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**A CONSIDERATION OF HIGH NICKEL
CONTENT ALLOYS FOR FTR CORE
STRUCTURAL MATERIALS**

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R. A. MOEN

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By

R. N. Johnson, E. A. Kovacevich,
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Development Section
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I. INTRODUCTION

The objective of this report is to recommend the materials for core structural components, especially fuel subassembly ducts, core support plates, reflector, etc. Type 304 stainless steel (304 SS) is presently specified for those portions of components exposed to the primary sodium, the original decision being made as early as August 1965.⁽¹⁾ This decision was further strengthened in October 1967 by a second publication⁽²⁾ which discussed primarily the use of 304 SS and 316 SS for the FTR fuel cladding.

More recently, the desire to consider an alloy with a higher nickel content in order to increase the magnitude of the negative Doppler coefficient in the split FTR core was expressed.⁽³⁾ This technical review will permit recommendations to be made on specific materials for use in the core. The specific questions to be answered by this review are as follows:

- 1) What alloys are practical?
- 2) Can high nickel materials be used in the FTR core in an unclad condition?
- 3) If high nickel alloys can be considered, what are their temperature limits?

This review will answer these questions by first enumerating the alloys that should be considered based primarily on practicality, experience, and preliminary physics requirements. These alloys will then be further screened from physics and corrosion standpoints. The thermal and irradiation stability of the materials will be examined, followed by a review of the fabricability and availability, and cost of the respective materials. The final step will be to make recommendations based on the findings of this review.

II. DEFINITION OF CORE STRUCTURALS

Core structurals are those members of the FTR inside the reactor vessel and wetted by the primary sodium. The individual rods or slabs of reflector material contained in the reflector subassemblies will be exposed to sodium for the purpose of removing gamma heat. An exception to this list is the fuel cladding which was discussed previously.⁽²⁾ The list of structures to be considered is shown in Table I.⁽⁴⁾

TABLE I. *FTR Core Components*

1. Driver Fuel Ducts - hexagonal cross section at active core
2. Reflector Assemblies
 - a. Removable Rod - tubular configuration next to hexagonal fuel duct (hollow tube in which instruments or experiments can be placed)
 - b. Fixed Rod
 - i. Duct
 - ii. Inner Rods
 - c. Fixed Cannister
 - i. Cannister (tapering sheets)
 - ii. Inner Rods
 - d. Main Radial
 - i. Cannister and/or
 - ii. Rods
3. Control Assemblies
 - a. In-core Rods
 - i. Guide Tube
 - ii. Control Rod
 - b. Reflector Rods
 - i. Guide Tube
 - ii. Control Rod
4. Support Hardware
 - a. Upper Tube Sheet (located below the core)
 - b. Lower Tube Sheet (below the upper tube sheet)

TABLE I. FTR Core Components (contd)

- 5. Flow Distribution Hardware
 - a. Supply Plenum
 - b. Low Pressure Area
- 6. Experimental Assemblies
 - a. Closed Loop Ducts
 - b. Open Loops
 - i. Duct
 - ii. Experiment (fueled tubes, structural materials)
 - c. Transient Facilities

For the purpose of discussing the effect of materials on the Doppler coefficient in the core, the core will be conservatively described as any material existing within 12 in. of the active core zone outlined in PNL Drawing SK-5-12879. Actually, a more realistic figure for effect of material on Doppler coefficient would be within 6 in. of the active zone.

Hard-facing and spring materials, integral parts of some components, will be treated separately in this evaluation.

III. PERFORMANCE REQUIREMENTS

The core components wetted by the primary sodium will range vertically in temperature from a minimum at the support tube sheets to a maximum at the hot spots on the driver fuel cladding. Temperatures radially will run from maximum at the fuel cladding hot spots within the active core zone down to about the inlet sodium temperature within the outer reflector assemblies.

The sodium temperature will vary from one part of the system to another, but the sodium chemistry should remain constant throughout the system.

Flux levels and the resulting fluence or total exposure received by components is determined by the time which the components reside in each particular flux region. Using flux values from W. L. Bunch,^(5,6) a "flux profile" can be approximated to characterize the component neutron environment.

The time each component will reside in the neutron environment depends on the ease of component removal and material's property limits of the component. Components have been divided into three groups indicative of their ease of removal; (1) permanent components, (2) replaceable components, and (3) temporary components. Temporary components are those such as driver fuel assemblies, control rod assemblies, and experimental loop assemblies which are replaced on a routine basis. Replaceable components are made of parts not welded to the primary vessel but requiring a considerable loss of plant availability for replacement. All of the core structural materials are in the latter two categories.

The stress state of each component is also an important environmental consideration. Those components seeing the outlet sodium temperatures will be subjected to thermal fatigue and relatively low steady state stress. The driver fuel assemblies, because of the high sodium velocities therein, may be subjected to high cycle fatigue (vibration). The lower gridplates supporting some of the core weight will be subjected to bending stresses, which will be moderately low in magnitude due to the massiveness of the structure. Closed tubes (control rods) containing material in which large quantities of gases are generated may have high pressure stresses. Members such as the reflector assemblies will be required to support only their own weight. The environments of the major core components are summarized in Table II. From this table, the greatest exposure to be accumulated by a 20 year component is about 8×10^{23} n/cm² and that by a short-term component is less than 8×10^{23} n/cm². The highest temperature seen by a long term (20 year) component, other than the reactor vessel, is about 1000 °F in the reflector assemblies. Short time component temperatures of up to 1200 °F will ultimately be experienced by the fuel and loop ducts. For this analysis, the core components which are classed as temporary will be considered

TABLE II. Summary of FTR Core Components Environment

	Flux, nv, ^(a) E > 0.1 MeV	Residence Time in FTR, years	Temperature, °F (Max)		Predicted Fluence ^(b) Based on Residence Time, nvt (Max)	Required Strength
			Initial	Ultimate		
Driver Fuel Ducts	7 x 10 ¹⁵	~1.5	~800-900	~1200	2.5 x 10 ²³	High
Reflector Assemblies						
Removable Rod	~7 x 10 ¹⁵	~5	~800-900	~1200	8.3 x 10 ²³	Low
Fixed Rod	1.2-1.7 x 10 ¹⁵	≤20	~800-900	~1200	8.0 x 10 ²³	
Fixed Cannister	~1 x 10 ¹⁵	≤20	~800-900	~1200	4.7 x 10 ²³	
Main Radial	3.5-6.2 x 10 ¹³	≤20	~800-900	~1200	2.9 x 10 ²²	
Control Assemblies						
In-core Rods	7 x 10 ¹⁵	~3	~800-900	~1200	5 x 10 ²³	Moderately High
Reflector Rods	~7 x 10 ¹⁵	~3	~800-900	~1200	5 x 10 ²³	
Support Hardware						
Upper Tube Sheet	1.2-3.7 x 10 ¹²	≤20	500-600	800	1.7 x 10 ²¹	Moderate
Lower Tube Sheet	1.3-6.2 x 10 ¹⁰	≤20	500-600	800	2.9 x 10 ¹⁹	
Flow Distribution Hardware						
Supply Plenum	2.4-4.9 x 10 ¹¹	≤20	500-600	800	2.3 x 10 ²⁰	Moderately Low
Low Pressure Area	0.8-3.3 x 10 ⁸	≤20	500-600	800	1.6 x 10 ¹⁷	
Experimental Assemblies						
Closed Loop Ducts	~1 x 10 ¹⁶	(c)	1000-1200	>1200	---	High
Open Loop Ducts	~1 x 10 ¹⁶	(c)	~800-900	1200	---	
Transient Facilities	~1 x 10 ¹⁶	(c)	~900		---	

(a) Based on 400 MWe operation

(b) Assuming 75% operating efficiency

(c) As required

to experience only initial environmental conditions, while those components that are classed as replaceable or permanent will be considered to see the ultimate environmental conditions.

IV. MATERIALS FOR CONSIDERATION

The structural materials under consideration for various core components are the austenitic stainless steels (Type 304, 316, 347, and 321), Incoloy 800, Inconel 600, and "pure" nickel. This list of alloys was selected because of preliminary physics considerations and the fact that all of these materials have some prior nuclear experience. These alloys fairly well cover the range of nickel content from 8 to 100% as shown in Table III.

TABLE III. Chemical Compositions, wt%

Element	Type 304	Type 316	Type 347	Type 321	Incoloy 800 (Nominal)	Inconel 600	Nickel 200
C	0.08 max	0.08 max	0.08 max	0.08 max	0.04	0.15	0.02
Mn	2.00 max	2.00 max	2.00 max	2.00 max	0.75	1.0	0.35 max
P	0.040 max	0.040 max	0.040 max	0.040 max	--	--	--
S	0.030 max	0.030 max	0.030 max	0.030 max	0.007	0.015 max	0.010 max
Si	0.75 max	0.75 max	0.75 max	0.75 max	0.35	0.5 max	0.35 max
Ni	8.0 to 11.0	10.0 to 14.0	9.0 to 13.0	9.0 to 13.0	32.0	72.0 min	99.0 min
Cr	18.0 to 20.0	16.0 to 18.0	17.0 to 20.0	17.0 to 20.0	20.5	14.0 to 17.0	--
Mo	--	2.00 to 3.00	--	--	--	--	--
Fe	Balance	Balance	Balance	Balance	46.0	6.0 to 10.0	0.40 max
Cu	--	--	--	--	0.30	0.5 max	0.25 max
Ti	--	--	--	5(C) to 0.6	0.30	--	--
Al	--	--	--	--	0.30	--	--
Nb + Ta	--	--	10(C) to 1.00	--	--	--	--

Promising materials for springs (control rod accelerators) are Inconel X-750 and Inconel 718. Two hard-facing materials under consideration are Stellite 1016 and Stellite 6B. The compositions of these materials are shown in Table IV.

TABLE IV. *Compositions of Spring and Hard-Facing Materials*

	<u>Inconel</u> <u>X-750</u>	<u>Inconel</u> <u>718</u>	<u>Stellite</u> <u>1016</u>	<u>Stellite</u> <u>6B</u>
C	0.08 max	0.05	2.5	1.1
Ni	70	53	--	3 max
Cr	15.5	18.5	32	30
Co	--	0.1	Balance	Balance
Mo	--	3.0	--	1.5 max
W	--	--	17	4.5
Fe	Balance	Balance	--	3 max
Ti	2.5	1.0	--	--
Al	0.7	0.5	--	--
Si	0.5 max	0.25	--	2.0 max
Nb	0.6	5.1	--	--
Mn	1.0	--	--	--
Cu	0.5	--	--	--

V. EFFECT OF STRUCTURAL MATERIALS ON DOPPLER COEFFICIENT IN FTR

The Doppler coefficient is determined by a number of factors, such as core geometry, fuel material and enrichment, reflector material, and core structural materials and cladding. All other factors being equal, the structural material that gives the greatest negative Doppler coefficient would be the best choice from a physics viewpoint.

Table V lists the Doppler coefficients that would result with a given choice of one material for all core structural and cladding applications in the present split-cone concept of the FTR. If, however, one material, such as Type 304 or 316, is used for the cladding and another material, such as Incoloy 800 is used as a fuel duct material, the Doppler coefficient will be compromised in proportion to the relative masses of each material present. This is also shown in Table V. Approximately 29% of the material within the bounds of the radial reflector is structural material. Of this structural material, 43% is cladding and the remaining 57% is flow ducts, loops, etc. In general, the higher the nickel content of the alloy, the better is the Doppler coefficient. However, the higher the amount of high cross-section elements used as alloying additions (such as molybdenum, tantalum, tungsten, and

TABLE V. *Variation of Doppler Coefficient
with Structural Materials^(?)*

	$T \frac{dk}{dt}$	% Improvement in Doppler ^(a)
All 304 system	-0.00414	0
All 347 system	-0.00407	-1.7
All 316 system	-0.00405	-2.2
All Incoloy 800 system	-0.00456	10
All Inconel 600 system	-0.00532	28.5
Mixed ^(b) 316 clad 304 structural	-0.00411	-0.7
Mixed 316 clad Incoloy 800 structural	-0.00434	4.8
Mixed 304 clad Incoloy 800 structural	-0.00438	5.8
Mixed 316 clad Inconel 600 structural	-0.00477	15.2

(a) An all 304 system is taken as the basis for comparison

(b) Total Doppler = 0.57 (Doppler for structural) + 0.43
(Doppler for clad)

niobium), the poorer is the Doppler coefficient. Therefore, we see in Table V that although both Type 316 and Type 347 have higher nickel contents than Type 304, Type 304 has about a 2% better Doppler coefficient than either due to the molybdenum in the 316 and the niobium and tantalum in the 347. Type 347 will actually be slightly poorer than that listed, since the calculations were based upon pure niobium being used in the alloy, and Type 347 normally contains a portion of the niobium value as tantalum, which has a higher nuclear cross section.

When Incoloy 800 (32% Ni) is used in the core structurals, a Doppler coefficient is available that is 10% better than that provided by the stainless steels; Inconel 600 (72% Ni) provides about a 30% better Doppler coefficient.

Type 321, which is not listed in Table V, would give about the same Doppler coefficient as the Type 304 since it is of similar composition except for the titanium content, which would have an insignificant effect. By extrapolation of data in Table V, Nickel 200 (pure nickel) would have a Doppler coefficient of about -0.00585, or about 40% better than that for Type 304.

VI. CORROSION

The present reference material for most of the FFTF core structurals (including ducts, support plates, and reflector ducts) is Type 304 SS. In a complex structure such as the FFTF system it is not likely that a monometallic system design can be maintained. In order to optimize the design, materials other than Types 304 and 316 SS undoubtedly will be employed. Valve inserts, bearing surfaces, springs, and seals are some applications in the FFTF system where these materials could be used. Materials normally used in these applications are the high strength nickel-base or cobalt-base alloys. The introduction of several materials into the same system complicates the prediction of the corrosion behavior. The available corrosion data has been reviewed, and the materials that are being surveyed are categorized into the austenitic stainless steels (Types 304, 316, 321, and 347), Incoloy 800, and Inconels (Inconel 600, Inconel X-750, and Inconel 718), and the hard-facing cobalt-base alloys (Stellite 1016 and Stellite 6B).

AUSTENITIC STAINLESS STEELS

Investigators have found that austenitic stainless steels exposed to sodium will have their contact surfaces altered to form a ferritic layer. This is a result of the sodium leaching nickel and chromium from the metal surface. Therefore, after this ferrite layer is formed, the material exposed to the sodium

will be essentially the same composition regardless of the original material. Time to form this ferrite layer under FFTF conditions (1200 °F maximum temperature) was stated as one year.⁽⁸⁾

The major contributor to sodium corrosion work is the General Electric Company. The results of this work were summarized by Zebroski⁽⁹⁾ et al. To date, Types 316 and 304 stainless steels have been studied exclusively.

As a result of these studies, a corrosion model⁽¹⁰⁾ for both removal rates and deposition rates has been established. For removal rate, the empirical formula is

$$R = V^{0.884} O_x^{1.156} \exp[12.845 - \frac{23847}{T + 460} - 0.00676 (L/D) + \frac{2.26}{t + 1}]$$

where V = sodium velocity, ft/sec

O_x = oxide level in sodium, ppm

T = corrosion site temperature, °F

L/D = downstream factor

t = exposure time, months

R = removal rate, mg/dm²-month

On the basis of the above model, the removal rates (as shown in Table VI) for Type 304 SS under FFTF conditions were calculated for various exposure times.

The deposition rate formula is

$$R = O_x^{0.94} \exp[(22.61 - 0.038 \Delta T) - (\frac{31.980 - 55.24 \Delta T}{T + 460}) - 0.0032 (L/D) + \frac{0.92}{t + 1}]$$

where O_x = oxide level in sodium, ppm

ΔT = maximum system temperature minus minimum system temperature, °F

L/D = downstream factor
 T = deposition site temperature, °F
 t = exposure time, months
 R = deposition rate, mg/dm²- month

TABLE VI. Removal Rate from Hot Section

Time, months	Removal Rate, mg/cm ² - month				
	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
4	0.0424	0.1409	0.4011	1.2982	6.076
6	0.0373	0.1238	0.3525	1.1409	5.340
8	0.0347	0.1153	0.3281	1.0619	4.970
12	0.0321	0.1067	0.3037	0.9830	4.601
18	0.0304	0.1010	0.2875	0.9304	4.355
24	0.0295	0.0981	0.2794	0.9043	4.232
30	0.0291	0.0965	0.2745	0.8886	4.159
36	0.0287	0.0953	0.2713	0.8781	4.110
40	0.0285	0.0947	0.2697	0.8729	4.086

Oxide Content, 10 ppm

Condition 1 T = 900 °F, ΔT = 350 °F, Vel = 30 ft/sec

Condition 2 T = 1000 °F, ΔT = 400 °F, Vel = 30 ft/sec

Condition 3 T = 1100 °F, ΔT = 500 °F, Vel = 30 ft/sec

Condition 4 T = 1200 °F, ΔT = 500 °F, Vel = 40 ft/sec

Condition 5 T = 1400 °F, ΔT = 500 °F, Vel = 40 ft/sec

Deposition rates (as shown in Table VII) were calculated for Type 304 SS under FFTF conditions.

As seen from these results, the total amount removed for any given set of conditions will depend upon the amount of surface area exposed to the sodium.

Future tests are planned at General Electric Company to evaluate Incoloy 800 along with AISI Types 304, 316, and 347 SS. A corrosion model will be established for these materials, and the tests to establish this model will be operated under FFTF conditions.

TABLE VII. *Deposition Rate in Cold Section*

Months	Deposition Rate, mg/cm ² -month				
	T ₁	T ₂	T ₃	T ₄	T ₅
4	0.0042	0.0154	0.0633	0.0902	0.1568
6	0.0040	0.0146	0.0600	0.0856	0.1488
8	0.0039	0.0142	0.0583	0.0831	0.1445
12	0.0038	0.0138	0.0565	0.0806	0.1400
18	0.0037	0.0135	0.0552	0.0788	0.1369
24	0.0036	0.0133	0.0546	0.0779	0.1354
30	0.0036	0.0132	0.0542	0.0773	0.1344
36	0.0036	0.0131	0.0539	0.0770	0.1337
40	0.0036	0.0131	0.0538	0.0768	0.1334

Maximum T₁ = 550 °F, Condition 1

Maximum T₂ = 600 °F, Condition 2

Maximum T₃ = 600 °F, Condition 3

Maximum T₄ = 700 °F, Condition 4

Maximum T₅ = 900 °F, Condition 5

NICKEL-BASE ALLOYS

Most of the pertinent corrosion data for nickel-base alloys have been developed in the United Kingdom. It was generally found that the corrosion rates increase with increasing nickel content. For Inconel 600, corrosion rates of 6 mils/year were encountered whereas Type 304 SS under the same conditions was 2 mils/year.

Thorley and Tyzack⁽¹¹⁾ found that the behavior of certain nickel-rich alloys of the Nimonic type showed that with the increasing nickel content the corrosion rates increased to values that were unacceptable for fuel element cladding. Table VIII shows the results of their investigations. These results are shown in Figure 1 with our alloy compositions overlayed for comparison. As seen from these results for the specified test conditions, those nickel alloys having a nickel content within the range of 35 to 50 wt% nickel had an average corrosion rate of 2.5 to 3.2 mils/year. Higher nickel content alloys (>50 wt% nickel) showed corrosion rates of 5 to 6 mils/year. Lower nickel content alloys (<30 wt% nickel) have average corrosion

TABLE VIII. *Data Obtained from Materials Exposed to Dynamic Sodium (30 to 40 ft/sec) Containing 25 to 30 ppm of Oxygen at 650 °C (1200 °F) for 1344 hr*

<u>Material (a)</u>	<u>Extrapolated Loss in Metal Section, thousandths of an inch per year</u>
Inconel 600	6.1
PE. 11	2.9
Nimonic 80A	4.9
PE. 16	2.9
Nickel (200)	3.9
18/8/1 Ti	2.4
316 SS	1.8
Nilo. 50	2.8
Nilo. K	0.95

(a) Compositions

Inconel 600	77 Ni, 6 Fe, 16 Cr, 0.02 C
Nimonic 80A	75 Ni, 20 Cr, 2.3 Ti, 1.4 Al, 0.06 C
Nickel (200)	99.99 Ni
18/8/1 Ti	18 Cr, 8 Ni, 1 Ti
316 SS	18 Cr, 11 Ni, 3 Mo, 0.06 C, Bal Fe
Nilo 50	50 Ni, 50 Fe, 0.03 C
Nilo K	53 Fe, 29 Ni, 16 Co, 0.03 C
PE. 11	35 Fe, 38 Ni, 18 Cr, 5.2 Mo, 2.2 Ti, 0.9 Al, 0.07 C
PE. 16	34 Fe, 43 Ni, 16 Cr, 1.2 Al, 1.2 Ti, 0.06 C

FIGURE 1. *Metal Loss as a Function of Nickel Content in the Alloy (1200 °F, Flowing Sodium)*

rates less than 2.5 mils/year. The corrosion rate for pure nickel is higher than that of Type 316 SS, but is lower than the high nickel alloys.

It was established by Thorley's tests that the mass transfer processes of high nickel materials exposed in circulating-sodium stainless steel loops are fairly insensitive to oxygen limits, but sensitive to liquid metal velocity. This condition implies that the rate of mass transfer is diffusion-controlled. Conversely, the rate of mass transfer of ferritic and austenitic materials is sensitive to oxygen content in the sodium and is proportional to velocity only up to some limiting Reynolds number.

High nickel alloys in flowing sodium systems have been investigated in the U.S.⁽¹²⁾ However, most of the work was at higher temperatures and lower sodium velocities than are planned for FFTF. Nevertheless, the general trend for corrosion rates show increasing corrosion with an increase in nickel content in the material.

Although not directly (quantitatively) applicable to FTR environments, Agapova⁽¹³⁾ et al. showed that simultaneous increase of temperature beyond 1470 °F and of sodium flow rate above approximately 10 ft/sec resulted in catastrophic destruction of high nickel alloys. Furthermore, this study concluded that tungsten or molybdenum alloying additions were desirable, but that a stainless steel surface in contact with liquid sodium should contain as little nickel as compatible with the mechanical strength requirements.

COBALT-BASE ALLOYS

No corrosion data were found for cobalt-base alloys in a sodium environment and under FFTF conditions. Although there is a lack of sodium data, there are results of cobalt-base alloys⁽¹²⁾ in NaK and potassium environments. These tests also are beyond the operating conditions for the FFTF. In general, the cobalt-base alloys demonstrated far superior corrosion

resistance than Type 316 SS. Some experience has been obtained with sodium valves in elevated-temperature, flowing-sodium systems. Most valve seats or valve plugs are hardfaced with Stellite 6B. Although the actual corrosion rate was not established for these seats or plugs, these sodium valves gave relatively long life services.

DEPOSITION EFFECTS.

In discussing the relative corrosion merits of each type of material under FFTF conditions, not only must the material's degradation be considered, but also the amount of corrosion products formed which will deposit elsewhere in the system is important. An increase in corrosion products of the suggested materials would result in an increase in the ^{58}Co radioisotope transport rate. Presently, this is of some concern with the fuel element cladding under FFTF conditions. It was calculated that under maximum FFTF conditions of 1200 °F peak clad temperature the amount of radioactivity from the fuel pin corrosion products was 6730 Ci/month.⁽¹⁴⁾ The major contributor to this is ^{58}Co formed from the $^{58}\text{Ni}(n,p)^{58}\text{Co}$ reaction. As one increases the nickel content in the alloy (such as Inconel) the ^{58}Co inventory will also increase, thus increasing the radioisotope transport rate.

In summary, there is a mass of data for the austenitic stainless steels in flowing sodium systems whereby a responsible extrapolation of the data can be applied to the FFTF design. Because of similarities in corrosion behavior, selection of the optimum stainless steel will not depend upon the corrosion behavior but upon other criteria. However, in the case of the nickel-base alloys, there is a scarcity of data to support a decision as to how high a nickel content one can tolerate in the FFTF design, the primary consideration being the amount of radioactive debris formed by corrosion processes. Since contact

maintenance is one of the FFTF design criteria, this condition must be carefully reviewed. Since a trend of increased corrosion is observed as nickel contents are increased, it is probable that allowable operating temperatures for nickel alloys will be lower than for stainless steels if the corrosion rate is to be kept the same; the magnitude of the corrosion cannot be determined with existing data. However, it appears that the corrosion rates for Incoloy 800 (30 wt% Ni content) may be tolerable. The higher nickel content alloys (>40 wt%) will be less desirable, particularly at 1200 °F. It is impossible at this time to ascertain a threshold temperature for a given composition of a nickel-base alloy because of the lack of lower temperature corrosion data. This indicates that until corrosion data are available, there would be considerable risk involved in selecting a nickel-base alloy for an FFTF application. Also, introduction of a large nickel alloy surface area would probably affect the nickel solubility relationship, alter the corrosiveness of the sodium to something different from an all stainless steel system, and could perturb the experiments in open loop positions.

Cobalt-base alloys such as Stellite 6B appear to be more corrosion resistant (NaK and K) than the austenitic stainless steels, this conclusion could be extrapolated to sodium systems as well.

VII. PHYSICAL AND MECHANICAL PROPERTIES

The comparative short-term mechanical properties of five alloys are shown in Figures 2 through 4. The ultimate and yield strength of the Inconel 600 is greater than the other alloys to about 1300 °F, after which 316 and 304 are stronger. From the standpoint of total elongation determined from the tensile tests, all materials show ductility figures better than 35% at all temperatures. Figures 5 and 6 show the low strain rate behavior (creep and stress-to-rupture) of the five materials. Incoloy 800 possesses the best creep and stress rupture characteristics of these materials for application to 1200 °F and above. At temperatures near 1500 °F, Inconel 600 has better creep and

FIGURE 2. *Yield Strength as a Function of Temperature for Five Alloys*

FIGURE 3. *Ultimate Tensile Strength as a Function of Temperature for Five Alloys*

FIGURE 4. *Total Elongation as a Function of Temperature for Five Alloys*

FIGURE 5. *Average Creep Strength of Five Alloys at 1200 °F*

FIGURE 6. *Stress-Rupture Strength of Five Alloys at 1200 °F*

stress-to-rupture properties than the other alloys (see Tables IX and X). Table XI shows that Inconel 600 and Incoloy 800 also possess superior high temperature impact strengths.

TABLE IX. *Stress to Produce 1% Creep in 10⁵ hr*

Temp, °F	Type 304	Type 316	Incoloy 800	Inconel 600 Solution Annealed	Nickel 200 (201)
900	30 (a)	--	--	--	4.3
1000	10.5	14.6 (a)	42	--	2.5
1100	7.8	9.6	28	--	2.1
1200	4.4	6.5	12	--	1.2
1300	3.9	4.2	5.5	4	0.5
1400	1.6	1.4	3.4	3.5	--
1500	1.3	0.8	2.2	2.8	--

(a) Minimum values

TABLE X. Stress to Cause Rupture in 10^5 hr

Temp, °F	Type 304	Type 316	Incoloy 800	Inconel 600	Nickel 200 (201)
900	30 ^(a)	-	-	-	-
1000	26	-	36	-	8.7
1100	13	20.5 ^(a)	20	-	6.7
1200	5.9	7	13	-	3.7
1300	3.5	8	6.9	5	-
1400	2.8	4	4	-	-
1500	1.6	1.1	2.5	2.8	-

(a) Minimum values

TABLE XI. Charpy Impact Strength, ft-lb

Temp, °F	Type 304	Type 316	Incoloy 800	Inconel 600	Nickel 200 (201)
RT	71	-	207	180	228
800	100	-	-	187	-
1000	90	-	-	160	-
1200	82	-	181	160	-
1400	-	-	176	154	-

The ASME Code design stress values are good indications of the reliability of materials for structural applications involving the requirement for high temperature strength. Table XII shows that both 304 and 316 SS are stronger than Incoloy 800 at temperatures below 1100 °F, but at 1200 °F and above Incoloy 800 is the strongest material. 316 SS has slightly higher allowable stresses than 304 SS at temperatures up to 1350 °F (or as low as 1250 °F depending on criteria used)⁽¹⁵⁾ but above that temperature, 304 SS is the stronger material.

Recent tests⁽³⁸⁾ measuring the stress-rupture properties of Incoloy 800 in sodium cast some serious doubts on the compatibility of the alloy in liquid sodium service, however. Thin walled tubes filled with sodium were tested statically at 1292 °F. Comparable tests without sodium were made. The results, shown in Figure 7, indicate that sodium has an adverse effect on the stress-rupture properties of Incoloy 800.

Similar experiments run on an alloy close to 316 SS in composition showed no deterioration in properties.

TABLE XII. ASME Code Design Stress, ksi

For Temps. not Exceeding °F	Type 304 SA312	Type 316 SA312	Incoloy 800 Grade 2	Inconel 600 SB-167	Nickel (LC) SB-161
100	20	20	15.6	20	8
200	20	20	13.4	19.3	7.7
300	19.8	20	12.1	18.8	7.5
400	17.6	19.4	11.1	18.5	7.5
500	16.4	18.2	10.4	18.5	7.5
600	15.6	17.1	10	18.5	7.5
700	15.1	16.2	9.6	18.5	7.4
800	14.8 ^(a)	15.6 ^(a)	9.3	18.5	7.2
900	10	10.3	9.1	16	4.5
1000	9.45	9.8	8.9	7	3
1100	8.25	9.45	8.8	3	2
1200	5.5	6.95	7.1	2	1.2
1300	3.4	4.0	4.15	-	-
1400	2.05	2	2.5	-	-
1500	1.25	1.15	1.5	-	-
Remarks			ASME Case 1325	Seamless, Low carbon cold nickel, seam- drawn, less pipe or less than tubing less 5 in. OD than 5 in. OD	
	(1965)	(1965)	(1965)	(1963)	(1962)

(a) Values for 100 to 800 from ASME Section III
Values for 900 to 1500 from ASME Section I

The two most important physical properties to be considered are thermal conductivity and mean linear thermal expansion. These data are shown in Tables XIII and XIV. Nickel 200, which is essentially pure nickel, has the highest thermal conductivity; 316 SS and Incoloy 800 show the lowest values. For thermal expansion, Nickel 200 and Inconel 600 are better than the Incoloy 800, and the two austenitic steels have the highest thermal expansion coefficients.

FIGURE 7. Stress-Rupture of Incoloy 800 at 1292 °F
with and Without Sodium

TABLE XIII. Thermal Conductivity Btu/hr-ft °F

Temp, °F	Type 304	Type 316	Incoloy 800	Inconel 600	Nickel 200
200	9.2	8.6	7.4	9.1	3.8
800	12.2	11	10.6	12.1	27.5
1200	14.2	12.6	12.7	14.3	35

TABLE XIV. Mean Linear Thermal Expansion in./in./°F $\times 10^6$

Temp, °F	Type 304	Type 316	Incoloy 800	Inconel 600	Nickel 200
200	9.3	9.3	7.9	7.4	7.4
800	10.05	10.05	9.2	8.1	8.3
1200	10.55	10.55	9.6	8.6	8.7

VIII. THERMAL STABILITY

The effects of thermal or microstructural instability in any alloy system can be observed with a microscope or can be detected by mechanical tests.

Carbide instability in the four austenitic stainless steels occurs in the temperature range of 800 to 1600 °F.⁽²⁾ Carbides form more rapidly in 304 than in the other three varieties due to the greater mobility of carbon in the simpler 18/8 composition. However, after a few thousand hours at elevated temperatures, the amount of carbides in each of the four alloys would be comparable.

Sigma phase can precipitate from ferrite or austenite in the temperature range of 1000 to 1700 °F.⁽²⁾ The ferrite-forming elements (titanium, niobium, molybdenum, etc.) enhance the sigma formation. Sigma phase formation is further enhanced by plastic deformation, small grain size, and possibly neutron irradiation.

Sigma phase in austenitic stainless steels is detrimental to ductility and stress-rupture properties. Of the four austenitic stainless steels, Type 304 (the simpler alloy) is the most stable of the group and the most resistant to sigma phase formation.

Precipitated phases found in the microstructure of Incoloy 800 are titanium nitrides, titanium carbides, and other metal carbides.⁽¹⁶⁾ Sensitization occurs in the 1000 to 1400 °F range. In addition to these phases, a gamma prime-type precipitate may be formed upon long exposure time to temperatures in the range of about 1000 to 1350 °F. This phase increases the strength and decreases the elongation. Sigma phase also forms in the range 1200 to 1600 °F.

Inconel 600 behaves similar to Incoloy 800 in that titanium nitrides and carbides and chromium carbides precipitate in the range of 1000 to 1800 °F.⁽¹⁷⁾

Microstructural stability is important, to the extent that instability products have an effect on mechanical properties. Since the austenitic stainless steels, Incoloy 800, and Inconel 600 have similar instability problems, we would expect their mechanical properties to be affected similarly.

IX. IRRADIATION EFFECTS

Due to the complexities and uncertainties involved in interpreting radiation effects and the associated quantitative changes in the mechanical properties of materials, it becomes necessary to merely look for the point at which catastrophic changes take place.

In a recent evaluation of the radiation effects on 304 and 316 SS⁽²⁾ little or no difference in behavior was noted between the two alloys. Willard,⁽¹⁸⁾ in an independent analysis, stated that there appeared to be no clear-cut difference between 304 and 316 SS.

In analyzing short-term tensile data on Type 304, one can use several approaches, but the one that provides the most data and indicates the quantitative trends is as follows:

- 1) Take data for all levels of irradiation exposure from $\sim 10^{18}$ to $\sim 2 \times 10^{22}$ fnvt.
- 2) Plot properties as a function of temperature only when the property was determined at a temperature equal to or exceeding the irradiation temperature.
- 3) Draw a continuous curve through the minimum point for each temperature.
- 4) The curve is then considered the effect of irradiation as a function of temperature for neutron exposures to 2×10^{22} fnvt.

The results of this type of irradiation effects study on short-term tensile properties indicate that: (a) yield and ultimate strengths are greater than those for unirradiated material until about 1000 °F after which they are about equal to the unirradiated values; (b) ductility (total elongation at failure) drops to about 3% over the range of temperatures from about 600 to 1500 °F. Recent studies by Comprelli, et al.⁽¹⁹⁾ show that elongations for 304 and 316 irradiated in EBR-II are in good agreement with the 3% figure quoted.

Generally, irradiation has little effect on creep rates, but does lower the time-to-rupture at a given stress level and the creep ductility.⁽²¹⁾

Incoloy 800 was initially selected for application in superheat reactors by GE and has just recently seen experience in sodium cooled fast reactor experiments. These first experiments were for temperatures of about 1000 °F and exposures to approximately 3×10^{21} .⁽²¹⁻²⁴⁾ These experiments showed short-term tensile behavior similar to what was observed for the 300 series stainless steels. However, recent GE-NMPO data show

promising postirradiation creep rupture behavior from the standpoint of strain at rupture (40%).⁽²⁵⁾ Comprelli⁽¹⁹⁾ reports a similar observation on short-term tensile tests on Incoloy 800 irradiated to 2.5×10^{22} fntv in EBR-II.

The majority of the irradiation work on Inconel 600 was performed by GEAP and BNW.^(21,22,23,26) These studies have been limited primarily to short-term tensile tests with little or no information available on low strain rate behavior, e.g., creep, stress-rupture. The primary concern with Inconel 600 is the ductility which approaches zero at the higher test temperatures (~ 1200 °F). Experimental preirradiation heat treatments can improve the postirradiation ductility, but the resultant loss is still five-fold.⁽²⁷⁾

"Pure" nickel behaves in a manner similar to that of Inconel 600 in that strength does not seem to be appreciably affected by irradiation, but ductility losses are high at 1200 °F.⁽²⁸⁾ These losses become greater with increasing exposure. Again, there are little or no low strain rate data on pure nickel.

Very little irradiation data on high exposures are available for Inconel X-750 and Inconel 718. Their behavior does, however, appear to follow that of the Inconel 600.

X. FABRICABILITY

All seven materials considered here (Types 304, 316, 321, and 347 SS, Incoloy 800, Inconel 600, and Nickel 200) are fabricable by all common processes such as forging, rolling, extruding, piercing, drawing, etc. All are available in a wide range of products, shapes, and sizes. Although all are considered to have relatively good fabricability, some differences do exist between the alloys in the group.

Type 304 SS exhibits the best overall fabricability of the alloys listed. With reasonable care, good quality products from 304 can be manufactured with relatively low scrap losses and low reject rates. Uniformity in quality, corrosion resistance, surface conditions, and weldability are expected and delivered commonly throughout industry with this material.

Type 316 SS has also enjoyed extensive use in industry, although its over-all use is only about 1/3 to 1/6 that of Type 304.⁽²⁹⁾ Good quality products are also available in the Type 316, but at a cost of 30 to 70% greater than for the equivalent product in Type 304 (see section on costs). These costs reflect predominately the difference in fabricability of the two materials with higher scrap losses and higher reject rates for the less fabricable 316. The main fabrication problem with 316 is its susceptibility to hot shortness or cracking during hot working. Special care is exercised not only in the hot working but also in the melting and adjustment of chemical composition in order to obtain a material which is hot workable. Some mills add small amounts of proprietary alloys to improve the hot working characteristics. Industry experience has shown that complaints of surface defects, variations in composition, grain size, corrosion resistance, and weldability are more common in Type 316 than in Type 304.⁽³⁰⁾ More detailed fabrication analyses of Types 304 and 316 have been presented in References 2 and 30.

Type 347 is another alloy which is subject to hot shortness and is difficult to form in heavy sections and to keep from cracking. Close compositional control and heat treatment are necessary for successful fabrication of Type 347.

The general fabrication of Type 321 is very similar to Type 304, and the fabricability is also very good with the exception that the Type 321 is more likely to be troubled with inclusions and surface defects arising from titanium carbonitride stringers.

Incoloy 800 shows good fabricability and would rank somewhere between Type 304 and Type 316 in this respect. Lubrication requirements in the extrusion and drawing of Incoloy 800 are more stringent than for Type 304. Incoloy 800 requires high hot-working temperatures and will not tolerate forging temperatures of less than 1850 °F for heavy working or 1600 °F for light working. No working should be done between 1200 and 1600 °F. Some users of this alloy have advocated the reduction or elimination of aluminum and titanium from the composition in order to obtain a higher ductility. The resulting alloy, however, suffers from hot shortness in fabrication, and lower long-term creep rupture strength.⁽³¹⁾ The titanium sometimes causes trouble with surface defects as in Type 321.⁽²⁹⁾ Experience in the fabrication of Incoloy 800 is not as widespread as fabrication experience in the 300 series stainless steels.

The fabricability of Inconel 600 is very similar to that of Incoloy 800, except that the Inconel 600 is more difficult to work, is more susceptible to hot shortness, and has a more restricted working temperature range.⁽²⁹⁾

Nickel 200 exhibits good fabricability and does not work-harden as fast as Inconel 600. Therefore, it is more economical to fabricate than the Inconel 600. This comparison is important when considering the economics of a choice of reflector materials for the FTR, where high nickel alloys such as Inconel 600 or "pure" nickel (Nickel 200) are under consideration. The base material cost of Nickel 200 is greater than the material cost of Inconel 600 due to the higher nickel content, but because of the ease of fabricating Nickel 200, the cost of Inconel 600 products soon exceeds the cost of the same products in Nickel 200 if much fabrication effort is involved in manufacture. Nickel 200 has a temperature working range that extends from below room temperature up to 2300 °F. Unlike Incoloy 800 or Inconel 600, Nickel 200

shows good workability in the temperature range of 1200 to 1600 °F, which means that it is not as subject to cracking during forging operations as Incoloy 800 and Inconel 600 if the surface temperature falls below 1600 °F.

XI. WELDABILITY

Nearly every metal component used in the FTR will be welded at some point during its fabrication or assembly. The cost of fabrication, the delivery of components on schedule, and, most importantly, the reliability of these components can be greatly influenced by the weldability of the materials used in their construction. The seven materials under consideration are all considered to have relatively good weldability, but some important differences exist.

Type 304 SS exhibits the best over-all weldability of the materials discussed. All common welding processes can be used successfully on Type 304. The material is exceptionally free from weld cracking tendencies and sensitivity to variations in welding procedure. With reasonable care, most weldors can weld Type 304 SS with no rejects.

Type 316, however, exhibits a definite tendency to hot shortness and weld cracking, especially in the welding of sections thicker than about 3/8 in. although, such cracking has also been reported in much thinner sections.⁽³²⁾ One reason for this cracking tendency is that in order to hot work Type 316 without cracking, the composition must be adjusted so that no ferrite is present in the structure. This is the opposite direction in composition to that which gives material that is easily welded. To eliminate weld cracking in 316 it is important to have a certain minimum amount of ferrite present in the weld, usually at least 3%. When the base material has been adjusted to give no ferrite in the structure, it is often difficult to get the required amount of ferrite into the weld even when using special filler wires.^(33,34)

Whereas autogenous welds (those without filler wire) are possible and often desirable in Type 304, Type 316 generally must be welded with filler wire or be welded to another alloy such as Type 308 to avoid cracking.^(33,34) Type 316 is also sensitive to variations in welding procedure. Variations in arc length, heat input, speed of travel during welding, and electrode diameter, which would not affect the quality of the weld in Type 304, can have a great effect on the quality of the weld in Type 316.

In hot ductility tests developed by Soldan and Schnabel⁽³⁵⁾ to screen austenitic steels for weldability, Type 304 proved to be completely crack insensitive, followed in order of increasing crack tendencies by a 16Cr-8Ni-2Mo alloy, Type 316, and Type 347. Type 321 appeared to have relatively good crack resistance, but an insufficient number of samples were run to be included in the ranking of alloys. In about 11 years of running these tests, Schnabel⁽³⁶⁾ has observed increasing crack sensitivity in Type 316, while Type 304 has maintained its high ductility and has improved in strength. In hundreds of tests on Type 304, Schnabel found only two samples that failed to show maximum hot ductility performance, and subsequent chemical analysis showed these samples to have an excessively high sulfur content.

Brown⁽³²⁾ has reported cracking in the weld heat affected zone in thin sections (0.040 in. thick) of Type 316. The cracking occurs regardless of welding procedure or filler metal alloy used. Brown found that the cracking was dependent on the composition of the parent metal, and good weldability in Type 316 could be demonstrated only if all three of the following criteria were met:

- 1) Hot ductility at 1550 °F should be 45% elongation minimum.
- 2) Heats should contain less than 1.5% excess nickel as determined by the Newell and Fleischmann formula (a formula

used to establish the minimum amount of nickel necessary to insure a completely austenitic structure).

- 3) Chemical balance should be in favor of ferrite as determined by Schaeffler formula.

Due to the complexity of incorporating all these factors into a purchasing requirement, Brown also studied the effect of carbon on the weldability of Type 316 and found that by holding the molybdenum to the high side of the range (2.5 to 3.0%) and fixing the carbon at 0.03% maximum (which falls in the Type 316L composition range) good weldability could generally be achieved.

Type 321 offers very good weldability and is almost as predictable in behavior as Type 304. However with some types of welding, such as metal-arc welding, titanium losses can be severe and Type 347 electrodes are often used in place of Type 321. Type 321 filler wire can be used in tungsten-inert-gas welding. Type 321 base metals can vary widely in cleanliness and sometimes relatively large quantities of titanium carbonitrides appear in the weld zone to give problems in welding.

Type 347 offers even more sensitivity to cracking than Type 316, especially in heavy sections. Composition control and homogeneity in the parent metal are very important in achieving good weldability in Type 347. For an exceptionally complete description of welding problems in Type 347 and their solutions, the reader is directed to Reference 37.

Incoloy 800 offers weldability approaching that of Type 304,⁽³¹⁾ and is weldable by all known processes. The maximum thickness of Incoloy 800 that can be welded without the use of a filler metal is about 0.10 in., but a crater may be left at arc-stoppage, which may cause some crater-cracking. The use of a filler metal at the end of the weld to eliminate this problem is recommended. Generally, a high nickel content filler

wire or electrode close to the composition of Inconel 600 is used to weld Incoloy 800 because electrodes closer in composition to the Incoloy 800 have produced welds subject to excessive sigma phase formation (a very brittle phase). Work aimed at developing a welding electrode that is closer in composition to Incoloy 800 and that will not have this problem is expected to be complete sometime in 1968.⁽³¹⁾

Inconel 600 also has good weldability and is almost as easily welded as Incoloy 800. Welding procedures for both materials are similar, and both materials are welded with the same electrodes or filler wires. Inconel 600 can also be welded by all major welding processes.

Nickel 200 is slightly more difficult to weld than either Incoloy 800 or Inconel 600, and cannot be welded by the submerged-arc process. Welds in Nickel 200 and all high nickel alloys are very susceptible to sulfur or lead embrittlement, and care must be exercised in surface preparation and cleaning and in heat treatment atmospheres to eliminate such contaminants.

XII. COSTS

Within certain boundaries, costs will not play a major role in the selection of materials for the FTR, since the primary consideration will be performance. Where two materials may perform a function equally well, however, the more economical material should be chosen. A comparison of costs also lends an insight to differences in fabricability.

In order to obtain a comparison of costs typical of the materials under consideration, lists of prices for four product forms, based upon 1 ton lots of each, were obtained from several suppliers. Table XV shows these cost comparisons.

TABLE XV. Materials Cost Comparisons

<u>Material</u>	<u>Small Tube^(a)</u>	<u>Large Tube^(b)</u>	<u>Rod^(c)</u>	<u>Plate^(d)</u>
304 SS	\$0.43/ft	\$18.63/ft	\$0.70/lb	\$0.56/lb
316 SS	0.71/ft	30.19/ft	0.91/lb	0.77/lb
321 SS	0.51/ft	21.76/ft	0.81/lb	0.75/lb
347 SS	0.58/ft	24.46/ft	0.92/lb	0.85/lb
Incoloy 800	0.46/ft	27.68/ft	1.45/lb	1.14/lb
Inconel 600	0.48/ft	33.33/ft	1.83/lb	1.62/lb
Nickel 200	0.44/ft	31.44/ft	1.70/lb	1.69/lb

(a) *1/4 in. diameter tube, 0.020 in. wall, cold drawn, random lengths.*

(b) *5 in. diameter tube, 0.258 in. wall, seamless, annealed.*

(c) *1/2 in. diameter rod, cold drawn, random lengths.*

(d) *1 in. thick plate, 5 ft x 3 ft, hot rolled, descaled, annealed.*

Price per foot was used for the tubing products since their application in the FTR is measured by length, whereas the rod and plate is priced per pound since in applications such as the reflector, the total mass involved is the measurement of interest.

The difference in cost between Types 304 and 316 is a measure of the difference in fabricability of the two materials. A comparatively small portion of the cost differential is due to the cost of the molybdenum in the alloy. For example, a tubular product in Type 304 sells for \$1.28/lb. If the most expensive grade of molybdenum additions are assumed, and if a 25% loss in melting is allowed (which is overly conservative), the Type 316 would sell for \$1.33/lb based on the increased materials cost alone. Actually, the same product in Type 316 sells for \$2.12/lb, which reflects the higher scrap losses and reject rate that occurs in 316 due to its relatively poorer fabricability.

DISCUSSION

The point was made in the section on corrosion that it is impossible at this time to determine a temperature at which the corrosion of a nickel-base alloy would be the same as the corrosion of Type 304 or 316 SS in flowing 1200 °F sodium. Until these data become available there is a certain risk involved in using an unclad high nickel content alloy of any type at the required temperatures of 800 to 1200 °F. In addition to poorer corrosion behavior, the nickel base alloys also undergo a severe loss of ductility upon irradiation.

The satisfactory corrosion performance of 304 or the other austenitic stainless steels at the temperatures of 800 to 1200 °F is reasonably assured. Incoloy 800 may also be satisfactory, but this point remains to be proven as little data now exist.

Duplex structures (e.g. clad components) with a high nickel alloy core and a stainless steel cladding would offer the advantages of an improved Doppler coefficient and adequate corrosion resistance. The cladding of nickel rods or plates for use in the reflector, for example, would be a straightforward operation with no special development required. However, for more complex components such as fuel ducts, the complexity of the fabrication and the stringency of the requirements placed on the components are several orders of magnitude greater than for the reflector. While development of clad fuel ducts would be possible, their use, at least in the first core of the FTR, is judged impractical for the following reasons:

- 1) The use of clad fuel ducts would require at least a three-fold increase in fabrication development effort.
- 2) Finding or developing qualified vendors would be difficult and expensive.
- 3) There are many more problems inherent to the use of clad components, such as possibilities of unbonding, difficulties

in welding, differences in thermal expansions, more difficult and elaborate nondestructive testing, etc.

- 4) Much more testing would be required, preferably including some irradiation testing to insure that the clad components would perform adequately in the FTR.
- 5) Delivery of clad components to the present schedule required for the first loading would be very difficult if not impossible. Cost would also be greatly increased.

The Doppler coefficient can be affected by the materials comprising the fuel ducts, control rods and guide tubes, open and closed loop ducts, and reflector subassemblies. The fuel cladding and fuel pin reflector, which also affect the Doppler coefficient, have been specified as 316 SS and nickel, respectively. Because it is not practical to fabricate most components from a high nickel base alloy clad with another material, core components such as fuel, ducts, open and closed loop ducts, and guide tubes must be constructed of a material that is easily fabricable and is compatible with high temperature flowing sodium.

The reflector subassemblies (rods) will contain small rods or slabs of a material giving the best Doppler coefficient for the core. Physics calculations have shown that of the practical materials under consideration, a high nickel material is necessary for best Doppler coefficient, flux, and neutron economy. For the first 6 in. (approximately) of reflector adjacent to the core, the Nickel 200 (100% Ni) is judged to be slightly better than Inconel 600 (72% Ni) from a physics point of view. Nickel 200 was chosen as the best material of the two for the following reasons:

- 1) Nickel 200 will probably be less expensive in the as-fabricated condition due to its better fabricability, even though base material cost is higher.
- 2) Nickel 200 offers better corrosion resistance to liquid sodium than Inconel 600. Although cladding will be required

on either alloy (based on present limited data), the consequences of cladding discontinuities would be less serious for the material with better corrosion resistance.

- 3) What little physics difference does exist between Inconel 600 and Nickel 200 is on the side of the Nickel 200. In the interests of economy, any reflector material outside the first 6 to 8 in. of reflector could be 304 SS, with negligible effect on the physics variables.

Since they have little or no effect on the Doppler coefficient the remainder of the core structural materials (grid plates, flow guide, etc.), should remain as they were originally selected (Type 304 SS) until detailed stress analysis indicates need for a stronger material.

For the first core there appears to be no evidence that would indicate that 304 should not be adequate for the flow ducts, loops, control rods, and flow guides. However, substitution of Incoloy 800 for these components would enhance the Doppler coefficient.

CONCLUSIONS

The following conclusions are based on the best information and data available to date on a number of materials.

- 1) High nickel alloys (>40% Ni) should not be used in the FTR core in the unclad condition.
- 2) Nickel 200 should be used in the reflector assemblies, but the rods or slabs should be clad in 304 SS.
- 3) The remainder of the core structural components should be constructed of 304 SS as originally planned. This decision is based on (a) stability, (b) irradiation performance, (c) fabricability, (d) weldability, and (e) cost.
- 4) Incoloy 800 could replace the 304 SS structurals providing experimental efforts indicate that the increased amounts of radioactive material in the sodium are acceptable and that further characterization of its fabricability and irradiation behavior are obtained.

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