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HEAT TRANSFER LIMITATIONS FOR DYNAMIC CONVERTERS

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Heat transfer considerations are major limiting factors in the design, development, and operation of dynamic conversion systems for space power plants. The nature of these limitations varies with the component. For example, in the heat source—whether nuclear or solar—thermal conduction affects the thermal stresses, thermal distortion, and local hot spots. These factors are likely to limit the practicable power density in the heat source to a lower value than might be permitted by the obvious problem of heat transfer from the heated solid surface to the fluid cooling it. The latter is likely not to be a difficult problem except for local hot spots caused by poor flow distribution or the like. Other heat transfer limitations include problems in the boilers and condensers for Rankine cycle systems and heat conduction, emission, and reflection in the radiator. This paper presents some typical examples of these problems that are particularly likely to be determining factors in the design of turbine-generator space power plants.

Les problèmes de transfert de chaleur limitent les possibilités de conception, développement et fonctionnement des convertisseurs d'énergie les sources de puissance spatiale. La nature de ces limitations varie avec l'élément considéré. Par exemple, dans la source chaude — qu'elle soit nucléaire ou solaire — la conduction thermique affects les contraintes thermiques, la déformation thermique et les points chauds. Ces facteurs risquent de limiter la densité de puissance que l'on peut réaliser pratiquement dans la source chaude à une valeur nettement moindre que celle qui permettrait l'étude du transfert de chaleur de la surface chaude au fluide de refroidissement. Ce dernier problème ne semble pas très difficile à résoudre, sauf dans le cas où par suite d'un écoulement non uniforme des points chauds apparaîtraient. D'autres limitations dues au transfert de chaleur comprennent les problèmes de bouilleur et de condenseur pour les cycles de Rankine et la conduction de chaleur, l'émission et la réflexion au niveau du radiateur. Quelques exemples typiques de ces problèmes qui risquent d'être des facteurs déterminant dans la conception des convertisseurs turbo-électriques pour application spatiale sont présentés.

HEAT CONDUCTION IN FUEL ELEMENTS

Heat conduction within the fuel element of a nuclear reactor presents problems because the internal temperature must be kept below some maximum allowable value to avoid difficulties caused by fission product gas

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release. A good example of these problems is given by sintered UO_2 fuel pellets enclosed in stainless steel capsules.

Experimental data from tests of fuel elements of this type for gas-cooled reactors indicate that the effective thermal conductivity of the UO_2 pellets is 1·5 Btu/hr-ft²-°F. This is somewhat less than the thermal conductivity of unirradiated UO_2 partly of dislocations in the crystal lattice caused by fissions and fast neutron damage, and partly because thermal stresses induce many cracks—the bulk of which are radial. Heat transfer across the gap is aided by filling the void in the capsule with helium, even though dilution by xenon and krypton during operation reduces the thermal conductivity of the gas in the gap. Fortunately, thermal radiation contributes greatly to the heat transfer process. Test data indicate that the conductance of the gap at 1600°F is about 750 Btu/hr-ft²-°F. Using this together with a value of 1·5 Btu/hr-ft²-°F/ft for the thermal conductivity of the UO_2, it was possible to construct the chart shown in Fig. 1. This gives the fuel-element centerline temperatures for a wide range of fuel-element diameters and power densities. For UO_2 fuel elements of this type, the centerline temperature should be kept below about 2800°F to avoid excessive fission product gas release and swelling of the fuel capsules. Similar problems are posed by other materials and types of fuel element.

In all types of reactor it is important to minimize the pumping horsepower, which means that the coolant temperature rise through the reactor core should be as large as possible. This in turn means that regions near the reactor core outlet will be substantially hotter than the average value for the core as a whole. If the axial power distribution through the core is assumed to follow a cosine curve, the heat flux and the temperature of both the cooling gas and the fuel element surface may be plotted as functions of distance from the reactor core inlet to give curves such as those of Fig. 2. The region yielding the peak fuel element surface temperature is often called the "hot zone", as it is in this zone that excessive fuel-element surface temperatures are most likely to occur.

A host of effects lead to variations in the basic temperature pattern indicated by Fig. 2. There are both gross and fine radial variations in the neutron flux which lead to variations in the nuclear power distribution and hence in the temperature distribution. Fuel-element burnup and variations in control rod position contribute further aberrations in the local heat flux. These effects may be cumulative in one or a few fuel elements and give local power densities from two to six times the average for the core as a whole.

The gross coolant flow distribution across the reactor core will also contribute to the hot spot problem. In channels in which the coolant flow rate is a little below the average, the gas temperature rise to the hot zone will run a corresponding amount above the average. In addition, the lower flow rate will lead to lower heat transfer coefficients in that channel, and these will cause difference between the mixed mean temperature of the gas stream and the fuel-element surface temperature to run greater than the average. The combined effects of the increases in the enthalpy rise and the

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film temperature drop will lead to a substantial increase in the hot zone fuel surface temperature for the low flow channels.
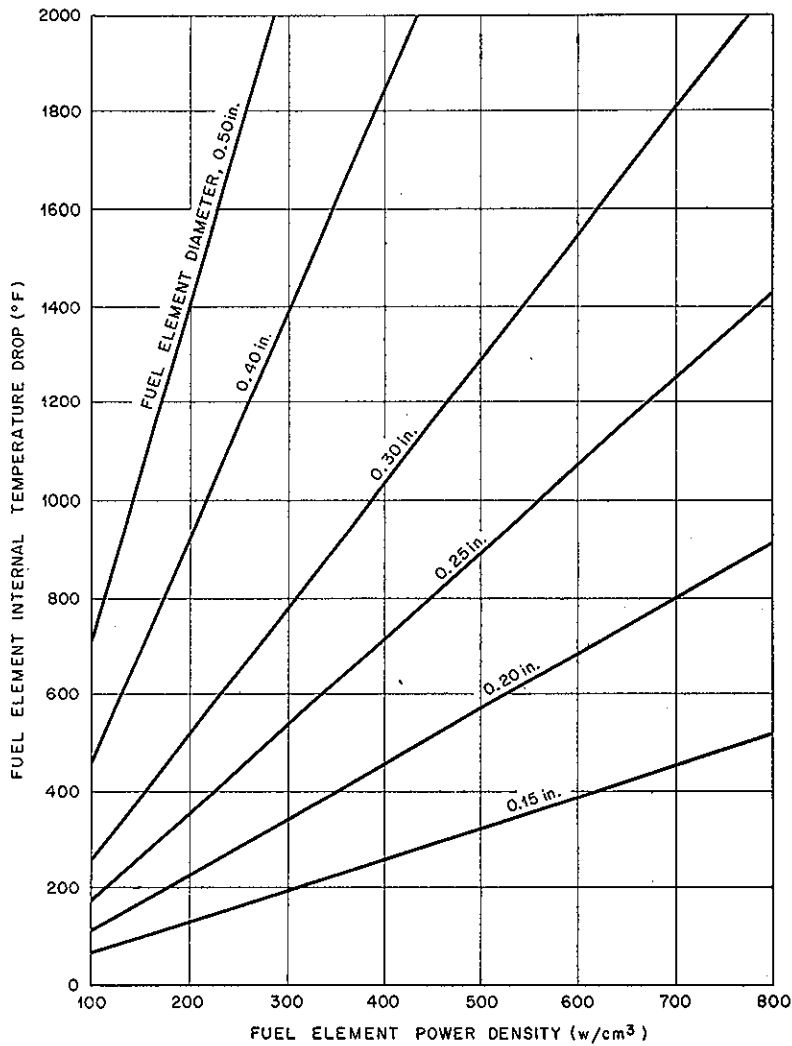

Fig. 1. Centerline temperatures in UO_2 *fuel pellets in stainless steel capsules for a range of capsule diameters and power densities.*

In reactors making use of moderately complex fuel elements in which there are possibilities of asymmetries, the flow distribution is likely not to be uniform within any given channel (Ref. 1). For example, in the seven-capsule fuel-element cluster for the EGCR (the Experimental Gas-Cooled Reactor

at Oak Ridge), asymmetries give large variations in the local temperatures of both the gas stream and the fuel-element surface. Figure 3 shows the velocity distribution prevailing in a typical section of the channel. Hot-spot problems are not peculiar to gas-cooled reactors, but they are more acute
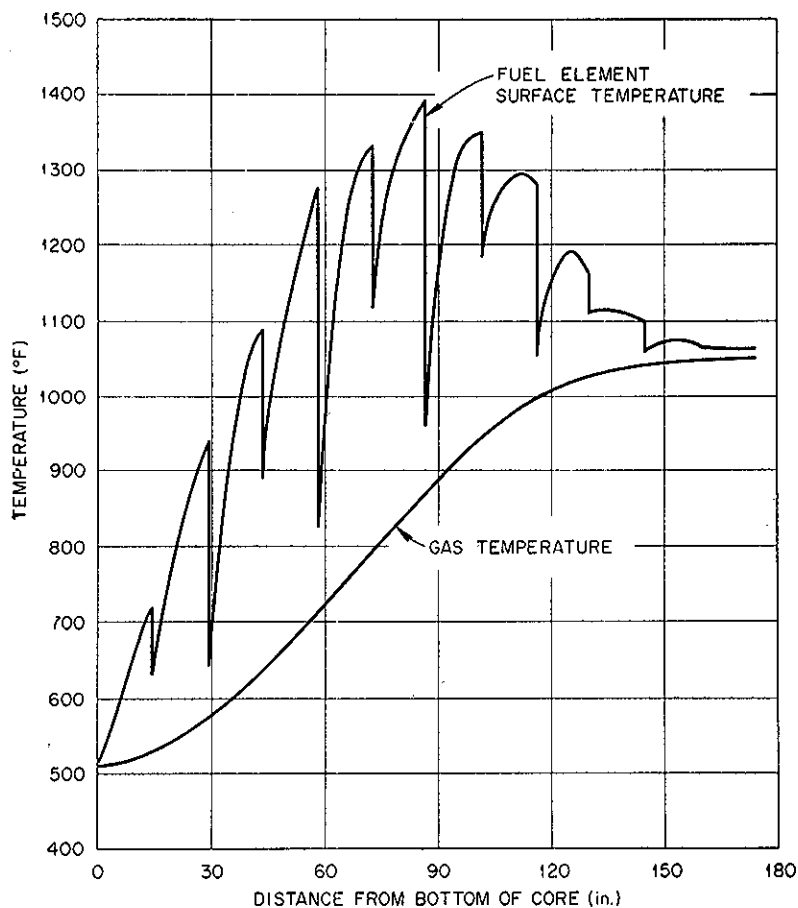

Fig. 2. Ideal axial temperature distribution in a gas-cooled reactor (the EGCR) having six fuel-elements in series with turbulating devices in the middle of each fuel-element.

than in water-cooled reactors because, in the latter, hot spots are relieved by local boiling. In gas-cooled or organic liquid-cooled reactors no beneficial effects from boiling can be expected.

Irregularities in the fuel-element surface temperature may not be objectionable in themselves, but they do cause bowing of the fuel elements. It should be noted that the EGCR fuel elements of Fig. 4 were designed with
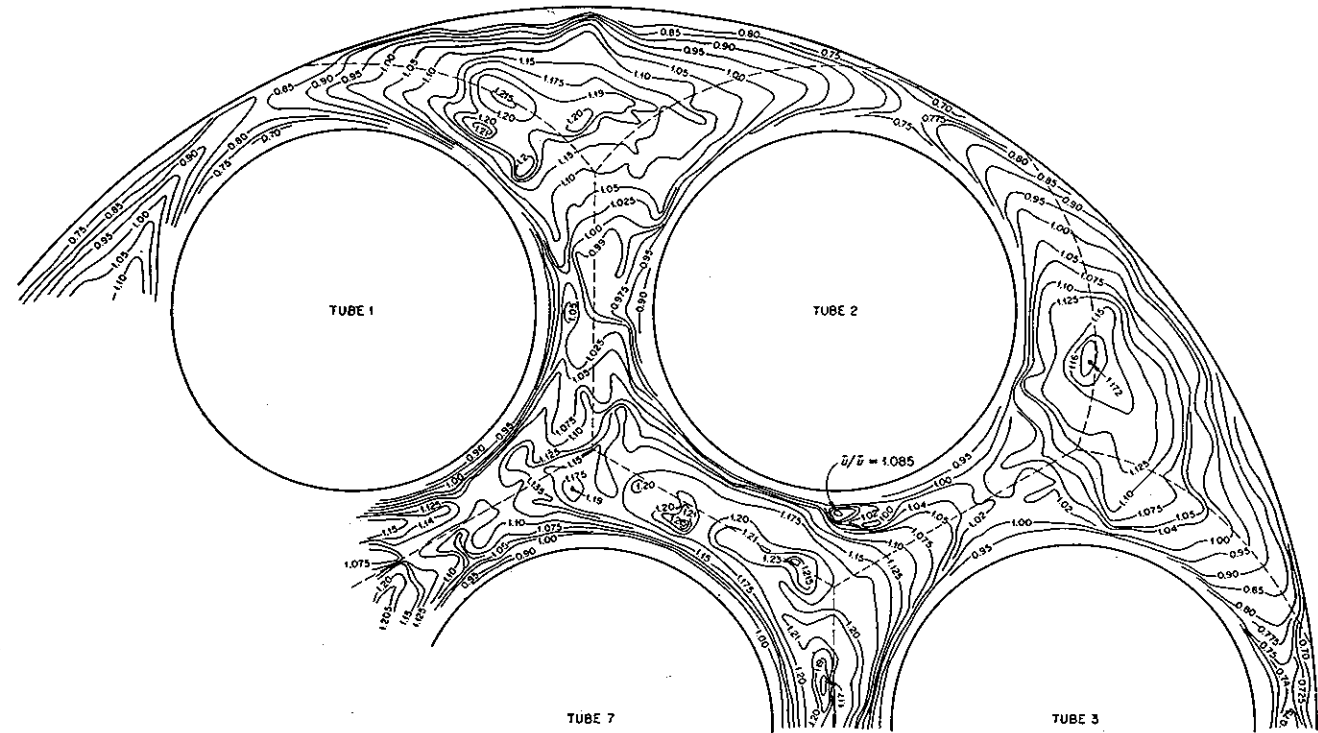
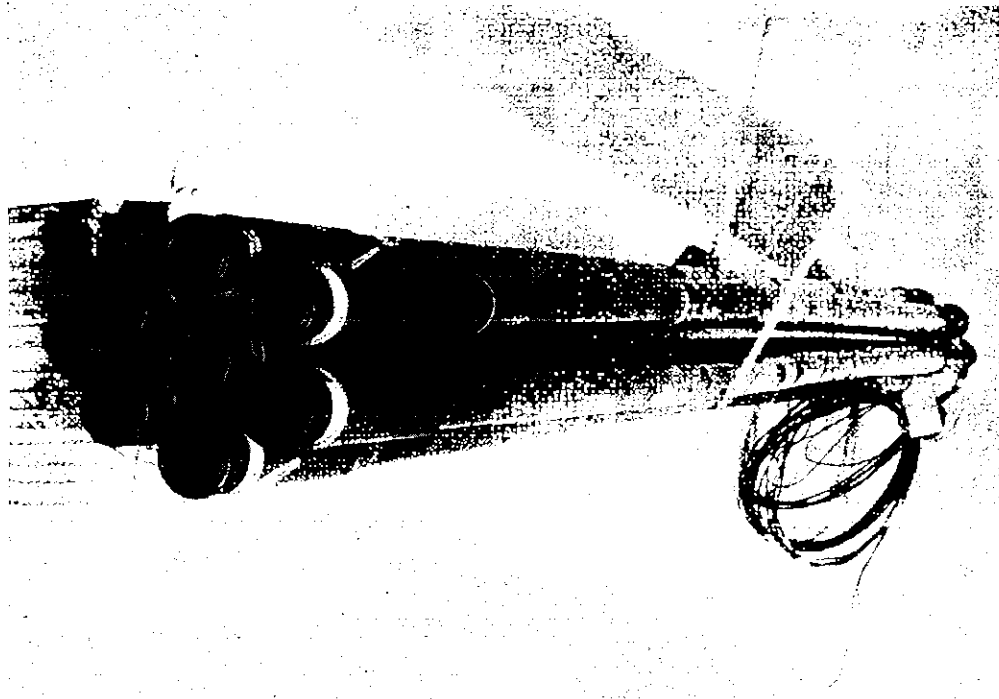*Fig. 3. EGCR fuel-element velocity distribution.*

Fig. 4. An electrically heated mock-up of a prototype fuel-element for the EGCR. Note that the rods have been warped by hot spots.

pin-jointed ends in order to avoid structural redundancies in the fuel-element assembly and the attendant severe local bending stresses that would otherwise occur in the thin walls of the fuel capsules. A diamtral temperature difference of 30°F across a $\frac{3}{4}$ in.-diameter EGCR fuel capsule will not lead to any appreciable thermal stress, but it would cause a 28-in.-long capsule to bow about $\frac{1}{16}$ in. Once such a deflection occurs it tends to restrict the gas flow past the hot side of the fuel capsule and this leads to a further increase in both gas and fuel-element surface temperatures, giving a further increase in the lateral deflection of the fuel capsule (Ref. 1). Depending on operating conditions, this cumulative process of deflections may reach an equilibrium at some small deflection with a relatively small resultant hot-spot effect, or it may progress and become unstable and lead to touching of adjacent fuel elements and burnout. Figure 4 shows a fuel capsule cluster damaged in this way in an electrically heated test rig. Note the bowed condition of the tubes after test. They were, of course, quite straight before the test began.

It might be hoped that substantial amounts of transverse mixing would occur where major flow channels through the reactor are subdivided into small parallel channels by the fuel-element fine structure. With a fuel-rod cluster, for example, it would be possible to introduce turbulators with the objective of promoting such transverse mixing. Another approach would be to interrupt the heat transfer surfaces at intervals in the direction of flow. Tests by a variety of investigators indicate that, unless a great deal of pumping power is dissipated in the mixing operations, the transverse mixing will not help greatly in reducing hot spot effects. Thus, it is highly desirable to proportion the fuel elements so that a good coolant flow distribution is inherent in the design. An important step in this direction is to make use of a relatively coarse type of fuel-element with a large spacing between surfaces so that small thermal distortions will have relatively little effect on the flow distribution through the parallel channels which make up the fuel-element. Unfortunately, for a given core size and power output, this reduces the surface area and increases the heat flux.

BOILERS FOR RANKINE CYCLE PLANTS

The problems of coping with free liquid surfaces under O-g conditions have appeared so formidable that most designers of boilers for space power plants have preferred to avoid them by employing once-through boilers in which liquid is supplied to the inlet of a tube and saturated or slightly superheated vapor emerges from the outlet. The problems associated with the design of such a boiler can be visualized by considering the sequence of events to be expected.

As the liquid temperature rises in passing through the first portion of a heated tube, a region is reached in which the wall temperature appreciably exceeds the boiling point of the liquid even though the liquid itself has not yet been heated to the boiling point. In this zone bubbles begin to appear on the heated surface, grow, are washed away, and then, as they lose heat to the surrounding liquid, they shrink and disappear. This growth and

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decay of the bubbles results from the temperature gradient through the boundary layer, i.e., the liquid in the boundary layer close to the wall is well above the boiling point while the bulk free stream may still be a bit below the boiling point. The bubbles increase in size after leaving the surface as they pass through the superheated liquid in the boundary layer and then shrink after they get out into the free stream. Examination of the frames from high-speed movies of this sort discloses that the bubbles usually form, break free of the surface, collapse, and disappear very rapidly, the entire cycle requiring a period of only about 0·001 sec (Ref. 2).

When the bulk-free stream temperature reaches the boiling point, the number of bubbles per cubic inch becomes much greater since the bubbles do not shrink by losing heat to the surrounding liquid. Instead, the bubbles coalesce in a short distance into larger bubbles that nearly fill the tube, and these move down the tube through an annular region of liquid between slugs of bubbly liquid.

As the volume fraction of vapor in the fluid stream increases to 50 per cent to 80 per cent, the nature of the flow changes markedly, and—if the fluid wets the wall—an annular flow regime prevails in which the vapor moves as a continuous stream down through the center of the tube while the liquid adheres to the wall and moves along in an annular film. The velocity of this annular liquid film is much lower than that of the vapor, i.e., the average liquid velocity runs from 3 to 5 per cent of the vapor velocity. Both the vapor and the liquid velocities increase with the fraction evaporated as the fluid progresses down the tube, and the liquid film traveling along the wall becomes progressively thinner. Of course, in this region the vapor flow rate on a volumetric basis is from five to ten times that of the liquid flow rate. Depending on the dynamic head and the Reynolds number in the vapor flow, and the Reynolds number and the Froude (or Weber) number in the liquid, waves form on the surface of the annular liquid film, and droplets are torn from the tops of the waves and are carried off entrained in the vapor.[3] This effect becomes more pronounced as the vapor and liquid velocities increase with increasing vapor quality.

The liquid film becomes progressively thinner with further progress along the length of the tube up to the region where the vapor quality runs from 50 to 90 per cent. Then, depending on the surface condition, the pressure, the flow rate, the surface tension, and the wetting properties of the fluid, the flow regime becomes very different in character; dry spots appear on the wall and these grow in number and extent until the rivulets between them dry up, and virtually all of the remaining liquid is in the form of fine droplets suspended in the vapor. The term "mist flow" is ordinarily used to identify this flow regime, although the droplet size is usually fairly large— of the order of 0·010 in. to 0·10 in. Because of the turbulent character of the vapor flow and waves in the liquid film, this transition from annular film flow to dry wall mist flow moves irregularly back and forth along a limited length of the tube.

The mist present in the vapor appears to originate partly in the transition region between slug flow and annular flow, and partly from droplets torn

from the tops of waves in the annular flow region. Surface tension is an important factor in determing the size and quantity of the droplets in the mist.

Perhaps the most important implications of these various flow regimes are those related to heat transfer. Where the liquid wets the walls, nucleate boiling ordinarily occurs so that the wall temperature seldom exceeds the temperature of the saturated liquid by more than the amount implied by heat transfer data from pool boiling experiments. In fact, for annular flow, the temperature differential between the wall and the liquid will commonly be less than for pool boiling since evaporation directly from the free liquid surface will serve to increase the heat transfer coefficient. This effect will increase with increasing vapor quality (Ref. 4) as the liquid film thickness decreases. In any event, wherever the liquid wets the walls, the heat transfer coefficient will be high irrespective of liquid velocity or whether bubbly flow, slug flow, or annular flow prevails.

In the dry wall region the heat transfer mechanism becomes drastically different. Usually the heat transfer coefficient between the vapor and the wall is relatively low except at the high mass flow rates obtainable at high pressures, e.g., steam at 2000 psi. At the lower pressures the bulk of the heat transferred is associated with the evaporation of liquid droplets that impinge on the wall. Thus, at low pressures the principal factor determining the heat transfer rate is not heat diffusion through the boundary layer, but rather the rate at which the liquid droplets diffuse from the free stream to the wall. Work with Freon evaporators has shown that a twisted ribbon or other turbulence promoting device may be very helpful in throwing the liquid droplets against the wall and thus in drying out the mist. This, of course, increases the heat transfer coefficient.

The notion that the boiling point of water at standard atmospheric pressure is a fixed and predictable quantity is one of the most sacred of engineering traditions. However, many people are aware that, if extremely pure water is placed in a meticulously cleaned glass beaker, it is possible to raise the water temperature to as much as 50°F above its normal boiling point with no sign of boiling. Such a condition is unstable, however, and if boiling once starts to occur, it is so violent as to appear to be explosive. This phenomenon of liquid superheating above the boiling point has been generally regarded as a laboratory curiosity. However, in recent years it has been found that "explosive" boiling may occur in engineering equipment when special precautions are taken to maintain the purity of the liquid to a very high level and the heated surfaces are smooth.

Observations of boiling under many different conditions has shown that bubbles invariably start at nucleation sites, usually tiny pits in the hot surface (Ref. 5). The bubbles grow, break free, are washed away, and then other bubbles grow from the same nucleation sites. With highly polished surfaces free of nucleation sites, there is little inclination for a bubble to form and hence substantial amounts of liquid superheating may occur if the liquid is sufficiently free of impurities so that there are no nucleation sites in the form of suspended particles or gas bubbles. It happens that the liquid

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alkali metals are especially likely to give difficulty since to avoid corrosion they must be used in meticulously clean systems, and the liquids must have a very high degree of purity. Experience has shown that the amount of superheat in alkali metals may exceed 500°F, and, when this occurs, it leads to violently explosive boiling.

Difficulties are sometimes experienced with poor wetting even in water systems. In mercury boilers the problem is chronic. The effects are ordinarily small for pool boiling or for bubbly flow, but they drastically reduce

Fig. 5. Frames showing dry spots on ½-in.-diam electrically heated rods boiling water under non-wetting conditions at about 5 per cent quality with a heat flux of 15,000 Btu/hr-ft². Two rods in a bundle of seven are shown. The water flowed vertically upward. The rods in the photos are about their actual size. The dry spot is on the right rod.

the burn-out heat flux obtainable under annular film flow conditions. Even with water, burn-out has been observed in rod bundles at heat fluxes as low as 15,000 Btu/hr-ft² with vapor qualities of around 5 per cent. Figure 5 presents frames from high-speed movies taken at these conditions, and shows the droplets skittering across a dry, hot surface. The condition was corrected by adding a small amount of sodium bicarbonate to the water.

CONDENSER

Control of free liquid surfaces presents problems in the condenser as well as in the boiler. Unless a space vehicle is spun to induce an artificial gravitational field, the principal forces acting on droplets of condensate will be

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surface tension or fluid-dynamic forces. The former will ordinarily be much smaller than the latter, except at very low loads.

One way of assuring condensate flow through a condenser under O-g conditions is to employ a jet condenser in which a subcooled jet of liquid is
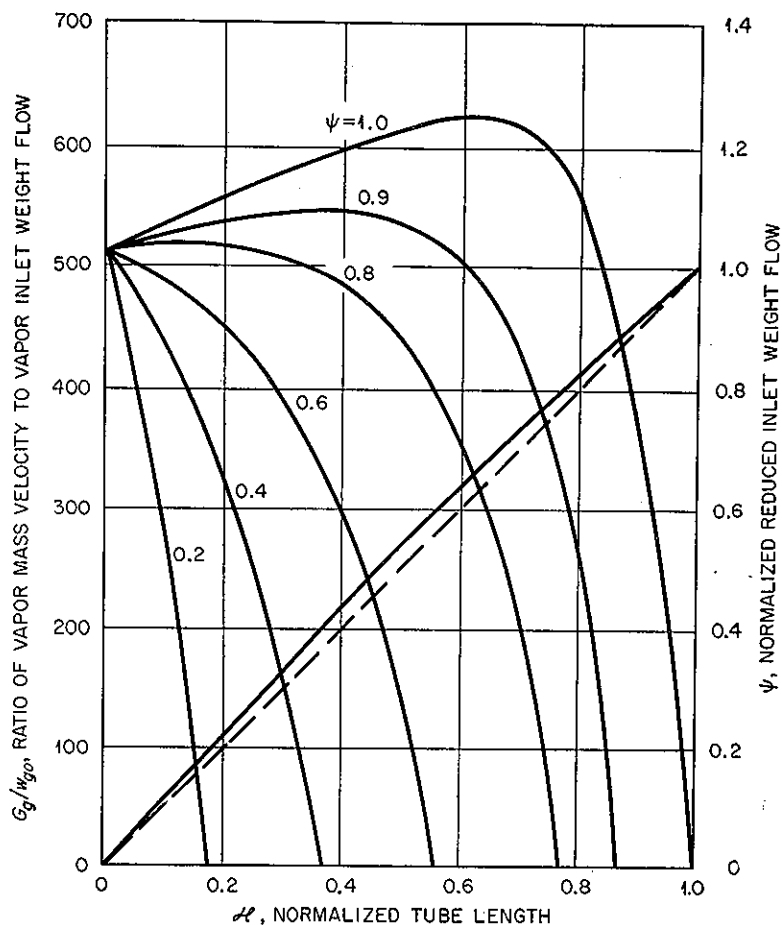

Fig. 6. Local vapor velocity parameter as a function of axial position in the tube for condensing flow through uniformly tapered tubes having fins proportioned so that the surface area per unit length is constant.

injected coaxially with the vapor stream at a high velocity into a converging channel. The momentum of the liquid and vapor suffice to carry the stream through the converging region where condensation takes place and a bubble-free liquid stream emerges sufficiently subcooled to assure freedom from vapor bubbles. Unfortunately, this approach requires that the radiator operate at an average temperature much below the saturation temperature at the inlet to the condenser.

If a surface condenser rather than a jet condenser is employed in order to maximize the radiator temperature, it is possible to use uniformly tapered tubes so that the velocity will be high throughout the tube length, and fluid-friction forces will serve to drive the condensate toward the outlet.

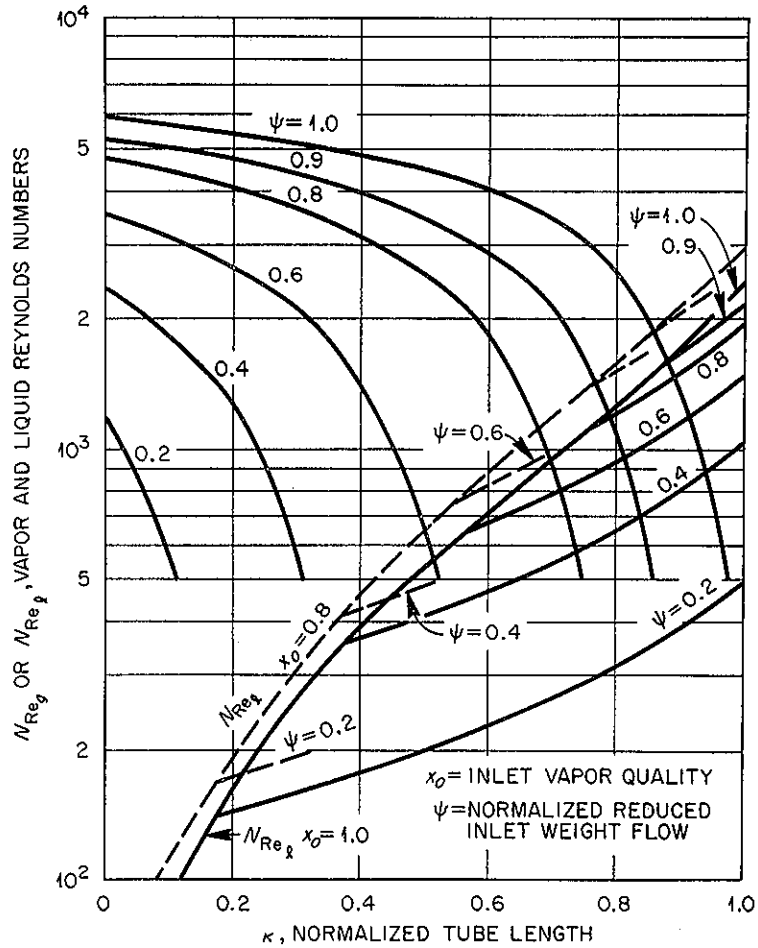The condensing flow in a tapered tube is difficult to analyze. Two-phase

Fig. 7. Local Reynolds numbers as a function of axial position in the tube for the conditions used in Fig. 6.

annular flow prevails throughout the length of the tube, but moderately complicated expressions are required to establish the Reynolds number in order to determine the local friction factor for each of the two phases (Ref. 6). Time does not permit a detailed discussion of this problem, but Fig. 6 shows the ratio of the local velocity to the inlet velocity as a function of axial position in the tube, while Fig. 7 shows the local Reynolds numbers

(Ref. 5). For analytical reasons the curves of Fig. 6 are plotted for a variety of flow rates expressed in terms of the parameter ψ which is simply the ratio of the local vapor mass flow rate to the inlet mass flow rate for which the tube taper was designed. Note that the velocity can be kept to a high value at the design-flow rate up to the last 5 per cent of the tube length, but at flow rates below the design value the velocity falls to zero well before the fluid reaches the tube outlets. Thus, the condenser would tend to load up with liquid at part load unless the system were designed so that the condenser pressure would drop with load sufficiently to avoid this difficulty. This could be accomplished by designing the condenser scavenging pump to have a greater capacity than required. Note that the area ratio does not vary exactly linearly with the tube length because the tube is a truncated cone. A second set of curves (see Fig. 7) indicates the Reynolds numbers for both the vapor and liquid streams as functions of positions in the tube. In this instance, two sets of curves are shown. The solid curves are for an inlet vapor quality of 100 per cent, while the dashed curves are for an inlet vapor quality of 80 per cent. Note that for full-load conditions the Reynolds number for the gaseous phase is in the turbulent region in all but the last portion of the tube, but the Reynolds number for the liquid phase would be in the laminar flow region except in the last 10 per cent or so of the tube.

THERMAL RADIATION TO SPACE

Since the only way that heat can be dissipated from a space vehicle is by thermal radiation, every effort is made to operate the heat sink for the thermo-dynamic cycle at as high a temperature as possible to take advantage of the fourth-power relationship between surface temperature and the radiated heat flux. Even for an optimized power plant with a radiator temperature of 1000°F, however, the size of the radiator required becomes quite unwieldy and presents a difficult problem in finding space for stowage during the launching operation. Some idea of the magnitude of the problem is provided by Fig. 8, which compares the size of an Atlas vehicle with a series of space power plants with 1000°F radiators in the form of truncated cones.

For surfaces having the projected area of the radiators in Fig. 8, there is a substantial probability that a meteoroid of appreciable size will strike the surface during the course of a year. One means of reducing the probability that a condenser leak will result is to make use of finned tubes so that most of the surface area will be in the fins rather than in the tubes. Another helpful step is to arrange the tubes on the surface of a cylinder and provide an involute reflector such as that in Fig. 9 to make the rear face of the tubes and fins nearly as effective as the front face in dissipating thermal energy. If the surface of the involute reflector is clean and bright, about three-quarters of the incident radiation from the back side of the tube-and-fin array should be reflected into space by specular reflection from the involute. About 25 per cent of the incident energy will be absorbed and re-emitted or reflected by diffuse reflection. Of this, approximately half will be emitted to space and about half will reimpinge on the surface of the tube. Thus,
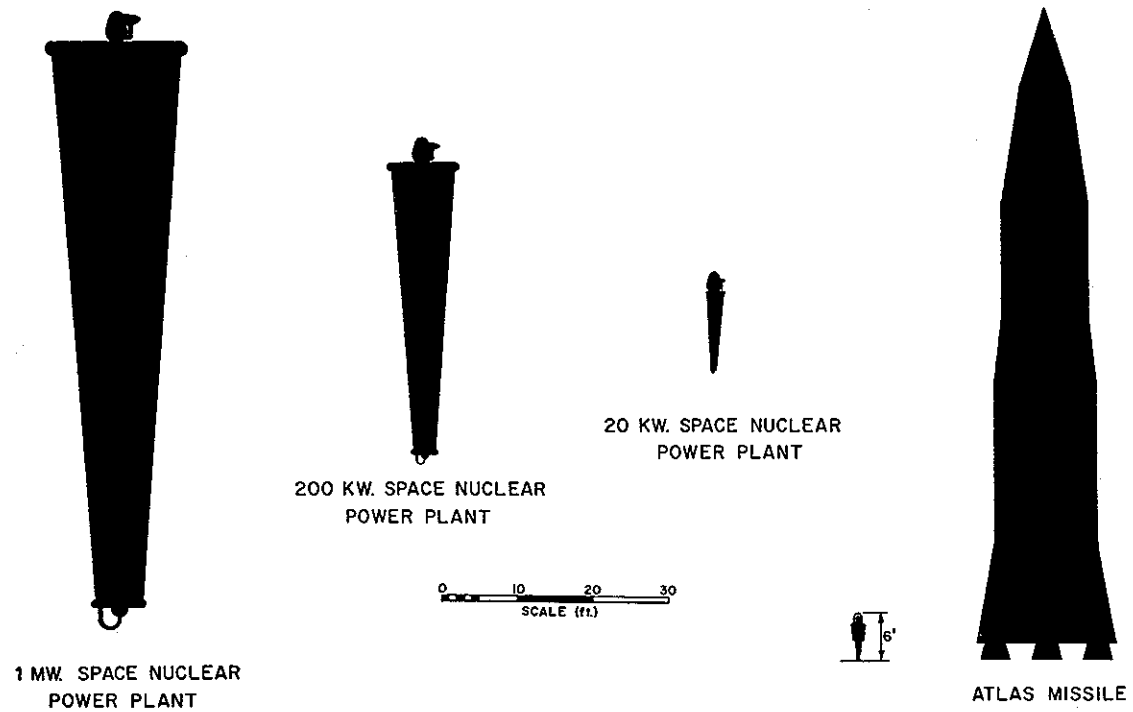
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1 MW. SPACE NUCLEAR
POWER PLANT

200 KW. SPACE NUCLEAR
POWER PLANT

20 KW. SPACE NUCLEAR
POWER PLANT

SCALE (ft.)

6'

ATLAS MISSILE

Fig. 8. Comparison of the sizes of three space power plants and an Atlas rocket.

the over-all effectiveness of the portion of the tube and fins facing the involute will be about 87 per cent of that of the portion radiating directly to space. Several arrangements for the fins can be employed, but that shown in Fig. 9 appears to be close to that for minimum over-all weight. Note that the front face of the tube has been thickened to provide meteoroid protection. This is not required at the rear since the involute reflector on the opposite side of the radiator acts as a bumper to shatter and disperse any meteoroid that penetrates it.

The suitability of a fin material depends on fabrication considerations, its density, and its thermal conductivity. Ideally, its coefficient of thermal expansion should be close to that of the tube material, its strength should be fairly good at the operating temperature, it should be ductile to resist shock and vibration, and it should be readily brazed to the tube material. If all of these conditions can be met, the suitability of the material is directly proportional to its thermal conductivity and inversely proportional to its density. Thus, the ratio of the thermal conductivity to the density is a good figure of merit for comparing different fin materials. It is interesting to note that copper with a $k/w = 20$ is about as good as beryllium for which k/w also is approximately equal to 20. Since copper is both readily available and easily brazed whereas beryllium is neither, copper is clearly the more attractive material in spite of its higher density.

Ideally, the emissivity of the tube and fin surfaces should be unity. Coatings can be applied to the tube and fin surfaces to provide emissivities close to unity. At first thought, these coatings should be black, e.g., black copper oxide or black oxidized stainless steel surfaces are obvious possibilities. Tests indicate that sand-blasting surfaces prior to oxidation improves their emissivity from values of around 0.8 to values of 0.9 to 0.93 as a consequence of the cavity effect. Less obvious coatings such as zirconium oxide also have some interesting possibilities. A white zirconium oxide coating, for example, has a high reflectance for solar radiation and yet has a high emissivity in the infrared region so that its use has appeared attractive for applications where absorption of solar energy would be a problem.

CONCLUSION

In closing, the author would like to express his regrets for being unable to do more than outline some of the many interesting heat-transfer problems associated with dynamic converters for space applications. Much further research and development work must be carried out before all of these problems are really well understood.

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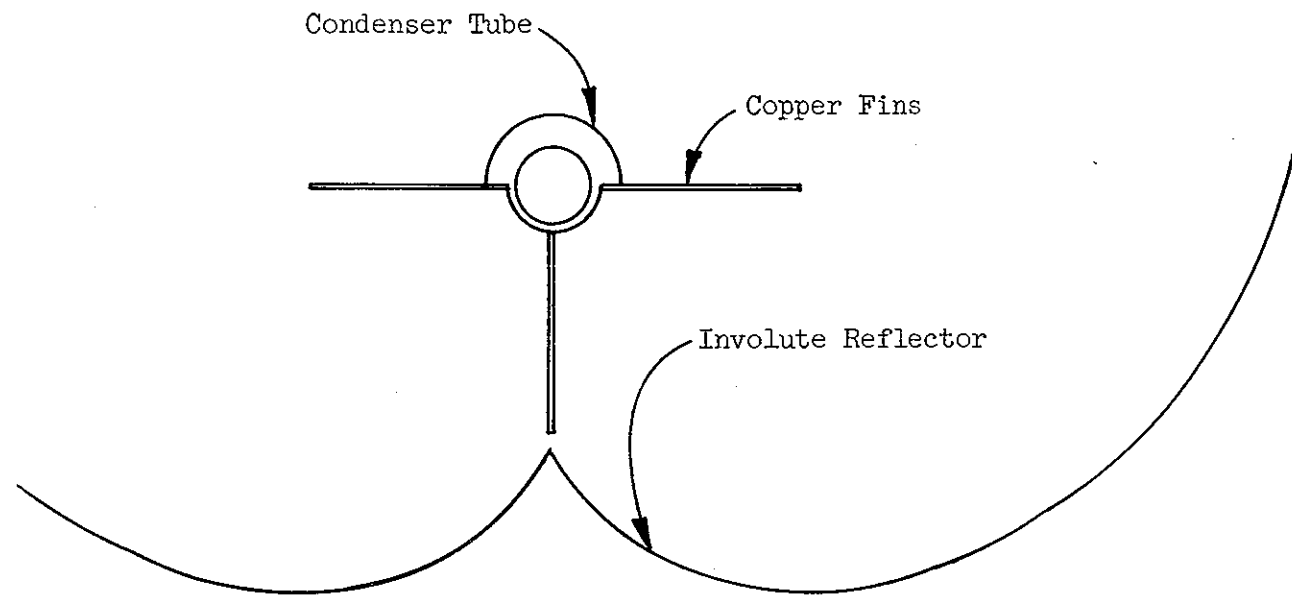
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Condenser Tube

Copper Fins

Involute Reflector

Fig. 9. *Section through a finned tube fitted with an involute reflector for installation in a cylindrical drum-shaped radiator.*

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DISCUSSION

PROFESSOR CHARLES F. BONILLA (Columbia University, New York, N.Y., U.S.A.): I wish to commend Mr. Fraas for his broad coverage and clear interpretations of many of the phenomena and design problems in the utilization of nuclear heat generation. Although many of the experimental results outlined were obtained for water as the coolant, they certainly apply to a substantial extent to the alkali metals, which are similar in density and some other properties. To complete the bibliographic record for the sake of readers, another very recent summary of these problems, though limited more to the heat transfer and fluid flow phases with alkali metals, might be mentioned.* It would seem that, given funds and patience, suitable space-power systems certainly will be developed in time.

As a specific point, it would be interesting to know the conditions (pressure, mass velocity, etc.) of Fig. 5, showing film boiling. More particularly, is this a stable condition (i.e., above a critical heat flux for these conditions), or an unstable one which might revert to nucleate boiling in a steady or random manner?

GEORGE W. SHERMAN

This is a very good outline and summary of the major heat transfer problems associated with the dynamic energy conversion systems for space vehicles.

The comments regarding the phenomenon of superheated liquid in the boiler and the associated problems of explosive boiling which it could cause are of significant interest. As Mr. Fraas pointed out, many people are aware of the fact that water can be superheated to approximately 50°F above its boiling point under controlled conditions before it begins to boil. However, the fact that 500°F of superheat can be obtained with liquid metals is probably not so well known. It would be quite interesting to know the test conditions and the particular liquid metal with which this high degree of superheat was obtained. From the comments made regarding the case of superheated water, liberty was taken to conclude that the high degree of

* R. D. Brooks, C. F. Bonilla, *Nucleonics,* 22, 43-48, March, 1964.

superheat obtained with the liquid metal was obtained in a pool boiler. If this was the case, what degree of superheat does the author feel would be obtainable with the same liquid metal in a forced convection boiler and how severe would the explosive boiling be?

The suggestion for the use of involute reflectors with the radiator is quite interesting. However, it does appear that the use of such a reflector concept would increase header lengths and subsequently increase the flow distribution problems. While the involute can be quite thin, it appears that a substantial structure would be required to enable the involute to survive the launch environment. With the necessary tube spacing which is indicated by Fig. 9 of the paper, it appears that the back sufaces of the tubes and fins might have a relatively high view factor to space if the involute were removed. Of course, the back side of the tubes would have to be fully protected; however, the over-all weight difference might diminish considerably or altogether with the involute and its structural weight eliminated. These considerations were probably taken into account in evaluating the involute reflector concept. If so, the results would be quite interesting.

C. Fouré (France)

Conduction dans les éléments combustibles

Devons-nous déduire du fait que l'auteur développe la question des réacteurs à gaz, que ce type de réacteur est considéré favorablement pour la génération de puissance dans l'espace? En tout cas, je crois qu'il n'est pas inutile de signaler, et l'auteur me donnera certainement son accord, qu'une partie des indications qu'il a fournies dans ce chapitre ne sont valables que pour les réacteurs à gaz:

— La valeur de 2800°F (1550°C), citée comme température maximum à respecter sur l'axe des éléments combustibles, paraît prudente si on la compare à celle admise dans un réacteur nucléaire à eau bouillante, tel que KRB, soit 3950°F (2175°C). L'auteur a vraisemblablement tenu compute des incertitudes sur les facteurs de point chaud dans les réacteurs à gaz pour cette limite.

— Les irrégularités de température à la surface de l'élément combustible semblent ne pas poser de problèmes aussi aigüs dans les piles refroidies par liquides. En outre les dipositifs pour accroître le mélange transversal peuvant alors être de grand intérêt, car les puissances de pompage des liquides sont relativement très faibles. Notons d'ailleurs que dans les piles à gaz à température assez basse pour qu'un matériau à faible section de capture neutronique, tel que le magnésium, puisse être utilisé pour la gaine et les ailettes, on dispose le plus souvent ces ailettes de façon à favoriser le mélange transversal.

Bouilleur pour conversion à cycle de Rankine

L'auteur rappelle la description des différents régimes qu'on rencontre dans l'ébullition, et il cite à propos de l'écoulement avec brouillard des diamètres de gouttes de 0,25 à 2,5 mm (0,010 à 0,100). Ces chiffres me

paraissent assez forts, à quelle nature de liquide et à quelles vitesses d'écoulement correspondent-ils ?

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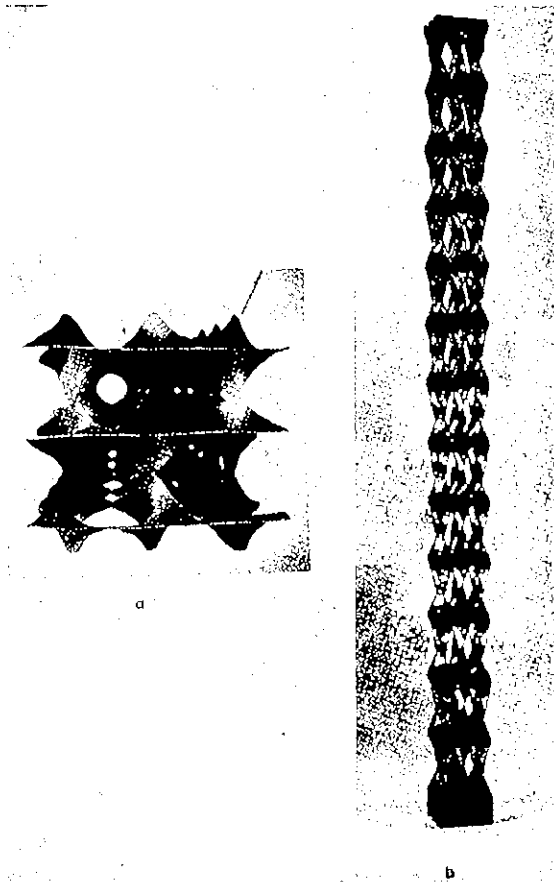

Fig. 1. Assemblage de vrilles cruciformes: (a) vue en bout; (b) vue latérale.

nombre de formules discordantes citées dans la littérature, et ce n'est pas la moindre des *limitations* auxquelles se heurte celui qui doit dimensionner un bouilleur. L'auteur peut-il apporter un complément sur ce sujet ?

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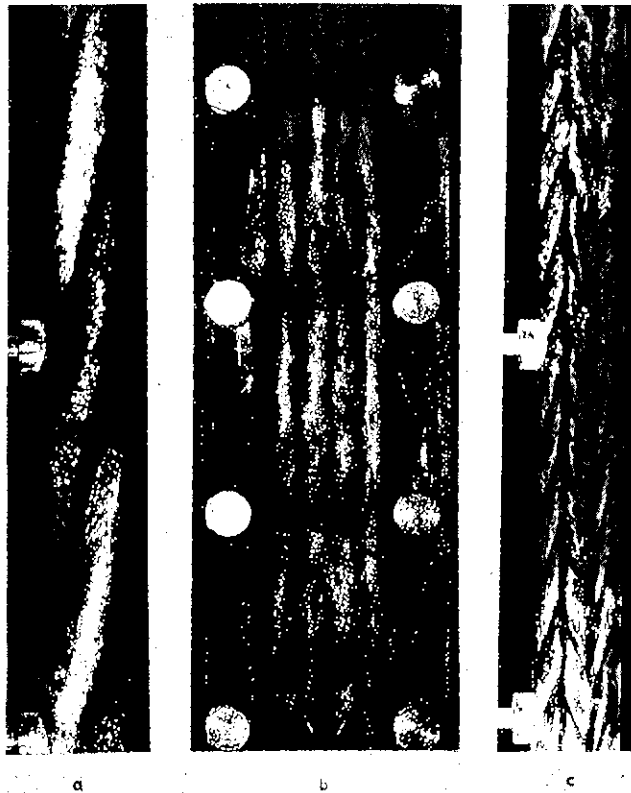

Fig. 2. *Visualisation de l'écoulement montrant le rassemblement de la phase gazeuse au voisinage des axes des vrilles: (a) tube circulaire (1 bande vrillée); (b) canal rectangulaire (4 bandes vrillées); (c) canal annulaire (6 bandes vrillées autour d'un barreau axial).*

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Les figures 1a et 1b montrent une fraction d'assemblage de bandes vrillées pour s'insérer dans un réseau de barreaux conbustibles. On notera les logements cylindriques pour les barreaux et les sens de rotation alternés d'une bande à l'autre.

La figure 2 montre des expériences de visualisation en mélange eau-air. On notera les cheminements de l'air voisinage de l'axe des bandes.

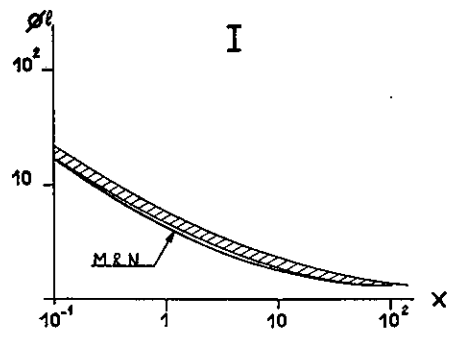Les diagrammes suivants montrent les résultats d'expériences sur les

Fig. 3. *Perte de charge. Comparison des résultats S.N.E.C.M.A. avec la courbe de Martinelli et Nelson (repérée M & N). Melange eau-air à la pression atmosphérique, titre x ⩽ 29 per cent. Vitesse de l'eau seule 0·25 et 4 m/s (I) sans vrilles (II) avec vrilles.*
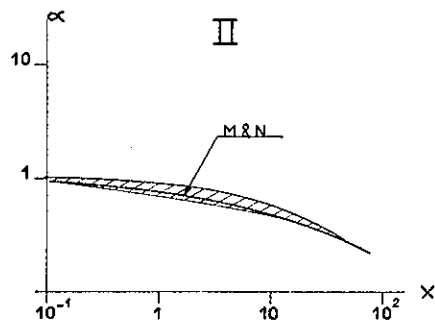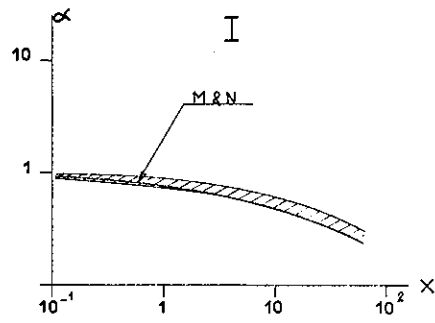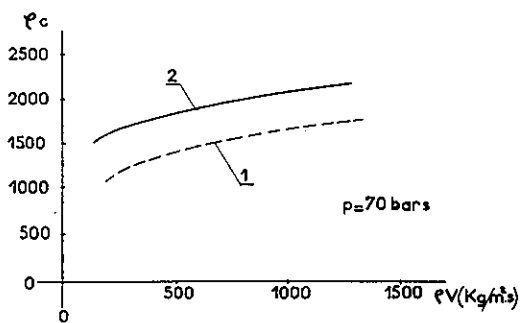
Fig. 4. Fraction de vide α. Comparaison des résultats S.N.E.C.M.A. avec la courbe de Martinelli et Nelson (réperée M & N). Melange eau–air à la pression atmosphérique, titre x ⩽ 29 per cent. Vitesse de l'eau seule comprise entre entre 0·25 et 4 m/s.
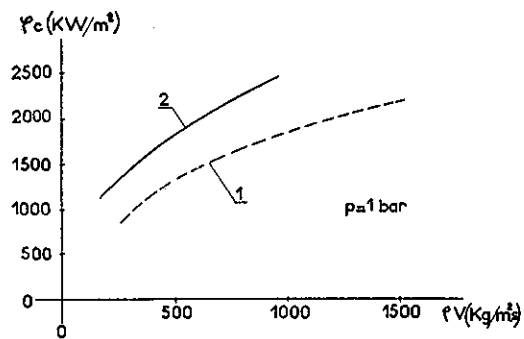
Fig. 5. Flux critique en fonction du débit surfacique. Entrée à la saturation (I) sans vrilles (II) avec vrilles cruciformes.

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chutes de pression et les fractions de vide en écoulement biphase avec et sans vrilles, en réseau carré.

Le rapport ϕ^2 des pertes de charge biphase/liquide sans puis avec vrille comparé à la corrélation de Martinelli et Lockhart est donné sur la figure 3, la fraction de vide sur la figure 4. Des expériences thermiques portant sur 4 barreaux chauffants, les parois du canal reproduisant la forme des 12 barreaux voisins, ont été faites pour déterminer les flux critiques avec et sans bandes vrillées. Les résultats obtenus avec eau entrant à la saturation à la pression atmosphérique ou a 70 bars, sont représentés sur la figure 5. On notera les augmentations obtenues, qui varient entre 25 et 45 pour cent. Ces dernières expériences ont été faites sur une installation de plus de 1 MW thermiques.

La configuration est bien entendu applicable à un bouilleur pour métal liquide, mais les résultats pour ce cas ne sont pas disponibles.

The following page(s) provide higher quality versions of graphics contained in the preceding article or section.
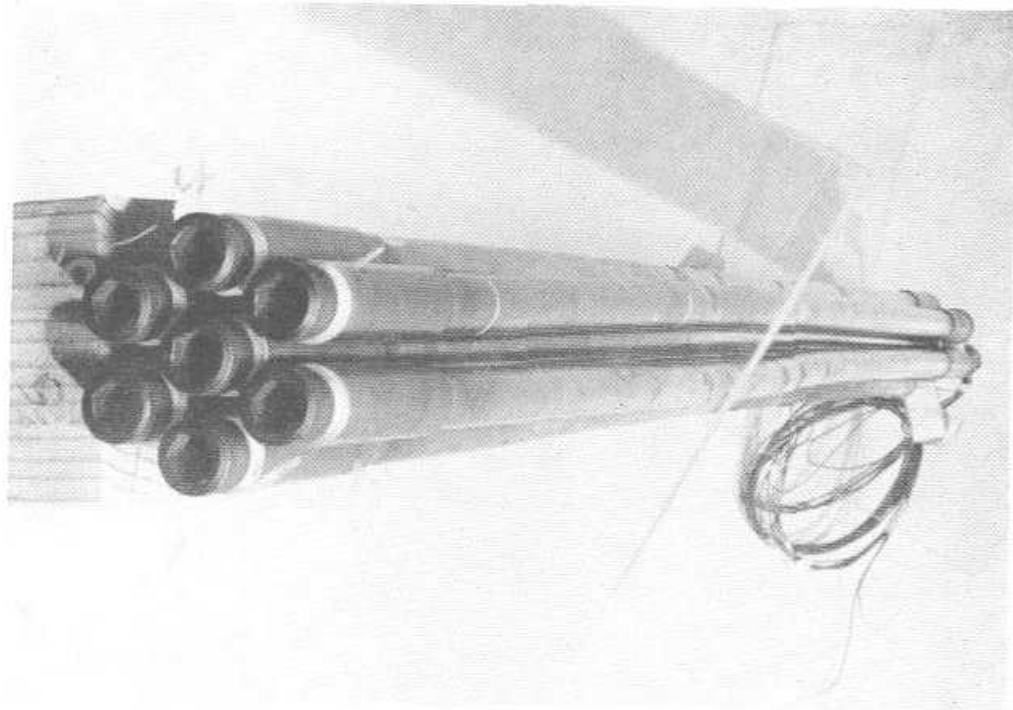
Fig. 4. An electrically heated mock-up of a prototype fuel-element for the EGCR. Note that the rods have been warped by hot spots.

alkali metals are especially likely to give difficulty since to avoid corrosion they must be used in meticulously clean systems, and the liquids must have a very high degree of purity. Experience has shown that the amount of superheat in alkali metals may exceed 500 F, and, when this occurs, it leads to violently explosive boiling.

Difficulties are sometimes experienced with poor wetting even in water systems. In mercury boilers the problem is chronic. The effects are ordinarily small for pool boiling or for bubbly flow, but they drastically reduce
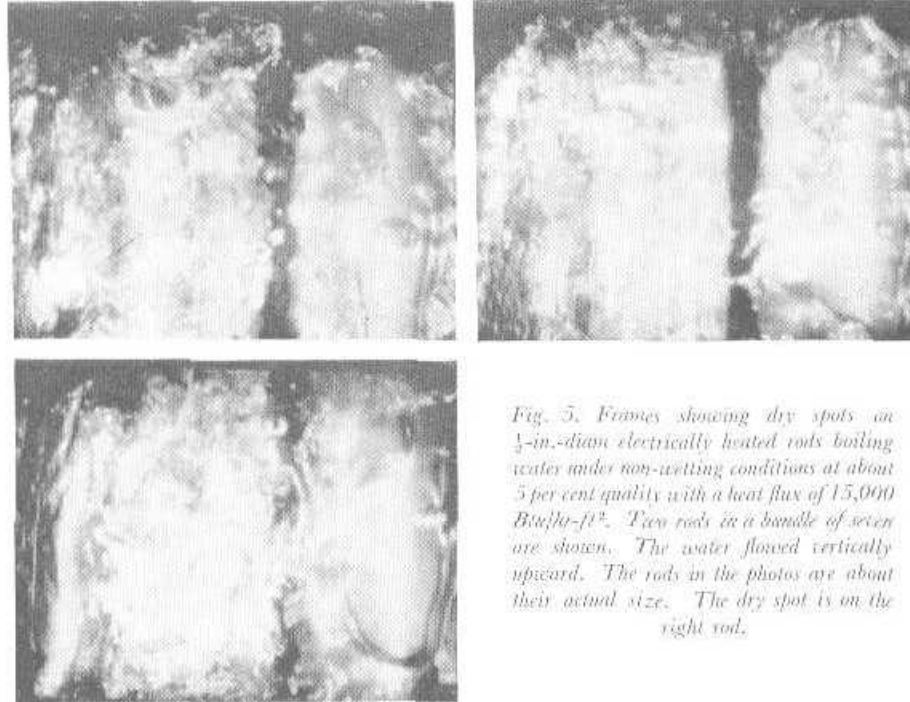

Fig. 5. Frames showing dry spots on ½-in.-diam electrically heated rods boiling water under non-wetting conditions at about 5 per cent quality with a heat flux of 15,000 Btu/hr-ft². Two rods in a bundle of seven are shown. The water flowed vertically upward. The rods in the photos are about their actual size. The dry spot is on the right rod.

the burn-out heat flux obtainable under annular film flow conditions. Even with water, burn-out has been observed in rod bundles at heat fluxes as low as 15,000 Btu/hr-ft² with vapor qualities of around 5 per cent. Figure 5 presents frames from high-speed movies taken at these conditions, and shows the droplets skittering across a dry, hot surface. The condition was corrected by adding a small amount of sodium bicarbonate to the water.

CONDENSER

Control of free liquid surfaces presents problems in the condenser as well as in the boiler. Unless a space vehicle is spun to induce an artificial gravitational field, the principal forces acting on droplets of condensate will be

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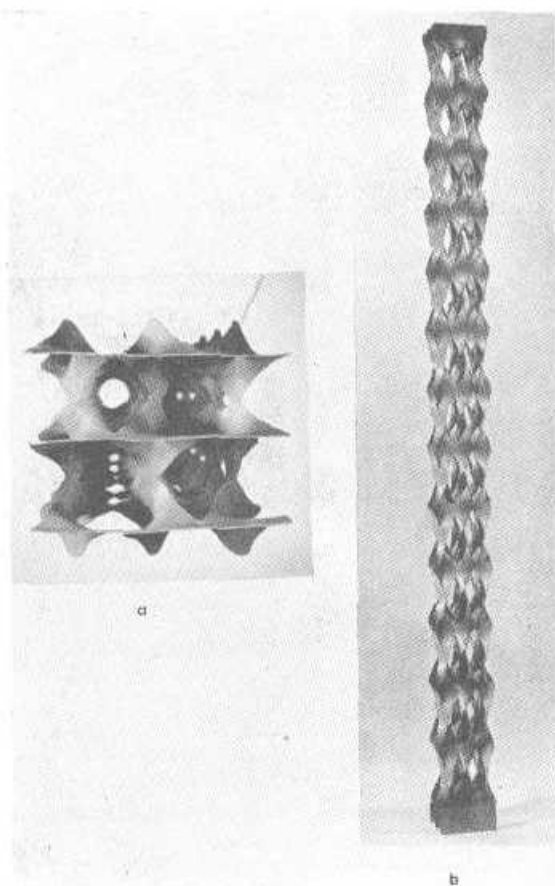

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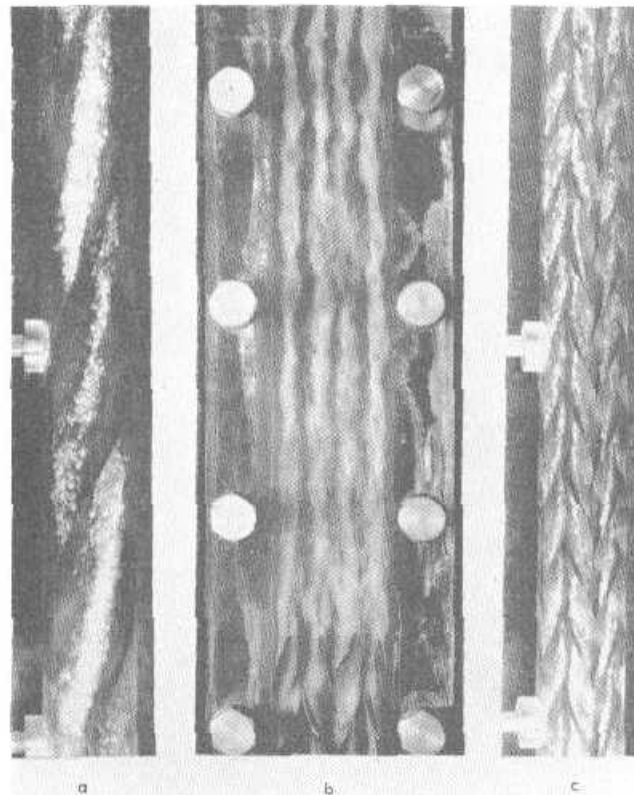

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