FAST REACTOR RESEARCH IN SWTZERLAND

XA9847033

R. BROGLI, M. HUDINA, S. PELLONI,
B. SIGG, A. STANCULESCU
Paul Scherrer Institute,
Villigen, Switzerland

Abstract

The small Swiss research program on fast reactors serves to further understanding of the role of LMFR for energy production and to convert radioactive waste to more environmentally benign forms. These activities are on the one hand the contribution to the comparison of advanced nuclear systems and bring on the other to our physical and engineers understanding.

1. Comparison of Advanced Nuclear Systems

In the 90s, industry and research have invested efforts in order to further develop nuclear technology in the direction of a "new safety quality" while preserving or even regaining competitiveness against today's most economic energy carriers (e.g. natural gas). Different plant concepts rely on different approaches (evolutionary - innovative), focus on diverging realisation periods and use passive systems or inherent safety features to a different extent. There are also considerable differences between fuel cycles either in the basic approach or in the details.

This study aims at a comparison of future reactor concepts, paying particular attention to aspects of safety, of the fuel cycle, the economics, the experience-base and the state of development. Representative examples of typical development lines, that could possibly be "of interest" within a time horizon of 50 years were selected for comparison. This can be divided into three phases:

- Phase I includes the next 10 years and will be characterised mainly by evolutionary developments of light water reactors (LWR) of large unit size; representative: EPR.
- Phase II, i.e. the time between 2005 and 2020 approximately, encompasses the forecasted doubling of today's world-wide installed nuclear capacity; along with evolutionary reactors, innovative Systems like AP600, PIUS, MHTGR, EFR will emerge.
- Phase III covers the time between 2020 and 2050 and is characterised by the issue of sufficient fissile material resources; novel fast reactor systems including hybrid systems can, thus, become available; representatives: IFR, EA, ITER‡ (the latter being).

The evaluated concepts foresee partly different fuel cycles. Fission reactors can be operated in principle on the basis of either a Uranium-Plutonium-cycle or a Thorium-Uranium-cycle, while combinations of these cycles among them or with other reactor concepts than proposed are possible. With today's nuclear park (comprising mainly LWRs), the world-wide plutonium excess increases annually by about 100 t. Besides strategies based on reprocessing like

- recycling in thermal and fast reactors with mixed oxide fuels ($(U, Pu)O_2$),
- plutonium "burning" in reactors with novel fuels without uranium or in "hybrid" systems

allowing a reduction of this excess, direct disposal spent fuel elements including their plutonium content ("once-through") is being considered.

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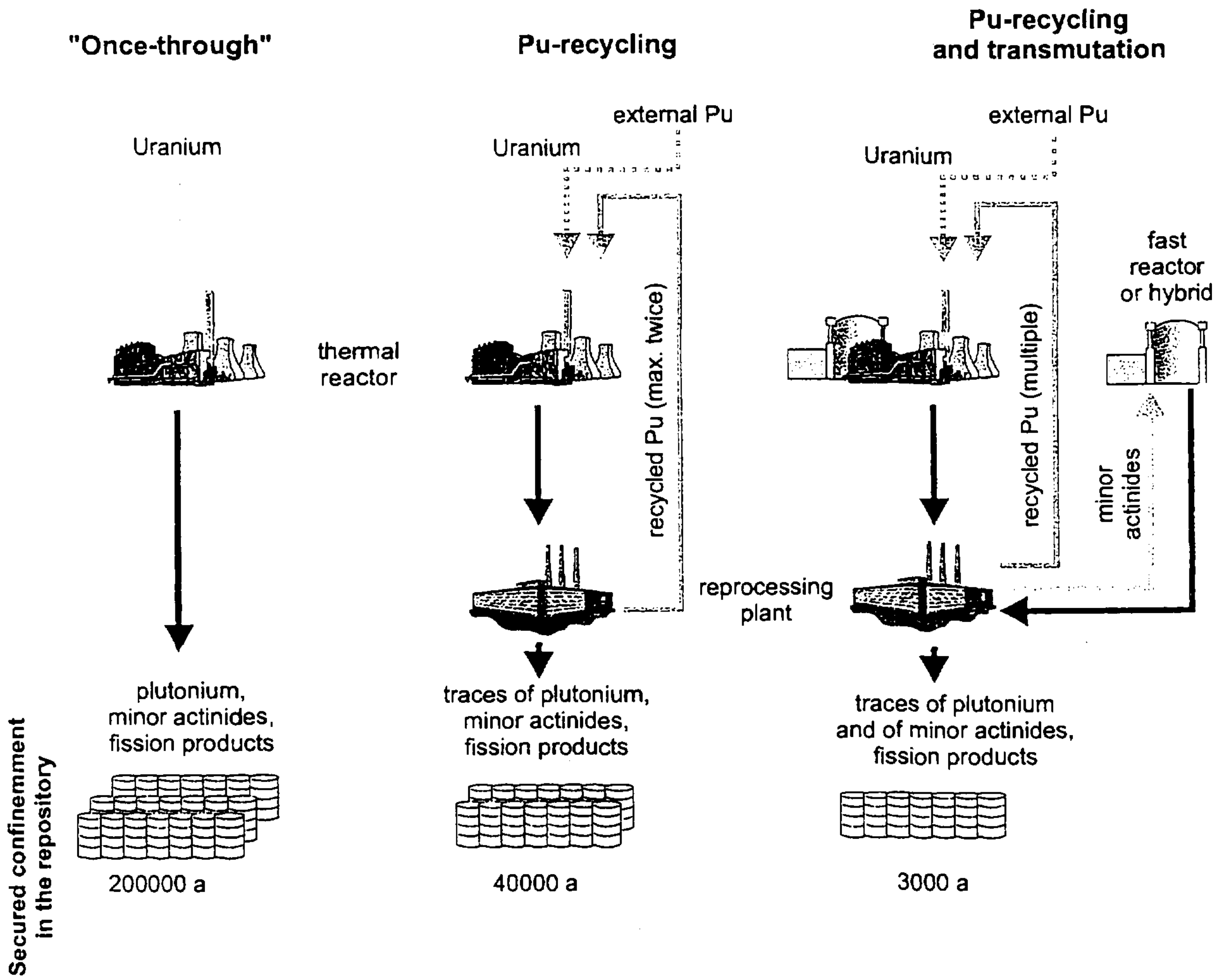
‡ Used as a comparison object that does not represent a true alternative in the time period considered.

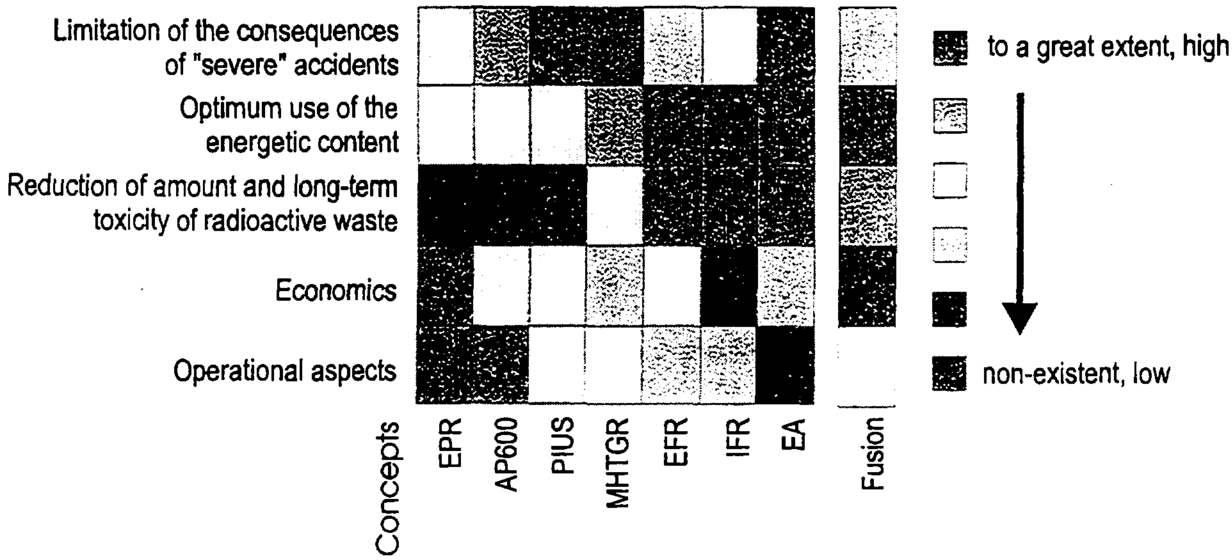
Problems relevant in the long-term are the radiotoxicity of the fuel and the long-term risk related to a final repository, which can be steered by an adequate choice of fuel cycle and reactor type. Moreover, it is possible to "transmute" very long-lived actinides and fission products into less toxic or stable nuclei by means of specific nuclear reactions. Following figure summarises these options for the back-end in the case of the uranium-plutonium fuel cycle.



The most important criteria for the assessment of the evaluated concepts are:

- **safety**, focusing on the limitation of the consequences of "severe" accidents beyond today's design basis,
- **use of the energetic content** of the uranium/thorium reserves,
- amount and radiotoxicity of **radioactive waste**, final repository risk,
- **economics** (investment and operating costs), and,
- **operational aspects** (experience, technical development status, robustness).

The results of the study with regard to these criteria can be represented in a matrix as follows, where present western technology is taken as departure and reference point:



In summary, the study leads to the following main findings:

- LWRs (with a thermal neutron spectrum) have a safety potential that should not be underestimated and which can be further exploited. This could allow them to fulfil all expected safety requirements in the foreseeable future. Exhausting this potential by innovative means (e.g. in PIUS) is, however, coupled to considerable economic penalties, as it implies smaller plants, eventually with lower power densities. In order to further improve the use of resources and to reduce the amount of radioactive waste, the fuel cycle should be further closed, which is only partially possible with a pure LWR-strategy.

- Reactors with a fast neutron spectum allow to perform a "quantum leap" in the use of resources (factor of ~100) and can further defuse the waste problem, as they allow the fuel cycle to be fully closed. They fulfil, therefore, an important postulate for a sustainable development. The quantum leap implies, however, a more expensive and complex technology (e.g. liquid metal cooling technology). By steadily exploiting advantages like the low coolant pressure, new developments (IFR, EA) could probably reach a safety standard that is at least equivalent, or even better than the standard of the "best" LWRs.

- Newly emerging fuel cycle technologies, will allow to keep the problem of high level waste under control, even with an increased and long-lasting deployment of nuclear energy. The reduction of the radiotoxicity and, thus, also of the long-term risk should take place primarily by minimising the amount of uranium, thorium and actinides in the waste. A reduction by a factor of 10 to 50 can be probably achieved with improved reprocessing and recycling technologies. At a similar level of fuel losses, switching from the uranium-plutonium cycle to the thorium-uranium cycle would reduce the toxicity of actinides for decay times up to 10000 years, but would not bring any advantage for longer decay times. The main issue being the best possible way of closing the fuel cycle, the improved fuel technologies are important mainly within the context of fast reactors (including the EA).

- Once plutonium is fully recycled and the use of uranium "waste tails" (from the enrichment and reprocessing process) becomes economically acceptable, the closing of the fuel cycle can be considered for the less abundant actinides Np, Am and Cm (transmutation) as well, thus further improving the sustainable character of nuclear energy. With a strategy relying mainly on fast reactors, the recycling of the less abundant actinides can take place in these reactors. However, combined strategies with LWRs and fast reactors in symbiosis with hybrid systems can be envisaged. In all these considerations, one should also keep in mind the radiotoxicity and the long-term risk of fission products, which depends only on the produced thermal energy. For the remote future, possibilities to transmute particularly long-lived fission products can be anticipated.

- With regard to proliferation, the INFCE study of the IAEA from 1980 has shown, that there are no technical means that allow to make the nuclear fuel cycle completely "proliferation-proof" and that the thorium cycle cannot resolve this problem either. Of primary importance is the question, whether the proposed fuel cycle foresees reprocessing or not, the latter being considered more favourable from a proliferation point of view. If one considers reprocessing for the aforementioned reasons to be nevertheless desirable, an (expensive) integration in the reactor plant, like in the IFR-concept, would be certainly advantageous. The increased build-up of higher isotopes through multiple recycling makes plutonium less attractive for theft, but does not provide an absolute protection.

This study confirms, that nuclear fission as a physical principle with the corresponding technology has chances also for the future: The potential to fulfil requirements even beyond the present ones is not exhausted. Developments are underway. The ultimately necessary industrial scale is, however, present only for the rather evolutionary concepts (e.g. EPR). A steady continuation of the developments under discussion, implies further important investments and times, which are the larger, the more the concepts are novel and the closer they still are to the "blueprint" stage. Similar considerations hold for their realisation chances: Cost-relevant additional requirements jeopardise competitiveness. The more a concept deviates from today's standards, the more a political will for a break with – presently strengthening – market rules (deregulation) is necessary. However, differenecs in economics between concepts are in general of the same magnitude as between single and multiple unit plants of the same concept.

The EA has, along with PIUS, MHTGR and also IFR, the largest potential to fulfil the criteria used in this study – as far as this can be assessed in the present early stage of its concept development. However, its competitiveness is at present still rated rather low; at least another 20 years are estimated to be necessary before the concept can reach commercial maturity, and this will necessitate considerable (public) funds. With this in mind, one should not overlook the potential of more "traditional" concepts that are closer to realisation to fulfil the criteria used, especially with a well-aimed use of their specific characteristics and in combination with fuel cycles tailored to future needs.

2. LMFBR Physics Research

2.1 Introduction

PSI's efforts in the area of LMFBR physics research and development were centred on three main topics.

- Adjustment of our deterministic calculational capabilities in view of their use in neutron physics analyses of plutonium burning fast reactor cores.
- Validation of aforementioned methods and data through comparisons with Monte Carlo results.
- Contributions to the development and validation of photon heating calculational capabilities within the framework of the European Code System ECCO/ERANOS [2, 3].

All our LMFBR physics R&D activities were pursued in close cooperation with our colleagues at CEA Cadarache.

2 Main Results

2.1 Adjustment of the Deterministic Codes

PSI's deterministic calculational path for fast systems is based on the cell code MICROX-2 [4]. The use of this tool for plutonium burning fast systems – i.e. fertile blanket lacking cores surrounded by important steel reflector regions – has revealed a few shortcomings of the code: both methods and coding approximations, as well as shortcomings in the use of the MICROX-2 results in the overall calculational route introduced unacceptably high uncertainty levels.

Two major methods adjustment topics have been dealt with:

a) Consistent cross sections calculation for discrete ordinate transport theory codes (S_N-codes). With regard to the broad-group cross sections generated by MICROX-2 for use in S_N-codes, two important improvements have been implemented:

   - the Legendre-moment dependence of the total cross section is consistently included through order P_3;

   - in addition to the "diagonal transport" approximation, three more accurate approximations (i.e.: Bell, Hansen and Sandmeier (BHS) or "extended approximation", "inflow transport approximation", and "inconsistent P_N approximation") have been introduced in order to correct the broad-group cross sections for the effect of the first neglected Legendre-moment

b) P_N spatial weighting

   The available MICROX-2 version did not treat properly the spatial dependence of flux moments higher than Po, particularly in the case of very heterogeneous, and optically very thick or thin regions. This, in turn, made the preparation of proper cell-averaged scattering matrices for Legendre-moments higher than Po impossible. Therefore, new spatial homogenization equations were implemented in MICROX-2, yielding accurate cell-averaged transport cross sections, also in the heterogeneous / high leakage cases mentioned above.

2.2 Validation Work

The validation effort was pursued in close cooperation with CEA Cadarache. Its aims were twofold: comparison between our deterministic route (MICROX-2/TWODANT) and the Monte Carlo (MCNP-4A) one, on the one side, and support for the validation effort on the European code system ECCO/ERANOS, on the other side. The work concentrated on three numerical benchmarks derived from the ZONA-2 series of the CIRANO experimental program (performed in the zero power facility MASURCA at Cadarache). For detailed results, see references [5, 6, 7]; here only a brief summary of the main findings is given.

The influence of the basic data was studied with the stochastic route (MCNP-4A employed continuos energy data based on ENDF/B-V, ENDF/B-VI and JEF-2.2). The deterministic results were obtained for JEF-2.2 data.

Regardless of the methods and data used, there is an increasing trend for the eigenvalues obtained for configurations having higher steel content (i.e. enhanced characteristics). However, this increasing trend is more pronounced in the deterministic route. The reason for this effect is not yet fully understood; it might be due to a different approach in the calculation of the slowing down source in the steel regions.

With regard to the effect of the basic data, it has been found that ENDF/B-V and JEF-2.2 based k_{eff}-results agree within the calculational errors, while the ENDF/B-VI values are slightly higher.

Finally, the comparison of flux traverses from deterministic and stochastic calculations show very good agreement.

2.3 Photon Heating Studies

This activity is also placed within the framework of the CEA/PSI cooperation agreement.

Given the importance of the photon heating contribution in plutonium burning fast reactor cores, a comprehensive validation work is under way for ECCO/ERANOS. Within this framework, PSI has contributed with both an experimental and an analytical effort. On the experimental side, thermoluminescent detector (TLD) measurements were performed in some of the aforementioned CIRANO configurations. With regard to methods/calculational aspects, an important effort was necessary to produce consistent neutron kerma factors and photon spectra data (from photon production due to radiative neutron capture, fission, and both elastic and inelastic neutron scattering).

First analysis work of the CIRANO experiments has started and is now well under way.

3. Conclusions

The review of PSI's activities within the framework of the fast reactor physics R&D has clearly shown that the main thrust for this work was to contribute to the understanding of the neutron physics characteristics of plutonium burning fast cores. The removal of the fertile blanket zones, the increase in plutonium content and the introduction of a considerable amount of steel surrounding the fissile zones alter both the operational and safety characteristics of such cores, making this data and calulational methods validation effort necessary.

3. Liquid Metal Thermohydraulics

3.1 Introduction

The LMFBR-related thermal-hydraulics research programme in Switzerland, referring to stratification phenomena between sodium streams of different temperature in the upper plenum of FBRs under decay-heat-removal conditions, was terminated end of 1996.

The main purpose of the experimental part of this programme was to investigate the thermal-hydraulic mixing phenomena between two horizontal fluid layers of different velocities and temperatures, with particular attention paid to the effects of Richardson number (experiments in a wide range of velocity and temperature differences between the two streams) and Prandtl number (use of two fluids water and liquid sodium).

In the analytical part of the programme, different available computer codes have been developed further and adapted in order to be used for mixing layer calculation. To accurately predict the flow fields and temperature distribution in the pools a satisfactory validation of codes, based on a reliable experimental data base, must be performed.

3.2 Short review of investigations

In the first phase of the programme, experiments with water were performed in a test-section made of acrylic glass (WAMIX I experiment). Visual observations, which primarily lead to a better qualitative understanding of the phenomena in the developing mixing layer, were followed by application of different experimental techniques (particularly the laser sheet technique) to investigate generation, formation and interaction of vortices. The visualisation by a moving laser sheet was used in order to investigate the formation of streamwise vortices. Extensive work of the WAMIX I experiment was also related to the design the sodium experiment.

Since 1995 the experimental work has been concentrated on preparation of the second phase of investigations in water (WAMIX II) and providing a comparable testing arrangement in sodium (NAMIX experiment). For measurements of local velocity (see Fig. 1) and temperature as well as their fluctuations in the WAMIX test-section, laser Doppler anemometry and resistance thermometry are applied in a modified test-section. To make these measuring techniques applicable, some modifications on the water loop were also made.

In parallel to the construction and mounting of other components of the sodium experiment NAMIX (Fig. 2) the test-section (Fig. 3) was designed and manufactured. Because of the delay in test-section delivery, the experiment was put in operation late in 1996.

The main objective of the analytical work was to check the ability of general-purpose fluid dynamics codes (like FLOW3D [8] or ASTEC [9],[10]) to reproduce (with reasonable accuracy) the overall development of stratified mixing layers at various Prandtl numbers and to provide a code for direct numerical simulation (modification of code FLOW-SB [11]). Particularly important was the participation of ASTEC as well as FLOW3D in different benchmark calculation tasks. The adaptation of the pseudo-spectral code FLOW-SB for the direct numerical simulation (DNS) of stratified mixing layers was very successful. Its ability to calculate the temporal development of flow structures and temperature fields is particularly important, and because of the possibility to visualise these structures, direct comparison with experimental observations (video records) is also feasible.

3.3 Achieved results and concluding remarks

In extensive experimental investigations, based on the combination of different visualisation and measuring techniques, important progress in understanding of phenomena (generation, formation and interaction of vortices) was achieved(Fig. 4)

The mixing-layer thickness as a function of distance from the splitter plate, Richardson number and velocity ratio was determined and semi-empirical correlations for their calculation were given.

By analysing the development of streamwise vortices, their wave length and their behaviour in relation to the spanwise vortices were determined.

An important influence of stratification on mixing was found. With increasing Richardson number (e.g. increase of the temperature difference between the layers) the formation of vortices is more and more suppressed and the growth of mixing layers reduced.

Measurements of local velocities and temperatures could not be finished up to the end of 1996. These are still under way and the complete results will be summarised in a separate doctoral dissertation.

The experimental results were used for comparison with codes, particularly with direct numerical simulations of the code FLOW-SB.

Detailed information about experimental investigations together with achieved results can be found in different reports (see references [12] to [15]).

The ability of the general-purpose turbulence codes was successfully shown already by using them as a help for the design of experiments, but particularly due to their good performance in different benchmark exercises (see e.g. [16]).

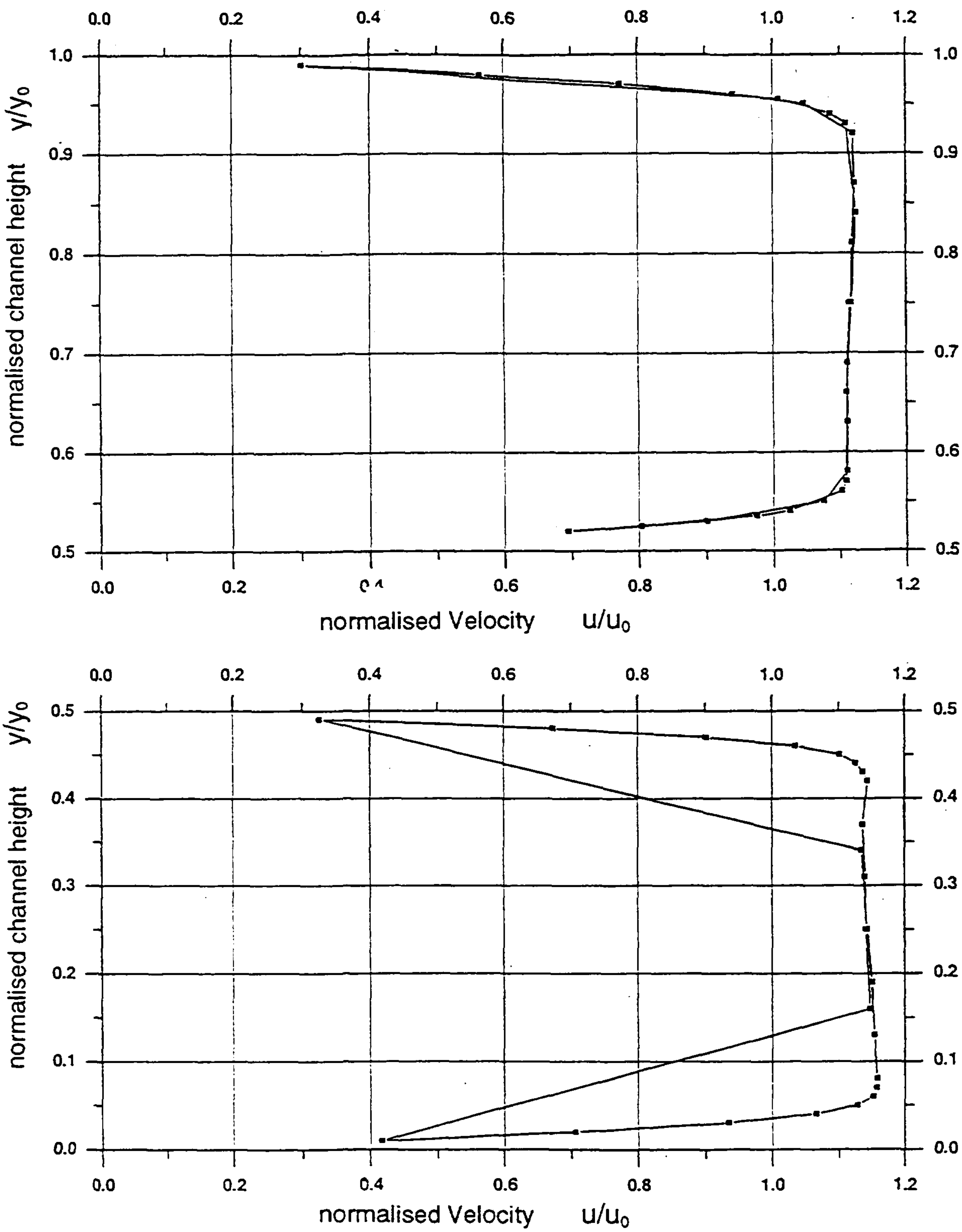
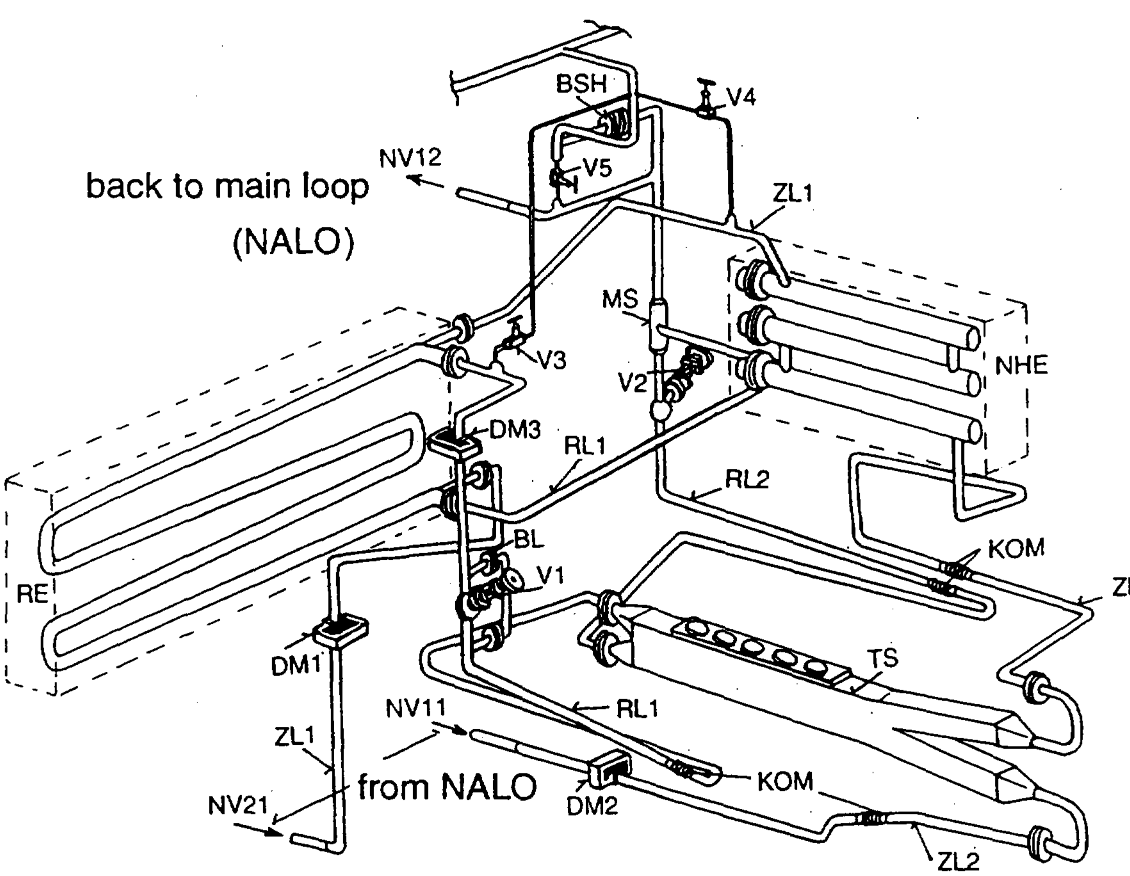


Fig. 1. Velocity (normalised: u/u_0, where u_0 = 55 mm/s) distribution in the subchannels (over the normalised channel height y/y_0, where y_0 = 100 mm), measured in the test section of WAMIX (lines connect subsequent measurement positions).



Legend

BL	- orifice in by-pass	MS	- mixing tee	RLi	- outlet tube i
BSH	- burst disk	NHE	- heating element	TS	- test-section
DMi	- flowmeter i	NVi	- valve i in NALO	Vi	- valve i
KOM	- compensator	RE	- recuperator	ZLi	- inlet tube i

Fig. 2. NAMIX experiment with important components of the experimental setup.

From the direct numerical simulation of mixing layers with the code FLOW-SB, detailed flow and temperature information in space and time can be obtained. A large number of simulations was performed (at relatively low Reynolds number) in a wide Prandtl number (Pr) range (from 0.00535 for liquid sodium, to 6.9 for water), where the Richardson number (Ri) varies from 0.0 (no stratification) to 0.2 (close to critical, stable stratification).

Investigating with particular attention the behaviour of entrainment and mixing in the layer, strong effects on varying Pr and Ri were found. Both quantities decrease with increasing Richardson and decreasing Prandtl numbers.

Some results of these simulations were reported at the EUROMECH 339 conference [17], but more complete information can be found in [18].

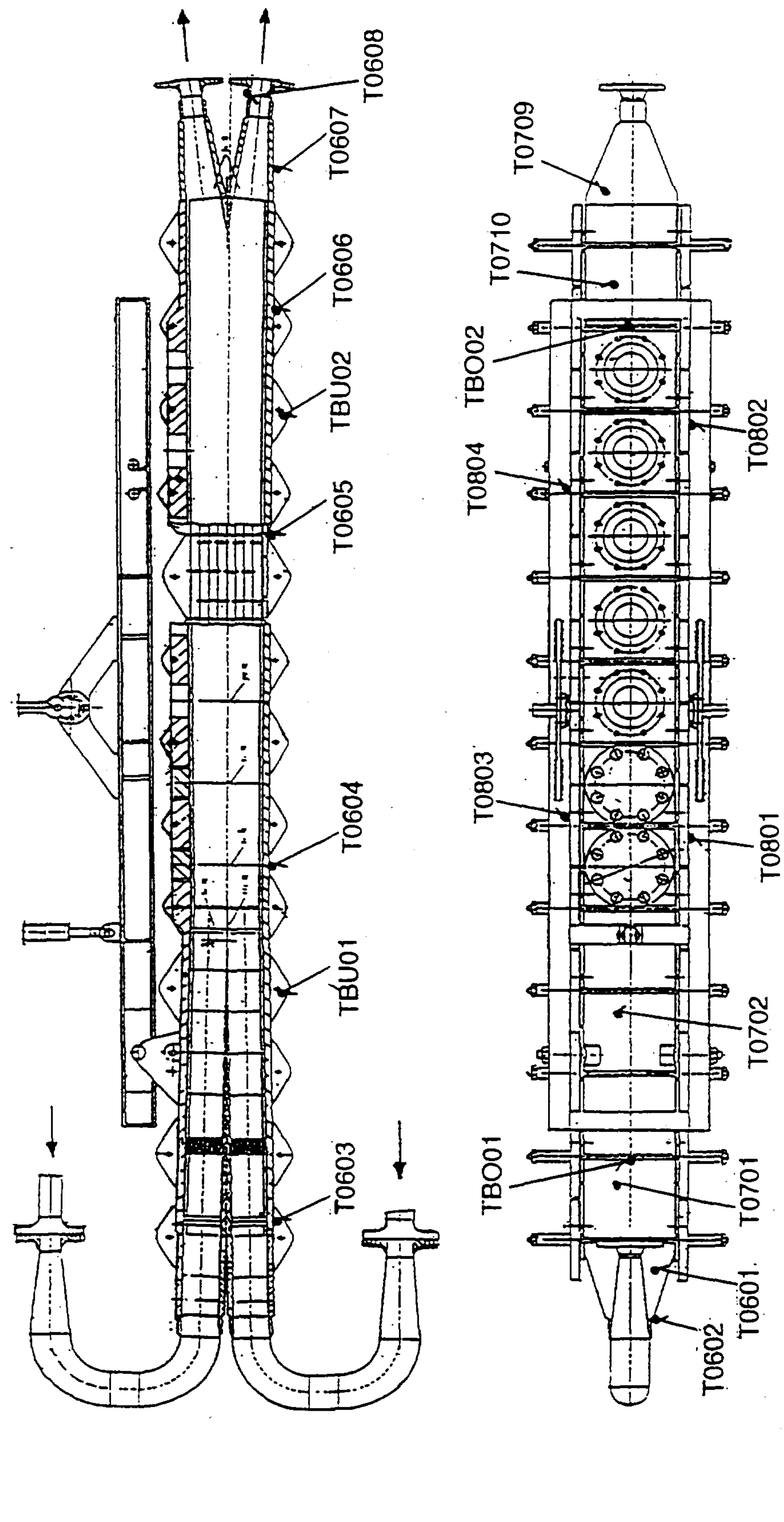
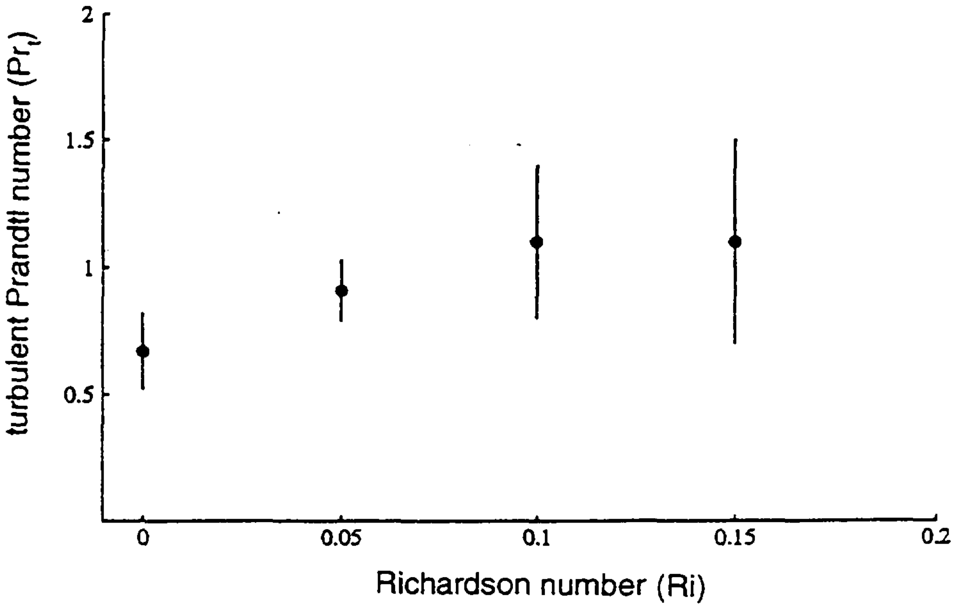


Fig. 3. Test-section of NAMIX experiment with indication of some important thermocouple positions.

a)



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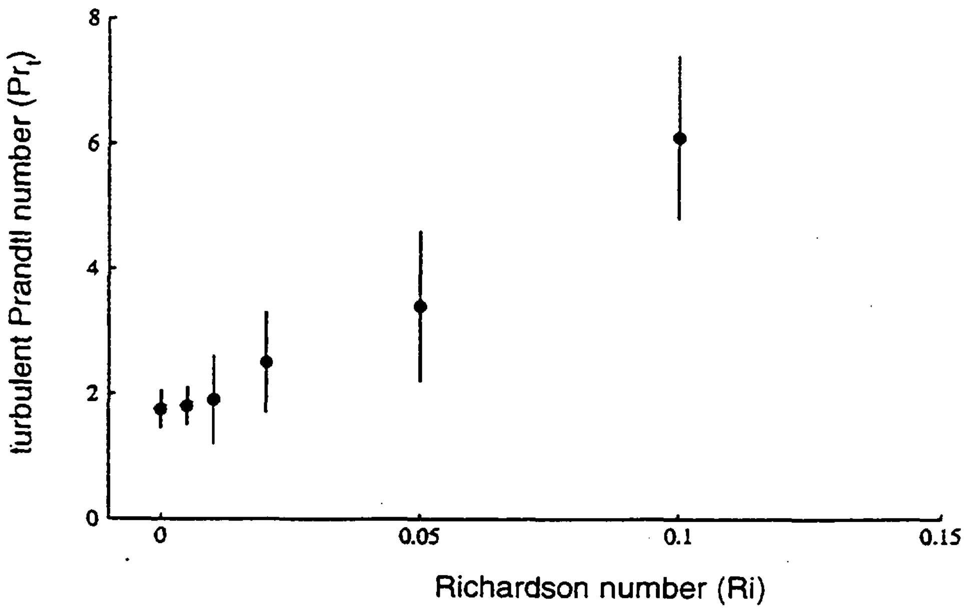

Fig. 4. Turbulent Prandtl numbers for air (Pr = 0.69, a) and for sodium (Pr = 0.00535, b) as a function of stratification (Ri).The values were obtained from the results of direct numerical simulations with the code FLOW-SB.

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