Final Progress Report July 31, 2015

Study of Compatibility of Stainless Steel Weld Joints with Liquid Sodium-Potassium Coolants for Fission Surface Power Reactors for Lunar and Space Applications

1. DOE Award Number DOE DE-SC0004797 University of Tennessee

2. “Study of Compatibility of Stainless Steel Weld Joints with Liquid Sodium-Potassium Coolants for Fission Surface Power Reactors for Lunar and Space Applications”

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3. July 31, 2015, for Period of August 1, 2010 through July 31, 2015
Approved Budget: $579,889.00

4. Participating National Laboratory: Oak Ridge National Laboratory

5. Abstract:

To make a manned mission to the surface of the moon or to Mars with any significant residence time, the power requirements will make a nuclear reactor the most feasible source of energy. To prepare for such a mission, NASA has teamed with the DOE to develop Fission Surface Power technology with the goal of developing viable options. The Fission Surface Power System (FSPS) recommended as the initial baseline design includes a liquid metal reactor and primary coolant system that transfers heat to two intermediate liquid metal heat transfer loops. Each intermediate loop transfers heat to two Stirling heat exchangers that each power two Stirling converters. Both the primary and the intermediate loops will use sodium-potassium (NaK) as the liquid metal coolant, and the primary loop will operate at temperatures exceeding 600°C. The alloy selected for the heat exchangers and piping is AISI Type 316L stainless steel.

The extensive experience with NaK in breeder reactor programs and with earlier space reactors for unmanned missions lends considerable confidence in using NaK as a coolant in contact with stainless steel alloys. However, the microstructure, chemical segregation, and stress state of a weld leads to the potential for corrosion and cracking. Such failures have been experienced in NaK systems that have operated for times less than the eight year goal for the FSPS. For this reason, it was necessary to evaluate candidate weld techniques

and expose welds to high-temperature, flowing NaK in a closed, closely controlled system.

The goal of this project was to determine the optimum weld configuration for a NaK system that will withstand service for eight years under FSPS conditions. Since the most difficult weld to make and to evaluate is the tube to tube sheet weld in the intermediate heat exchangers, it was the focus of this research. A pumped loop of flowing NaK was fabricated for exposure of candidate weld specimens at temperatures of 600°C, the expected temperature within the intermediate heat exchangers. Since metal transfer from a high-temperature region to a cooler region is a predominant mode of corrosion in liquid metal systems, specimens were placed at zones in the loop at the above temperature to evaluate the effects of both alloy component leaching and metal deposition. Microstructural analysis was performed to evaluate weld performance on control weld specimens.

The research was coordinated with Oak Ridge National Laboratory (ORNL) where most of the weld samples were prepared. In addition, ORNL participated in the loop operation to assist in keeping the testing relevant to the project and to take advantage of the extensive experience in liquid metal research at ORNL.

6. Description of Accomplishments

Introduction

A proposed Fission Surface Power (FSP) system has been proposed to power outposts on the moon and, at a later time, on Mars. Such a reactor system is proposed to use the liquid metal, sodium-78% potassium (NaK) as a coolant since liquid metals are highly efficient heat transfer media, and they enable a compact system. NaK has the additional advantage that it remains liquid at room temperature and can be kept liquid during a launch. The coolant is proposed to operate at 600°C in a system of AISI Type 316L stainless steel. However, the interaction between the high-temperature coolant and stainless steel welds remains an uncertainty for the projected eight year life of the system.

The present design of the intermediate heat exchangers (IHX) is shown in Figure 1 where it can be seen that there are numerous tube-to-tube sheet welds. Leakage from the primary to the intermediate loops over the eight year mission is not desirable since it increases the radiation level throughout the system. One of the key design issues related to the intermediate heat exchangers is, therefore, related to stresses that will occur at the tube-to-tube sheet joints. The appropriate material specification, joining, and inspection techniques to be followed to ensure that the IHX will meet mission requirements must be determined. These processes will be based on the mechanical configuration of the joint, the interaction of irradiated NaK with the joints, and the impact of welding on the base and filler metal in the heat affected zone.

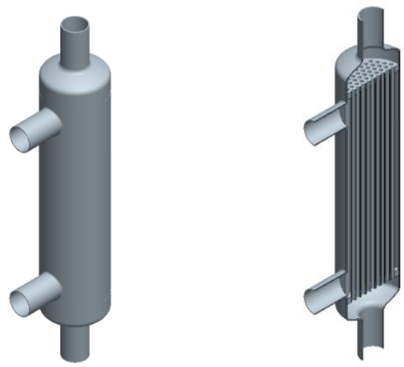


Fig. 1 View of the Intermediate Heat Exchanger

Welding, brazing, thermal diffusion bonding, and mechanical clamping are the likely means for joining materials. Brazing is limited to the outer surfaces of the primary and intermediate systems, because brazing cannot be used in contact with NaK. The preferred method for tube-to-tube sheet joint fabrication and sealing components is welding, although welding alone may not be adequate to support joint stresses throughout an 8-year mission.

Results of Project

The original goal of the project was to recommend a weld configuration for space reactors based upon NaK exposure extrapolated to eight years. Making a very high temperature compact NaK test loop proved far more difficult than originally anticipated. Such a loop was fabricated but failed to maintain flow for extended periods at the highest temperature. Much useful information was gained in the process, and some guidance on the weld configuration was obtained based upon the unexposed welds. The system is being modified to correct the deficiencies and will continue to be operated to obtain exposure data using overhead funds and volunteer work. Dr. Grossbeck has worked nearly free for the past two years to conserve funds for the project. This work will continue.

Design of the NaK loop:

A compact natural circulation loop was designed and fabricated to fit into an inert gas glove box. The inert atmosphere permitted the NaK to be handled during set up and permitted safe operation at elevated temperatures in case of a NaK leak. Such a level of safety was essential for a university situation. Fig. 2 shows a schematic diagram of the NaK loop, and the actual loop without thermal insulation is shown positioned in the glove box in Fig. 3.

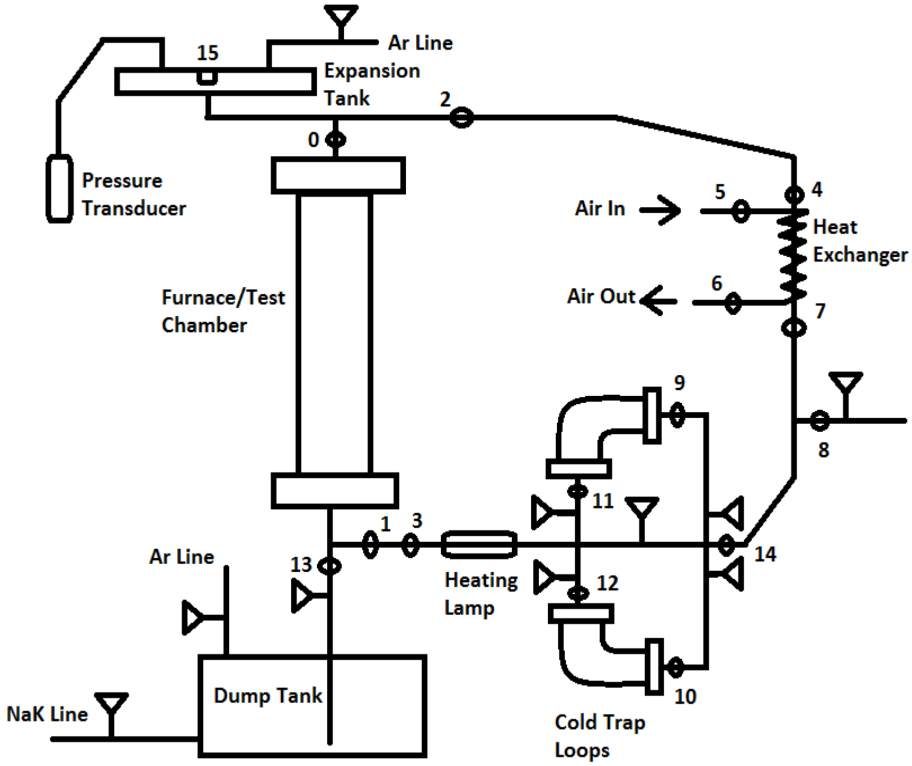


Fig. 2. Diagram of the NaK test loop with components labeled. The numbers indicate thermocouple positions. Note: both cold trap legs are below the lower horizontal leg.

Fig. 3 NaK loop positioned in an inert gas glove box

The dump tank and the expansion tank are standard features of liquid metal loops. However, the purification loop is a feature that was added to remove oxide from the NaK. The oxygen concentration is of high importance in corrosion behavior, and it can be controlled by precipitation of the oxygen in solution as sodium and potassium oxides which are filtered out. Since flow could be initiated at 250°C, an oxygen concentration of 50 wt. ppm in the NaK can be attained. Once circulation is started, it is likely (although not tested in this investigation) that flow will remain at a lower temperature. A temperature of 150°C would result in an oxygen level below 5 wt. ppm as can be seen from Fig. 4.

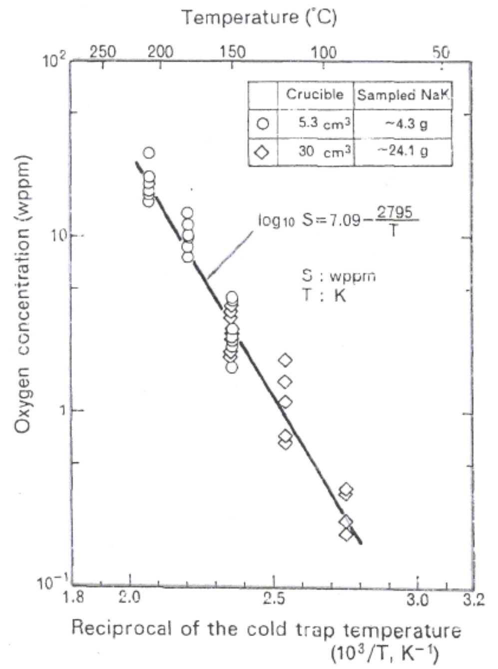


Fig. 4 Relationship between oxygen concentration and reciprocal of cold trap temperature (T. Sakai et al. Determination of Oxygen Solubility in NaK-78 by Vacuum Distillation Method, J. Nucl. Sci. and Tech 20, 1983, 1032.)

An air cooled heat exchanger was necessary to insure that the cold leg temperature was maintained in order to insure natural circulation. Air was pumped through the copper coil from the external atmosphere. A quartz lamp was used to produce a thermal spike which was traced around the loop by the numerous thermocouples in order to estimate flow velocity. The initiation of flow was easily observed by an increase in temperature of the hot NaK in the upper portion of the loop and the decrease in temperature in the lower leg of the loop upon the arrival of cold NaK from the cooled vertical section of the loop. Such a measurement indicated a flow velocity as high as 0.31 cm/s. (D.J. Rowekamp, A.V. Giminaro, and M.L. Grossbeck, Nuclear & Emerging Technologies for Space, Albuquerque, NM, 2013.) Pressure was monitored to guard against over pressurization of the loop as temperature was increased.

In order to fit into the available glove box, the expansion tank inlet was placed at the level of the hot leg. This is considered a candidate for the malfunction of the loop at the highest temperature. Even though the loop was purged several times, it remains possible that bubbles remained in the loop. A new glove box has been purchased with University funds that will permit the expansion tank to be raised above the hot leg to eliminate this problem.

Specimen Preparation:

Since Type 316L stainless steel is the leading candidate for the space reactor, this alloy was used for this research. To simulate heat exchanger welds, specimens were made by welding a short length of tubing into a plate. Tubing 3/8" (9.53 mm) in diameter with a 0.02" (0.508 mm) wall was welded to a disk 0.25" (6.35 mm) in thickness and 0.50" (12.7 mm) in diameter. This sample was welded in four configurations as shown in Table 1. Tungsten inert gas (TIG) welds were made by two welders in different shops, and electron beam welds were made by a single shop. A limited number of TIG welds were made using tubing with a wall thickness of 0.040" (1.02 mm), and several welds were made in a butt well configuration also by TIG. In addition, a hot isostatic press joint was included. The specimen matrix is shown in Table 1.

Recommendations for Space Reactors

Since crevice corrosion is a major concern in liquid metal systems, the necessary crevice between the tube and the plate should be kept as narrow as possible. As shown in Fig. 5, electron beam welding results in a very narrow crevice. It is believed that thermal expansion and contraction during the arc welding process resulted in a more open crevice. From this result, it is recommended that electron beam welds be used wherever possible in the heat exchangers. The effect of NaK exposure will be determined by further testing.

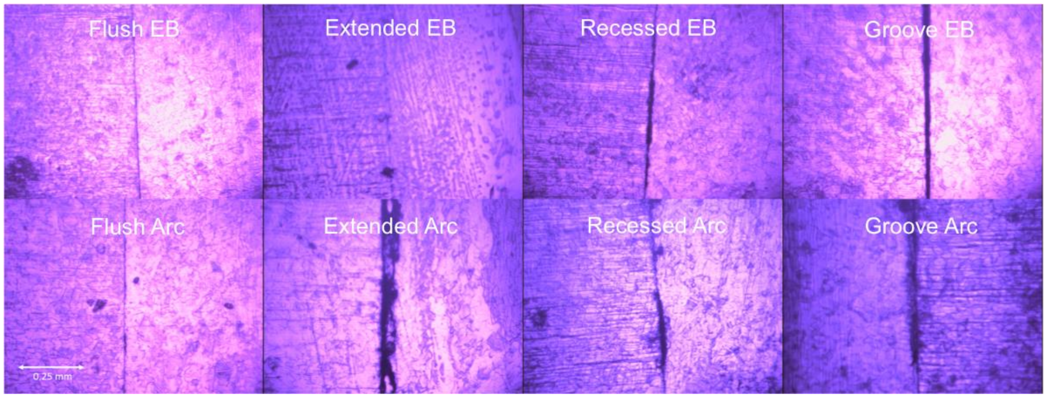
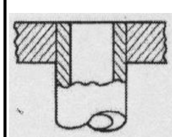
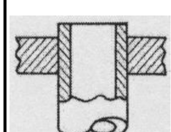
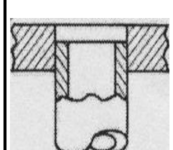
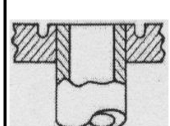


Fig. 5. Weld specimens showing the plate-to-tube crevice at a 100x magnification

An important accomplishment of this project is the education of three students who obtained Master of Nuclear Engineering degrees from the research. Since they are nuclear engineering students, and the research is focused on materials science, the project was not used for Ph.D. thesis research. A B.S. nuclear engineering degree coupled with a materials related M.S. degree qualifies a student to address many current problems in nuclear science. One of the students is currently working on a Ph.D. in nuclear engineering, and the other two are employed in the nuclear field.

Table 1. Weld Specimen Matrix

		TIG Welder No. 1			**Electron Beam**	**TIG Welder No. 2**		**Thicker Pipe**
Time		3 months	1 year	3 year	1 year	3 months	1 year	1 year
Flush Weld		F-J-0-1	F-J-1-1	F-J-3-1	F-E-1-1	F-W-0-1	F-W-1-1	F-T-1-1
		F-J-0-2	F-J-1-2	F-J-3-2	F-E-1-2	F-W-0-2	F-W-1-2	F-T-1-2
Extended Weld		E-J-0-1	E-J-1-1	E-J-3-1	E-E-1-1	E-W-0-1	E-W-1-1	E-T-1-1
		E-J-0-2	E-J-1-2	E-J-3-2	E-E-1-2	E-W-0-2	E-W-1-2	E-T-1-2
Recess Weld		R-J-0-1	R-J-1-1	R-J-3-1	R-E-1-1	R-W-0-1	R-W-1-1	R-T-1-1
		R-J-0-2	R-J-1-2	R-J-3-2	R-E-1-2	R-W-0-2	R-W-1-2	R-T-1-2
Groove Weld		G-J-0-1	G-J-1-1	G-J-3-1	G-E-1-1	G-W-0-1	G-W-1-1	G-T-1-1
		G-J-0-2	G-J-1-2	G-J-3-2	G-E-1-2	G-W-0-2	G-W-1-2	G-T-1-2

	TIG Welder No. 1		Electron Beam	
	3 months	1 year	3 months	1 year
Butt Welds	B-J-0-1	B-J-1-1	B-E-0-1	B-E-1-1
	B-J-0-2	B-J-1-2	B-E-0-2	B-E-1-2

7. List of papers

1. D.J. Rowekamp, A.V. Giminaro, and M.L. Grossbeck, "A Compact NaK Coolant Test Loop in an Argon Atmosphere," Nuclear & Emerging Technologies for Space, Albuquerque, NM, February 25-28, 2013.
2. D.J. Rowekamp, "A Compact, Convective Flow NaK Test Loop for Material Exposure Contained in an Argon Atmosphere, Thesis for Master of Science in Nuclear Engineering, The University of Tennessee, 2013.
3. M.G. Pastis, "A Sensor for Oxygen in a Potassium-Sodium Alloy, Thesis for Master of Science in Nuclear Engineering, The University of Tennessee, 2014.
4. A.V. Giminaro, "Effects of NaK on the Corrosion of Heat Exchanger Tube-Sheet Welds: A Preliminary Analysis, Thesis for Master of Science in Nuclear Engineering, The University of Tennessee, 2015.

8. List of project personnel

Personnel	Position	Level Funded	Time Period
M.L. Grossbeck	PI	30%	8/31/2010 -- 7/31/2013
		4.2%	7/31/2013 – 7/31/2014
		1.8%	7/31/2014 – 7/31/2015
A.L. Qualls	Co-PI	Not funded	
D.J. Rowekamp	Research Asst.	20 hrs/wk	8/18/2010 – 4/30/2013
Andrew Giminaro	Research Asst.	20 hrs/wk	6/30/2012 – 4/30/2014
Michael Pastis	Research Asst.	20 hrs/wk	5/31/2013 – 9/30/2014
David Shell	Undergrad. Asst.	4 hrs/wk	2/12/2012 – 4/22/2012

9. Other Support

Consultation was provided by A.L. Qualls of ORNL, but no funding was provided by ORNL. Equipment purchased by other programs was used for the project. In addition, University of Tennessee overhead funds were used to purchase additional equipment near the end of the project.

10. Cost Status:

Total budget for three year period	$579,889.00
Details of expenditures:	
Salaries and benefits	$270,947.79
Equipment and Supplies	78,356.65
Tuition	65,638.81
Travel	7,121.81
Overhead	157,823.95
Total Expenditures	579,889.01

Cumulative Salary Expenditures

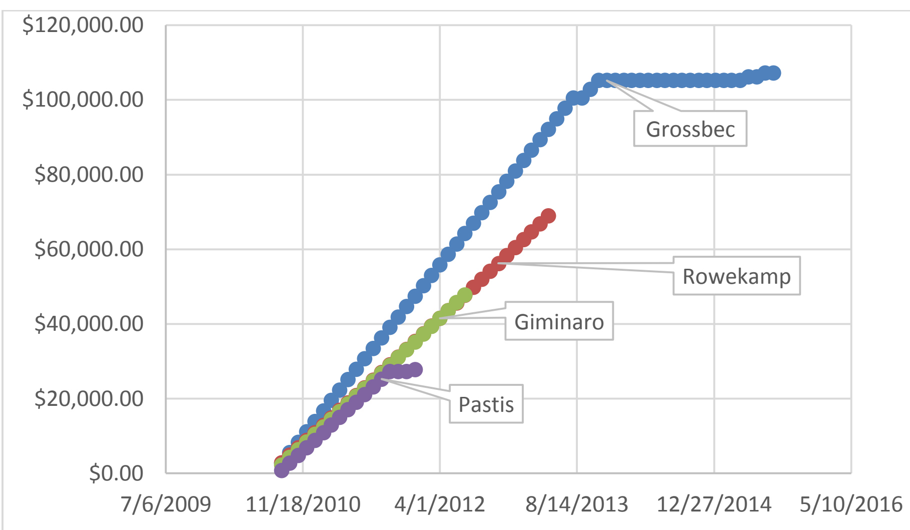


Fig. 3 Cumulative Expenditures for Present Year