

INTRODUCTION

The Specialists' Meeting on Technology of Steam Generators for Gas-Cooled Reactors was organized in the framework of the International Working Group on Gas-Cooled Reactors (IWGGCR). It took place in Winterthur, Switzerland, from 9-12 March 1987 and was hosted by Sulzer Brothers Ltd., Winterthur, Switzerland. 47 participants from France, the Federal Republic of Germany, Israel, Japan, Spain, Switzerland, the USSR, UK, USA and IAEA attended the meeting presenting 26 papers.

The purpose of this meeting is to provide an opportunity to review and discuss the state-of-the-art and recent progress made in the development, design and fabrication of steam generators in gas-cooled reactors, their lay-out, testing, and operational performance to identify areas in which additional research and development are needed and to define possible areas for international co-operation.

The technical part of the meeting was subdivided into 4 sessions:

- A. Operating Experience
- B. Steam Generators for Next Step on Gas-Cooled Reactors
- C. Materials Development and Corrosion Problems
- D. Thermohydraulics

During the meeting papers were presented by the participants on behalf of their countries or organizations. Each presentation was followed by open discussion in the general area covered by the paper.

RESUMES OF PAPERS

RESUME OF PAPERS ON STEAM GENERATOR DESIGN

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More than 10 papers were dedicated to design related subjects. With regard to the short available time I shall not discuss them individually but rather concentrate on a limited number of features I personally consider essential. Thus, I may not give due attention to all the interesting presentations and appologize in advance for any shortcomings.

The latest AGR steam generators are those for Heysham II and Torness which are presently in the commissioning phase. They are once-through boilers using reheat with an auxiliary decay heat unit at the cold end to ease start-up and shut-down procedures. Boiler units are made up from serpentine tube platen and installed within the annular space between reactor gas baffle and PCRV inner wall, following Magnox and early AGR practice.

Two other AGR stations, Heysham I and Hartlepool were commissioned in 1983 but have not reached rated power yet. Feed flow redistribution by refrerruling with two-stage orifices improved the performance. The once-through steam generators with reheat are made up from helically coiled tube cylinders and installed in separate pods around the core vault. The tube support structure is assembled from individual straps extending the whole height of the surface.

A similarly assembled tube support is proposed for the German HTR-100 "in-line" reactor concept. The single helical steam generator unit incorporates two independent water/steam loops. The flexible support structure is designed to compensate for different thermal expansion in case of one-loop operation. There appears to be an inherent risk of uneven tube spacing in normal operation, which may lead to varying heat input and superheat in some tubes (Assembled support structures for helically coiled boiler tubes have been used before in Niederaichbach [CO₂] and Super Phenix [Sodium]).

A different tube support is proposed for two other modular reactors, the German HTR Module and the US MHTGR, both employing the "side-by-side" concept. This helical boiler tube support consists of radially extending, drilled support plates into which the precoiled tubes are threaded. The rigid plates allow defined and accurate spacing of tubes and tube cylinders. The design problem here is to limit the so-called "bearhug" loads to acceptable values. (Such support plates have been used before in EL-4 [CO₂], Fort St. Vrain and THTR-300 [both Helium]).

An alternate heat surface configuration is proposed for the USSR VG-400 HTR plant. Small diameter helical coils of coil to tube diameter ratio between 3 and 14 are assembled in hexagonal boxes (cassettes). A steam generator is built up from a multitude of such modules and is designed to combine advantages of both straight tube and helicoil bundles, namely easy manufacture, compactness, good gas side mixing and accommodation of thermal expansion.

While there is a tendency to simplify recent HTR concepts by eliminating nuclear reheat, a proposal was made to install an intermediate Nitrogen circuit which could alternatively reheat steam or remove decay heat by natural convection.

At the time of this conference the German THTR-300 is under commissioning. First measured steam generator data show good agreement with theoretical predictions. The steam generator consists of six podded helical units each incorporating a HP and a RH section. The surface tubes are collected by means of bifurcations in order to halve the number of feedwater and steam leads penetrating the double steel closure. The steam leads are collected in an outer cylindrical I-800 header the inelastic analysis of which revealed the life limiting mechanism to be ratchetting rather than fatigue.

Stability control is achieved by fix orifices in each tube and adjustable throttling valves in each of the feedwater lines.

Since the THTR-300 has the first nuclear steam generator employing downward boiling, a high degree of information on the operational behaviour was considered essential. Therefore, one of the six steam generator units was heavily equipped with thermocouples to measure gas (21 locations) and water/steam temperatures (50 locations).

RESUME OF PAPERS ON OPERATING EXPERIENCE

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Four papers specifically describing Operating Experience with Steam Generators have been presented.

These were: A1 by Mr. C. Fernandez Palomero, Spain, A2 by Mr. R.N. Razzell, UK, A4 by Mr. A.J. Mathews, UK and A7 by B. Jürgens, Federal Republic of Germany.

Several other papers dealt with some aspects of experience, notably papers A3 by Mr. M. El-Nagdy, UK, C1 by Mr. D.W. James, UK, C2 by Mr. G.S. Harrison, UK, D4 by Mr. J.E. Newell, UK, D7 by Mr. Ch. Henry, UK, and Mr. C. Elter, Federal Republic of Germany, D9 by Mr. J. Wolters, Federal Republic of Germany.

The following aspects of Steam Generator Operation have been considered:

a. The serious aspects of erosion/corrosion in carbon steel tubing. At Vandellos large numbers of leak were received, as at Wylfa. The successful measure of using AMP dosing was described, including a full description of the development of the technique by Mr. Harrison in paper C2. Prior to these AMP developments, palliative measures such as power reduction, sulphate dosing and morpholine treatment were necessary.

b. Flow induced vibration. Experience at Wylfa and the corrective measures were described. Fretting was due to design problems with tube clamping arrangements. The good performance at Hinkley, Hartlepool and Heysham I, showed the value and importance of good tube clamping arrangements and the value of instrumentation. The former aspect is obviously being addressed by the HTR designers but instrumentation and thorough testing on prototype designs is obviously very important. Are our HTR designers over-confident in this area ?

c. Thermal performance

The conference has concentrated on Helically Wound Steam Generators.

Mr. Jürgens paper (A7), supported by the detailed results of Mr. Henry (D7) indicated reasonably good agreement between design assumptions and commissioning results, whereas my paper indicated that at Hartlepool and Heysham I, problems with clearances at the outer and inner radial boundary could lead to major temperature variations. The design is obviously sensitive to three factors. Good instrumentation and the ability to adjust flow patterns rapidly and easily must be a firm conclusion of this conference, although it must obviously increase the design cost of a commercial plant. My view is that this price must be paid. There is no room for compromise with this type of Steam Generator, because it is not tolerant of dimensional variations. The inlet geometries set by reactor considerations (e.g., the use of bypass cooling) can "throw" the best efforts of the SG designers.

Temperature transients following reactor trips were described on THTR. The transients are large, but the THTR design is tolerant. Will other designs incorporating tube plates be as tolerant ?

Thermo-hydraulic models should be compared by using identical test cases.

Inlet geometry of reactor can affect inlet trip and flow distribution to the forks - thus can throw the SG design.

The correction of errors or faults can lead to more rapid developments in technology because money is instantly provided.

Temperature transients on tube plate when individual Safeguards are isolated and then reconnected.

RESUME OF PAPERS ON MATERIALS

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1. Selection and performance of materials for use in gas-cooled reactor steam generators is in a favorable position.
2. The Meeting did not identify any outstanding problems. No new or improved materials were required. The "exotic" anti-galling coatings applied to tube surfaces and fixings in helium cooled reactors were judged to be adequate. The nickel-titanium "shape memory" alloys were shown to have use for low temperature sealing/plugging applications.
3. Generally speaking, gas-side oxidation and water side corrosion were adequately allowed for by design, and choice of materials presented no major problems. A paper summarizing the corrosion behaviour of Incoloy 800 would have been welcomed, however.
4. A material property that is of prime importance to high temperature steam generator design is thermal fatigue or cyclic creep resistance. This is usually missing from materials data sheets. It is recognized, however, that the nature of the thermal cycle is critical, (heating and cooling rates, hold times, etc.). An improved assessment route for thermal fatigue damage is urgently required; ASME Code N47 is hopelessly inadequate.
5. The chief areas of concern identified by the Meeting were the bimetallic (transition) joint between ferritic and austenitic steam generator tubes, and erosion-corrosion damage in the low temperature regions of the boiler.
 - a. Transition Joints. Materials must be selected for good creep and thermal fatigue resistance, as well as their resistance to stress corrosion cracking. Pressure stresses are usually small compared with thermally induced stresses. Conditions under which such joints are wetted should be minimized or avoided completely. The designer should aim for the maximum operating window. This means (since the superheat margin or lower temperature limit is usually fixed) that good creep resistance for the weld and the ferritic alloy is vital.
 - b. Erosion-Corrosion. Carbon steels should never be used where erosion-corrosion damage is anticipated. Relatively small alloying additions (chromium in particular) confer much improved erosion-corrosion resistance. Amine dosing (e.g. morpholine and AMP) is effective but requires adequate condensate polishing plant capacity if high dose rates (10 v.p.m.) are to be used. Weld procedures and inspections must ensure that local flow disturbance is not produced by the weld.
6. Steam generator failure statistics tend to support the foregoing conclusions. Massive tube leaks sufficient to cause a significant safety risk have not occurred to date. Failure statistics for more modern plant seem to be better than for the early Magnox designs. Apart from manufacturing faults which occur during early operation, the majority of subsequent failures have been due to waterside (corrosion) damage.

RESUME OF PAPERS ON THERMOHYDRAULICS

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My comments are addressed specifically to the papers dealing with thermo-hydraulics, that is, papers D3 (Mr. Gröhn), D4 (Mr. Newell), D5 (Mr. Achenbach), D6 (Mr. Weber), D7 (Mr. Henry), D8 (Mr. Pospelov) and D10 (Mr. Meister).

Considerations of thermo-hydraulic behaviour and steam generator performance have been a major theme of the conference along with the interaction of such considerations with design and operating problems. We have heard much about the relationship of thermo-hydraulic behaviour to bi-metallic transition joints in tubes and operating stability over all load conditions.

The papers, I am commenting on, can be grouped in four areas:

1. Basic information needed by the designer

Papers D3 (Mr. Gröhn), D5 (Mr. Achenbach) and D8 (Mr. Pospelov) deal with such basic information. Mr. Gröhn's paper provides information on the effects of yaw angle (helix angle) on heat transfer and pressure drop which must be considered when helix angles are greater than about 10° . The experiments and numerical results described by Prof. Achenbach provide information of turbulent mixing which is needed for two- or three-dimensional calculations of tube bundle performance. Prof. Achenbach's results suggest that the turbulent Peclet number is not so dependent on Reynolds number and not heavily dependent on tube bundle geometry. Mr. Pospelov's paper provides basic information needed for the comparison of the "corkscrew"-type tube geometry with other types.

2. THTR-related design considerations and results

Paper D6 (Mr. Weber) describes the philosophy of design for THTR relative to static stability of the tubeside water/steam flow. Mr. Weber's contribution demonstrates the need for orifices and throttle valves in THTR.

Paper D7 (Mr. Henry) describes the operating temperature measurements for the instrumented steam generator of THTR. The operating results agree well with predictions, confirm design assumptions and illustrate the design decision of the throttle valves as a means to adjust (fine-tune) the tube side flow.

3. Feedback of thermo-hydraulics on Operation and Maintenance Considerations

Mr. Newell's paper (D4) gives an excellent illustration of the reality of dealing with orifices during operation. A very clever and creative approach for modifying the orifices in service was presented.