LMFBR FUEL ASSEMBLY CHANNEL WALL CROSS SECTION OPTIMIZATION

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SUMMARY

A basic problem in the application of applied mechanics principles is to optimize the mechanical design of a component. The problem addressed in this paper is the optimal design of an LMFBR fuel assembly channel, subject to realistic material properties, operating environment and reactor geometric limitations.

An LMFBR fuel assembly channel is a hexagonal thin-walled tube surrounding the fuel pin bundle to facilitate fuel handling and to control the flow of coolant through the core. The channel is subject to the internal pressure of the high temperature sodium coolant and also to a high flux of fast neutrons. This environment results in a ballooning of the channel from its original hexagonal shape due to irradiation swelling, thermal and irradiation enhanced creep, and the elastic pressure deformation of the channel material.

The cross-sectional shape of the hexagonal channel is limited primarily by the principal stress and the total channel radial growth. It is presently considered preferable that adjacent channels do not touch from channel ballooning due to concerns about safety and refueling considerations. Reactor core optimization requires an understanding of how to allocate a given amount of material in the fuel assembly channel walls in such a way so as to increase the time for channel-to-channel contact as much as possible.

A computer program, WALLOP, has been developed as described in this paper to derive the wall shape of such an optimum channel, given realistic design and material constraints. Within WALLOP, an initial cross-sectional shape is chosen and a beam model of the wall is used to determine the elastic deflection. By assuming any changes in the axial direction along the assembly length to be gradual, a transverse slice of one wall may be reduced to a variable thickness, plain-strain, fixed-end beam with a non-planar centroidal surface and subject to transverse loading (internal coolant pressure) and axial loading (hoop force constraining the internal pressure). The deflection is combined with swelling and creep rate data on the chosen wall material and with core geometric parameters to evaluate the time for channel-to-channel contact. The computer program then sequentially perturbes the wall cross section and repeats the process until channel life is maximized. This sequential search optimization process is similar to the "Rosenbrock" Algorithm without rotation of the search axes.

For prototypic 1200 MWe LMFBR cores, comparing uniform thickness channel walls and optimized cross section walls generally shows that wall optimization yields about a 25% to 50% increase in allowable channel life for the same amount of material; or for the same channel life, a reduction of about 25% in the required quantity of material. These improvements are estimated to be worth approximately 0.8 or 0.4 mills/kw-hr, respectively.

As demonstrated in this paper, channel wall optimization results can help establish upper bounds on the benefits that can be realized through channel redesign, can provide a consistent method to evaluate the performance of competing channel designs, and can guide the design of less costly to produce "near-optimum" channels. The methods demonstrated in this paper may also be easily adapted to solve a wide range of complex structural mechanics optimization problems.

1.0 INTRODUCTION

Significant improvements can be made in LMFBR core economics and breeding performance through optimization of the fuel assembly channel wall cross section. A fuel assembly channel is a hexagonal thin-walled tube surrounding the fuel pin bundle to facilitate fuel handling and to control the flow of coolant through the core. In the core region, the channel is subject to the internal pressure of the high temperature sodium coolant and also to a high flux of fast neutrons. This environment results in a ballooning of the channel from its original hexagonal shape due to irradiation swelling, thermal and irradiation enhanced creep, and the elastic pressure deformation of the channel material.

The cross-sectional shape of the hexagonal channel is limited primarily by two parameters. The first is the principal stress at the hex corners caused by the internal pressure. The second limit is the total channel radial growth. It is presently considered preferable that adjacent channels do not touch from channel ballooning due to concerns about safety and refueling considerations. To accomodate this radial growth, the channels are installed in the core with an initial gap. However, large interchannel gaps degrade the reactor breeding and economic performance, so it is desirable that the interchannel gap be made as small as possible, consistent with safety and refueling requirements and that the total channel radial growth be minimized. The channel radial growth cannot, however, be reduced by arbitrarily increasing the channel wall thickness since thicker walls increase the quantity of structure in the core region and decrease the reactor neutronic performance because of increased neutron absorption.

Reactor core optimization requires the allocation of the wall material in the fuel assembly channel walls so as to increase the time for channel-to-channel contact as much as possible without penalizing nuclear performance. Parametric relations between the residence times for optimized wall cross sections and the amounts of channel material provide the basic input to broader optimization studies that balance inventory and residence time effects to determine the minimum cost core design.

A computer program, WALLOP, has been developed as described in this paper, to derive the wall shape of such an optimum channel, given realistic constraints such as material properties, expected levels of fast flux and temperature,and typical reactor geometric limits.

As demonstrated in this paper, channel wall optimization results establish upper bounds on the benefits that can be realized through channel redesign, provide a consistent method to evaluate the performance of competing channel designs, and guide the design of less costly to produce "near-optimum" channels. Implementation of channel wall optimziation into LMFBR core designs will require balancing core performance cost savings against fabricability considerations to arrive at a best overall design. The methods demonstrated in this paper may also be easily adapted to solve a wide range of complex structural mechanics optimization problems.

2.0 ANALYSIS

2.1 Key Loading and Geometry Assumptions

The key assumptions employed in the model are:

1. The differential pressure contained by the channel varies gradually along the axial length of the channel (typically, 1 psi/axial inch,or less).
2. Any axial variation in channel wall thickness along the channel length is gradual.
3. Elastic deflections of the channel wall are small compared to its thickness.

2.2 Derivation of Beam Equations

2.2.1 Beam Elastic Deflection

The mechanical model is shown in Figure 1. A small segment of the hexagonal tube may be reduced to a plane-strain beam with fixed ends. The beam length, L, is the distance between the centers of adjoining corners of the hexagonal channel. The beam thickness, h(x), is the variable thickness of the channel wall. The transverse beam load, P, is the differential pressure across the channel wall. F_a, the axial beam load, is the channel hoop force restraining the internal pressure. Due to symmetry in the beam loading and end conditions, the center of the beam, x = L/2, is a plane of symmetry and only the region from x = 0 to x = L/2 needs to be modeled.

The shear force along the beam is found by integrating the transverse loading, P, and noting that by symmetry of the transverse loading the shear at each end of the beam is the same.

$$V(x) = P \cdot x + \frac{P \cdot L}{2} \qquad (1)$$

The moment equation may be found by integrating the shear force equation and then correcting it to include the moment contribution from the axial force applied to the beam. If the thickness changes along the beam are evenly distributed on both sides so that the centroidal surface remains a plane, the desired correction term is simply due to the beam deflection, and the moment equation is

$$M(x) = \int V(x)\,dx$$
$$= \frac{P \cdot x^2}{2} + \frac{P \cdot L \cdot x}{2} + C_2 - F_a \cdot \delta_e(x) \qquad (2)$$

where C_2 is the constant of integration, and δ_e is the elastic beam deflection.

If all the thickness changes along the beam are limited to one side, the moment equation requires a correction term to include the effects of axial force acting along a curved centroidal "plane". The required correction term (if the side of the beam being acted on by the pressure loading is flat) is

$$F_a \cdot [(\frac{h(o) - h(x)}{2}) - \delta_e(x)] \qquad (3)$$

The total moment equation then becomes

$$M(x) = \frac{-P \cdot x^2}{2} + \frac{P \cdot L \cdot x}{2} + C_2 + F_a \cdot [(\frac{h(o) - h(x)}{2} - \delta_e(x)] \tag{4}$$

At the beam end (x=0), the deflection $\delta_e(x)$, is zero. Thus, the constant of integration, C_2, is simply the end reaction moment required to maintain zero slope at the fixed ends.

$$C_2 = M_o$$

From beam theory, the beam deflection shape and moment are related by

$$E \cdot I(x) \cdot \frac{d^2 \delta_e(x)}{dx^2} = M(x) \tag{5}$$

E is Young's Modulus, and $I(x) = \frac{h^3(x)}{12(1-u^2)}$ for a unit width beam, where u is Poisson's Ratio,

thus,

$$E \cdot \frac{d^2 \delta_e(x)}{dx^2} = \frac{12 \cdot M(x) \cdot (1-u^2)}{h(x)^3} \tag{6}$$

Equation (6) is an ordinary, second-order, non-linear differential equation that can be solved numerically when h(x) is specified.

2.2.2 Beam Area

The volume fraction of channel material in the core is proportional to the cross-sectional area of the beam in its side view.

$$A = \int_0^L h(x)\, dx \tag{7}$$

2.3.3 Beam Life

The life of the channel is evaluated by using creep and swelling rates to modify the beam elastic deflection and determining the time until the first point along the beam violates, or touches, the outer surface of the hexagonal reference envelope. As shown by the model geometry in Figure 1, the summation of dimensions results in

$$G = h(x) + \dot{S} \cdot T(x) + \delta_e(x) \cdot (1 + \dot{K} \cdot E \cdot T(x)) \tag{8}$$

$\dot{S}$ is the linear swelling rate and $\dot{K} \cdot E$ is the creep rate. $\delta_e(x)$ is the elastic deflection along the length of the beam. T(x) is the time each point of the outer wall surface contacts the centerline of the channel-to-channel gap. The channel life for a given geometry and loading is found from the minimum value of T(x).

$$T_{ch} = T(x)|_{min} = \frac{G - h(x) - \delta_e}{\dot{S} + \dot{K} \cdot E \cdot \delta_e} \Big|_{min} \tag{8}$$

2.3 Computer Modeling and the Optimization Process

Within WALLOP, an initial cross-sectional shape is chosen and the beam model of the wall is used to determine the elastic deflection. The deflection is combined with swelling and creep rate data on the chosen wall material and with core geometric parameters to evaluate the time for channel-to-channel contact. The optimization program then sequentially perturbs the wall cross section and repeats the life evaluation process until channel life is maximized. This sequential search optimization process is similar to the "Rosenbrock" Algorithim(1) without rotation of the search axes. Basically, it is a methodical search of beam shapes in which the thickness at each calculational station along the beam is varied and the resulting objective function, channel life, is examined to determine whether the thickness change improved it or made it worse. As shown in the block diagram of Figure 2, each improved shape is kept until a better one is found. Unimproved shapes are not kept, but help direct successive search steps just as the improved shapes do. The process by which the wall life is evaluated at each optimization iteration is numeric integration of the wall bending moment equation as shown in Figure 3. Additionally, at each iteration of the optimization process, peak wall stress, minimum wall thickness, and the peak rate of change of thickness are evaluated and compared to limiting values as constraints to the design.

3.0 RESULTS FOR PROTOTYPIC CORES

For large prototypic LMFBR core designs, comparing uniform thickness channel walls and optimized cross section walls generally shows that channel wall optimization yields about a 25% to 50% increase in allowable channel life for the same amount of material. Conversely, for the same channel life, a reduction of about 25% in the required quantity of channel material is achievable. Figure 4 plots a typical life comparison of channel designs for a 900 MWe core with the wall cross-sectional area variable and all other core geometric and operating conditions parameters fixed. As may be seen, the life of a fully optimized channel wall is about 20% greater than the best attainable life of a uniform thickness wall.

An optimized channel wall cross section has the characteristic shape shown in Figure 5. This wall shape applies in general to all of the parametric study results. Only minor shape variations are found among the cases run. The wall is thickest at the corner and center because the bending moment is greatest in those locations and material redistributed to those areas has the greatest effect in reducing elastic and creep deflection and increasing life. Material is removed from the "one-quarter point" of the wall because the bending moment is near zero in that area and the only significant loading comes from axial (hoop) force and the transverse shear force and result in small stresses and deflections. The central region of the wall has a slight thinning taper superimposed on its increased thickness to allow additional gap for creep deflection without significantly increasing the wall deflection and so results in an increased channel life.

Help in reducing the deflection of the central wall region comes from the offset in the wall centroidal "plane" (curved surface) when the inside wall surface is held flat and all the thickness changes occur on the outer wall surface. Through the central wall region, this offset in the centroidal "plane" and the channel hoop force cause a bending moment component that tends to reduce the outward deflection of the wall center and makes possible a limited amount of thinning in the central region. In the corner region, this phenomena has the opposite effect, tending to increase the outward deflection and forcing additional thickening of the wall corner region.

At end of life the entire central region of the wall has deflected to the centerline of the channel-to-channel gap and the originally dished surface has become flat. At the wall corner, swelling at the end of life causes contact with the centerline of the channel-to-channel gap. A slight thinning taper away from the corner provides room for the creep deflection to be added to the swelling and results in a portion of the corner region of the wall contacting the centerline of the channel gap at the end-of-life. As shown in Figure 5, the only portion of the wall that has not grown out to the centerline of the channel gap at the end-of-life is the region around the one-quarter point of the wall where the wall is considerable thinned.

4.0 REFERENCES

(1) J.L. Kuester and J.H. Mize, Optimization Techniques With Fortran, pp. 320-330, McGraw-Hill Book Company, New York (1973).

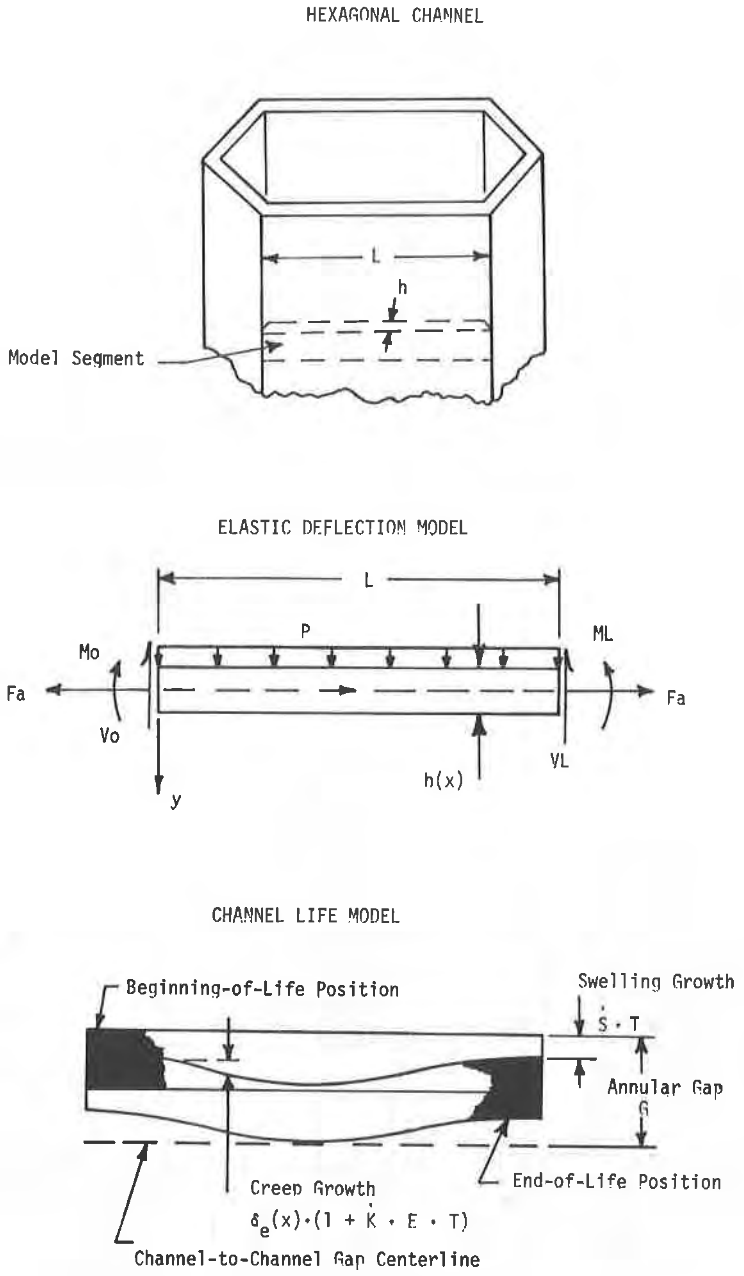

FIGURE 1. Fuel Assembly Channel and Modeling

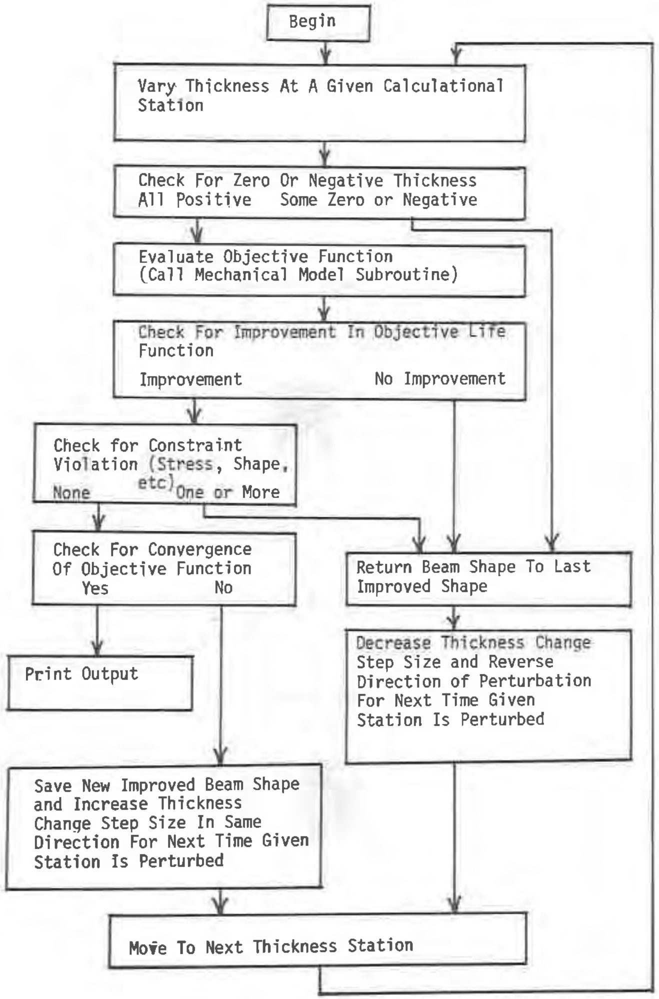

FIGURE 2. Optimization Flow Diagram

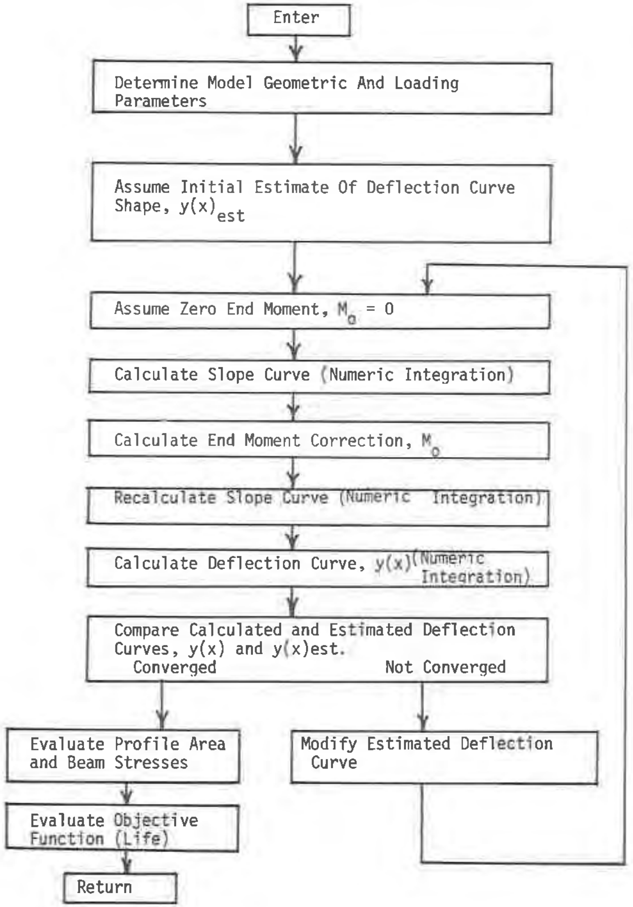

FIGURE 3. Mechanical Model Flow Diagram

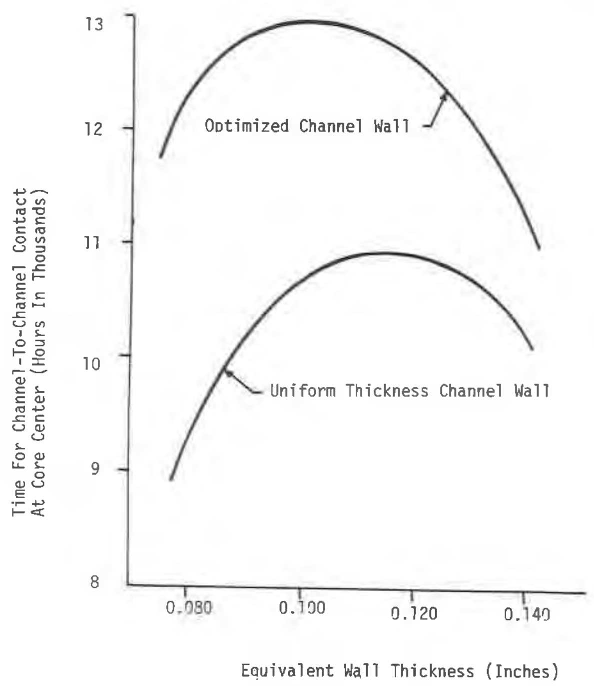

FIGURE 4. Channel Life Comparison For A Prototypic 900 MWe Core

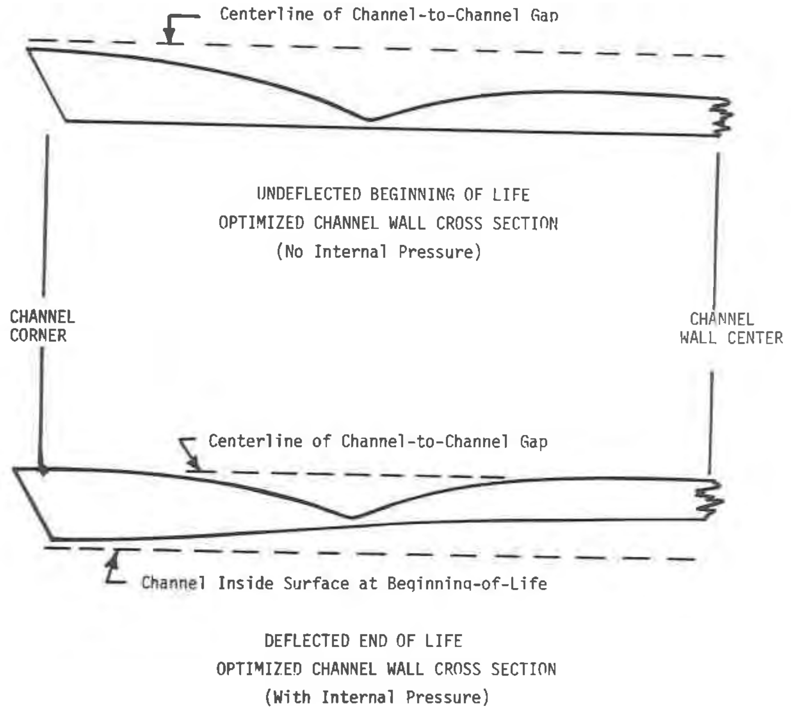

FIGURE 5. Life Optimized Channel Wall Cross Section For Large Prototypic Cores