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MASTER

LMFBR STEAM GENERATOR DESIGN AND DEVELOPMENT*

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ROUGH DRAFT

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INTRODUCTION

The essence of the Westinghouse LMFBR steam generator development program is to develop an economical steam generator with an inherent capability to remain "on-the-line."

In an LMFBR plant the steam generator represents an essential link in the production of electrical power. Operational experience has underscored the technical difficulties and the basic inability of sodium-heated steam generators to remain functional. Failure, mal-performance, or loss of availability of the steam generator, for any reason, would impose an economic burden that could seriously jeopardize the feasibility of the plant. Clearly, if an LMFBR plant is to be an economically successful power producing facility, the steam generator must be developed with high availability and must be developed within the technical and economic context of the entire heat transport system.

In 1970, a comprehensive plant cycle and steam generator conceptual study was completed. The aim was to select a steam generator concept and a plant cycle that would offer the potential for high availability and approach minimum power generation costs. The study evaluated fifteen unique plant cycles and six steam generator concepts and resulted in the following recommendations:

1. Steam generators to be developed for future commercial LMFBR plant applications shall have the flexibility to operate with either a reheat or with a non-reheat cycle.
2. The modular "J" steam generator shall be developed as the reference steam generator concept.

This paper presents a discussion of the modular "J" concept and a description of supporting research and development activities.

"J" MODULAR STEAM GENERATOR CONCEPT

A modular steam generator has been selected by Westinghouse for development as the reference concept for the 1000 MWe LMFBR plant. The "J" modular concept was selected because it satisfies, first, the fundamental criteria for steam generators and, secondly, because it offers the potential for increased availability of the heat transport system. The evaluated consequence in developing this new and unique "J" modular concept is increased availability and a lower cost for power generation.

As stated earlier, the essence of the LMFBR steam generator program is to develop steam generators that remain "on-line." Operational history has underscored the difficulties and basic inabilities of steam generators to remain functional. Hence, with the development of a reliable steam generator as the objective, the design philosophy embraced the following tenets:

- ① Features for maintainability must be designed into the steam generator. Considerations for maintenance of the unit should not be "after-the-fact" thoughts but should be incorporated into the design of the steam generator. The "J" modular concept provides for removal of the "J" module from the base plenum, as a unit, to enable ease of replacement and the lessening of loop downtime. Upon removal of a module from the loop, the tube bundle can be easily removed from the shell to enable direct inspection and/or repair of the exposed tube bundle. The simple "J" tube configuration, non-orificed, with large bends permits I.D. inspection of tubes with present state-of-the-art techniques.

- ② Thermal and hydraulic performance must be predictable.

To avoid the malperformance experienced by earlier once-through steam generators, a thermal-hydraulic analysis was performed to examine the stability of the water/steam behavior on the "J" tube module. The study analyzed six different steam generator concepts, and revealed that the "J" module evaporator is more inherently stable, dynamically, than a once-through unit with integral superheat (see Thermal/Hydraulic Considerations).

- 0 Provide structural integrity through design.

Complexity in design and complexity in analysis introduces a greater risk in component reliability over more simplified designs. While the relatively straightforward geometry of the "J" module relieves some of the problems inherent in complex geometries, some features of the concept, such as the base plenum, are still complex geometries and are the object of conceptual design efforts currently in progress.

- 0 Minimize fabrication complexity.

Complexity of fabrication, in general, will require more handling and working of critical parts and thereby increases the risk in not achieving maximum reliability. The "J" module concept has relatively simple internal components ("J" tubes, plate baffles, etc.) and tubesheet and header arrangements. It is intuitively believed that increased complexity of any subcomponent, such as tube bundle assemblies, will substantially increase the probability of failure-causing defects. Consequently, a "simpler" component configuration should strongly imply a potential for increased reliability.

- 0 Quantify a predictable maximum extent of damage in the event of a sodium-water reaction.

A notable distinction of a modular concept is that a physical boundary for maximum damage to the unit due to a sodium-water reaction is implicitly established. Use of modules increases the level of confidence in the prediction that a major sodium-water reaction will damage, or at most destroy, the internals of only one module. Thus, with a predicted value for the maximum extent of damage possible, preparation for a mishap can become a more routine-type maintenance task. The emphasis then shifts to economic considerations -- namely, how much damage is economically feasible or permissible? Clearly, the answer to this question will substantially influence the size of a steam generator and the eventual trade-off of unit cost versus plant availability will determine the practicability of maintaining a spare module on-site.

General Description

The steam generator is essentially a shell and tube type heat exchanger utilizing non-radioactive liquid sodium as the heat source on the shell side to preheat, evaporate, and subsequently superheat tubeside feedwater in a once-thru mode of operation. See Figures 1. and 2.

The modular "J" steam generator was initially developed for utilization in a series-parallel reheat plant cycle arrangement and is comprised of two separate heat exchangers, an evaporator and a superheater both operating in series; the superheater operates in parallel with the reheater. A schematic of this flow configuration is shown in Figure 3. Additionally, because of the two unit arrangement (evaporator/superheater), the steam generator may be utilized in once-through non-reheat and recirculating type applications. Data are shown in Table 1.

The evaporator unit is comprised of six heat transfer modules of equal size, shape, and thermal rating operating in parallel. These six modules are separated into two base plenums of three modules each. The base plenum is a common mixing chamber for the effluent sodium of three modules. Similarly, the superheater is comprised of three modules in a single base plenum.

The basic unit of the modular "J" steam generator is the "J" module heat exchanger which is capable of being utilized as an evaporator and/or superheater. The module is made up of two shells, a primary (tall leg) shell and a secondary (short leg) shell, both connected by a common oval flange. The tubes are bent to a "J" configuration with large radius bends. These tubes are supported by a baffle nesting arrangement consisting of the supports, stay rods and spacer sleeves.

The major subcomponents of the modular steam generator are:

1. Shell and oval flange assembly
2. Tube bundle assembly (includes clam-shell shroud)
3. Base plenum assembly

The shell and oval flange assembly represents the primary boundary between the liquid sodium and the atmosphere. This subassembly includes

Figure 3 Series-Parallel Reheat Arrangement

Table 1

EVAPORATOR AND SUPERHEATER DATA SUMMARY

3 Loops per Plant

(Series-Parallel Cycle Arrangement)

	<u>Evaporator</u>	<u>Superheater</u>
Unit Rating		
Total per loop	510 MWt	183 MWt
Per module	85 MWt	61 MWt
Shell Side		
Fluid	Secondary Sodium	Secondary Sodium
Flow rate	4.0×10^6 lb/hr	4.7×10^6 lb/hr
Inlet temperature	894°F	1040°F
Outlet temperature	655°F	894°F
Design temperature	950°F	1100°F
Nominal pressure	50 psig	65 psig
Pressure drop	20 psi	15 psi
Design pressure	200 psig	200 psig
Material	304 S.S.	304 S.S.
Tube Side		
Fluid	Water/Steam	Steam
Flow rate	4.1×10^5 lb/hr	8.2×10^5 lb/hr
Inlet temperature	492°F	725°F
Outlet temperature	725°F	1004°F
Design temperature	800°F	1050°F
Outlet pressure	2660 psia	2483 psi
Pressure drop	40 psia	86 psi
Design pressure	2800 psig	2800 psig
Material tube	Incoloy 800	Incoloy 800
Tube O.D.	0.625 in.	0.625 in.
Tube wall thickness avg.	0.072 in.	0.072 in.
Number of tubes	318	500
Active tube length	75.0 ft	71.0 ft

the primary shell, the secondary shell, the oval flange, the sodium inlet nozzle, an upper rupture disc nozzle and the shell-to-head flanges. The primary and secondary shells are right circular cylinders (approx. 32" diameter) with the upper portion of the shell expanded to accommodate the sodium inlet distribution system.

The tube bundle, comprised of 5/8 inch diameter tubes, is housed in a clam-shell shroud. Ring-type vibration supports are welded to the circumference to support the shroud within the shell and to prevent sodium bypass flow. In addition to preventing bypass and channeling the sodium flow through the bundle, the shroud also prevents impingement of sodium-water reaction products on the primary shell over the major portion of its length. The entire tube bundle assembly is supported from the tubesheets.

The base plenum assembly houses the "J" module and consists of a horizontal flat head on top of a pressure vessel shell. A sodium outlet nozzle is centrally located at the bottom of the shell. Flange openings are provided on the head for mounting the modules. The entire steam generator is supported by a support skirt located on the base plenum.

Sodium from the intermediate heat exchanger enters each superheater module at the upper end of the primary shell, is routed circumferentially up and around the primary shell by the inlet flow guide and then spills over the flow guide. The sodium then flows downward through the tube bundle and discharges into the base plenum below the sodium level maintained in this plenum. During its downward flow, the sodium transfers heat to the water/steam flowing upward in the tubes. Flow distribution on the sodium side of the modules is accommodated by combination tube supports/flow baffles and by a bundle liner which acts as a flow guide. Sodium exits from the superheater through a single nozzle located at the lower end of the base plenum.

From the superheater, the sodium is routed to the evaporator where it enters the unit at the top of the primary shell in each module. When the steam generator is utilized in a series-parallel reheat cycle arrangement, sodium from both the superheater and reheater combine prior to entry

into the evaporator. After spilling over the inlet flow guide, as in the superheater, the sodium flows downward through the tube bundle and exits the base plenum through the outlet nozzle. Sodium returns to the IHX via the secondary sodium piping.

Feedwater enters the evaporator at the inlet plenum of the secondary shell (short leg of "J") and is distributed into the tubes. The water is preheated as it flows downward in the short leg of the "J". During its upward flow in the long leg of the "J", the water is evaporated into steam and subsequently superheated before leaving the evaporator at the top of the primary leg. The superheated steam from the evaporator is then routed to the superheater where it is further heated to the steam outlet temperature of 1000°F.

Manufacturing Considerations

Minimizing complexity in fabrication is a major design goal of the "J" modular steam generator. Critical subcomponents, such as tube bundles, if complex in design, will require increased handling during fabrication and will substantially increase the probability for failure-causing defects. Consequently, a "simple" component configuration utilizing proven state-of-art fabrication techniques provides a tangible basis for achieving increased reliability.

The modular "J" steam generator is a relatively simple design from a manufacturing standpoint. The modular design utilizes simple two-dimensional U-type tube bends which are conducive to present state-of-the-art manufacturing techniques. Considerable experience has been gained in manufacturing through the utilization of similar tube configurations in PWR steam generators. In addition to manufacturing expertise, the "J" tube and its associated length (< 100 feet) and large radius bends lend themselves to current tube supplier technology. Tube lengths greater than 100-120 feet generally require either special supplier facilities (long draw bench, etc.) and/or tube-to-tube butt welds. While the former results in a cost penalty, the latter generally results in tube-to-tube welds under sodium and the increased potential for a severe under-sodium reaction. The "J" modular steam generator, to avoid both these possibilities, utilizes tube lengths less than 100 feet with no intermediate tube welds.

The tube bundle for the "J" modular concept is fabricated and assembled separately from the shell. The tube bundle is tubed at bench-top height with the baffles and tube-to-tubesheet area completely exposed. Complete access of the tubesheet during fabrication provides conditions for both producing high quality tube-to-tubesheet welds and for their inspection and possible repair. The tubesheets, being relatively small in diameter and comparatively thin, can be drilled and machined to closer tolerances using present shop practice.

One unique feature of the design which is beneficial from a manufacturing viewpoint is the lack of a closure weld on the shell. The closure seam on nuclear vessels has been traditionally difficult to weld with still greater difficulty found in providing for and inspecting the weld. The "J" modular

shell, fabricated as a subcomponent, is completely welded and radiographed prior to assembly with the completed tube bundle. The final weld after assembly of the bundle and shell is a seal weld (omega-type) on the water and steam headers.

Although not always apparent, no avenue offers greater potential in enhancing steam generator reliability than the optimization of fabrication techniques and the simplification of component geometry. Fabrication should be considered as one of the major determining factors in the selection of a heat transfer geometry. Inattention or deferred consideration to fabrication techniques and details, while contributing to gross inefficiency, costly shop mistakes, and critical time delays, will endanger the integrity, service life, and maintainability of heat exchangers.

Maintenance Considerations

Failure of a steam generator in an LMFBR plant will cause an unscheduled outage (depending on the magnitude of the failure, leak, etc.) lasting from several days to perhaps several weeks. Since outage in a 1000 MWe LMFBR will cost approximately \$100,000 a day, it becomes increasingly clear that maintainability -- or in essence, how soon will the plant be "on-line" -- becomes an important economic consideration.⁽¹⁾⁽²⁾

If the average length of a shutdown could be decreased by, for example, two days, the two-day cost advantage will be approximately \$200,000. A strong economic incentive thus exists for providing the steam generator with features inherent in the design that permit rapid and effective inspection and maintenance.

Because of the severe cost penalties associated with unscheduled plant outages, the modular unit, responsive to the criteria for high availability, is designed for maximum ease of maintenance and inspection. The time required for placing the "J" modular steam generator on-line following an outage was determined to be much less than for a full-size unit. In the recently completed plant cycle/steam generator study, results indicated that in-place repair of small leaks required approximately 1/3 to 1/2 the time required for the equivalent repair of a full-size unit. Removal and replacement of the "J" module from the base plenum required significantly less time, approximately 1/2 the time, than equivalent tasks with other steam generator concepts.

The major significance of this design from a maintenance point of view stem from (1) the ability to remove and replace modules in the event of a malfunction, (2) the capability for performing I.D. inspection of the tubes, (3) the inherent capability in the design for leak detection, and (4) the length of time involved in performing these tasks. The module to be removed from the base plenum must only be raised 10-20 feet. Once the module is removed from the base plenum, the entire tube bundle and tube-tubesheet weld area are exposed by sliding the bundle out of the shell and then removing the bundle shroud. This feature enables complete inspection and repair of the module in the event of a failure.

Presently, if a tube rupture or leak occurs, there are three repair alternatives -- tube plugging, tube bundle repair, or tube bundle replacement. Tube plugging at the tubesheets is the least time consuming method of

repairing a small leak. Ultrasonic and/or eddy current internal tube probes would be utilized to inspect the damaged and the surrounding tubes. The inspection methods, however, require that tube complexities (e.g., fixed orifices, small bend radii, bend distortion) be minimized to permit access and signal interpretation. All tubesheets in the "J" modular concept are in the horizontal position and are easily accessible. The "J" tubes are unorificed with large diameter bends (24 inches mean radius) and enable I.D. inspection of the tubes from either end. Providing for this inspection technique in the design assists considerably in minimizing loop downtime during repair of the steam generator.

Access to the tube bend area is gained through a 20" diameter manway in the plenum cover. This permits direct visual inspection of the "J" bends which are provided to accommodate the differential thermal expansion of the tubes. During scheduled plant shutdowns, direct access for inspection of this critical area will be highly desirable for preventative maintenance.

Another aspect of plant maintenance is the ability to detect which tube is leaking in the event of a sodium-water reaction. This has proven very difficult and time consuming for large full-size units. A suggested approach to this problem for the modular design is as follows:

After reaction detection, the faulty loop is shut down and the water/steam blown off to prevent further reaction. The water/steam side is then pressurized with inert gas preferably one module at a time. The module that will not maintain pressure is obviously the faulty one in which the reaction occurred. The resulting benefit is to decrease the number of tubes to be examined for leaks. By using this method, considerable time may be saved in locating the leaking tube or tubes. In the case of the evaporator, this method immediately decreases the total tubes to be inspected to one-sixth of the total--with a subsequent reduction in downtime.

This method would be particularly beneficial in those cases where the reaction detection system failed to identify the leaking module such as a leak in the base plenum area or a very small leak where no significant reaction products were present.

Considering the potential gain in availability versus the cost of a tube bundle, it appears economically attractive to store a replacement bundle on site as one approach to minimizing downtime. The "J" modular concept providing, by design, a tube bundle that is removable from the shell, requires only that a spare tube bundle be maintained on-site.

Thermal/Hydraulic Performance

Performance of steam generators is primarily dependent upon considerations given to the thermal/hydraulic characteristics of the unit. Important for satisfactory performance of once-through steam generators is knowledge of the stability behavior throughout the load range for which good control and response is desired.

Recent operational experience has stressed the fundamental importance of thermal/hydraulic performance in enabling the steam generators to remain on-line. Both the Fermi and the ALCO steam generators have been plagued with malperformance attributed to waterside instabilities. The ALCO unit tested at the Sodium Components Test Installation (SCTI) never was able to achieve design conditions.⁽³⁾

Intent upon circumventing the stability problems of earlier steam generators, the dynamic and static stability characteristics of three representative once-through evaporator concepts were investigated. The question of stability in this study was addressed to the water/steam behavior within a system of parallel circuits (dynamic) and the hydraulic sensitivity of a module or ensemble of circuits performing within a steam generator.

The analysis of the boiling flow oscillation phenomenon required a comprehensive dynamic description which encompassed two-phase slip flow, subcooled nonboiling and boiling flow conditions, transient response of the tube wall and spatial variation of the mass flow rate.

Stability criteria utilized in control system theory was applied to determine if the boiling channel was unstable, i.e., if flow oscillations would appear. Results of the dynamic analysis are listed in Table 2. The summary indicates the amount of orificing necessary to dampen the tendency of the steam generator to develop self-excited oscillations. Hence, results of the analysis revealed that a separate evaporator unit such as a "J" modular is inherently more stable dynamically than a once-through with integral superheat.

It is noted that dynamic instability refers to the tendency of a once-through boiling circuit to develop self-excited oscillation in temperature and flow which result from the density change of the fluid.

The resulting instability is commonly called a "density-wave" oscillation to reflect the physical mechanism involved. Thus, because the density gradient of the fluid in the circuit tends to control the behavior of the dynamic instability phenomenon, a unit with integral superheat (i.e., evaporator/superheater combined) will tend toward dynamic instability more readily than an evaporator with a smaller degree of superheat.

The static stability of the various concepts was examined by analytically perturbing the feedwater flow and then determining the response of the demand pressure drop. Various boiling static stability indices have been proposed to define circuit stability. The index used in this analysis is written in the form:

$$I = \frac{\delta \Delta P / \Delta P}{\delta w / w} *$$

The results of the static stability analysis (Table 2) indicate that an integral superheat steam generator concept is inherently unstable; consequently orifices of 50 psi pressure loss are required in the individual tubes to render that design equivalent to the stability inherent in the unorificed "J" tube evaporator.

* The dimensionless index formed represents the normalized slope at a given location on the steady state demand pressure drop versus flow rate characteristic curve for the heated channel. When the index is less than or equal to zero, it becomes an indication of static instability of the flow excursion class. When greater than zero, the index is a qualitative indicator of a flow maldistribution tendency. It becomes necessary then that the index be > 0 to avoid an excursion instability and, furthermore, that it be of a large enough magnitude that an acceptable flow distribution is realized under the worst conditions of heating imbalance, dimensional tolerances, etc. The upper bound of the index is ~ 2 , representing a nonboiling flow condition. (4)

In summary, preliminary analysis of the static and dynamic stability characteristics of the "J" modular steam generator has revealed that the concept is inherently stable. The "J" modular steam generator, as the reference steam generator concept, will be the object of continued development and experimentation in the area of thermal/hydraulic performance.

Table 2

Summary of Dynamic and Static Stability Predictions

Dynamic Analysis

	<u>Integral Superheat</u>	<u>Bayonet Evaporator</u>	<u>J-Tube Modular Evaporator</u>
Full Load	10 psi orifice for marginal damping	stable w/o orificing	stable w/o orificing
20% Load	stable with above orifice	stable w/o orificing	stable w/o orificing

Static Stability Index
(no orificing considered)

	<u>Integral Superheat</u>	<u>Bayonet Evaporator</u>	<u>J-Tube Modular Evaporator</u>
Full Load	-0.12*	+0.65	+0.40
20% Load	+0.57	+0.30	+0.72

* Approximately 50 psi orifice required - includes a margin equivalent to an index = +0.40.

Sodium-Water Reaction Quantified

Clearly the most influential factor in steam generator design development is the possibility of a sodium-water reaction with its inherent ramifications; the design must contain features or provisions to anticipate, prevent, accommodate, and/or permit assessment of resultant damage.

Anticipation and accommodation of a reaction necessitates provisions for safe relief of reaction products -- i.e., rupture discs, a low inertia path for the flow of reaction products, internals that yield with or contain the reaction. Prevention of a reaction implies greatly enhancing reliability in all phases of steam generator design, fabrication, and operation. Nevertheless, even with these provisions, a fundamental question remains unanswered -- what will the extent of damage be to the steam generator if there is a sodium-water reaction. With the state-of-technology of sodium-water reactions in pressure vessels still in its infancy and until the steam generators are proven to be ultra-reliable, the question cannot be adequately answered. Thus, not knowing the extent of damage that can be predicted, the component designer's most logical choice is to establish a physical boundary as a limit to reaction damage.

A notable distinction of a modular concept is that a physical boundary for maximum damage to the unit due to a sodium-water reaction is implicitly established. Use of modules increases the level of confidence in the prediction that a major sodium-water reaction will damage, or at most destroy, the internals of only one module. Thus, with a predicted value for the maximum extent of damage possible, preparation for a mishap can become a more routine-type maintenance task. The emphasis then shifts to economic considerations -- namely, how much damage is economically feasible or permissible? Clearly, the answer to this question will substantially influence the size of a steam generator and the eventual trade-off of unit cost versus plant availability will determine the practicability of maintaining a spare module on-site.

Thus, the utilization of modules results in a predetermined "quantified" risk associated with a sodium-water reaction -- with the "worst" credible mishap necessitating the replacement of a module.

Sodium-Water Reaction Considerations

The potentially damaging consequence of a sodium-water reaction is a critical aspect of an LMFBR steam generator. Since the possibility of a sodium-water reaction cannot be completely eliminated, the steam generator must be designed to (1) minimize the damaging effects of a reaction, and to (2) safely accommodate and relieve the products of a reaction. The "J" modular steam generator is addressed to both these objectives.

The most effective method to minimize the reaction consequences is to locate critical leak-prone areas of the steam generator in an inert gas environment. Experience has demonstrated the ability of steam generators to survive a massive sodium-water reaction that occurred at the sodium-inert gas interface. It is well recognized, however, that the reaction would have been more severe had it occurred under sodium. Thus, to diminish the consequences of a reaction, all tube-to-tubesheet joints for the "J" modular concept (identified as critical leak-prone areas) are located in an inert gas space.

An additional, less-heralded consideration in determining tubesheet location is the recent tubesheet failure of the ALCO unit at the SCTI. This tubesheet failure could have grave implications if the failure is found to be symptomatic of tubesheets under sodium. Thus, even if one ignores the considerations of sodium-water reaction, placing tubesheets in the inert gas space appears to be the most prudent design approach to follow.

The accommodation of a reaction necessitates provisions for the safe relief of reaction products. Based on a fluid mechanics analysis, the following guidelines were established to maintain the integrity of the shell and to minimize internal damage:

1. Maintain a low inertia path between a potential leak location and the free surface (cover gas interface) or rupture disc; the reaction is intensified in the initial stages by high relief resistance. Additionally, attention should be given to reduce form drag of internals to minimize secondary damage during a reaction.
2. Locate rupture discs for quick response to a reaction in a potential "worst" leak area (under sodium).

The "J" modular steam generator provides cover gases in the upper shell of each module and at the lower tubesheet in the base plenum. Individual rupture discs are provided in each cover gas.

Detection of a sodium-water reaction is considered less difficult and more precise in the "J" modular design. For example, with a known leak rate, the concentration of reaction products in solution increases with a decrease in sodium volume. With in-sodium leak detectors placed in each base plenum of the "J" modular, the reaction products concentration would be approximately double that of a full-size unit; similarly, with leak detectors located at the exit of each module, the reaction product concentration would be significantly increased. Consequently, because of the higher concentration levels, rapid detection of a reaction could be realized. This is considered extremely advantageous because early detection of a reaction permits rapid isolation of the reactants by simultaneously dumping both sodium and water from the unit -- and results in the obvious minimization of a reaction.

Material Considerations

Material selected for steam generator application should have sufficient engineering data available to permit, with assurance, the accurate prediction of its characteristics and mechanical properties under the unit's lifetime environment. Additionally, along with the desirable characteristic of good material properties at high temperatures (1000°F to 1200°F), the selection of materials for LMFBR steam generators must be based on consideration of:

- Sodium corrosion resistance
- Resistance to chloride and hydroxide stress corrosion
- Compatibility with secondary heat transfer system
- Weldability
- Resistance to sodium-water reactions
- Cost

Incoloy 800 was selected as the W reference tubing material because it is considered to have the best potential for meeting these requirements. Briefly, it permits utilization of a single material in both the boiling and superheat regions of the steam generator; its material characteristics are compatible with both sodium and water; and it has shown a high resistance to corrosion-erosion during sodium-water reactions.

Type 316 stainless steel was eliminated from consideration because of its susceptibility to chloride stress corrosion. A consideration of high temperature mechanical properties, as shown in Table 3 indicates that Inconel 625 and Incoloy 800 are the next choices after Type 316 stainless steel. Inconel 625 is not considered sufficiently characterized at this time, but merits consideration for future use. Use of Inconel 600 or 2-1/4 Cr-1 Mo would necessitate either lowering the design temperature or thickening the tube wall and could result in economic penalties. Tables 4 and 5 show the acceptability of Incoloy 800 for sodium corrosion and superheated steam corrosion conditions, respectively.

Incoloy 800, although susceptible to chloride and hydroxide stress corrosion cracking, is better than the 300 series stainless steels for this application. It is believed that the ferritic materials (2-1/4 Cr-1 Mo) are more susceptible than Incoloy 800 to caustic stress corrosion cracking.

Full flow demineralization, zero solids, low oxygen and chloride, and high pH on the water chemistry are expected to provide adequate protection against chloride stress corrosion cracking for Incoloy 800.

Studies to evaluate the corrosion and mass transfer characteristics of Incoloy 800 in conjunction with the other materials and environment of the intermediate sodium loop and with the materials and environment of the steam and feedwater system are continuing in materials test loops at the Westinghouse Waltz Mill laboratories.

Table 3

Code Allowables (ASME B&PV Code, Section III)

<u>Material</u>	<u>Allowable Stress K.S.I.</u>			
	1050°F	1000°F	950°F	900°F
Seamless Tubing				
Incoloy 800	13.6	13.8	14	14.2
Inconel 600	5	7	10.5	16
2-1/4 Cr-1 Mo	5.8	7.8	11	13.1
Inconel 625 *	26	26	26	26*
Type 316 SS	13.3	14	14.55	14.85

* Code case pending

Table 4

Sodium-Water Reaction

Comparison of Various Materials*

30 mls. water injection over 30 minutes

Na Temp. 500°C

3 lb Na Charge

<u>Material</u>	<u>Total Wt. Loss (G)</u>
Type 316	0.015
2-1/4 Cr-1 Mo	0.436
Incoloy 800	0.004

* Reference 5

Table 5

Corrosion in Superheated Steam

Estimated Metal Loss⁽¹⁾ after 30 Years

<u>Material</u>	<u>Temperature °F</u>			
	1050	1100	1150	1200
Incoloy 800 ⁽²⁾	1		2.5	
Inconel 600 ⁽²⁾	0.5		8.5	
Inconel 625 ⁽²⁾	1		1	
2-1/4 Cr-1 Mo ⁽³⁾		30		245

(1) Metal loss in mils of thickness

(2) Reference 6

(3) Reference 7

STEAM GENERATOR DEVELOPMENT ACTIVITIES

The goal of the steam generator R&D activities is to develop a reliable, economic steam generator that has the potential for high availability and low power-generating cost. R&D activities at Westinghouse are focused on support of the development of the modular "J" steam generator concept.

Of the development programs in progress, the activities receiving the greatest emphasis are those related to resolving problems that have plagued earlier steam generators. These programs thus emphasize the resolution of uncertainties in performance, stability, tube-to-tubesheet joints, materials, and the mechanical effects of a sodium-water reaction.

This section will briefly discuss R&D activities supporting the development of the "J" modular steam generator.

Thermal and Hydraulic Performance Tests

In company-sponsored steam generator development, one of the major activities in progress is the testing of once-through steam generator. The 1 MWt steam generator, designated as HTM-1, is demonstrating the operational feasibility of a once-through steam generator in an integrated environmental test.

As the focal point for the thermal/hydraulic performance activities, the major objectives of the test program are:

1. To obtain heat transfer performance data under various steady state conditions, and
2. To provide reliable data for the evaluation of static and dynamic stability phenomena of once-through boiling circuits.

The HTM-1 (Figure 4) is a vertical once-through steam generator containing an array of nine tubes, three of which are active. The tube materials are Incoloy 800 (reference material) and Inconel 600. To date, the model has operated at steady state conditions for 700 hours -- producing superheated steam at 950°F. The steam generator has achieved all design loads with well-behaved operation. Nominal test conditions and operational history at steady state for the model is shown in Tables 6 and 7, respectively.

In the current series of experiments, the 1 MW model is being tested under both stable and unstable operating regimes. This phase of testing, subsequent to steady state operation, is being conducted in order to precisely define unstable behavior in once-through boiling circuits and is being explored to avoid the instability problems that have plagued earlier steam generators.

The unstable behavior is achieved by subjecting the model to extreme, off-design conditions of excess sodium flow. Instrumentation has been provided in the model to detect interactions between multiple tube circuits in both instability domains. Existing computer codes, developed to examine thermal/hydraulic characteristics in steam generators are being utilized to predict the inception conditions for instability.

It is interesting to note that the tests demonstrating the stability behavior of the 1 MW serpentine tube circuit are directly applicable to the "J" tube configuration. The principle reason for this applicability is that

the physical mechanisms which induce instability are independent of circuit configuration. Dynamic instability refers to the tendency of a once-through boiling circuit to develop self-excited oscillations in temperature and flow. This phenomenon results primarily from the density change of the fluid in the direction of flow and is commonly called a "density-wave" oscillation to reflect the physical mechanism involved. Thus, since the density gradient of the fluid which is independent of the tube configuration tends to control the dynamic behavior of the boiling circuit, the experimental results of the 1 MW model will be directly applicable to the "J" modular steam generator.

In summary, the current series of induced instability tests are of fundamental importance to the understanding of the instability phenomena. The successful completion of this test program will yield a better understanding of a once-through steam generator -- and will allow the designer to more accurately predict the performance of the steam generator.

Construction of the model has served to examine techniques to fabricate high quality sodium components. More specifically, the model prototypes the tube-to-tubesheet joint, a critical area of sodium steam generator. Metallurgical analyses of the welds after completion of testing are expected to yield meaningful information (see Material Development).

1 MWt SODIUM HEATED TEST MODEL

Figure 5

Table 6

HTM-1 Nominal Test Conditions
(Steady State)

<u>Percent Load</u>	<u>Feedwater Flow Rate lb/hr</u>	<u>Feedwater Inlet Temp., °F</u>	<u>Steam Outlet Temp., °F</u>	<u>Steam Outlet Pressure psig</u>	<u>Sodium Flow Rate lb/hr</u>	<u>Sodium Inlet Temp., °F</u>
25	780	359	950	2400	7,600	Varied
50	1,670	424	950	2400	15,700	to
75	2,640	472	950	2400	25,200	Maintain
100	3,660	505	950	2400	35,600	950°F Steam

Table 7

HTM-1 Steady State Operating History

Total Operating Time (at temperature)	700 hours
25% load	230 hours
50% load	280 hours
75% load	100 hours
100% load	100 hours
Cold Start-ups	20
Hot Start-ups	8

Material Development

The performance of Incoloy 800, the reference tubing and tubesheet material in the Westinghouse steam generator, is currently being evaluated, particularly with regard to its compatibility with the heat transfer media of the LMFBR. This program is being carried out in three phases.

Phase 1 - A major portion of the steam generator will be located in a deposition region of the secondary system. However, that portion of the heat transfer tubes located at the sodium inlet or hot end of the steam generator will experience a slight amount of material loss or corrosion as a result of the sodium exposure. In a program conducted at Westinghouse Advanced Reactors Division, corrosion rates of Incoloy 800, the reference steam generator material, have been measured as a function of system operating variables, in sodium loops which mock up the secondary system of the Westinghouse LMFBR. The results of these tests are summarized in the following table. Corrosion rates, obtained from the literature, for other possible steam generator or superheater materials are included in Table 8 for comparison purposes.

Table 8
Estimated Corrosion Penetration of
Steam Generator Tubes After Thirty Years (mils)^(a)

Material	Thickness Loss at 1000°F		Thickness Loss at 900°F	
	5 ppm O ₂ ^(b)	10 ppm O ₂	5 ppm O ₂	10 ppm O ₂
Incoloy 800	1.7	5.9	0.8	2.7
Inconel 600	12.6	12.6	6.0	6.0
Inconel 625	9.0	9.0	7.5	7.5
Type 316 Stainless Steel	1.2	2.2	0.6	1.3
Type 304 Stainless Steel				
2 1/4 Cr-1 Mo Steel				

Note: These data do not take account of positional (L/D) effects.

(a) Total loss of thickness in mils after 30 years at steam generator entrance. Flow at 10 fps system $\Delta T = 300^\circ\text{F}$.

(b) Oxygen impurity level in the sodium.

Several other observations that have been made in this program are as follows:

1. There is no rapid, selective microstructural attack of the Incoloy 800 tubing alloy by the sodium at steam generator temperatures.
2. The interstitial elements (carbon and nitrogen) are relatively stable in the Incoloy 800 alloy with no appreciable changes occurring in the concentration of these elements after 4-5 months sodium exposure.
3. There is no selective attack of tube-to-tubesheet welds under typical system conditions.

Phase 2 - Stress-corrosion cracking studies are being carried at the Westinghouse Research Laboratories on three materials of interest to steam generator designers: Incoloy 800, Inconel 600, and Type 304 stainless steel. The environments being studied include high temperature caustic solutions, dilute lead solutions, very dilute chloride solutions, and high-purity water. To date, the Incoloy 800 and Inconel 600 specimens have proven resistant to cracking in both 10% NaOH (50 hrs. at 600°F) and 50% NaOH (3 hrs. at 700°F). However, Type 304 stainless steel was extensively cracked after exposure to each environment.

Phase 3 - The behavior of Incoloy 800 in sodium and water/steam environments is being further characterized during operation of the 1 MW serpentine tube, steam generator model, which contains tubes of prototypic, full scale dimensions operating under realistic heat flux conditions.

Sodium compatibility performance of the model will be determined at the conclusion of about one year of operation, by examination of corrosion tabs which were placed at strategic locations throughout the model. These will be weighed, analyzed, and metallographically characterized to establish corrosion or deposition rates and rates of transfer of individual elements, particularly carbon and nitrogen, which could affect mechanical properties.

On the water/steam side, a planned series of experiments will subject selected tubes to chemistry excursions simulating condenser leakage,

sodium-water reaction products, etc. At the completion of all testing, the model will be destructively examined to determine the effects of prototypic geometry and the chemistry transients on dry-out, stress corrosion susceptibility, and general corrosion behavior, in order to increase confidence in the ability of the reference materials to withstand a wide range of operating conditions. In addition to the materials performance work above being carried out in Westinghouse, other current AEC-sponsored programs will provide mechanical property data on Incoloy 800 for ASME Code purposes. Earlier work, both in this country and abroad, has demonstrated the superior resistance to tube wastage of Incoloy 800 under sodium-water reaction conditions.

Mechanical Effects of a Sodium-Water Reaction

The ability of the LMFBR steam generator structure to sustain the mechanical effects of a sodium-water reaction is presently under study. The evaluation of this capability involves: (1) determination of the temperature and pressure loadings to which the structure will be subjected, (2) the dynamics of the structure after the loading, and (3) the adequacy of the structural configuration and materials to withstand the temperature and stress without failure of the structural boundary.

In order to perform a relevant structural analysis for credible failures of the sodium-water structural boundary, pressures and temperatures must be established locally and throughout the structure. This requires the application of sodium-water reaction technology to the geometric complexities of the design concepts. Presently, an APDA quasi-transient network fluid mechanics code is being utilized to provide pressure/time histories on the steam generator structure. The pressures generated during the postulated reaction are of a sufficiently large magnitude that a subsequent solid mechanics analysis must recognize dynamic effects and large deformation. Examples of possible loading conditions on the vessel wall in case of a sodium-water reaction in the system are shown in Figure 5. The assumption is that the reaction will induce an axisymmetric ring loading (x msec.) causing momentary or permanent bulging or failure of the vessel wall; moments later an equally divided axisymmetric pressure load over the length of the vessel wall will cause overall radial deflection and/or failure of the wall (x+y msec.). Since the pressure loadings are dynamic, pressure wave propagation will take place in radial as well as in the longitudinal direction.

In the context of the steam generator vessel, large deformations under dynamic loading imply plastic strains and a requirement for structural analysis under these conditions severely limits the number of applicable analytical techniques. Thus, to enable verification of the steam generator structure, techniques are being developed for time-dependent, large deformation plastic analysis due to the pressure loading of a sodium-water reaction. In parallel with this effort, activities are under way to determine the dynamic behavior of steam generator materials during a

reaction, and the accident basis for which steam generators should be designed. Material data acquisition has focused upon establishing true stress versus true strain curves as functions of strain rate and temperature for Incoloy 800 and Stainless Steel 304. While the development activities in progress are analytical efforts, experimental model programs are being planned to demonstrate the applicability of the developed solid mechanics techniques to verify structural integrity. Material tests required to demonstrate the adequacy of materials under dynamic loading conditions of a sodium-water reaction are also being planned.

An additional facet of this program is addressed to the secondary aspects of small reactions, such as wastage/erosion/corrosion, and the assessment of internal damage. Organization of data and information on small water/steam leaks in a liquid sodium environment is being performed. Attempts are being made to correlate wastage (material loss) rate information with various parameters to establish the influence of the small sodium-water reaction on steam generator design.

Examples of Possible Loading Conditions on the Vessel Wall for Sodium-Water Reaction

Figure 5

Tube-to-Tubesheet Weld Development

The tube-to-tubesheet weld currently under development is a crevice-free fusion weld between the tube and the tubesheet boss. As a critical boundary (leak prone -- historically) between sodium and water, the tube-to-tubesheet weld must embody a demonstrated high integrity.

Development of a high integrity weld requires (1) investigation of the chemical composition limits for the materials selected, (2) establishment of optimum welding parameters, (3) development of tubesheet cladding techniques, (4) development of tooling and fixturing, (5) development of reliable nondestructive testing techniques, and (6) the analytical and experimental investigation of the tube-to-tubesheet joint under transient conditions. All these activities are currently in progress.

In early development activities, two thermal shock models, TST-1 and TST-2, were designed, fabricated, and tested. The primary purpose of these models was to evaluate the integrity of various tube-to-tubesheet weld configurations when subjected to repeated thermal transient conditions. Of the various weld configurations, two in particular represented candidate welds for steam generator development: a fillet weld between the tube wall and the face of the tubesheet (PWR-type) and a crevice-free butt weld between the tube and the tubesheet boss. The transients were in the nature of hot shocks simulating loss of steam generator feedwater and cold shocks simulating a reactor trip. The magnitude and severity of the thermal transients and the number of cycles which were achieved during the testing approximated values that are predicted for a steam generator during its service life. Based on test results and subsequent analysis, the integrity of the tube-to-tubesheet welds under short-term thermal cycling was successfully demonstrated.

Compositional effects on the weldability of Incoloy 800 are currently being investigated at the corporate R&D Laboratory. Residual elements such as phosphorous, sulfur, aluminum, titanium, manganese can affect the weldability of nickel-rich alloys. The commercial compositional specifications of Incoloy 800 allow significant variations in the concentrations of these elements. While the practical effects of these elements on welding are known, quantitative information is necessary. A given heat of material,

for example, may have a chemistry which is susceptible to weld hot cracking. Material specimens fabricated from heats with differing compositions are being subjected to hot ductility (Gleeble) tests, Varestraint tests, and cast pin-tear tests. Tubing from these same heats are then welded to machined bosses to verify the applicability of the laboratory results.

Because of this known weldability question, techniques are being developed for cladding the Incoloy 800 tubesheet with a weld overlay. In the tube-to-tubesheet joint design being considered, the bond strength and leak tightness of the overlay are of primary importance since the clad actually serves the same function as the tube wall. Tubesheets may be clad using a variety of methods; however, plasma arc appears to be one of the more attractive processes relative to production costs, bond integrity, and chemical dilution control. Fundamental parameters (amperage and travel speeds) have been determined for the plasma arc process. Principal efforts are presently devoted to developing a qualified procedure as determined by chemistry side bends and nondestructive testing.

A tungsten inert gas fusion welding process is utilized for the tube-to-tubesheet weld. Preliminary results (Figure 6) with Incoloy 800 tubes indicate good quality welds are being obtained. Using Incoloy 800 tubes and Inconel 82 cladding, a high metallurgical quality fusion line has been achieved on both the tube and boss side of the fusion weld. In addition, various mixtures of these two materials (Incoloy 800 and Inconel 82) are being cast in the laboratory to determine the optimum chemical mixture.

The integrity of the fabricated tube-to-tubesheet joints is being investigated using both destructive and nondestructive testing techniques. Postweld evaluation of welds include metallographic, room and elevated temperature mechanical properties, stress rupture creep and microprobe examination. Although an internal source X-ray technique presently appears most promising, alternate NDT methods, such as eddy current and ultrasonics are being investigated. Sensitivity requirements for these methods if developed for tube-to-tubesheet weld inspection would be similar to X-ray technique requirements.

In parallel with these activities, an elastic-plastic analysis is being conducted to ensure structural integrity of the weld for transient

and steady state service requirements. Test samples representing the entire joint, as well as those for individual material zones (e.g., weld overlay, tubing, fusion zone, and heat affected zones), are being tested for tensile, creep-rupture and fatigue properties at operating temperature. A correlation of NDT indications with metallurgical structure and mechanical property observations will enable meaningful weld acceptance criteria to be established.

Figure 6 Exterior View of Typical Butt Weld
(Mag. 1.25x)

"U" MODULAR STEAM GENERATOR SYSTEM

MODULAR STEAM GENERATOR SYSTEM

MODULAR STEAM GENERATOR SYSTEM