reproduced, these results led to the decision to resume normal operation. The steamgenerator tests were concluded in last June, no further leakindications were measured.

Small leakindications

Beside the described serious leakindications, smaller fluctuations of the hydrogen signal do occur occasionally.

A number of these can be ascribed to malfunction of coldtrap control of the temperature fluctuations in the hydrogen detectorloops, in some other cases no explanation could be found. An example of such an unsolved problem is given in Fig.6 . During a low load test a hydrogen signal appeared on the detectors in the outlet of both the superheater and the evaporator indicating a leak in the superheater. Because of the rather low rate of rise (0.001 ppm/min.) no safety action was taken, the indication leveled off after about 20 minutes and disappeared.

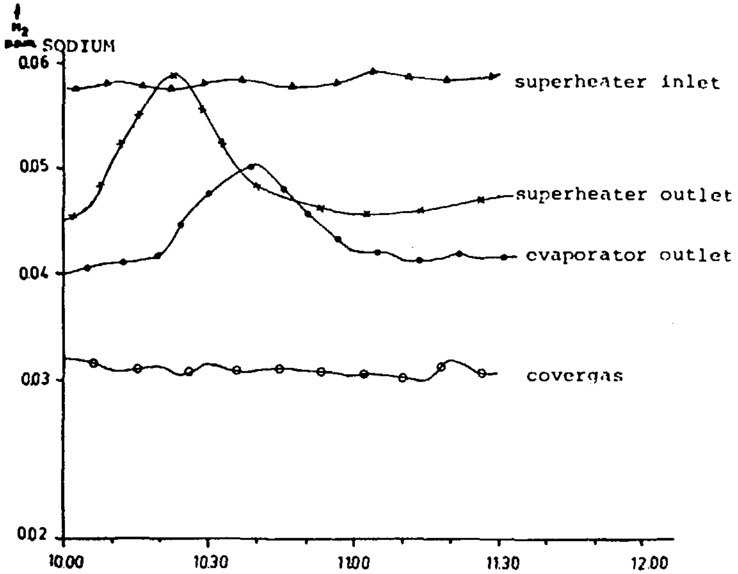

FIG. 6. HYDROGEN FLUCTUATIONS MONITORED MAY 1974.

Recommendations

a) To obtain optimal protection from the hydrogen detector equipment it is essential to reduce the hydrogen fluctuations by maintaining a very low plugging point. A hydrogen level of 0.05 ppm/min. was proved to be possible.
b) It is advisable to develop methods to remove hydrogen from the coldtraps to prevent hydrogen fluctuations caused by coldtrap manipulations.
c) Proven methods should be developed to leaktest a steamgenerator after a leak-indication. Pressurizing with a hydrogen-inert gas mixture seems very promising but not enough is known about H_2-diffusion through oxydized ferritic material.

L.1. Questions raised in Developing Fast Reactor Steam Generator Designs

P. A. Taylor
O. Hayden
United Kingdom

ABSTRACT

The most important component in the achievement of satisfactory L.M.F.B.R. reliability is the steam generator. When the failure statistics of other nuclear steam generators and the implications of a sodium water reaction are considered, there is some cause for concern. It is apparent that considerable improvement in technology is necessary and until more experience on operating plant is available a conservative design approach must be taken.

Many solutions have been proposed, varying from forced circulation straight tube modular to large single vessel once through helical designs. The paper poses what are considered to be the main questions which arise when making a choice of fast reactor steam generator type and tube configuration. The aim is to promote discussion amongst the assembled experts on their relative design approaches and the importance placed upon the various factors in reaching our common goal of ensuring the success of the L.M.F.B.R. in its essential role of conserving world energy resources.

1. INTRODUCTION

A designer wishing to select the main features for liquid metal cooled Fast Reactor Steam Generators, to be used in large commercial Power Stations, must seek answers to certain basic questions before detailed design and development testing can proceed.

A world-wide survey of fast reactor Steam Generators, in operation or under development in the many design establishments, shows a considerable diversity of types - once through, recirculating, partial recirculating and many forms of tubing configurations - straight, "L", "J", helical, "U", bayonet, as well as a selection of materials for tubing, shells, etc. indicating little or no agreement on the basic features. This lack of agreement appears to arise from the different values which particular designers or operators place upon the different available options according to their different experiences in designing or operating fossil fuelled or other types of nuclear plant. Many factors, which are often impossible to quantify, are involved and a considerable amount of individual judgement is required in assessing a boiler design. The boiler operating conditions are not unduly onerous in comparison with boilers for fossil-fired stations or for high temperature gas cooled reactors and in some respects, can be much simpler. However, the serious effects on availability, of even small leaks make potential buyers and operators scan designs very carefully in the light of their own experiences with large units, both in normal operation, with fault conditions on other components affecting the boiler such as turbine condensers and in inspecting and repairing plant.

Tube leaks, on L.M.F.B.R. Steam Generators, could lead to outage times which are considerably longer and more expensive than on current water and gas cooled reactors and for this reason standards of leak tightness achieved in manufacture and during operation of sodium heated Steam Generators must show a substantial improvement over current reactors. This note poses questions affecting integrity which arise during the design process in an attempt to provoke discussion amongst the assembled experts into how they rate these factors in the pressing need to improve the availability to a point compatible with the special needs of the L.M.F.B.R.

2. DESIGN CONSIDERATIONS

(i) Should the Steam Generator type be Once Through, Recirculating or Partial Recirculation?

There is no doubt that the pure once through type will have the lowest first cost, a major factor in this being that single vessel designs are practicable with some tube configurations whilst the partial recirculation type will be intermediate in cost between the pure once through and "full" recirculation types.

Some parties, however, have reservations about the dryout zone and increased potential for phase separation at changes in tube geometry which cannot be avoided except in full recirculating types, suggesting that any savings on first cost of the types with dryout will be quickly outweighed by loss of availability. These reservations are in regard to possible deleterious effects of thermal cycling and concentration of any aggressive salts present in the dryout zone and possible differences in behaviour between liquid sodium heating and the conditions in fossil-fired boilers where most operating experience with once through boilers arises.

In the U.K. serious consideration is being given to the adoption of a design in which dryout occurs as this suits the particular restraints imposed by the rest of the plant. Compared to the PFR the core outlet temperature has been reduced, the core flow limit retained, and the T.S.V. pressure retained. The resulting secondary sodium line makes it difficult or impossible to adopt a recirculating boiler concept similar to PFR without changing the system design ground rules. Therefore, the once through system is favoured but final selection will not be made until the reservations concerning dryout zone behaviour have been eliminated. This question is a major part of sodium heated testing and corrosion studies.

Once Through boilers for fossil fuels are well established in some major industrial countries, notably Germany, with satisfactory operation. Therefore, the main concern is whether the sodium environment gives rise to more deleterious conditions than other heating media due to possibly greater heat flux cycling and increased potential for wetting and rewetting. An additional concern stems from the fact that most experience is with river cooled stations and in the U.K. sea water will be the rule, increasing the chance of ingress of salts via the condenser.

Much of the information to hand concerning the adverse effects of dryout is of a generalised nature without quantitive substantiation and direct application to the conditions appertaining in a sodium heated boiler. Tight control of feed water purity and smaller temperature differences at the dryout point could possibly make substantial differences to the problem.

(ii) What Tube Configuration is most suitable?

The many different configurations in the steam generators for L.M.F.B.R.'s already working or under development indicates the difficulties in answering this question. Included in the discussion necessary to arrive at a conclusion are the following factors:-

(a) Once through boilers require long tubes, recirculating types require many tubes.

(b) Any water side draining requirements.

(c) Means to allow differential expansion between tubes and between tubes and shell, particularly under transient and plugged tube conditions.

(d) In general, operators prefer to avoid small bore tubes, but large bore tubes may aggravate the large leak incident and length.

(e) Requirements for access for inspection tools or probes to the tube bore or external surfaces; in situ and away from the shell.

(f) Possibility of fretting between tubes and supports.

(g) Easy removability of tube bundle.

(h) Confidence with tube welds under sodium.

(i) Possibility of instabilities with sodium being cooled, with density increasing, in up flow or "downhill" boiling of water.

(j) Performance sensitivity with plugged tubes.

(k) Confidence with use of tubes with relatively large amount of manipulation.

(l) Reinstatement difficulties following a Na/H_2O reaction.

(iii) Should the Tubes be Terminated at Tubeplates or Penetrate the Shell with Thermal Sleeves?

Again, examples of both can be found in the designs in use or under development. Where tubeplates are used, thermal stresses arising during controlled or fault transients must be carefully considered, particularly at regions where the perforated sections merge with solid rims or hubs. With small capacity or modular units the tubeplate thickness may be small enough to limit these stresses to manageable values. Is it certain that these same transients will not cause undue damage to thermal sleeves with the materials or material combinations selected?

(iv) What size of Unit should be selected?

Modular units have advantages in that a unit may be easily removed for repair, perhaps after a tube leak, and a spare unit installed quickly in its place. A philosophy possible on an 8 secondary circuit station layout is that as soon as trouble (suspect tube leakage or confirmed tube leak) arose, a circuit would be taken off load and the bundle replaced with a spare. If this is done rapidly the remaining 7 circuits could be run at an overload capacity condition to maintain station output for say a 2 week period During this limited overload period the heat flux would be allowed to increase and margins used up. Thus, the very high replacement electricity charges could be minimised.

There are some grounds for believing that this is the only way of achieving high availability, but, of course, this depends greatly on the number of leaks expected to be experienced.

Predicting how many tube leaks are going to occur over the 30 year life of a new type of boiler where even the very smallest leak could be critical is impossible to quantify until much more true operating power station experience has been accumulated.

Small units also effectively increase the sensitivity of the leak detection system by reducing the "dilution" of the hydrogen in sodium at the sample point. However, there is no doubt that cost increases result from the use of a modular concept over "large unit" arrangements.

(v) What Measures shall be Provided for In-situ Inspection of Tubes, Shells and Shell Internals?

It has been suggested that such inspection is necessary to give confidence in the suitability of a unit for continued service at scheduled maintenance periods or perhaps after a tube leak incident where tubes or other components may be thinned or damaged by sodium-water reaction products. If inspection of the tube bore is required this may set the minimum bore to allow passage of the eddy current or ultrasonic probes and tube bends may have to have minimum radius of curvature for the same reason. Shell side inspection will probably require special access arrangements with some tube configurations being more difficult in this respect than others. Ease of removability also comes into this consideration if the unit is not suitable for inspection through man-ways or hand holes.

(vi) What Material should be selected for the Tubes?

This important question is discussed in a companion paper and the factors involved in the choice are not repeated here. However, it must be emphasised that the tube material choice has significant effects on all areas of the design - thermal, hydraulic and structural, and in the important area of design for sodium-water reactions and leak detection. A property of particular interest is the tube material resistance to corrosion on the water/steam side - the significance of necessary corrosion allowances and their thermal resistance is important in a sodium heated boiler.

(vii) How do the Tubes in a Bundle Differ from each other in Thermal Behaviour?

The selection of parameters in some types of designs can depend on the difference in thermal behaviour between the tubes in the bundle, e.g. the choice of mixture steam quality generated in a recirculating evaporator or in effect the recirculation ratio. Tubes will differ in this because of many factors of which the most important will be variation in thermal conductivity, wall thickness variations due to manufacturing tolerances, corrosion loss variations, mal-distribution of sodium and water flows and variation in fouling coefficients. Having established the magnitude of each effect one must then decide whether to summate by adding directly or to use a statistical approach.

(viii) Should each Heat Exchanger be Provided with a Gas Space?

A gas blanket or cushion can conveniently reduce thermal stresses by avoiding contact between, for example, a tube plate and the liquid sodium. Other advantages claimed include a reduction of the initial pressure pulse resulting from a large sodium-water reaction and ease of leak detection by sampling the cover gas for Hydrogen. Against these claims are put the experimental observation that a gas space can intensify secondary sodium-water reaction pressure pulses and the complication of gas systems necessary to make up gas lost by entrainment or solution in the sodium. In addition, there have been experimental observations indicating interaction between gas spaces in series leading to sodium flow oscillations.

(ix) What Development Potential should be "Built-in" to the Chosen Design?

Although the Designers' first task is to select a design style suitable for the immediate application, the possible development potential leading to greater economy on later stations should be kept in mind. This development may be in the direction of larger unit size, larger tube bore with consequent reduction of number of tube circuits. Possible trends to higher steam temperature, as confidence grows in ability to predict material behaviour in liquid sodium at higher temperatures must also be considered when making a choice of tube material.

3. DISCUSSION

Obviously there are many other questions to be answered when selecting the design and design parameters, in various areas of heat transfer, hydraulics and material choice. These include margins to be applied for uncertainty in performance and for tube plugging, capacity for overload, sodium side and water side fouling factors, material for shells and tube supports. However, the questions posed can perhaps be regarded as covering the basic features of the steam generators.

Valuable evidence to assist in the choice of these basic features is now coming forward from the fast reactor stations in use, being commissioned or under design. In addition, carefully planned and executed tests on specialist sodium heated rigs to obtain specific information will produce valuable information providing the tests are adequately instrumented.

For later fast reactor stations there will always be an incentive to reduce boiler capital costs, but the experience accumulated in single wall boiler tube design concepts from the next generation of steam generator units will largely dictate the trend when considering so called"improvements" to up date a design.

The single wall concept has yet to be proven as a long term high availability proposition. The next several years must show that the integrity of design and engineering is such that very few leaks occur and/or that the method of dealing with them can involve acceptable "downtime" penalities.

To design a sodium heated boiler as a good, flexible heat transfer machine is a relatively easy task compared to that of judging what will be its availability over the 30 year life of the plant.

Thus it would appear advisable to have a back-up design of unit which could offer a step change in protection against sodium-water reaction damage and repair - or offer new standards of high integrity engineering to reduce to an acceptable level the number of leaks occurring.

Shrouded tube and duplex tube designs have been considered by most countries, including the U.K. and these and other concepts should be developed in detail to provide back-up designs,

A concept being studied involving a radical change would be to put the sodium in the tube with the steam-water on the outside. This concept would cost more money but could provide a step change in protection against the sodium-water reaction problem.

4. CONCLUSIONS

(a) To avoid the extensive outage times which will result from boiler tube leaks, L.M.F.B.R. Steam Generators will demand much higher standards of design, manufacture and operation than currently in use for water and gas cooled reactor systems.

(b) Factors affecting integrity are numerous and have a complex relationship requiring an increase in operating experience and more sodium testing for their resolution.

(c) There are features of the associated plant which affect the steam generator environment, such as water chemistry, control functions and transients, which need careful attention to ensure reliability.

(d) Without significant operating experience it is necessary to keep the design simple without too much emphasis upon economy in prime cost, avoiding all but essential manufacturing operations on the sodium/water boundary.

(e) Ease of periodic tube inspection and maintenance during short shut down periods is a necessary feature. In addition the tube bundles should be capable of removal from the shell and replacement to ease the investigation of real and supposed leaks and so minimise outage time.

(f) All designers should be mindful of the damage and programme delay that could be suffered in the evolution of the L.M.F.B.R. by chasing alleged economy in first cost at the expense of inherent integrity.

L.2. Generateurs de vapeur developpes en France pour Super Phenix

M. G. Robin — France

RESUME :

On décrit les nouveaux générateurs de vapeur , à tubes en hélice ou à tubes droits, développés en France pour Super Phénix et on compare leurs caractéristiques à celles des appareils en fonctionnement sur PHENIX.

SUMMARY :

"Steam Generator Development for Super Phenix Project"

The development program of steam generators studied by Fives-Cail Babcock and Stein Industrie Companies, jointly with CEA end EDF, for the Super Phenix 1200 MWe Fast Breeder Power Plant, is presented. The main characteristics of both sodium heated steam generators are emphasized and experimental studies related to their key features are reported.

I - INTRODUCTION

Les générateurs de Phénix (250 MWe) correspondent à l'état de la technique française vers 1965. Ils ont déjà produit, au 15/9/1974, 1. 650. 000 t de vapeur et fonctionnent selon les prévisions; mais, très encombrants et peu extrapolables, les modules conviendraient mal à une