0.603   5.1
    1300       25      2000.0   602.4   3.029   0.365   5.1
    1300       26      2000.0   399.3   3.990   0.926   5.1
    1300       27      2000.0   500.1   4.005   0.740   5.1
    1300       29      1600.0   497.9   0.498   0.212   5.1
    1300       30      1600.0   499.9   1.005   0.308   5.1
    1300       31      1600.0   500.0   2.004   0.455   5.1
    1300       32      1600.0   499.8   3.008   0.566   5.1
    1300       36      1200.0   198.5   0.501   0.346   5.1
    1300       37      1200.0   400.2   0.501   0.292   5.1
    1300       38      1200.0   498.6   0.503   0.242   5.1
    1300       39      1200.0   207.6   1.003   0.550   5.1
    1300       40      1200.0   399.6   0.998   0.428   5.1
    1300       41      1200.0   500.8   1.004   0.356   5.1
    1300       42      1200.0   397.5   2.002   0.631   5.1
    1300       43      1200.0   499.3   2.000   0.477   5.1
    1300       44      1200.0   401.6   2.999   0.779   5.1
```

```
     1300          45          1200.0   501.0    2.995    0.583    5.1
```

(WAPD-14)

```
REF          Fighetti, C. F. and Reddy, D. G., Parametric Study of CHF Data,
            EPRI-NP-2609, Vol. 3, Pt. 2, Sep. 1982.
ITS         EPRI-601
BRL          Circular   Unheated
LTC          Mixed1
UNT           British
GMT
            NRT          19
            NRH          19
            PRP
            DRH            0.780
            DRU
            SRW            0.060
            ZHT           72.000
            AFT            3.9184     (3.918       Report)
            RCC
            DTF            4.068
            EOD
APS          Uniform
NAP
APF          (Z/Zh)      (Q/Qa)
NTC            1
ZTC          71.250
NZG            7
NKG            1
CKG            1.000       (0.000        Report)
ZGS          (Type)      (Z)
             1             9.00
             1            18.00
             1            27.00
             1            36.00
             1            45.00
             1            54.00
             1            63.00
NWW
PWW
DWW
RNS          (NRing DRing PRod)                                                                  (NRing DRing PRod)
             1   3.1680   0.81994      1    2    3    4    5    6    7    8    9   10   11   12    (1   3.1680   0.8294   Report)
             2   1.63988 0.81994     13   14   15   16   17   18                                   (2   1.6400   0.8587   Report)
             3   0.0000   0.0000      19                                                          (3   0.0000   0.0000   Report)
RPF
             1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117   1.117
             0.803   0.803   0.803   0.803   0.803   0.803
             0.778
TMP           0.005
IRC          0
ICC          0
EOD

EPRI-601    (AE)            34
( SN      RN        PE          TI          GI          QA        N1)
(                  psi            F Ml/hf2 MB/hf2          )
   601       1    1000.   526.0   0.505   0.207    19.0
   601       2    1000.   495.0   0.504   0.216    19.0
   601       3    1000.   449.0   0.506   0.227    19.0
   601       4    1000.   412.0   0.500   0.233    19.0
   601       5    1000.   363.0   0.507   0.257    19.0
   601       6    1000.   526.0   0.996   0.314    19.0
   601       7    1000.   490.0   0.996   0.322    19.0
   601       8    1000.   452.0   0.996   0.333    19.0
   601       9    1000.   410.0   0.993   0.349    19.0
   601      10    1000.   365.0   1.002   0.368    19.0
   601      11    1000.   526.0   2.006   0.403    19.0
   601      12    1000.   490.0   1.991   0.419    19.0
   601      13    1000.   452.0   1.992   0.439    19.0
   601      18     750.   491.0   0.496   0.227    19.0
   601      19     750.   441.0   0.503   0.242    19.0
   601      20     750.   377.0   0.500   0.254    19.0
   601      21     750.   493.0   0.995   0.363    19.0
   601      22     750.   443.0   0.994   0.384    19.0
```

601	23	750.	372.0	0.996	0.403	19.0
601	24	750.	492.0	2.024	0.461	19.0
601	27	1200.	544.0	0.497	0.190	19.0
601	28	1200.	491.5	0.510	0.206	19.0
601	29	1200.	423.0	0.500	0.218	19.0
601	30	1200.	543.0	1.008	0.284	19.0
601	31	1200.	421.0	1.002	0.313	19.0
601	32	1200.	487.5	0.993	0.289	19.0
601	33	1200.	543.0	1.989	0.373	19.0
601	34	1200.	492.0	2.005	0.402	19.0
601	35	1200.	431.0	2.018	0.449	19.0
601	36	1200.	543.0	3.004	0.457	2.0
601	38	500.	452.0	0.499	0.245	19.0
601	39	500.	441.0	0.996	0.395	19.0
601	40	500.	368.0	0.990	0.425	19.0
601	41	500.	359.0	0.508	0.260	19.0

부록-5. CHF 예측 모형

(가) Bowring mixed flow 상관식

Functional form: $q''_{CHF} = \dfrac{A + B\cdot\Delta h_{sub}}{C + Z\cdot Y}$	$B = 0.25\cdot G\cdot d_{he}\exp\left(-0.2\cdot G\right)$, $C = 60\cdot d_{hy}^{0.57}\cdot G^{0.27}\cdot\left(1+\dfrac{Y-1}{G+1}\right)$
(1) at P < 1250 psia, $A = \dfrac{242.4\cdot F_1\cdot G\cdot d_{he}}{1+\dfrac{1.52\left(F_p d_{he}\right)^2 G}{F_2\cdot d_{hy}^{1.3}\cdot\left\{1+G\cdot\left(0.8F_p\dfrac{d_{he}}{d_{hy}}-1\right)\right\}}}$, $F_1 = \left[1-0.04P_T\left(1+0.47P_T^2\right)^{0.5}\right]^2$ $F_2 = 0.45+1.25P_T$ for P<415 $= 0.424+1.959P_T$ $-1.556P_T^2$ for 415<P<650 $=\left(3.2-P_T\right)\times$ $\left(0.32+0.135P_T\right)$ for P>650 psia	(2) at P > 1250 psia $A = A_2 + \left(2.250-P_T\right)\cdot\left(A_1-A_2\right)$ where, $A_1 = \dfrac{242.4\times 0.8726\cdot G\cdot d_{he}}{1+\dfrac{1.52\left(F_p d_{he}\right)^2 G}{0.953 d_{hy}^{1.3}\left\{1+G\left(0.8F_p\dfrac{d_{he}}{d_{hy}}-1\right)\right\}}}$ $A_2 = 18.0\cdot G + \dfrac{9.5Gd_{he}}{0.1+G}$
Applicable ranges: Pressure (6 to 155) bars, Mass velocity (50 to 4000) kg/m^2/s, Inlet temperature (subcooled), Channel hydraulic diameter (7.6 to 35.6) mm, Heated length (1.5 to 4.6) m, F_{xy} (1 to 1.32), F_z (1 to 1.38)	
Parameters: P_T = P/1000 (P = pressure in psia), d_{hy} = channel hydraulic diameter, in d_{he} = heated equivalent diameter, in $\triangle h_{sub}$ = inlet subcooling, Btu/lb q''_{CHF} = critical heat flux, MBtu/hr/ft^2	G = mass flux, Mlb/h/ft^2 F_p = radial peaking factor in the bundle, Y = Bowring's Y factor, $Y = \dfrac{1}{Z}\int_0^Z \dfrac{q''(z')}{q''(Z)}dz'$.

(나) PI-3P 상관식

Functional form:

$$q''_{CHF} = F \cdot \frac{1 + q''_{CHF}\, F_{xy}}{k_2 + q''_{CHF}\, F_{xy}} \cdot \left(\frac{3 + 2P_r}{2 + \chi_{in} + k_3 F_{xy} q''_{CHF}} - 1 \right)^{k_1} \cdot F_g$$

$$F = 1.75 \times \frac{f_A \cdot f_B}{f_C \cdot f_D}$$

$$f_A = \left(\frac{1}{1 + (1 - P_r)^2 \cdot \left(\frac{60}{G} \right)} + 0.0013 \cdot GP_r \right)^{0.65}$$

$$f_B = 1.4 - P_r - \chi_{in}$$

$$f_C = (2 - P_r) \cdot \left(P_r^{1.6} + 0.16 \right) \cdot \left(1 + \frac{5}{16 + 10^6 \cdot P_r^3} \right)$$

$$f_D = 1 + \max\{0, X\}$$

$$X = 0.005 \cdot \frac{Z_{CHF}}{d_{he} \cdot F_{xy}} + 3.2 \cdot \left(F_z^{0.6} - 1 \right)$$

$$k_1 = 0.26 + \frac{0.02}{0.1 + P_r^2}$$

$$k_2 = 1.96 + \frac{0.04}{(0.1 + P_r)^2}$$

$$k_3 = \frac{4}{G \cdot h_{fg}} \cdot \frac{Z_{CHF}}{d_{he} \cdot F_{xy}}$$

Applicable ranges: Pressure (2.8 to 187) bars,
Mass velocity (36 to 7500) kg/m^2/s,
Inlet quality (−1.1 to 0.3), Local quality (greater than −0.2),
Channel hydraulic diameter (5 to 19) mm,
Heated length (0.4 to 4.4) m, P/D ratio (1.02 to 2.48),
F_{xy} (1 to 1.81), F_z (1 to 1.68)

Parameters:

P_r = relative pressure (= P/(221.15 bar))
G = bundle average mass velocity, kg/m^2/s
d_{he} = subchannel equivalent diameter, m
Z_{CHF} = distance from inlet to CHF location, m
h_{fg} = latent heat, MJ/kg
F_z = axial peaking factor
F_{xy} = radial peaking factor
q''_{CHF} = critical heat flux, MW/m^2

(다) KfK-3 상관식

<table>
<tr>
<td>Functional form:
$$q''_{CHF} = \frac{A + B \cdot \Delta h_{sub}}{C + Z \cdot Y}$$</td>
<td rowspan="2">$$A = \frac{0.25 \cdot G F_p d_{hy} h_{fg} F_1 Q_1}{1 + Q_2 F_2 G \left(d_{hy} F_p \right)}$$
$$F_1 = P_r^{0.982} \exp\left[1.17 \left(1 - P_r \right) \right]$$
$$F_2 = P_r^{0.841} \exp\left[1.424 \left(1 - P_r \right) \right]$$
$$F_3 = P_r^{1.851} \exp\left[1.241 \left(1 - P_r \right) \right]$$</td>
</tr>
<tr>
<td>$$B = 0.25 \cdot G \left(d_{hy} F_p \right)$$
$$C = C'V \left(1 + \frac{Y - 1}{1 + G} \right), \quad C' = \frac{Q_4 F_3 \sqrt{G d_{hy} F_p}}{d_{hy}}$$
Q_1=1.748, Q_2=7.540, Q_4=8.783</td>
</tr>
<tr>
<td>(1) for grid type spacer,
$$V = -0.252 - 2.789 e^{-3.874G} + 1.915 e^{-0.234G}$$
,for G≤3.5 Mlb/hr/ft^2
$V = 0.59$, otherwise.</td>
<td>(2) for wire-wrap spacer,
$$V = 1 - FF \left[0.336 + 0.09G - 0.697 e^{-2.68G} \right]$$
$$FF = 2.6695 \left(F^{0.915} - 1 \right)$$
$$F = \sqrt{\frac{p}{d}} + \left[7.6 \frac{\left(p/d \right)^3}{H/d} \right]^{2.16} n_s^{1.58}$$</td>
</tr>
<tr>
<td colspan="2">Applicable ranges: (grid)/(single wire)/(six spiral ribs) spacers
Pressure (29 to 160)/(70 to 100)/(70 to 160) bars,
Mass velocity (70 to 6000)/(650 to 5550)/(1000 to 7000) kg/m^2/s,
Steam quality (-0.52 to 0.96)/(-0.04 to 0.53)/(-0.53 to 0.09) ,
Pitch to diameter, p/d, ratio (1.02 to 1.36)/(1.05 to 1.41)/(1.116)</td>
</tr>
<tr>
<td>Parameters:
n_s = number of wire starts
d_{hy} = coolant channel hydraulic diameter, in
F_p = radial peaking factor in the bundle
P_r = P/1000 (P = pressure, psia)
q''_{CHF} = critical heat flux, MBtu/hr/ft^2</td>
<td>G = mass flux (Mlb/h/ft^2)
Z = distance from channel inlet, in
$\triangle h_{sub}$ = inlet subcooling, Btu/lb
Y = Bowring's Y factor
V = grid spacer parameter</td>
</tr>
</table>

(라) EPRI-1 상관식

Functional form: $q''_{CHF} = \dfrac{AF_a - \chi_{in}}{CF_cF_gC_{NU} + \left[\dfrac{\chi - \chi_{in}}{q''_{loc}}\right]}$	
$A = a_1P_r^{a_2}G^{(a_5+a_7P_r)}$, $C = a_3P_r^{a_4}G^{(a_6+a_8P_r)}$ a_1 = 0.5328, a_2 = 0.1212, a_3 = 1.6151, a_4 = 1.4066, a_5=−0.3040, a_6 = 0.4843, a_7 =−0.3285, a_8 =−2.0749	F_a = 1 & F_c = 1, for matrix channel $F_a = G^{0.1}$ & $F_c = 1.183G^{0.1}$, for corner channel $F_g = 0.7 + 0.3\ C_g$ $C_{NU} = 1 + \dfrac{Y-1}{1+G}$
Applicable ranges: Pressure (13.8 to 168.9) bars, Mass velocity (271 to 6103) kg/m^2/s, Local quality (−0.25 to 0.75) , Channel hydraulic diameter (8.9 to 14.0) mm, Heated length (0.76 to 4.27) m, Rod diameter (9.7 to 17.3) mm,	
Parameters: C_g = grid loss coefficient q''_{CHF} = critical heat flux, MBtu/h/ft^2 q''_{loc} = local heat flux, MBtu/h/ft^2 G = local mass velocity, Mlb/h/ft^2	P_r = reduced pressure ($P/P_{critical}$) Z_{CHF} = distance from inlet to CHF location χ = local thermodynamic quality χ_{in} = inlet thermodynamic quality

(마) Bowring tube상관식[11]:

$$q''_c = \frac{A + B\left(h_f - h_{in}\right)}{C + L}$$

여기서, $A = \dfrac{2.317 \cdot \left(\dfrac{h_{fg} \cdot G \cdot D}{4}\right) \cdot F_1}{1 + 0.0143 \cdot F_2 \cdot D^{0.5} \cdot G}$, $B = \dfrac{GD}{4}$,

$$C = \frac{0.077 \cdot F_3 \cdot D \cdot G}{1 + 0.347 \cdot F_4 \cdot \left(\dfrac{G}{1356}\right)^n}, \qquad n = 2.0 - 0.5 \cdot P_r, \quad P_r = 0.145 \cdot P$$

when $P_r<1$;

$$F_1 = \frac{1}{1.917}\left(P_r^{18.942} e^{20.890(1-P_r)} + 0.917\right),$$

$$\frac{F_1}{F_2} = \frac{1}{1.309}\left(P_r^{1.316} e^{2.444(1-P_r)} + 0.309\right)$$

$$F_3 = \frac{1}{1.667}\left(P_r^{17.023} e^{16.658(1-P_r)} + 0.667\right), \qquad \frac{F_4}{F_3} = P_r^{1.649}$$

when $P_r \geq 1$;

$$F_1 = P_r^{-0.368} e^{0.648(1-P_r)}, \qquad \frac{F_1}{F_2} = P_r^{-0.448} e^{0.245(1-P_r)}$$

$$F_3 = P_r^{0.219}, \qquad \frac{F_4}{F_3} = P_r^{1.649}$$

q''_c : critical heat flux (kW/m^2)
D: channel diameter (m), 집합체 적용 시 d_{he} 사용.
G: mass flux (kg/m^2/s), 집합체 적용 시 평균 유속 사용.
h_f / h_{in}: saturated / inlet enthalpy (kJ/kg)
L: heated length from inlet to CHF location (m)
P: pressure (MPa)

Applicable ranges:

Pressure	0.2 to 19 MPa
Diameter	0.002 to 0.045 m
Heated length	0.15 to 3.7 m
Mass flux	136 to 18600 kg/m^2/s

(바) Katto 상관식

$$q''_c = q''_{c0} \cdot \left(1 + K \cdot \frac{h_f - h_{in}}{h_{fg}}\right)$$

when $\dfrac{\rho_g}{\rho_f} < 0.15$; $q''_{c0}=q''_A$, for $q''_A<q''_B$

$q''_{c0}= \min\{q''_B, q''_C\}$, for $q''_A>q''_B$
$K = \max\{K_A, K_B\}$

when $\dfrac{\rho_g}{\rho_f} \geq 0.15$; $q''_{c0}=q''_A$, for $q''_A<q''_D$

$q''_{c0}= \max\{q''_D, q''_E\}$, for $q''_A>q''_D$
$K = K_A$, for $K_A>K_B$

$$K = \min\{K_B, K_D\}, \qquad \text{for } K_A<K_B$$

where,

$$\frac{q''_A}{Gh_g} = C\cdot\left(\frac{\sigma\rho_f}{G^2L}\right)^{0.043}\cdot\frac{1}{(L/D)},$$

$$\begin{aligned} C &= 0.25, & L/D<50 \\ &= 0.25+0.0009(L/D-50), & 50<L/D<150 \\ &= 0.34, & L/D>150 \end{aligned}$$

$$\frac{q''_B}{Gh_g} = 0.10\cdot\left(\frac{\rho_g}{\rho_f}\right)^{0.133}\cdot\left(\frac{\sigma\rho_f}{G^2L}\right)^{1/3}\cdot\frac{1}{1+0.0031\cdot(L/D)}$$

$$\frac{q''_C}{Gh_g} = 0.098\cdot\left(\frac{\rho_g}{\rho_f}\right)^{0.133}\cdot\left(\frac{\sigma\rho_f}{G^2L}\right)^{0.433}\cdot\frac{(L/D)^{0.27}}{1+0.0031\cdot(L/D)}$$

$$\frac{q''_D}{Gh_g} = 0.234\cdot\left(\frac{\rho_g}{\rho_f}\right)^{0.513}\cdot\left(\frac{\sigma\rho_f}{G^2L}\right)^{0.433}\cdot\frac{(L/D)^{0.27}}{1+0.0031\cdot(L/D)}$$

$$\frac{q''_E}{Gh_g} = 0.0384\cdot\left(\frac{\rho_g}{\rho_f}\right)^{0.60}\cdot\left(\frac{\sigma\rho_f}{G^2L}\right)^{0.173}\cdot\frac{1}{1+0.280\cdot\left(\sigma\rho_f/G^2L\right)^{0.233}\cdot(L/D)}$$

and,

$$K_A = \frac{1.043}{4\cdot C\cdot\left(\sigma\rho_f/G^2L\right)^{0.043}}$$

$$K_B = \frac{5}{6}\cdot\frac{0.0124+(D/L)}{\left(\rho_g/\rho_f\right)^{0.133}\cdot\left(\sigma\rho_f/G^2L\right)^{1/3}}$$

$$K_D = 1.12\cdot\frac{1.52\cdot\left(\sigma\rho_f/G^2L\right)^{0.233}+(D/L)}{\left(\rho_g/\rho_f\right)^{0.60}\cdot\left(\sigma\rho_f/G^2L\right)^{0.173}}$$

q''_c : critical heat flux (kW/m^2)
D: channel diameter (m), 집합체 적용 시 d_{he} 사용.
G: mass flux (kg/m^2/s), 집합체 적용 시 평균 유속 사용.
h_f / h_{in}: saturated / inlet enthalpy (kJ/kg)
L: heated length from inlet to CHF location (m)
σ: surface tension (N/m)
ρ_f / ρ_f: liquid / vapor density (kg/m^3)

(사) Shah 상관식

(a) Upstream Condition Correlation (UCC)

$$B_{o,UCC} = 0.124\cdot\left(\frac{D}{L_E}\right)^{0.89}\left(\frac{10^4}{Y}\right)^n\left(1-\chi_{in,E}\right)$$

$n = 0,$ for $Y \le 10^4$
$n = (D/L_E)^{0.54},$ for $10^4 < Y \le 10^6$
$n = 0.12/(1-\chi_{in,E})^{0.5},$ for $Y > 10^6$

$L_E = L$ and $\chi_{in,E} = \chi_{in}$ for $\chi_{in} \le 0$

$L_E = L_B$ and $\chi_{in,E} = 0$ for $\chi_{in} > 0$,
$L_B = L + \chi_{in}/(4B_o)$

$$Y = P_e \cdot F_r^{0.4} \cdot \left(\mu_f / \mu_g\right)^{0.6}$$

(b) Local Condition Correlation (LCC)

$$B_{o,LCC} = F_E \cdot F_\chi \cdot B_{o0}$$

$F_E = 1.54 - 0.032(L/D)$, if $F_E<1$ then use $F_E=1$

$$B_{o0} = \max\left\{B_{o01}, B_{o02}, B_{o03}\right\}$$

$$B_{o01} = 15 \cdot Y^{-0.612}$$

$$B_{o02} = 0.082 \cdot Y^{-0.3}\left(1 + 1.45 \cdot P_r^{4.03}\right)$$

$$B_{o03} = 0.0024 \cdot Y^{-0.105}\left(1 + 1.15 \cdot P_r^{3.39}\right)$$

$F_\chi = F_3\left[1 + \dfrac{\left(F_3^{-0.29} - 1\right)\cdot\left(P_r - 0.6\right)}{0.35}\right]^c$, for $\chi_c > 0$

$$F_3 = \left(\frac{1.25\times10^5}{Y}\right)^{0.833\cdot\chi_c}$$

c = 0 for $P_r \le 0.6$, c = 1 for $P_r > 0.6$

$F_\chi = F_1\left[1 - \dfrac{\left(1 - F_2\right)\cdot\left(P_r - 0.6\right)}{0.35}\right]^c$, for $\chi_c \le 0$

$$F_1 = 1 + 0.0052\cdot\left(-\chi_c\right)^{0.88} Y^{0.41}, \quad \textit{for} \quad Y \le 1.4\times10^7$$

$$= 1 + 0.0052\cdot\left(-\chi_c\right)^{0.88}\left(1.4\times10^7\right)^{0.41}, \quad \textit{for} \quad Y > 1.4\times10^7$$

$$F_2 = F_1^{-0.42}, \quad \textit{for} \quad F_1 \le 4$$

$$= 0.55, \quad \textit{for} \quad F_1 > 4$$

(c) CHF 계산

$$B_o = B_{o,UCC}, \quad \textit{for} \quad Y \le 10^6,\ \textit{or} \quad L_E > \frac{160}{P_r^{1.14}}$$

$$B_o = \min\left\{B_{o,UCC},\ B_{o,LCC}\right\}, \quad \textit{for} \quad Y > 10^6$$

B_o: Boiling number (=$q''_c/G/h_{fg}$)
D: channel diameter (m), 집합체 적용 시 d_{he} 사용.
L: heated length from inlet to CHF location (m)
P_e: Peclet number (=GDc_{pL}/k_L)
F_r: Froude number (=$G^2/\rho_f^2/g/D$)
P_r: reduced pressure (=P/P_{crit})
χ_c: critical quality

Applicable ranges:

L/D	1.3 to 940
Diameter	0.315 to 37.5 mm
Pressure	0.3 to 212 bar
Mass flux	3.9 to 29051 kg/m^2/s

Inlet quality	-4 to +0.85
Critical quality	-2.6 to +1.0

(아) AECL 1995 CHF Table

1995 AECL-IPPE CHF table은 30000여 개의 원형관 실험 자료로부터 개발되었고, 압력은 1~200 bar 사이를 21개로, 질량 유속은 0~8000 kg/m^2/s을 20개로, 그리고 국부 건도는 -0.5~1.0 사이를 23개로 구분하여, 이전에 개발된 1986 CHF table에 비하여 CHF 예측 성능 및 적용 범위가 개선된 것이다. CHF table은 모두 8 mm 직경의 원형관에 대한 자료로 표준화 되어 있다. 따라서 직경이 이와 다른 채널에 적용할 경우 직경에 대한 보정 인자를 적용해야 하는데, CHF lookup table의 경우 이는 아래와 같은 형태로 제시되었다.

$$K_1 = \left(\frac{8}{d_{eff}} \right)^n$$

1986 CHF table의 경우에는 $d_{eff}=d_{he}$, n=1/3이 제시되었으며, 1995 CHF table에서는 $d_{eff}=d_{hy}$, n=1/2가 적용되었다. 수로 직경이 CHF에 미치는 영향에 대하여 여러가지 연구가 수행되었으나 단순한 모형으로 표현되기 어려운 것으로 파악되고 있다. 지지 격자의 영향을 보정하는 인자(K_3)와 가열 길이의 영향을 보정하는 인자(K_4)는 각각 아래와 같이 표현된다.

$$K_3 = 1 + 1.5 \cdot K_{grid}^{\;0.5} \cdot \left(\frac{G}{1000} \right)^{0.2} \cdot \exp\left(-0.1 \times \frac{L_{sp}}{d_{hy}} \right)$$

$$K_4 = \exp\left(e^{2\alpha} \cdot d_{hy} / L \right)$$

여기서, K_{grid}는 지지격자 압력 손실 계수이며, L_{sp}는 지지격자 간격을 나타낸다. 그리고 L은 가열 길이이며, α는 homogeneous model을 사용하여 아래와 같이 평가한다.

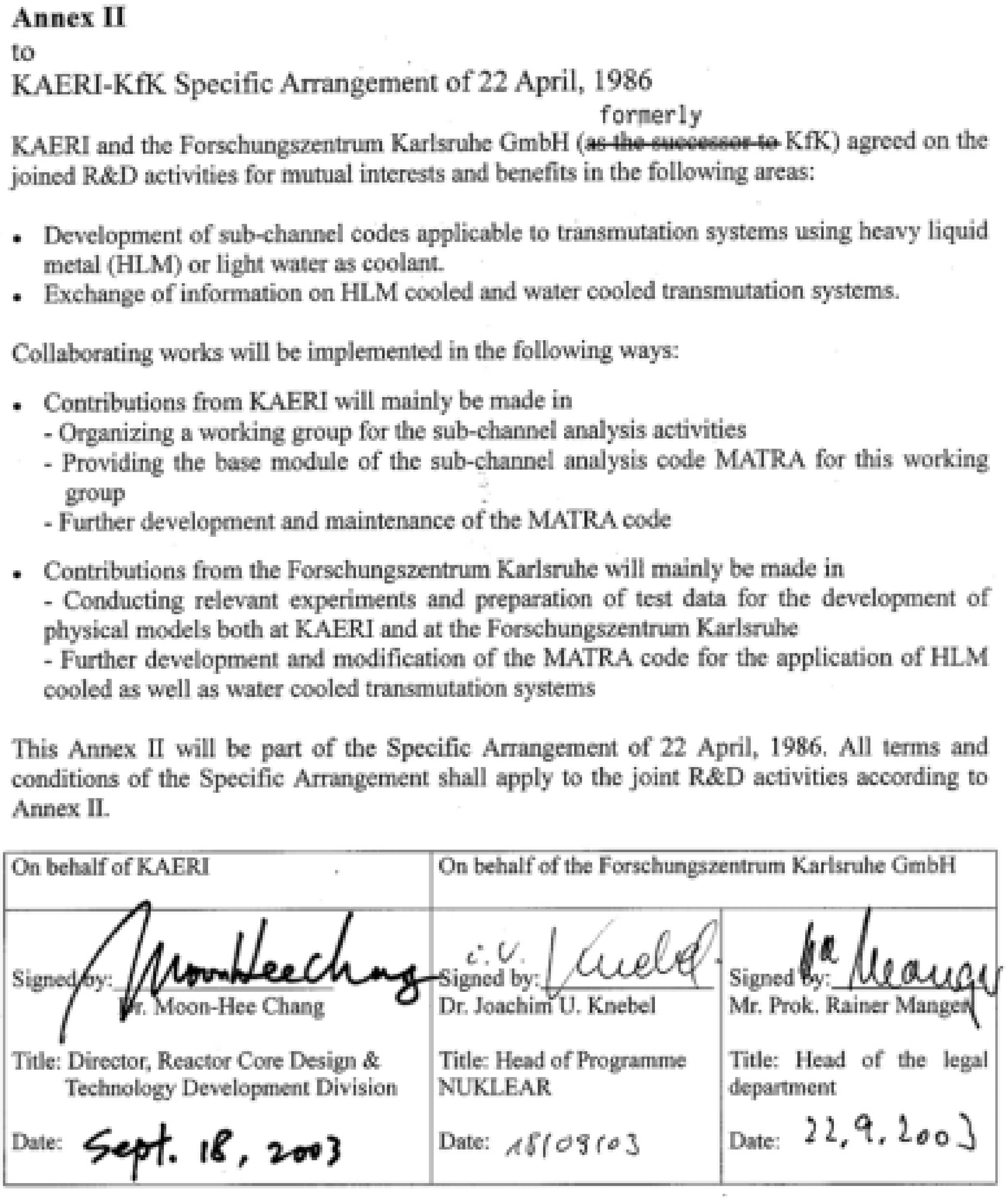
$$\alpha = \chi \big/ \left[\chi + (1-\chi)\, \rho_g / \rho_f \right]$$

이로부터 임의의 채널에 대한 CHF는 아래와 같이 계산한다.

$$CHF = CHF_{D=8mm} \times K_1 \times K_3 \times K_4$$

부록-6. KAERI-FZK 공동 연구

(가) 공동 연구 협약



Annex II
to
KAERI-KfK Specific Arrangement of 22 April, 1986

KAERI and the Forschungszentrum Karlsruhe GmbH (formerly ~~as the successor to~~ KfK) agreed on the joined R&D activities for mutual interests and benefits in the following areas:

- Development of sub-channel codes applicable to transmutation systems using heavy liquid metal (HLM) or light water as coolant.
- Exchange of information on HLM cooled and water cooled transmutation systems.

Collaborating works will be implemented in the following ways:

- Contributions from KAERI will mainly be made in
  - Organizing a working group for the sub-channel analysis activities
  - Providing the base module of the sub-channel analysis code MATRA for this working group
  - Further development and maintenance of the MATRA code
- Contributions from the Forschungszentrum Karlsruhe will mainly be made in
  - Conducting relevant experiments and preparation of test data for the development of physical models both at KAERI and at the Forschungszentrum Karlsruhe
  - Further development and modification of the MATRA code for the application of HLM cooled as well as water cooled transmutation systems

This Annex II will be part of the Specific Arrangement of 22 April, 1986. All terms and conditions of the Specific Arrangement shall apply to the joint R&D activities according to Annex II.

On behalf of KAERI	On behalf of the Forschungszentrum Karlsruhe GmbH	
Signed by: Dr. Moon-Hee Chang	i.V. Signed by: Dr. Joachim U. Knebel	Signed by: Mr. Prok. Rainer Manger
Title: Director, Reactor Core Design & Technology Development Division	Title: Head of Programme NUKLEAR	Title: Head of the legal department
Date: Sept. 18, 2003	Date: 18/09/03	Date: 22.9.2003

(나) Working group 구성

Minutes of Meeting

based on the Annex II to KAERI-KfK Specific Arrangement
KAERI, 19 May, 2004

Participants:
KAERI Dae-Hyun HWANG FZK Xu CHENG
Tae-Hyun CHUN
Young-Gyun KIM
Chungho CHO

According to the agreement between KAERI and FZK for the development of a subchannel code technology, representatives of both parties have a meeting to discuss relevant issues. As the result, the agreements were made for the following items.

1. Organizing working group

As the first step of bilateral cooperations, it was agreed to organize a working group. The list of participants for the working group are provided at the end of this MOM. The information provided to the working group will be shared with all participants.

2. Work plan

The list of unresolved problems from various application areas will be prepared by all participants of the working group. On the basisi of the list of problems, the work sharing and execution plan will be discussed later.

3. Information exchange

The information relevant to this joint R&D works will be exchanged by post or e-mail. The working group will have meetings through international conferences, or through irregular meetings at KAERI or FZK, if necessary.

4. Code maintenance

KAERI will provide the strategy for MATRA code maintenance as soon as possible.

<u>List of Participants for the Working Group:</u>

KAERI:

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Sub-channel Analysis of LBE-Cooled Fuel Assemblies of Accelerator Driven Systems

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ABSTRACT

In the frame of the European PDS-XADS project, two concepts of the sub-critical reactor core cooled by liquid lead-bismuth eutectic (LBE) were proposed. In this paper, the local thermal-hydraulic behavior of both LBE-cooled fuel assemblies was analyzed. For this purpose, the sub-channel analysis code MATRA was selected, and modification was made for its applications to XADS conditions. Compared to the small core concept, the large core concept has a much lower temperatures of coolant, cladding and fuel pins. This enables a short-term realization of the core design using available technologies. The high power density of the small core results in high local temperatures of coolant, cladding and fuel. Both coolant velocity and cladding temperature are such that special attention has to be paid to avoid corrosion and erosion damage of cladding materials. A parametric study shows that under the parameters considered, mixing coefficient has the biggest effect on the coolant temperature distribution, whereas the cladding temperature is strongly affected by the selection of heat transfer correlations.

KEYWORD: Sub-channel analysis, Heavy liquid metal, ADS

I. INTRODUCTION

Accelerator driven sub-critical systems (ADS) are promising machines to transmute long-lived radioactive wastes, such as minor actinides. In the frame of the European PDS-XADS project, three concepts of the sub-critical reactor core are proposed (Carluec 2002). Two of them are cooled by liquid lead-bismuth eutectic (LBE). These two LBE cooled reactor cores have significantly different design configurations (Mansani 2002, Malambu 2004).

Various types of numerical codes can be applied to analyze flow conditions in reactor cores and in fuel assemblies. Sub-channel analysis is the most widely applied approach in the design of fuel assemblies. It divided one fuel assembly into a large number of individual flow channels, the so called sub-channels. With this approach the local thermal-hydraulic condition of the hot sub-channel and the hot fuel pin can be analyzed. Recently, more and more interest was arisen in the application of Computational Fluid Dynamics (CFD) codes to fuel assembly analysis. This approach requires a further division of one sub-channel into a huge number of computational cells. Due to the requirement on a huge storage need and computing time, application of this approach is still limited.

Although both LBE-cooled XADS reactor cores have been proposed during the PDS-XADS project, they were based on preliminary design analysis, especially related to thermal-hydraulic analysis. Due to the limited availability of numerical tools at that time stage, thermal-hydraulic design analysis was made using lumped parameter approaches (Struwe 2004). No detailed investigation was carried out on local conditions in all sub-channels. Therefore, further analysis was necessary to provide detailed knowledge about the local thermal-hydraulic behavior of both LBE cooled reactor cores.

The main objective of this work is study the thermal-hydraulic performance of the two LBE-cooled reactor cores, and to provide some basic information for the selection of European ADS facilities. For this purpose, the sub-channel analysis code MATRA is applied, which was originally developed and issued by Korea Atomic Energy Research Institute (KAERI 1998). In the frame of a bilateral collaboration between KAERI and the Forschungszentrum Karlsruhe, the MATRA code was modified for ADS applications. The local sub-channel conditions in the hot fuel assemblies of both LBE cooled reactor cores are presented and discussed.

II. LBE-COOLED REACTOR CORES

Two designs of LBE-cooled reactor cores for the European ADS facility were proposed with various application purposes (Carluec 2002). The main purposes of the large core design with a thermal power of 80 MW are to investigate the operating performance of ADS under the coupling of accelerator, spallation target and sub-critical reactor core, and to gather experience for designing an industrial scale transmutation machine. For this design, a low heat density of the reactor core is selected, to guarantee a safe heat removal and low temperature of structural material for minimizing corrosion damage. In contrary, the small LBE-cooled ADS facility is mainly designed as a testing station for a wide spectrum of applications. For various testing purposes, high neutron fluxes are required, which in turn lead to a high heat density in the reactor core. The structural material is exposed not only to a high irradiation load, but also a high thermal load. Details of both LBE-cooled reactor cores can be found in (Mansani 2002, Malambu 2004). Some of the parameters relevant to the present study are summarized in table 1.

Table 1: Parameters of both LBE-cooled reactor cores

Parameters	Large core	Small core
Core average parameters		
Reactor power, MW	80	51
Number of FAs in core	120	45
Coolant	LBE	LBE
Inlet coolant temperature, °C	300	300
Outlet coolant temperature, °C	400	455
Hot FA parameters		
Power, MW	0.775	1.465
Number of fuel pins	90	91
Pin diameter, mm	8.5	6.55
Pitch, mm	13.41	8.55
Wrapper-to-pin gap, mm	2.5	1.0
Outline pin length, mm	1272	1200
Active height, mm	870	600
Upper section height, mm	202	180
Lower section height, mm	200	420
Number of grid spacers	3	3
Axial power factor	1.14	1.27
Radial power factor	1.14	1.04
Cladding thickness, mm	0.565	0.50
Fuel outer diameter, mm	7.14	5.55
Fuel material	MOX	MOX
Fill gas	Helium	Helium
Coolant flow rate, kg/s	40.78	50.0
Coolant inlet temperature, °C	300	300
Coolant outlet temperature, °C	416	500

The FAs have a typical hexagonal structure which is surrounding the inner cavity foreseen for spallaton target. The fuel core has been surrounded by FA-like dummy assemblies, which are filled up with LBE. The core power distributions were analyzed in (Burn 2004, Malambu 2004). The coolant flow through the FAs is established such that the coolant heat-up in the large core is 100°C and in the hottest fuel assembly of the small core is 200°C. The small LBE core has a much smaller fuel pin diameter (6.55 mm) and smaller pitch-to-diameter ratio (1.308). This gives a much smaller FA size and coolant flow area. Furthermore, the average FA power (1.13 MW) is higher than that in the large core (0.67 MW). To remove the heat, thus, a higher coolant flow velocity is required. For the present analysis, the hottest fuel assemblies, i.e. those with the highest heat release, are taken into consideration.

The radial power distributions, i.e. the power of each fuel pin, in both hot fuel assemblies are taken from (Malambu 2004, Burn 2004). The fuel pins closer to the spallation target have higher power. The radial power factor in the small core is 1.04, much smaller than that in the large core (1.14). A uniform distribution of peripheral heat flux for each fuel pin is assumed. One single axial power distribution for fuel pins is taken for each reactor core. The large LBE-cooled reactor core has a much smoother axial power distribution than that of the small reactor core. The axial power factor is 1.27 in the small core and 1.14 in the large core, respectively. Moreover, in the small reactor core, the maximum heat flux is as high as 1.7 MW/m², which is about five times of that in the large reactor core. The maximum linear power is about 350 W/cm. Therefore, a detailed analysis of the thermal-hydraulic behavior, including the individual fuel pins, is highly required, especially for the small reactor core.

III. SUB-CHANNEL ANALYSIS CODE MATRA

The sub-channel analysis code MATRA (Multi-channel Analyzer for Steady Sates and Transients in Rod Arrays) is the thermal-hydraulic analysis code being developed at the Korea Atomic Energy Research Institute (KAERI) based on the sub-channel analysis code COBRA-IV-I. Compared to

COBRA-IV-I, the MATRA code has been provided with an improved structure, additional functions and models to give a more convenient user environment and to increase the numerical accuracy. A detailed description of MATRA can be found in (KAERI 1998).

For the analysis of LBE cooled ADS fuel assemblies, modification of the MATRA code is necessary. First of all thermal-physical properties and some physical models for LBE have to be implemented into the code.

Thermal-physical properties

In the original version of COBRA-IV-I, only properties at the saturating lines are read via input deck as a look-up table. The sub-cooled properties are calculated by interpolating the saturated properties. Obviously, this would lead not only to an undesired error, but also to a serious numerical problem, especially for fluids with very low saturating pressures, e.g. LBE. As an alternative approach, a steam table routine has been implemented into the MATRA code. Therefore, sub-cooled properties can be accurately calculated. This approach is then taken for implementing the properties of LBE into the MATRA code. The LBE properties used in this study are taken from Cevolani (1998).

Heat transfer correlations

Studies on turbulent heat transfer of liquid metal flows in rod bundles began as early as 50's. Since then many heat transfer correlations were proposed in the open literature. Similar to liquid metal flow in circular tubes, heat transfer coefficients for rod bundles are also described in the following form:

$$Nu = A + B \cdot Pe^{C} \quad (1)$$

Here Nu stands for Nusselt number and Pe for Peclet number. The coefficients A, B and C depend mainly on bundle geometric data, especially the pitch-to-diameter ratio. A review on heat transfer correlations for liquid metal flow in rod bundles was recently carried out by Cheng et al. (Cheng 2005). It was pointed out that in the open literature only one correlation was specifically developed for LBE flows in rod bundles, i.e. the correlation of Orlov (Subbotin 1965):

$$Nu = 0.58\left(\frac{d_h}{D}\right)^{0.55} Pe^{0.45} \quad (2)$$

In this equation, D is the fuel pin diameter and d_h the hydraulic diameter of the fuel assembly. This correlation is valid for hexagonal as well as for square rod bundles with a pitch-to-diameter ratio from 1.1 to 1.5. The Peclet number ranges from 400 to 4000.

Figure 1 compares the calculated Nusselt number versus Peclet number for the regular sub-channels of both LBE-cooled cores. For comparison, the correlation of Kirillov (2001)

$$Nu = 4.5 + 0.018 Pe^{0.8} \quad (3)$$

is also indicated in this figure, which was proposed for liquid metal flows in circular tubes. The thermal-physical properties needed in figure 1 are calculated by assuming a coolant temperature of 300°C. It is seen that the Nusselt number in the large core is higher than that in the small core. The Peclet numbers are 870 in the large core and 1350 in the small core, respectively. The Kirillov's correlation proposed for circular tubes gives much lower Nusselt number, especially for the large core configuration. In spite of higher Nusselt number, the heat transfer coefficient (12.2 kW/m²K) in the large core is much lower than that in the small core (26.4 kW/m²K). To investigate the effect of heat transfer correlations on the sub-channel results, both correlations are applied.

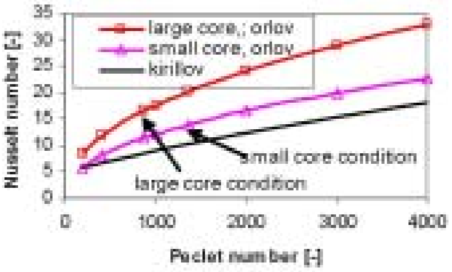


Figure 1: Nusselt number in regular sub-channels according to various correlations

Turbulent cross flow of mass

Although both approaches, i.e. zero net volume exchange and zero net mass exchange, are implemented into the MATRA code, it should be pointed out that the undirected natural cross flow is resulted by the turbulent fluctuation of velocity in the gap. Any velocity fluctuation inside one sub-channel does not directly contribute to the inter-channel mass transfer. Therefore, for calculating turbulent cross flow of both directions, the fluid density on the gap boundary should be used. This gives a zero net cross flow of mass. The zero net mass exchange approach was widely used in the earlier sub-channel analysis codes. However, the sub-channel community recognized that the zero net volume approach would give a better prediction of local conditions in sub-channels.

Detailed and reliable knowledge about turbulent mixing of LBE flows is still missing. Most recently, a systematical analysis using CFD code was performed by the present authors to study the phenomena of turbulent mixing in heavy liquid metal (HLM) cooled rod bundles (Cheng, 2005). This study indicates that the velocity fluctuation is proportional to the mean axial flow velocity. Figure 2 shows the average amplitude of the velocity fluctuation across the gap, normalized by the shear velocity. The results show that in both lattice arrangements, triangular or square, the difference in the normalized velocity fluctuation is negligibly small. The average amplitude of the velocity fluctuation across the gap has its maximum close to the wall. It decreases with the distance to the wall. On the average, the normalized velocity fluctuation across the gap is about 0.5.

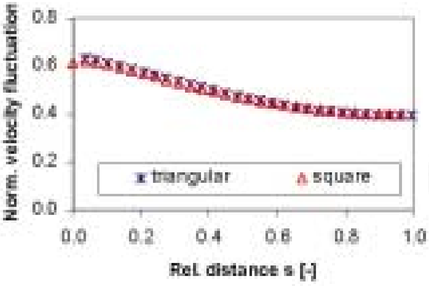


Figure 2: Normalized velocity fluctuation across the gap in both triangular and square lattices (Cheng, 2005)

In the figure, the shear velocity is calculated by

$$u_* = \sqrt{\frac{\tau_W}{\rho}} = \sqrt{\frac{f}{8}}\, u \qquad (4)$$

Here τ_W is wall shear stress, ρ density, u axial mean flow velocity and f friction factor, which is determined using the conventional Blasius correlation

$$f = \frac{0.3164}{\mathrm{Re}^{0.25}} \qquad (5)$$

This gives a turbulent mixing coefficient

$$\beta = \frac{\overline{|v'|}}{u} = \frac{c \cdot u_\tau}{u} = c \cdot 0.20 \cdot \mathrm{Re}^{-0.125} \qquad (6)$$

Equation (6) has the similar form as that proposed by Rogers & Rosehart (1972). The coefficient c depends mainly on sub-channel geometry, and also increases slightly with increasing Reynolds number (Cheng 2005). For the conditions considered in this study, equation (6) gives a mixing coefficient of about 0.02, larger than the value calculated using the Roger's equation (0.008).

Natural cross flow of energy

In the MATRA code, similar to other sub-channel analysis codes, the diffusion term of energy does only contain the molecular diffusion. In the reality, thermal diffusion consists of both molecular and turbulent diffusion. Therefore, the turbulent diffusion of energy e_{TD} is introduced in the present study, i.e.

$$e_{TD} = \lambda_t \frac{T_I - T_J}{l_{IJ}} \qquad (7)$$

Here λ_t stands for turbulent thermal conductivity, l_{IJ} for the effective distance between two neighboring sub-channels I and J. By using the turbulent eddy viscosity approach and turbulent Prandtl number, the turbulent thermal conductivity can be expressed as:

$$\frac{\lambda_t}{\lambda} = \frac{\mathrm{Pr}}{\mathrm{Pr}_t} \cdot \frac{\mu_t}{\mu} \qquad (8)$$

Compared to conventional fluids such as water and air, the molecular Prandtl number Pr of HLM is much smaller. Thus, the directed cross flow of energy resulted by turbulence is less significant. A CFD analysis of Cheng et al. (2005) showed that the turbulent Prandtl number Pr_t ranges from 1.0 to 2.0, and the normalized turbulent viscosity μ_t/μ across the gap increases with the distance to the wall. It varies in the range from 5 to 60, and has an average value of about 40 over the entire gap. Furthermore, the normalized turbulent viscosity is approximately proportional to the mean axial velocity in sub-channels. Considering that the molecular Prandtl number of LBE is about 0.02, the normalized turbulent thermal conductivity has a value in order of 1.0. This indicates that for LBE flows in rod bundles the turbulent diffusion is in the same order as the molecular diffusion.

IV. RESULTS AND DISCUSSION

In this section, the hot fuel assemblies of both reactor cores are taken into consideration. The effect of some parameters is investigated, i.e. turbulent mixing coefficient and heat transfer correlations. Figure 3 indicates the division of one fuel assembly into sub-channels, the numbering system for sub-channels and fuel pins. The relative direction of the hot fuel assemblies to their core centre is also indicated.

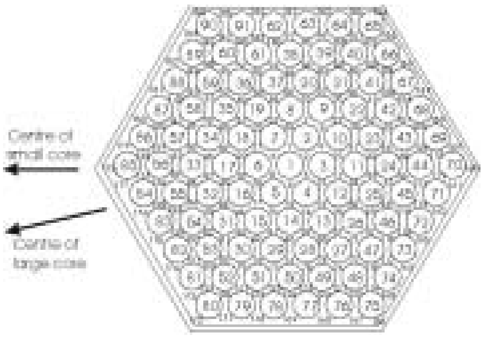
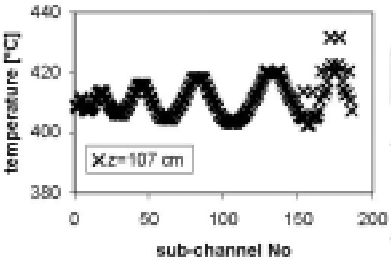


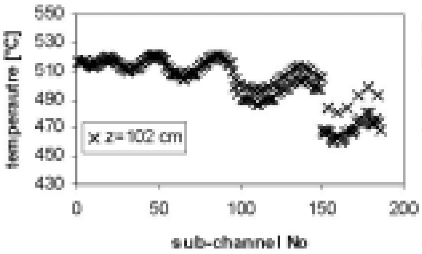
Figure 3: Numbering system of sub-channels and fuel pins

1. Reference case

The coolant temperatures in all 186 sub-channels at the upper end of the active height are presented in figure 4. In each fuel assembly several coolant temperature peaks are recognized. In the large core concept, the largest enthalpy rise is obtained in the sub-channels SC-172 and SC-178. The enthalpy rise through sub-channels in the small core concept is much higher than that in the large core concept. The maximum coolant temperature is as high as 520°C. The ratio of the temperature rise in the hot sub-channel to the bundle average value is 1.16 in the large core and 1.10 in the small core.

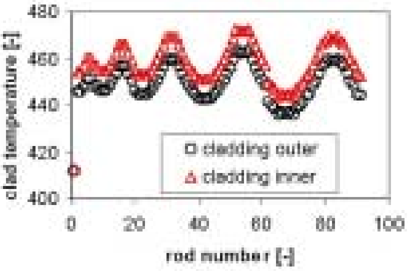


(a) large core concept

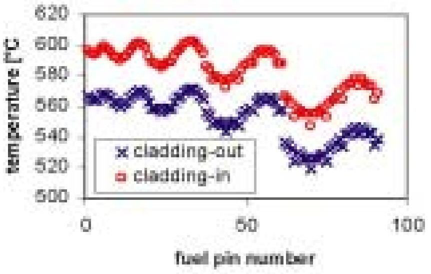


(b) small core concept
Figure 4: Coolant temperatures in sub-channels at the upper end of the active height

Figure 5 indicates the temperatures on the cladding inner surface and on the cladding outer surface for all 91 fuel pins. Five temperature peaks are observed in each fuel assembly. In the large core concept, the temperature peaks occur in the fuel pins FP-6, FP-17, FP-32, FP-54 and FP-84. In the small core concept the fuel pins with temperature peaks are FP-6, FP-17, FP-33, FP-56 and FP-85. In the small core concept, the maximum outer cladding temperature is as high as 550°C. Therefore, measures have to be taken to avoid a strong corrosion damage of cladding materials.



(a) large core



(b) small core
Figure 5: Cladding temperatures of all fuel pins

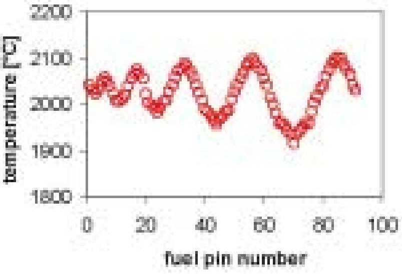


Figure 6: Maximum fuel temperatures

Figure 6 shows the maximum fuel temperature of all 91 fuel pins of the small core concept. It is found that the fuel temperature peaks occur in the same fuel pins as the cladding temperature peaks. The maximum fuel temperature in the small core concept is as high as 2100°C. Obviously, the safety margin to the melting temperature of oxide fuel (about 2400°C for PuO_2) is low. Safety analysis should be carried out for various transients, to check the onset of fuel melting.

2. Parametric studies

Figure 7 shows the effect of turbulent mixing coefficient on coolant temperatures in the hot sub-channels SC-178 in the large core, where the turbulent mixing coefficient has a stronger effect on the coolant temperature than that in other sub-channels. Considering that the average coolant temperature at the bundle exit is 416°C, a well uniform coolant temperature in the fuel assembly is achieved using a turbulent mixing coefficient of 0.1. A reduction in the turbulent mixing to 0.002 results in a much stronger non-uniformity of coolant temperature distribution.

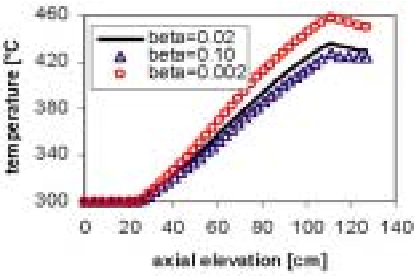


Figure 7: Effect of turbulent mixing coefficient on coolant temperatures in the hot sub-channels

Figure 8 indicates the effect of heat transfer correlations on the cladding temperature of the hot fuel pins, i.e. FP-33 in the small core concept. A strong effect of heat transfer correlations is obtained. Using the correlation of Orlov leads to a reduction in the maximum cladding temperature about 20°C.

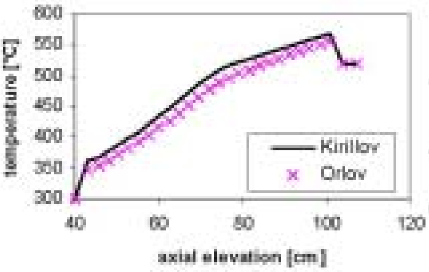


Figure 8: Effect of heat transfer correlations on the cladding temperature of FP-33

V. SUMMARY

Sub-channel analysis was performed using the code MATRA, to study the thermal-hydraulic performance in LBE cooled fuel assemblies and to provide basic information for the selection of European ADS facilities. Modification of the MATRA code was made for its applications to ADS conditions. Using the modified MATRA code, local sub-channel conditions as well as local fuel pin temperatures of the hot fuel assemblies in both LBE-cooled reactor cores have been analyzed. The results achieved can be summarized as below:

- Compared to the small core concept, the large core concept has a much lower temperatures of coolant, cladding and fuel pins. This would enable a short-term realization of the core design using available technologies.
- Due to high power densities, the maximum temperature of the cladding outer surface is as high as 570°C in the small LBE-cooled core. Corrosion damage of cladding materials at such high temperature becomes a serious problem. Measures to reduce the cladding temperature peak and to protect cladding materials from corrosion damage are highly required. The acceptance of this high cladding temperature has to be checked by the performance of the cladding material during the entire reactor operation period.
- In the large core concept, the hot sub-channel is one of the corner sub-channels, whereas in the small core concept, the highest coolant temperature occurs in one of the regular sub-channels. The radial peak factor of coolant temperature is 1.14 in the large core and 1.07 in the small core, respectively.
- Under normal operating conditions of the small core concept, only a small safety margin exists to the melting point of fuel materials. A thorough check on the onset of fuel melting has to be made under various transient scenarios.
- Inter-channel exchange is one of the major physical phenomena which require further investigations. The mixing coefficient shows a stronger effect on the coolant temperature distribution than the other parameters considered in this paper.
- For the cladding temperature, selection of heat transfer correlations plays an important role. Due to the sensitive effect of temperatures on corrosion behavior of cladding materials at high temperatures, reliable heat transfer correlations are thus highly required, especially for the design of the small LBE-cooled reactor core.

It has to be pointed out that reliable physical models, e.g. for heat transfer, for LBE flows in rod bundles are still missing, which, however, are responsible for the accuracy of the present analysis, and of crucial importance for the detailed engineering design of ADS fuel assemblies. Thermal-hydraulic rod bundle experiments will be performed at the Forschungszentrum Karlsruhe with the main purpose to study the thermal-hydraulic performance of an ADS fuel assembly, such as pressure drop, heat transfer and inter-channel exchange. In addition, CFD analysis is carried out to provide understanding and basic data base for developing new physical models for ADS prototypical conditions.

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서지정보양식

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연구위탁기관			계약번호		

초록 (15-20줄내외)

다양한 핵연료 및 노심 형태와 냉각재를 사용하는 신개념 원자로에 대한 부수로 해석 코드 기술 개발 및 적용성 평가 연구를 수행하였다. 부수로 해석 코드의 기본 모듈은 기존 경수로 노심 열수력장 해석을 위하여 한국원자력연구소에서 개발중인 MATRA 코드를 바탕으로 개발하였다. 코드 입력 오류를 줄이고 사용자 편이성을 높이기 위하여 입출력 GUI를 개발하였다. 다양한 냉각재에 대한 물성치 계산 모듈을 보완하였으며, 그 결과 액체금속, 개스, 냉매, 그리고 초임계압수 등에 대한 부수로 해석이 가능하다. 부수로 해석 코드를 사용하여 신개념원자로에 적용될 수 있는 다양한 형태의 비정방형 집합체에 대한 CHF 시험자료를 분석하고 예측 성능을 평가하였다. 그리고 고온가스로 및 초임계압 원자로 조건에 대한 부수로 해석 코드의 적용성 평가를 수행하였다. 독일 FZK 연구소와 국제공동 연구를 수행하여 액체 금속을 냉각재로 사용하는 원자로 조건에 대한 부수로 해석을 수행하였다. 그리고 OECD/NRC의 code benchmark에 참여하여 부수로 기포율 분포에 대한 부수로 해석 코드의 예측 성능을 평가하였다.

주제명키워드 (10단어내외)	부수로 해석, 신개념원자로, MATRA

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Abstract (15-20 Lines)

A study has been performed for the development and assessment of a subchannel analysis code which is purposedto be used for the analysis of advanced reactor conditions with various configurations of reactor core and several kinds of reactor coolant fluids. The subchannel analysis code was developed on the basis of MATRA code which is being developed at KAERI. A GUI (Graphic User Interface) system was adopted in order to reduce input error and to enhance user convenience. The subchannel code was complemented in the property calculation modules by including various fluids such as heavy liquid metal, gas, refrigerant,and supercritical water. The subchannel code was applied to calculate the local thermal hydraulic conditions inside the non-square test bundles which was employed for the analysis of CHF. The applicability of the subchannel code was evaluated for a hightemperature gas cooled reactor condition and supercritical pressure conditions with water and Freon. A subchannel analysis has been conducted for European ADS(Accelerator-Driven subcritical System) with Pb-Bi coolant through the international cooperation work between KAERI and FZK, Germany. In addition, the prediction capability of the subchannel code was evaluated for the subchannel void distribution data by participating an international code benchmark program which was organized by OECD/NRC.

Subject Keywords	Subchannel analysis, Advanced reactor, MATRA