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MECHANICAL AND THERMAL PROBLEMS OF WATER-COOLED NUCLEAR POWER REACTORS

by

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I. INTRODUCTION

Many problems are faced in the design of a nuclear power reactor. As more reactors are built, some of these problems are being answered; others are being found. It is the purpose of this paper to discuss some of the principal problems faced in the mechanical and thermal design of the PWR core. The PWR is being designed and developed by the Westinghouse Electric Corporation for the Atomic Energy Commission and is to be operated by the Duquesne Light Company, of Pittsburgh, Pennsylvania, as part of its integrated electric service system (1).[1]

It is not the intent of this paper to outline the method for designing such a core, but rather to delineate some of the more important design problems and to outline areas in which more work is to be encouraged. The problems covered in this paper are discussed below under three major categories; thermal problems, mechanical problems, and the interplay of these problems with the requirements of other technologies.

II. THERMAL PROBLEMS

A. Criteria

In the design of a normal heat conversion plant, two important factors come into play:

1. All parts of the plant must be sized so that with the throttle fully opened the plant will produce the maximum design power.

2. With the throttle fully opened, operating temperatures and stresses to produce this power must be well below conditions which would cause failure.

In the design of a nuclear power plant these same factors become even more important. This is true because the nuclear core can reach almost any level of heat production during operation, yet it is coupled to a cooling system that has a limitation in its ability to carry the heat away. As a result, if one tries to obtain more heat from the reactor than the cooling system can remove, a fuel element melt-down or burnout could occur. This is especially true if the throttling unit is grossly oversized with respect to the cooling system and its demand is directly tied to the reactor control system. Hence, it is desirable to design the reactor cooling system so as to be able to handle all the heat production that may be asked of the reactor by the turbine. This includes the internal cooling means in the reactor, as well as the primary plant circulation and heat transfer capabilities.

[1] Numbers in parentheses refer to the Bibliography at the end of the paper.

II. A. (Cont'd)

Beyond this premise there exists the problem of identifying the circumstances under which the cooling system will adequately cool the core to meet these turbine demands. This is the basic problem of reactor thermal design. It is made up of many facets on which development work has been required.

The adequacy of the cooling system is dependent upon the limiting temperature conditions in the fuel elements. In general, fuel elements are clad to prevent the release of fission products; hence, the rating of a core is dependent on the maximum power that can be released without violating the integrity of the fuel element and cladding. The considerations of fuel element integrity are basically metallurgical in nature and involve knowledge of melting temperatures and phase transformation temperatures. The melting temperature is important because exceeding it destroys the cladding and permits release of fission products. The phase transformation temperature is important because changes in dimension are usually encountered at this temperature. These dimensional changes could cause rupture of the cladding or warping of the fuel elements. Therefore, the basic problem in determining the safe operating level of a reactor requires the computation of the temperatures of the fissionable material and the cladding during all operating conditions.

B. Heat Generation and Removal

1. Fuel Element Temperatures

In the computation of fuel element temperatures, the temperature difference between the temperature of the bulk water flowing past a fuel element and the surface temperature of the cladding is of importance. If the cladding surface temperature is always below the saturation temperature of the water, then the computation of this temperature difference is straightforward. The McAdams (2) dimensionless correlation is used for this computation. However, this correlation has not been thoroughly investigated for many of the fuel element geometries used in reactor design, and in certain designs it may be necessary to further evaluate the geometry effect.

If the cladding surface temperature should rise above the water saturation temperature, the problem of calculating the temperature difference between the bulk water and the cladding surface is magnified many times. The reason for this is that vapor bubbles form at the surface of the cladding when it is heated above the saturation temperature of the water. If conditions are such that these vapor bubbles do not immediately collapse into the bulk water, but stay and cover or blanket the fuel element surface, then the insulating effect of this vapor blanket sends the fuel element temperature up to the melting, or "burnout" point. The ability to predict this burnout point is one of the basic thermal problems of reactor design.

II. B. 1. (Cont'd)

The phenomenon of burnout has long been recognized, but the early studies were made with so-called pool boiling. The water is stagnant in this type of boiling except for natural convective flow induced by the temperature differences emanating from the heated element. However, in reactors one is concerned with burnout occurring with flowing water. Studies to date for the PWR have been concentrated on uniformly heated channels, with up-flow of hot water at 2000 psi. Additional study is needed to evaluate and correlate the effect of other reactor operating conditions and to understand the fundamental process of burnout. Many variables are involved, but those usually of interest are as follows:

a) Geometry
b) Water chemistry
c) Surface roughness and chemistry
d) Flow rate and direction of flow
e) Length of and heat distribution along flow path
f) Effect of heated parallel flow channels
g) Temperature or quality of bulk fluid
h) Magnitude of heat flux

2. Flow

Even if one knew the combinations of the above parameters limiting safe operation, there arises the question of assuring that the flow conditions desired are attained. Several significant flow problems are faced in assuring adequate flow rate and distribution to the fuel element flow channels. The distribution problems start at the inlet nozzles of the reactor vessel, where one wishes to insure the desired flow distribution to the core cross-section under all operating conditions. In general, this is a 3-dimensional problem that is not amenable to analysis, and thus a flow model must be set up to evaluate the performance of the design.

After the flow distribution to the fuel elements has been established, the pressure drop through the core is used to determine total flow and to evaluate the ratio of flow in the hot channel to flow in the average channel. In steady state calculations, if only single-phase flow occurs, the calculations are relatively straightforward, since it has been found that the use of the Fanning formula for pressure drop, plus the use of the Moody curves (3) for friction factors, is satisfactory for the highly turbulent flow encountered in fuel element cooling channels. However, the situation is complicated if boiling should occur, either during steady state conditions or during both operational and accidental transients. The reason for this is that the pressure drop can increase during local and bulk boiling by amounts that are dependent on variables very similar to those discussed previously for the burnout phenomenon. This increase in pressure drop is a basic limitation on the thermal performance of the reactor core, since it determines the flow in the hot channel, and is therefore factored into the cladding surface temperature and burnout calculations.

II. B. 2. (Cont'd)

A satisfactory theory is not available for predicting local boiling pressure drop as a function of the reactor operating conditions. Therefore, the values must be obtained experimentally. Studies of local boiling pressure drop in rectangular channels operating with 2000 psi water has shown that the pressure drop with local boiling increases beyond the isothermal pressure drop. However, further work is necessary to extend these data to new reactor geometries and operating conditions with the ultimate aim of obtaining a general correlation and avoiding continuing experiments.

In the case of bulk boiling or two-phase flow, two models exist, namely, the Kelly-Woods Fog Flow Model (4) and the Martinelli-Nelson Slip Flow Model (5), for the evaluation of two-phase pressure drop. However, further experimental work is necessary to establish the validity of these models, particularly in the region of low-quality steam, where these models predict bulk-boiling pressure drops lower than the experimentally determined local-boiling pressure drops discussed above. Density data on local-boiling and two-phase mixtures are needed in the establishment of the validity of these models.

Intimately tied in with the question of increased pressure drop during local boiling and two-phase flow is the question of flow redistribution among parallel channels.

3. Instrumentation

The provision of sufficient and satisfactory information about the behavior of the core and core structure during all phases of operation presents an extremely vital problem. The instrumentation of a high pressure-high temperature water system presents many difficulties. These difficulties are further compounded by the neutron and radiation fields associated with the reactor. Nevertheless, it is essential that, within their design aims, reactors be instrumented as completely as possible to provide the presently lacking operational information, such as axial and radial power distributions, power peaks at water holes, fuel element and core structure temperatures. This information is necessary to permit evaluation of the thermal design criteria with the purpose of increasing the output of the reactor.

III. MECHANICAL DESIGN PROBLEMS

While the mechanical problems of reactor design can be grouped into headings similar to those encountered on structures in other fields, the criteria for evaluating these problems are different. Because of problems associated with induced activity, materials used for structural parts and moving parts must be such that wear and corrosion products do not add to the shielding and leakage problems. Because of the radiation effects, there is not the opportunity to use normal lubricants. Because of space limitations in the reactor, the designer's ingenuity is challenged in arrangement and simplification of complex patterns of assemblies. Because of the inaccessibility of core components, he must assure a high degree of reliability. These considerations can be grouped into three major headings: materials, operational reliability, and maintenance.

III. (Cont'd)

A. Materials

In the design of nuclear reactors, two separate types of materials problems arise. These are materials applications problems such as wear and corrosion, and, for industrial application, the problems of obtaining code approvals for new materials.

All of the material used in reactor design must first be compatible with the cooling fluid in the plant. Water, although it is often considered a rather non-corrosive material, becomes corrosive at high temperatures. The basic material used in high temperature water for the static parts of the reactor such as core structural supports is stainless steel, AISI type 304 or 347.

For application to fuel elements there is the requirement, not always overriding, that in order to conserve fuel inventory the fuel element cladding materials should have low neutron absorbing properties. This has led to the extensive use of zirconium and zirconium alloys. Power cores, however, have been proposed using stainless steel cladding.

For application to components such as mechanisms and control-element drive shafts, it is necessary to have materials that not only will withstand the corrosive effects of the high-temperature water, but also have good wear characteristics when in rubbing contact with other pieces of metal without any lubrication other than the high temperature water itself. In many cases, these mechanisms must function satisfactorily, even after stationary prolonged exposure to water. Inasmuch as most of the materials that have the best corrosion-resistance have inherently poor wear-resistance and vice versa, judgment based on experimental data is required in determining the combination of metals that present the best compromise for various applications. Rubbing parts on PWR are made of hardened stainless steel, such as 17-4 PH or chrome plated stainless steel, and the various grades of Stellite.

In the design of pressure vessels, the chief problem is that of achieving heavy sections with stainless steel suitably bonded to carbon steel so as to obtain the corrosion resistance of the stainless with the relative strength, weldability, and availability of the carbon steel. There is also the problem of predicting the reliability of the vessel without encountering brittle fracture, particularly where heavy sections are involved.

The second materials problem encountered in the design of core components of a pressurized system, particularly for industrial application, is that of obtaining code approval. This should appear at first glance to be a straightforward job, but the selection of materials not specified by the code and the desire in some cases to include vessel penetrations not normal to vessel design practice requires close working with ASME and state code agencies to assure acceptance. In PWR, for example, the pressure vessel code has no provision for use of ferritic stainless steel, AISI type 410, but this material becomes necessary on the mechanism housings of the PWR reactor vessel because of its magnetic properties. In addition, the code has no provisions for design of the numerous penetrations required by the core design. Yet, by appropriate tests and analysis code acceptance of this arrangement has been obtained.

III. (Cont'd)

B. Operational Reliability

While operational reliability is a most important consideration in the design of any mechanical equipment, it becomes an item to be particularly stressed in reactor design because of the relative inaccessibility of components for routine maintenance or correction of faults. This factor is further compounded by the lack of operational experience in identifying areas of trouble. As a consequence, extensive testing of prototype features becomes necessary to assure reliable core operation.

The problem of operational reliability involves concentrated attention to details. While many details exist in the design of a reactor, certain of these details have required more than the usual attention given in mechanical design of equipment. These include fasteners, ability to clean components, warpage, three-dimensional stress problems, tolerances, and alignments for control element operation.

Fasteners:

Although the problems of fasteners are encountered in every engineering design, they are highlighted here because of the inaccessibility of these fasteners for maintenance and the consequences of their failure on not only the pieces being joined, but on related operating parts. In addition, differential expansions and associated thermal stresses brought on by radiation heating of parts must be faced. Welding provides the most reliable form of fastening, providing the integrity of the unit is not impaired by untenable thermal stresses due to radiation heating in the welded assembly. In PWR, however, many joints have required the use of threaded fasteners. The three chief problems associated with threaded fasteners have been galling of threads, adequacy of locking devices, and differential expansion between the threaded parts due to insufficient cooling of the radiation heating.

Galling must be considered not only for initial assembly, but also for remote underwater disassembly of components. It can be avoided by attention to eliminating burrs, obtaining good thread forms, providing adequate clearance, and, where necessary, chrome plating threads. Locking devices must be positive, not depending on friction, and must be so designed that an adequate controllable plastic strain is provided which does not depend on the workman's skill to accomplish. But, in addition, these locking devices must be serviceable by remote handling. Differential expansion problems leading to failure of threaded parts can be avoided by use of thin sections wherever possible, and by adequate cooling.

Ability to Clean Components:

The ability to clean components is important because the components must be freed of small particles of dirt or machining chips which might be carried to the core during operation and possibly lodge in the many small core flow passages. This means that incomplete welds, for example, may often need seal welds on the reverse side to prevent forming a pocket for machining chips or weld flux that might be released later during core operation. These pockets must also be avoided to prevent trapping of cleaning agents which may later cause corrosion.

III. B. (Cont'd)

Warpage:

Warpage of fuel elements, control elements, and structural parts is always a problem in a nuclear reactor because of the uneven heating and cooling experienced by these parts. Careful attention to this point during design will avoid difficulties in operation. However, it must be appreciated that clearances for operation of warped components should not be any larger than absolutely necessary because of the local peaking of neutron flux occasioned by the water in these clearances.

Stress Problems:

Complex stress patterns arise out of the fact that stresses in core structural components are three-dimensional combinations of mechanical, thermal, and hydraulic stresses. Analytical treatment of the thermal stresses in combination with other stresses is particularly difficult because of complex structural geometries and non-uniform radiation heating. Further development of analytical treatments for stress analysis of grids such as used in PWR is needed to avoid continued experimental explorations.

Tolerances:

Tolerances and the evaluation of out-of-tolerance components are among the designer's most constant problems. When a large amount of heat transfer surface is being crowded into a compact region, the distances between heat transfer elements become small, so that small deviations from nominal dimensions produce significant changes in performance. Attention to tolerances must be provided early in the design, and performance calculations must reflect the anticipated tolerance range.

Alignment:

The question of alignment of core components for free passage of control elements bears heavily on the safety of the plant. The design of the control drive mechanisms, the reactor vessel head on which these mechanisms are often located, the guide bearing systems for the control elements, and their passages, must be made to provide the facilities for obtaining the desired alignments. If the alignments are not satisfactory, binding of control elements during fast insertion or scramming may be encountered. This means that not only must the components be designed for adequate alignment within themselves, but also among each other; not only at room temperature and pressure, but also under steady state and transient operating temperatures and pressures.

III. (Cont'd)

C. Maintenance

While emphasis has been placed on designing for maximum reliability because of the inaccessibility of components, every effort should be made to provide as many features for maintenance as practical. In a core such as PWR, for example, maintenance of control drive mechanisms has been enhanced by placing them above the reactor vessel head. In addition, facilities have been provided for unlatching a stuck control rod so that the guide system above it can be removed through the reactor vessel head to provide easy access to the stuck rod. The design also permits withdrawal of the control rod through a port directly above it.

Maintenance also includes the ability to detect and remove an assembly containing a fuel element on which there has been a cladding failure, without the prolonged shutdown involving removal of the reactor vessel head and wiring and cooling piping contained on it. This same feature of refueling through penetrations in the head also permits rearrangement of fuel assemblies within the core to gain maximum life, and permits installation of experimental fuel assemblies.

Not all of these features may be desired in every application, but their worth must be evaluated early in the design to provide for easy maintenance later.

IV. INTERPLAY OF TECHNOLOGIES

One of the most unique features of a nuclear power reactor is that its design involves closely inter-related application of several technological judgments.

Let us take as an example of this interplay, the establishment of radial positions for locating control rods in a reactor such as PWR. The desire for controlling the uranium necessary for long life, coupled with the need for adequate shutdown, would dictate putting the rods in location where they provide the most effective shutdown. The desire for obtaining the maximum core output without unduly complicating the internal core cooling requirements would dictate placing the rods in locations where the most uniform radial power production pattern would be obtained. However, the desire for reliable driving of control rods and for easy replacement of the rods and drives would dictate placing control rods where they are compatible with the necessary penetrations in the reactor vessel head. These penetrations on PWR were not only large enough to accommodate shafts for driving the rods from the mechanisms above the head, but also to accommodate replacement of the control rods without removing the head. These three factors may also be complicated by a fourth desirable factor, as they were on PWR, namely, the desire to locate the control rods in such a fashion so that their driving means would not interfere with refueling of any of the fuel assemblies in the core through other penetrations in the reactor vessel head.

Even a single question such as this is complicated by a number of related questions such as the material to be used for the control rods, the size of the control rods, the shrouding of the control rods against hydraulic forces, and the alignment required to produce reliable control-rod action under all operating and emergency conditions.

IV. (Cont'd)

Resolving this question has required extensive development and experimentation in both the physics and engineering fields. Because of a lack of adequate analytical techniques, in order to answer physics questions of reactivity and shutdown, full-scale zero-power critical assemblies of the PWR core had to be built and tested. Again, because of the lack of adequate analytical techniques, the engineering design of the reactor vessel head with the necessary penetrations had to be confirmed by tests on models and mock-ups. Preliminary evaluation of the penetration pattern had to be made by use of three-dimensional photoelasticity techniques. Since the Poisson's ratio for the plastic is different than for steel, a final stress evaluation was made using a quarter-scale model. On the PWR, because of the pioneering nature of the reactor vessel and head design, it was necessary to build a full-scale prototype of the vessel, head and closure to establish the effects of thermal cycling and to determine permissible rates of heating and cooling.

This question of interplay of various technological disciplines must be provided for in the design of a reactor. A good background in related scientific fields therefore becomes important for the engineer, because the task of integration falls to him in preparing the design for construction.

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