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RADIATION HEAT TRANSFER IN THE FUEL OF NUCLEAR ROCKET

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ABSTRACT

Nuclear power propulsion for space applications is essential for long term high payload missions. Several nuclear reactor types were investigated between the late 1950's and early 1970's under the National Aeronautical and Space Administration's (NASA) Nuclear Engine for Rocket Vehicle Application (NERVA). The NERVA reactors developed had various geometrical configurations using the same common materials and propellant, namely graphite moderated fuel elements impregnated with uranium carbide (UC) fuel particles surround by a beryllium reflector with hydrogen as the propellant. The hot hydrogen propellant flowing through the graphite core led to substantial corrosion problems and several efforts were made to protect the graphite from corrosion by the hot hydrogen propellant. Although several coating types and methods were employed only partial success was achieved. The effects of corrosion can lead to changes in heat transfer characteristics, flow changes, and reactivity degradation. This study, supported by NASA, focuses on the effects of hydrogen induced corrosion on the emissivity of the graphite fueled core. The reference data is primarily taken from the NERVA reactor identified as the Pewee Nuclear Rocket. An overview of the postmortem results of corrosion on the fuel of Pewee is described. The effects of corrosion from hydrogen exposure on graphite and the coatings used to protect the fuel elements are given. A model to calculate the effective emissivity coefficient inside a coolant channel due to varying stages of corrosion is developed. Lastly, the implementation of the effective emissivity coefficient into the radiative heat transfer equation with a brief discussion on surface area effects is provided.

INTRODUCTION

Nuclear power propulsion for space applications is essential for long term high payload missions. Nuclear rockets are able to provide increased thrust over traditional oxygen-hydrogen propelled chemical rockets since nuclear rockets use a lighter molecular weight gas such as hydrogen [1].

NASA explored the use of these hydrogen propelled nuclear rockets with extensive research and testing during the NERVA program [2]. In order to get the necessary impulse to carry nuclear rockets through space the reactors have to be lightweight with high power density cores leading to high propellant exit temperatures. These design requirements lead to the development of the lightweight graphite-uranial cores as the platform reactor for NERVA. The basic concept was very simple. It consists of a graphite-uranial core as a heat source, high temperature hydrogen as a propellant, a nozzle through which the hydrogen gas expands, and a turbo pump to force the hydrogen through the system [3]. A typical representation of a NERVA is given in Figure 1.

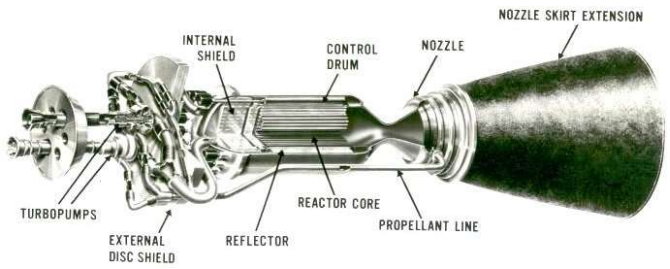


FIGURE 1: TYPICAL NERVA ROCKET DESIGN [4].

One of the major challenges for the graphite reactor design is the effect of corrosion on the graphite core by hot hydrogen gas [5 - 8]. Corrosion of the core causes several

problems thermally, structurally, and neutronically. Thermally, due to enhanced heat transfer from corroded surfaces (changing emissivity, convection, conduction length, and surface area), but also detrimentally from widened coolant passages that don't allow the necessary propellant temperatures for thrust; structurally from corroded web structures and turbulent flow induced vibrations that can lead to cracks, fractures, and displacement of broken fuel elements; neutronic changes are induced by mass loss of graphite moderator and mass loss of uranium particles ultimately leading to a decrease in the required excess reactivity to reach needed power density levels.

An illustration of a typical NERVA graphite reactor core design is given in Figure 2**.** The NERVA reactor designs used either a pyrolytic-carbon-coated particle matrix or a composite matrix. The graphite substrate is coated with hydrogen corrosion resistant materials such as niobium-carbide (NbC) or zirconium-carbide (ZrC).

The reference NERVA nuclear rocket [3, 5] core, Pewee, contained 402 fuel elements from a number of fuel fabricators. There were 267 fuel elements fabricated by Las Alamos Scientific Laboratory (LASL), 11 fabricated by the Y-12 National Security Complex, and 124 fabricated by the Westinghouse Astronuclear Laboratory (WANL). The length of each 19-hole fuel element is 52 in. (1.321 m) with a flat-to-flat dimension of ~ 0.75 in. (19 mm). The nominal diameter of each coolant channel is 0.100 in. (2.54 mm) with a web thickness between coolant channels of ~ 0.030 in. (76 mm). The web thickness between coolant channels and the fuel element wall is slightly smaller than 0.030 in. (76 mm). The fuel in 93% enriched uranium-235 with a standard ratio of 525 g/cc uranium to graphite substrate. The density of the standard 525 g/cc fuel element is 2.38 g/cc [6].

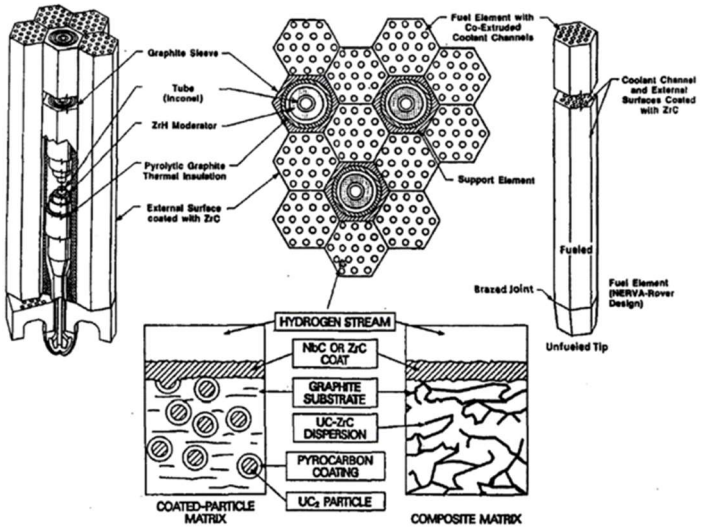


FIGURE 2: TYPICALNERVA REACTOR CORE DESIGN [9].

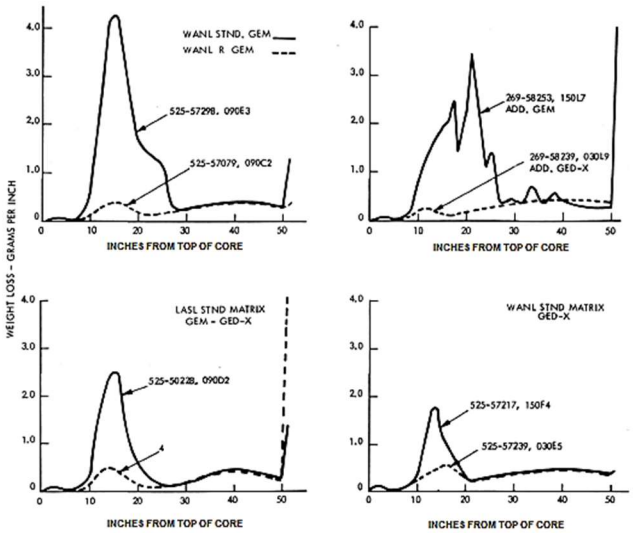
Under this reactor design several attempts to control corrosion were made, but with only partial success [2]. Corrosion of graphite by hydrogen is highly temperature dependent. No detectable reaction occurs at temperatures up to about 620 K. As the temperature increases, the rate of reaction increases rapidly, according to the Arrhenius expression [10]:

$$\ln(K) \propto E/RT \quad (1)$$

Corrosion of graphite is accomplished from the reaction of hydrogen and carbon leading to the creation of methane (CH_4) or acetylene (C_2H_2) [8]. To protect the elements from corrosion either NbC or ZrC is applied [11]. In addition a molybdenum overcoat can be applied [12]. For the Pewee rocket, coatings were applied through chemical vapor deposition (CVD). This process was only partially successful because the differing coefficients of thermal expansion (CTE) between the graphite matrix and the NbC/ZrC lead to microcracks where hydrogen could interact with the graphite. The CTE for NbC and ZrC are 6.6 and 7.7 μm/m K respectively [8]. For the graphite in the Pewee core (type GL 1008) CTE is around 3.3 μm/m K [13]. Pewee contained both NbC and ZrC coated elements as well as some overcoated with molybdenum.

To minimize coating cracks from differing CTE the CVD process took place at elevated temperatures. Although this helped during reactor heat up, cracks developed during reactor cool down and perpetuated through the cycling process.

During the Pewee test the fuel elements in general performed well except for higher-than-expected corrosion at the core periphery and unexpectedly high mid-band losses in most elements. Specifically the following observations [5] were made during disassembly and postmortem examination. See Figures 3 and 4 for illustrations of the postmortem examination.



WANL: Fabricated by Westinghouse Astronuclear Laboraty
LASL: Fabricated by Los Alamos Scientific Laboratory
GED - X: G end diffusion coating of bores and O.D. surfaces with NbC followed by bore over-coating with Molydenum
GEM: G end, low temperature, methane assited coated of bores and O.D. surfaces with NbC
STND: Normal four, thermax, and varcum matrix
R: Standard matrix impregnated with niobium resinate
ADD: Standard matrix with 2.5 volume percent NbC powder additive
Numbers on the various corrosion profiles are the serial numbers for the elements in specific locations.

FIGURE 3: INCREMENTAL MASS LOSSES OF SOME WANL AND LASL PEWEE FUEL ELEMENTS [6]

- The average fuel element mass loss was 20 g (3%), with a range from 8 to 53 g (1%-8%).

- Mass loss per unit length (MULE) showed unexpectedly high mid-band losses from 10 to 20 in. from the entrance of hydrogen into the coolant channels.
- Many elements at the core periphery and in the outer two or three rows of the core were severely corroded externally.
- Of the 402 elements, 46 were too broken or badly corroded to be weighed during disassembly.

As was previously stated, corrosion affects heat transfer, neutronics, structural integrity, etc. The following is a discussion on how corrosion affects emissivity.

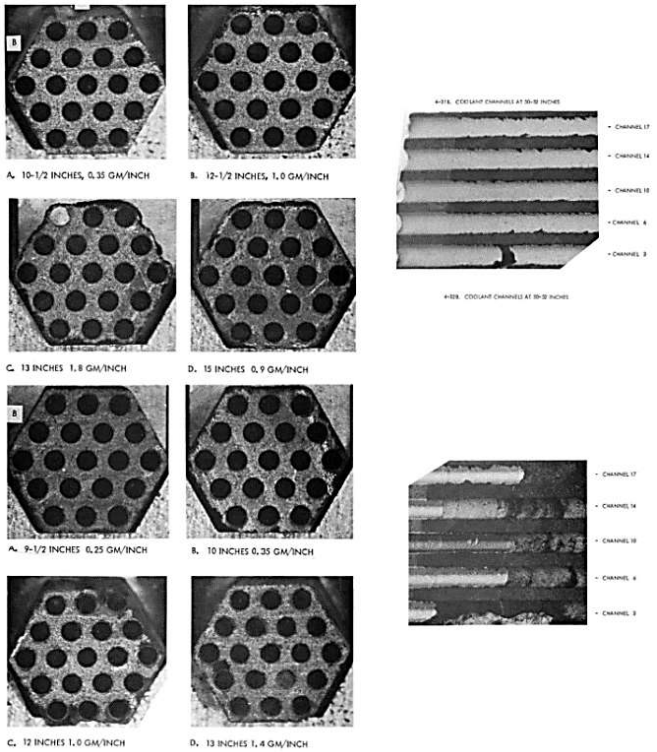


FIGURE 4: FUEL ELEMENT CORROSION ALONG THE AXIAL LENGTH OF CHANNELS AND FACES [6]

Emissivity

Emissivity is a surface phenomenon that results from surface roughness, surface temperature, porosity, and chemical makeup. Corrosion can affect all of these parameters. The corrosion in the Pewee test was quantified by measuring the mass loss. Corrosion's effect on mass loss is important in nuclear design as isotopic masses are used to inform neutronic effects, such as critical loadings, reactivity hold down, and excess reactivity. Mass loss is also important as the structural integrity of the nuclear rocket is jeopardized. What seems to be at the bottom of the list in importance is corrosion's effect on emissivity.

The measurement of emissivity before and after the nuclear rocket tests appears to be non-existent in the literature. This is unfortunate since emissivity plays a key role in radiative heat transfer at high temperatures and corrosion is also highly temperature-dependent on corrosion. To compound a lack in emissivity data for each specific material used in these nuclear reactor designs, the corrosion taking place in Pewee involves multiple material face exposure to hydrogen gas. The tests were at relatively high temperatures to conventional gas reactors. It is difficult to quantify surface effects to existing data since corrosion often involves severe roughing and pitting of the surface, not just mild abrasion. It is difficult to tie emissivity to mass loss since a percentage of mass loss in one geometrical configuration could yield the same emissivity as a different geometrical configuration with a different mass loss. First, an explanation of emissivity is given, then an effort to piece together existing data for model development is provided.

The general radiative property for emission from an opaque surface is its spectral directional emissivity, defined as

$$\boldsymbol{\varepsilon'_{\lambda}(T,\lambda,\hat{s}_0)} = \frac{\mathbf{I_{\lambda}(T,\lambda,\hat{s}_0)\cos\theta_0 d\Omega_0}}{\mathbf{I_{b\lambda}(T,\lambda)\cos\theta_0 d\Omega_0}} = \frac{\mathbf{I_{\lambda}(T,\lambda,\hat{s}_0)}}{\mathbf{I_{b\lambda}(T,\lambda)}} \quad (2)$$

The spectral directional emissivity compares the actual spectral directional emissive power with that of a black surface ($\boldsymbol{\varepsilon_b = 1}$) at the same conditions [14]. Simply put, $\boldsymbol{\varepsilon}$ (emissivity) is the ratio of power that is emitted relative to what would be emitted by a perfect (black) surface. The prime on emissivity distinguishes the directional emissivity from the hemispherical emissivity and the subscript $\boldsymbol{\lambda}$ (wavelength) to distinguish spectral emissivity from total emissivity. $\mathbf{I}$ denotes the intensity, $\mathbf{T}$ temperature, $\hat{\mathbf{s}}_0$ to emphasize that, for emission, only directions away (outgoing) from a surface are considered. The last part of equation 2 ($\boldsymbol{\cos\theta_0 d\Omega_0}$) is the polar and solid angles formed from the surface $\mathbf{dA}$ (see Figure 5).

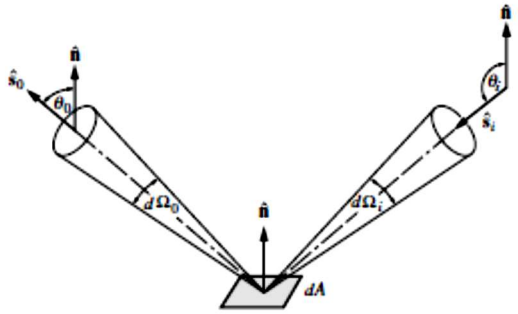


FIGURE 5: POLAR AND SOLID ANGLES FROM AN AREA dA [14]

From (2) it can be shown that the total directional emissivity is

$$\boldsymbol{\varepsilon'(T,\hat{s})} = \frac{\mathbf{I(T,\hat{s})}}{\mathbf{I_b(T)}}, \quad (3)$$

where the spectral hemispherical emissivity is

$$\varepsilon_{\lambda}(T,\lambda) = \frac{I_{\lambda}(T,\lambda)}{I_{b\lambda}(T,\lambda)}, \quad (4)$$

and the total hemispherical emissivity is

$$\varepsilon(T) = \frac{I(T)}{I_{b}(T)'} \quad (5)$$

For the purposes of this report only the total hemispherical emittance is considered. Total hemispherical emittance can be applied for these fuel surfaces since the Pewee fuel has surfaces that are gray and diffuse, fuel temperatures are relatively high, and since most of the power comes from the infrared spectrum [14].

RESULTS AND DISCUSSION

Levels of Corrosion and Effects

The level of corrosion for Pewee postmortem examination is described qualitatively by [5] as fuel elements with (a) no damage, (b) moderate corrosion, or (c) heavy corrosion. Fuel elements with no damage are described as slight flaking of the NbC/ZrC coating. Moderate corrosion is described as corrosion between flaking of the coating and up to, but not penetrating, the next bore(s). Heavy corrosion is described as corrosion significant enough to penetrate from one fuel channel bore to the next fuel channel bore(s). Described quantitatively in [5] is the gross mass loss per fuel element in units of MULE which for Pewee ranged between 8 – 53g (1% - 8% mass loss), the average being 20 g (3%).

In order to correlate the Pewee fuel element mass loss effects (or corrosion effects) on emissivity additional data is provided here for comparison. Mass loss and temperature effects on emissivity for several types of nuclear grade graphite are given in Table 1 [7]. As can be seen, an increase in mass loss from corrosion causes emissivity to increase and an increase in temperature causes emissivity to decrease. Since the temperature range in Table 1 is relatively low compared to Pewee operating temperatures, an equation from [10] is used to quantify emissivity dependence of pyrolytic graphite (pyrolytic graphite is most representative of what was used in Pewee) on temperature [$\varepsilon = 0.641 - (5.70 \times 10^{-5})T$ where T is the temperature in K]. This equation is good for a temperature range of 2300 K – 3000 K.

Applying the equation above for emissivity dependence on temperature for pyrolytic graphite to Pewee's operating temperature of 2100 – 2800 K gives emissivity values between 0.57 and 0.45 for a 0% mass loss scenario. Now that emissivity is brought within the proper temperature range the effects of corrosion on emissivity can be quantified. The next step involves taking Table 1 values for emissivity at 500℃ for 0%, 5%, and 10% to create a trendline relating mass loss to emissivity. This trendline is then applied to the emissivities on the 0% mass loss line. Figure 6 shows these results.

To summarize the above steps, an equation from [10] that related emissivity of pyrolytic graphite to temperature is used to get emissivity within Pewee temperature range. Then the trendline generated by comparing mass loss effects in Table 1 are used to extrapolate out what mass loss effects may be in Pewee.

TABLE 1: THERMAL EMISSIVITY OF NUCLEAR GRADE GRAPHITE [7]

wt. loss	Temperature	Thermal emissivity			
	(K)	IG-110	PCEA	IG-430	NBG-18
0%	373	0.681	0.731	0.682	0.737
	473	0.601	0.663	0.626	0.627
	573	0.585	0.645	0.657	0.609
	673	0.582	0.587	0.646	0.538
	773	0.558	0.596	0.647	0.649
5%	373	0.786	0.861	0.815	0.847
	473	0.776	0.797	0.808	0.777
	573	0.771	0.795	0.816	0.729
	673	0.759	0.681	0.818	0.681
	773	0.666	0.691	0.755	0.738
10%	373	0.835	0.866	0.854	0.890
	473	0.783	0.850	0.812	0.834
	573	0.775	0.803	0.819	0.756
	673	0.764	0.718	0.824	0.694
	773	0.675	0.696	0.800	0.738

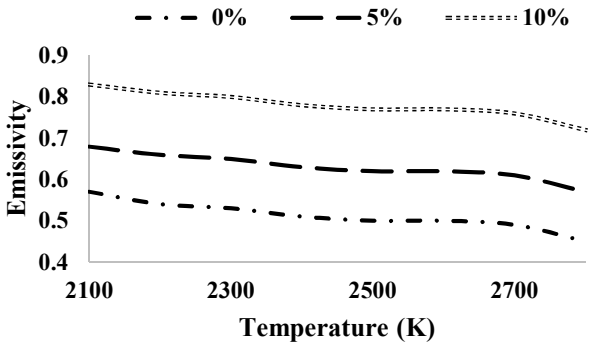


FIGURE 6: EMISSIVITY OF PEWEE EXPOSED GRAPHITE SURFACES UNDER VARYING MASS LOSS. THE 0% LINE IS CREATED FROM THE EQUATION [10].

Now that the corrosion effects on emissivity of graphite is understood, the coating's dependence on corrosion is addressed. Table 2 shows the emissivity results for NbC and ZrC for a polished surface, rough surface, surface after thermal treatment, and surface after hydrogen exposure. The coatings here were applied directly to a graphite surface and then emissivity measurements were taken under various conditions; however, corrosion was not significant enough to expose the graphite substrate. A rough surface in Table 2 indicates one that has been sanded with 240 grit sandpaper and polished surface with 4000 grit sandpaper. Thermal treatment involved

placing the samples in a vacuum over for 1 hour at temperatures in the range shown. Hydrogen exposure involved putting these materials in an oven at 1536 K for 2 hours with hydrogen gas present. ZrC is unaffected by the effects while NbC emissivity decreases with thermal treatment and hydrogen exposure. Surface roughness doesn't show any effect on these two carbides since they are so porous to begin with that roughing the surface has negligible effects [15]. It appears from the results in Table 2 that a roughened surfaced from corrosion will not change the emissivity of the coating; however, elevated temperature and hydrogen exposure does affect the emissivity of NbC. It should be noted that the level or roughness shown in Figure 4 would be much greater than that achieved by 400 grit sandpaper. The corrosion in Pewee isn't just indicated by a rough surface, but by pits, cavities, and extensive surface deterioration.

TABLE 2: EMISSIVITY OF NBC AND ZRC [15]

	NbC	ZrC
Temperature Range (K)	1700-2200	1700-2200
Polished Surface	0.79	0.9
Rough Surface	0.79	0.9
Thermal Treatment	0.72	0.9
Hydrogen Exposure	0.71	0.9

Effects of corrosion, temperature, and hydrogen exposure on graphite and coatings are now understood within the data provided from experiments. Described next is the model developed to understand the total hemispherical emissivity that results on multiple exposed coolant channel material surfaces.

Model Development

The model describes the evolution of corrosion effects on the emissivity of a fuel element (Figure 7). The method used below takes area weighted emissivities of each material exposed to hydrogen propellant.

$$\boldsymbol{\varepsilon = \sum_{i=1}^{n} R_{A_i} \varepsilon_i} \tag{6}$$

where $\mathbf{n}$ is the number of materials and material corrosion states that exist in the coolant channel. In the analyzed case there are 2 materials (graphite and exterior coating) with multiple states of corrosion for each material. (Note: The effect of thermal treatment and hydrogen exposure on coatings will be included in the weighting.) The variable $\mathbf{R_{A_i}}$ is the ratio of a specific material's (graphite or coating) area that is exposed to hydrogen coolant to the total area of all materials exposed to hydrogen coolant.

$$\boldsymbol{R_{A_i} = \frac{A_i}{A_T}} \tag{7}$$

An example (assuming the higher Pewee operating temperature of 2670 K) of using equation 6 is given here for a corroded coolant channel. If the total area of the coolant channel consisted of 10% fresh NbC, 30% hydrogen exposed NbC, 15% uncorroded graphite, and 45% corroded graphite than the final emissivity value would be:

Material	R_{A_i}	ε	$R_{A_i}\varepsilon$
Fresh NbC	10%	0.79	0.1(0.79)
Hydrogen Exposed NbC	30%	0.71	0.3(0.71)
Uncorroded Graphite	15%	0.49	0.15(0.49)
Corroded Graphite	45%	0.76	0.45(0.76)
			$\varepsilon = 0.71$

Two special cases exist where the fuel is in a new state where the emissivity is that of polished NbC ($\boldsymbol{\varepsilon = 0.79}$) or polished ZrC ($\boldsymbol{\varepsilon = 0.9}$), and the case where the coating is completely removed and only corroded graphite remains ($\boldsymbol{\varepsilon = 0.76}$). It can obviously be stated that emissivity is going to range from ~ 0.49 to 0.79 from NbC coated elements and ~ 0.49 to 0.9 for ZrC coated elements. Those that were coated additionally with molybdenum are not considered here.

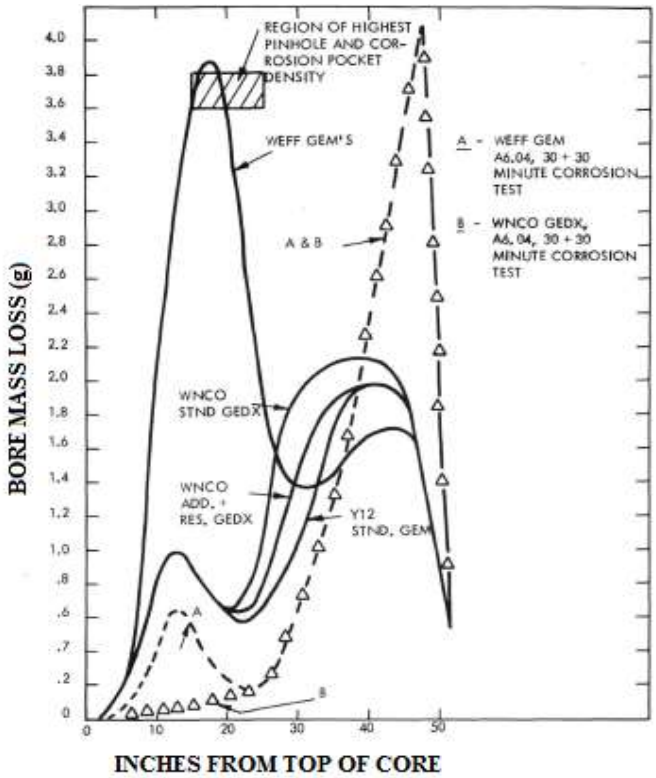


FIGURE 7: BORE MASS LOSS FOR SEVERAL ELEMENT TYPES [6]

To illustrate some emissivities that may occur, let's look back at the top left corner graph in Figure 3. Let's replot that graph in Figure 8 with mass loss and identify the likely materials and their states.

The percentages in Figure 8 are percent of mass per inch. For example the peak mass loss per inch is 33% while overall the mass is loss is around 7.6%. The line with the large dashes

is the interface between the coating and the graphite substrate. The reason the line increases linearly from the top of the reactor to the bottom is because the coating is not applied uniformly. The coating's CVD runs from ~ 0.8 g/in. at the cool end to ~ 3 g/in. at the hot end on average [6]. Anything below this line is still coating and everything above is graphite. If this line is the interface between the graphite and coating then 5% and 10% mass loss above that line would represent 5% and 10% mass loss into the graphite substrate. In other words, since there is more coating mass at the bottom of the fuel element than the top, more mass loss is necessary at the bottom to achieve the same results as the top.

Taking the higher operating temperature of Pewee and assuming that 2% mass loss in the coating is sufficient to achieve hydrogen and thermal exposure then it appears 15% of the exposed surface is fresh coating, 60% of the exposed surface is hydrogen/thermally exposed coating, 6% of the exposed surface is fresh graphite, 4% is graphite will a mass loss between 5% and 10%, and 15% of the surface is graphite at a mass loss rate of 10% or greater. Thus, the effective total hemispherical emissivity would be 0.15(0.79) + 0.60(0.71) + 0.06(0.45) + 0.04(0.57) + 0.15(0.76) = 0.71. That value may be reasonable for that specific case, but there are several others and an infinite case of possible scenarios.

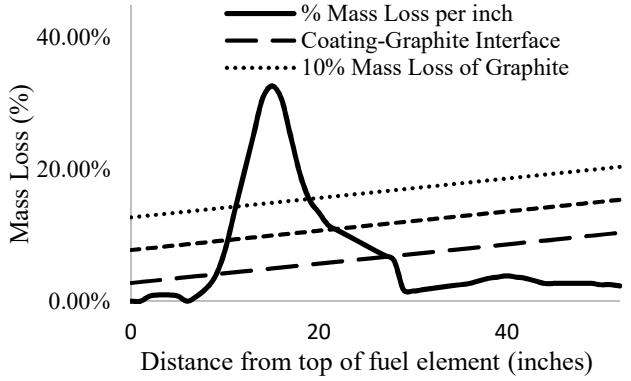


FIGURE 8: MASS LOSS PERCENT PER INCH.

Another scenario might be uniform corrosion over a 60 minute full power run where the coating is thermally exposed to hydrogen, then stripped away, exposing graphite that continues the corrosion process (see Figure 9).

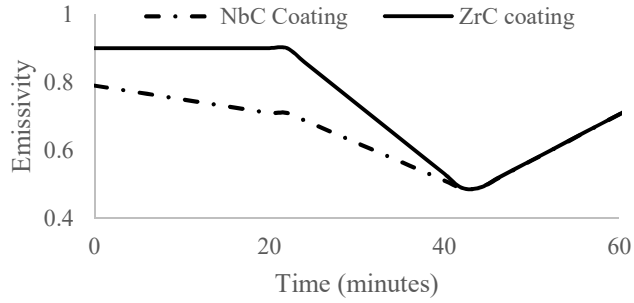


FIGURE 9: EVOLUTION OF UNIFORM CORROSION ON EMISSIVITY

Table 3 shows the results of twenty series of four-random-numbers-each that add to one (100% of the total area covered by the percentage of each specific material's area). The subscripts c, cc, g, and cg correspond to surfaces for coating, corroded coating (thermally and hydrogen exposed), graphite, and corroded graphite respectively. The randomly selected surfaces were then weighted similar to earlier examples. As expected the values fall between the upper and lower limits of fresh graphite surface emissivity and NbC/ZrC polished surface emissivities. Although corrosion enhances the emissivity of graphite it decreases the global emissivity in the coolant channel since the coating (with the higher emissivity) is removed. As the corrosion evolution continues emissivity will increase but not beyond what it was in the initial fresh fuel state.

TABLE 3: AREA WEIGHTED EMISSIVITY WITH VARIOUS STAGES OF CORROSION.

R_{A_c}	$R_{A_{cc}}$	R_{A_g}	$R_{A_{cg}}$	ε NbC	ε ZrC
0.06	0.04	0.52	0.38	0.62	0.63
0.19	0.14	0.65	0.02	0.58	0.63
0.17	0.03	0.25	0.55	0.7	0.72
0.08	0.3	0.33	0.29	0.66	0.72
0.43	0.08	0.39	0.1	0.66	0.73
0.38	0.1	0.36	0.16	0.67	0.73
0.41	0.03	0.33	0.23	0.68	0.73
0.04	0.48	0.26	0.22	0.66	0.76
0.05	0.51	0.28	0.16	0.66	0.76
0.5	0.01	0.2	0.29	0.72	0.78
0.25	0.34	0.21	0.2	0.69	0.79
0.19	0.24	0.09	0.48	0.73	0.8
0.05	0.56	0.19	0.19	0.68	0.79
0.41	0.17	0.14	0.28	0.73	0.8
0.54	0.1	0.17	0.19	0.73	0.8
0.05	0.68	0.23	0.04	0.67	0.8
0.45	0.35	0.16	0.04	0.71	0.83
0.18	0.39	0	0.43	0.75	0.84
0.05	0.67	0.04	0.24	0.72	0.85
0.37	0.45	0.03	0.15	0.74	0.87

Implementing Model into the Radiation Heat Transfer Equation

The radiation heat transfer inside the coolant channel is given by the following equation:

$$\dot{\mathbf{Q}} = \boldsymbol{\varepsilon\sigma\mathbf{A}_T(\mathbf{T}_s^4 - \mathbf{T}_c^4)} \quad (8)$$

where

$\dot{\mathbf{Q}}$ = heat transfer from the surface to the surroundings,

$\boldsymbol{\sigma}$ =Stefan-Boltzmann constant ($\mathbf{5.67\ x\ 10^{-8} W/m^2 K^4}$),

$\mathbf{A_T}$ = surface area,

$\mathbf{T_s}$ and $\mathbf{T_c}$ = the temperature of the surface and the coolant respectively.

Substituting the equation for emissivity from (6) into the radiative heat transfer equation (assuming constant temperature of the surroundings) gives:

$$\dot{\mathbf{Q}} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{R_{A_i}} \boldsymbol{\varepsilon_i}\, \boldsymbol{\sigma} \mathbf{A_T} \left(\mathbf{T_{s_i}^4} - \mathbf{T_c^4} \right) \tag{9}$$

Recalling that $\mathbf{R_{A_i}} = \mathbf{A_i}/\mathbf{A_T}$, the equation can be rewritten as:

$$\dot{\mathbf{Q}} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{A_i} \boldsymbol{\varepsilon_i}\, \boldsymbol{\sigma} \left(\mathbf{T_{s_i}^4} - \mathbf{T_c^4} \right) \tag{10}$$

In this case corrosion is not only affecting the effective emissivity but also with changing the surface area either through roughing the surface area (see Figure 10 for effect) or corroding the surface away. Interestingly as corrosion occurs in Pewee overall emissivity will decrease from its original state, but surface area will also expand. Radiative heat transfer will initially decrease from emissivity changes, but if corrosion continues radiative heat transfer will increase as the area grows and the graphite is corroded.

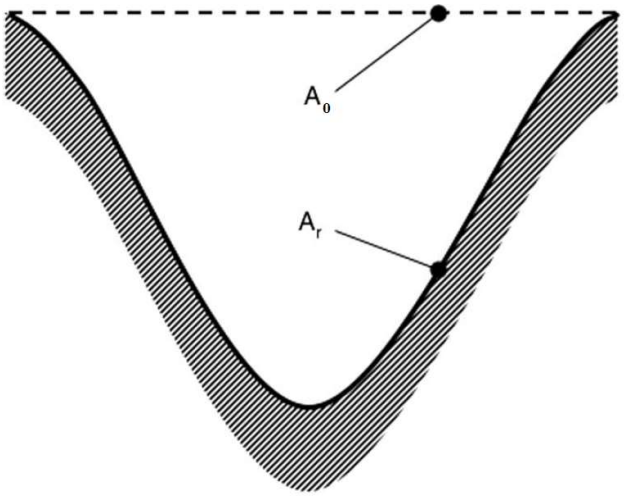


FIGURE 10: SURFACE ROUGHENED BY CORROSION. A_0 IS THE ORIGINAL SURFACE AND A_r IS THE ROUGHENED SURFACE [16]

CONCLUSION

This paper discussed the corrosion taking place in the Pewee nuclear rocket. Corrosion in Pewee is quantified by measuring the mass loss per inch from the top to the bottom of the element. Photographs from post operational runs of Pewee provide qualitative data that shows extent of corrosion including and deteriorated fuel element surface conditions. Also shown were the changes of emissivity for several nuclear grade graphite in relation to mass loss. This experimental data is used to inform effects of mass loss on emissivity in Pewee. A model was creating to incorporate the overall effect of corrosion on total hemispherical emissivity. The model is demonstrated against experimental results of mass loss in a fuel element from Pewee. Also shown is a time evolution of uniform corrosion and the resulting emissivity, and an array of other possible corrosion scenarios.

Corrosion effects on the emissivity in the nuclear rocket was shown to decrease from the original state. This is the case since the coating has an emissivity value higher than graphite. This coating is removed by hydrogen induced corrosion during full power operation exposing the graphite. The effect of decreased emissivity from removed coating is minimized by the increased emissivity of graphite through its corrosion process.

Although emissivity decreases overall long term corrosion increases radiative heat transfer since the heat transfer takes into account the change in surface area along with emissivity. The surface increases takes place by channel expansion due to material loss or by roughing of the surface through pitting or expanded micro cracks.

ACRONYMNS

NASA	National Aeronautics and Space Administration
NERVA	Nuclear Engine for Rocket Vehicle Application
UC	Uranium Carbide
LASL	Los Alamos Scientific Laboratory
WANL	Westinghouse Astronuclear Laboratory
CVD	Chemical Vapor Deposition
CTE	Coefficient of Thermal Expansion
MULE	Mass Loss Per Unit Examination
EPSCOR	Experimental Program to Stimulate Competitive Research

NOMENCLATURE

A	Area
E	Activation energy
I	Radiation intensity
K	Reaction rate
$\hat{\mathbf{n}}$	Normal unit vector
n	Number of materials
$\dot{Q}$	Heat transfer
R	Universal gas constant/Ratio of area of material to total area
$\hat{\mathbf{s}}_o$	Outward vector away from a surface
T	Temperature
ε	Emissivity
θ	Polar angle
λ	Wavelength
σ	Stefan-Boltzmann constant
Ω	Solid Angle

Subscripts

0	Original surface
A_i	The ith surface area
A_c	Area ratio of coating to total area
A_{cc}	Area ratio of corroded coating to total area
A_{cg}	Area ratio of graphite to total area
A_g	Area ratio of corroded graphite to total area
b	Blackbody
c	coolant
i	The ith component of a variable
r	Roughened surface

s Surface
T Total Surface
λ Denotes spectral

Superscripts
‘ Denotes directional

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