Research in Support of the Use of Rankine Cycle Energy Conversion Systems for Space Power and Propulsion

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SUMMARY

President Bush has recently proposed an exciting new vision for NASA; in particular, a robust program for the exploration of our Solar System, involving the establishment of a lunar base and a manned-mission to Mars.

To accomplish this vision, significantly higher power levels will be needed for spacecraft power and propulsion than were used on previous NASA missions. This will likely require that onboard phase-change systems and processes be extensively used. In particular, a Rankine cycle power plant has some significant advantages over other competing energy conversion systems, and thus it is a primary candidate for use in NASA's new missions.

This is the report of a Scientific Working Group (SWG) formed by NASA to determine the feasibility of using a liquid metal cooled nuclear reactor and Rankine energy conversion cycle for dual purpose power and propulsion in space. This is a high level technical report which is intended for use by NASA management in program planning.

The SWG was composed of a team of specialists in nuclear energy and multiphase flow and heat transfer technology from academia, national laboratories, NASA and industry. The SWG has identified the key technology issues that need to be addressed and have recommended an integrated short term (~ 2 years) and a long term (~ 10 year) research and development (R&D) program to qualify a Rankine cycle power plant for use in space. This research is ultimately intended to give NASA and its contractors the ability to reliably predict both steady and transient multiphase flow and heat transfer phenomena at reduced gravity, so they can analyze and optimize designs and scale-up experimental data on Rankine cycle components and systems. In addition, some of these results should also be useful for the analysis and design of various multiphase life support and thermal management systems being considered by NASA.

It appears that a Rankine cycle power plant is an attractive energy conversion system for NASA and that its operational characteristics at reduced gravity can be verified and reliably predicted by performing the recommended R&D programs. A programmatic recommendation is also given by the SWG as to how NASA might implement the proposed research programs to help assure its success. Significantly, the recommendations of the SWG are consistent with prior studies [Viskanta, 2000], [McQuillen et al., 2003] on the research needed to support the extensive use of multiphase systems and processes in space.

1.0 INTRODUCTION AND BACKGROUND

Rankine cycle Energy Conversion Systems, employing liquid metals as the primary coolant, represent well established technology on earth. Several test facilities, including nuclear reactors, have been designed, fabricated, and operated worldwide for many years. Examples are the Fast Flux Test Facility (FFTF) and the EBR-II reactors in the United States [USNRC, 1978], the SUPERPHENIX reactor in France [LaCroix et al., 1990], and the Joyo and Monju reactors in Japan [Fukazawa et al., 1990]. All these reactors have been based on a Rankine cycle for energy conversion and utilization and there have also been numerous experimental and analytical studies reported in the literature in support of the design and operation of liquid metal cooled nuclear reactors.

Some of the advantages of these systems are that they operate at low pressures but high temperatures and thus have high thermodynamic cycle efficiencies. The thermal properties of liquid metals are also very attractive from the point of view of heat transfer. Moreover, a number of studies based on previously conducted experimental work showed [George, 1990], [Gilland and George, 1992] that Rankine cycle based power systems become very attractive for space application when the power needs are in the multi-megawatt range. Because of these inherent features, liquid metal cooled nuclear reactors which use a Rankine cycle for energy conversion represent a very promising alternative for propulsion and energy production in advanced spacecraft. Recognizing this, NASA conducted in the 1960's and 1970's significant research and development (R&D) work on Rankine cycle, liquid metal cooled, nuclear reactor systems under the SNAP and MPRE programs [Sankovic, 2003]. Proof of concept hardware was designed, built and tested on earth for hundreds of hours for typical Rankine cycle power systems. Moreover, there was also a limited amount of flight testing for SNAP-10a. However, before these activities could lead to full implementation of these systems in space, the direction of the program was changed. Subsequently, the Space Exploration Initiative (SEI) in the 1980s and NASA's recent Human Exploration and Development of Space (HEDS) program, once again energized interest in the use of Rankine cycles for NASA's deep space missions.

President Bush has proposed an exciting new initiative for space exploration [Bush, 2004]. The goals and objectives of his vision are given below.

The President's Initiative

The basic goal embedded in the President's vision is to advance America's scientific, security, and economic interests through a robust space exploration program. In order to achieve this goal, the United States will [Bush, 2004]:

- "Implement a sustained and affordable human and robotic program to explore the Solar System and beyond,"
- "Extend human presence across the Solar System, starting with human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations,"
- "Develop the innovative technologies, knowledge, and infrastructures required to explore and support decisions about the destinations for the human exploration," and,

- "Promote international and commercial participation in space exploration to further America's scientific, security and economic interests."

In order to achieve the President's vision for the exploration of our Solar System, deep space missions of relatively long durations must be undertaken. The power and propulsion needs of such missions go well beyond those that can be met with solar or chemical power systems in any economically feasible manner. Nuclear fission power systems are ideally suited for this purpose as they can provide large amounts of continuous power (in the multi-MW range) for propulsion during travel of the spacecraft to various destinations, can provide enough power to carryout demanding scientific and technical missions, and provide for reliable life support and communication infrastructure with earth.

To meet the power needs for exploration of the Solar System, NASA in 2003 established Project Prometheus [Nainiger, 2004].

Project Prometheus

Project Prometheus is focused on developing the means to efficiently produce power for advanced spacecraft, thereby fundamentally increasing our capability for Solar System exploration. Increased power for NASA spacecraft means not only traveling farther and faster, but it also means exploring our Solar System more efficiently with enormously greater scientific return in both manned and unmanned missions. Higher levels of sustained power would enable a new era of Solar System missions designed for agility, longevity, flexibility, and comprehensive scientific exploration.

One of the main purposes and objectives of NASA's Project Prometheus and its programs is to develop technology and conduct advanced studies in the area of radioisotope and nuclear fission based power and propulsion systems for use in various deep space missions. Under Project Prometheus, which is organized within NASA's Office of Space Science (Code-S), a nuclear powered spacecraft is to be developed by the USDOE-NR. It will be demonstrated that such a system can be operated safely and reliably during deep space missions of long duration. The project will support the Jupiter Icy Moons Orbiter (JIMO) mission, and will develop power and propulsion technology for more ambitious space missions beyond JIMO (e.g., a manned-mission to Mars). In the area of power conversion, three types of nuclear power conversion systems are being actively considered:

(i) A Rankine cycle utilizing liquid metals as the working fluids. This system will employ boiling/condensation and two-phase flow in the secondary loop connected to a turbo-generator. It is an extension of the power systems previously proposed for SNAP-50 and MPRE.

(ii) A Brayton cycle employing either an inert gas coolant throughout the system (i.e., a direct cycle), or a liquid metal cooled primary loop and a heated inert gas in the secondary loop (i.e., an indirect cycle) which is connected to a turbo-generator.

(iii) A thermoelectric cycle based on the principle that electric potential is generated when dissimilar materials are subjected to temperature differentials. The system employs segmented thermoelectric multi-couple converters.

A leading near term candidate for space craft propulsion is nuclear electric propulsion (NEP). This concept utilizes electric power to create the propellant ions which are then accelerated to produce thrust. Both electrostatic and electromagnetic options are being considered. In the electrostatic option, ions are accelerated through an applied electric field where as, in the electromagnetics option, acceleration of the ions occurs as a result of combined electric and magnetic fields. A NASA mission to Comet Borelly, which employed electrostatics to accelerate the ions, was flown successfully in 1997. Moreover, ion thrusters are now in common use on commercial geostationary communication satellites.

In order to further strengthen and guide the ongoing activity for the possible use of Rankine cycle power conversion systems under Project Prometheus, NASA appointed a special Scientific Working Group (SWG). The goal of the SWG, which includes specialists from academia, national laboratories, NASA, and industry, was to develop a high level work plan and research road map (both short range ~ 2 years and long range ~ 10 years) that could guide NASA in planning research and development activities for the successful use in space of Rankine cycle power conversion system technology. The membership of the SWG, the NASA organizing committee of this Working Group, and the charter of the SWG are given next.

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Charter of the SWG

The charter of the SWG, which was developed by the NASA Organizing Committee, is:

The SWG will identity and define the key microgravity related issues that need to be resolved to advance a Rankine Cycle power conversion system to the next higher technology readiness level. Specifically, we are interested in scientific issues related to the use at reduced gravity of engineering designs involving: (1) boiling and condensation heat transfer, (2) liquid/vapor phase distribution and separation, and, (3) system instabilities.

Once the key issues have been identified, the SWG will identify the research that needs to be conducted to resolve them and define a broad experimental concept and top level requirements. The research may include flight experiments, ground-based low-gravity and normal-gravity (1g) experiments, modeling and analyses, computational simulations, and future ISS experiments. An integrated technical approach and plan will be developed to provide the information that is needed for designing Rankine cycle power conversion systems of any scale for operation at reduced gravity.

The SWG met twice (February 5-6 in Los Angeles and February 27-28 in Atlanta). The results from the deliberations of the SWG are contained in this report.

2.0 RANKINE CYCLE ENERGY CONVERSION SYSTEMS

As discussed previously, a number of thermodynamic energy conversion cycles are currently under consideration by NASA for use on various proposed manned and unmanned missions. In particular, for Project Prometheus, in which a nuclear fission reactor will be the primary on-board energy source for proposed missions focused on the exploration of our Solar System. One very attractive candidate is a Rankine cycle. This energy conversion cycle has been widely used on earth in both fossil and nuclear power plants. It can be configured as a direct boiling Rankine cycle, or, as shown in Figure 1, an indirect, two-loop, Rankine cycle, in which a suitable coolant (e.g., liquid metal) goes through the nuclear reactor core but does not boil while phase change occurs on the secondary side. That is, the working fluid in the secondary loop comes into the boiler as a subcooled liquid and leaves as a vapor which, in turn, goes through a turbine-generator, condenser, and boiler feed pump before returning to the inlet of the boiler. The secondary loop represents a typical Rankine cycle.
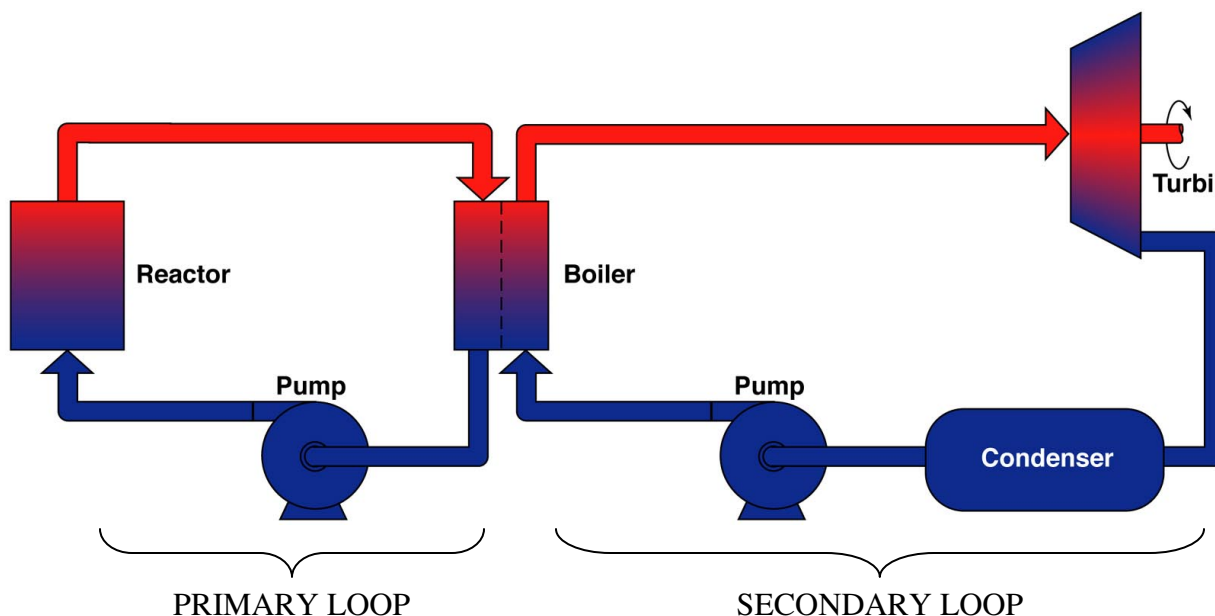

Figure 1. A typical indirect two-loop Rankine cycle power plant.

As can be seen in Figure 2, due primarily to the radiator design requirements, a Rankine cycle has inherent power/weight advantages over other competing energy conversion cycles at the higher power levels (≥ 1.0 MW$_e$) which will be required for the human exploration and development of space, such as the manned-mission to Mars proposed by President Bush [Bush, 2004]. One reason for this superior performance is that a Rankine cycle features heat addition and rejection at near constant temperature (i.e., during boiling and condensation). This implies higher radiator temperatures, and thus significantly lower radiator volume and mass, and lower reactor operating temperatures than in single-phase systems. If a liquid metal is used as both the coolant and working fluid, one can operate with relatively low pumping power, low system pressure and yet high operating temperatures, thus achieving relatively high energy conversion efficiencies approaching 30%. It should be noted that high thermodynamic cycle efficiencies reduce the power requirements of the nuclear reactor and thus its weight, shielding and heat rejection requirements.
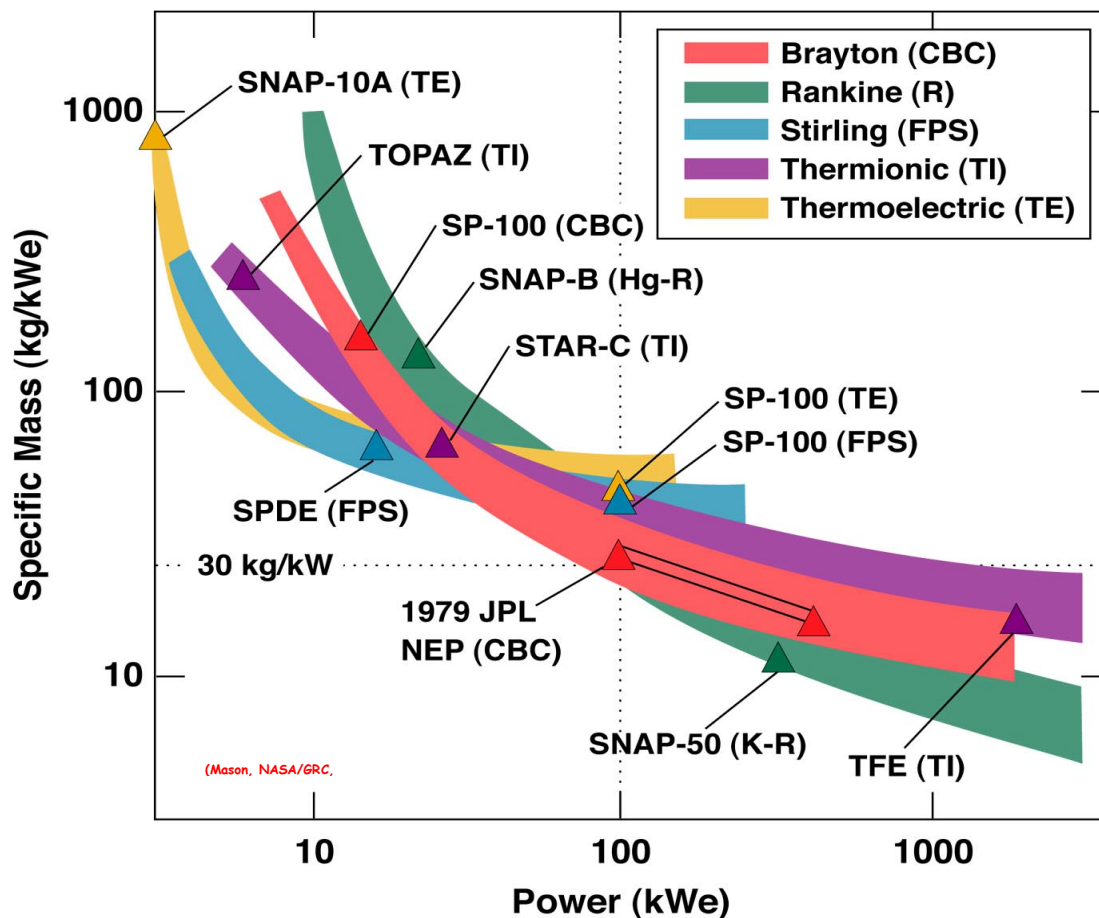

Figure 2. Comparison of various thermodynamic cycles [Mason, 2002].

These are obviously very desirable attributes, however, a Rankine cycle is a phase change system and thus, for it to be a viable candidate for use on NASA missions, one must be able to reliably use multiphase flow and heat transfer systems and processes at reduced gravity $(1.0 > g/g_e \geq 10^{-6})$, such as the microgravity environment which will occur in space (μg), on the moon ($1/6g_e$), or other planetary bodies such as Mars ($3/8g_e$).

As noted previously, a significant amount of prior R&D was done in the 1960s and 1970s in support of NASA's programs, in which a Rankine cycle was used. Nevertheless, some important technical concerns and issues still remain.

2.1 RESEARCH ISSUES

The SWG focused on identifying and prioritizing the multiphase research issues associated with normal and off-normal operating conditions and with postulated accidents in Rankine cycle power plants. Important technical issues include:

Critical Issues Associated with Reduced Gravity

- Phase separation
- Phase distribution (i.e., flow regimes)
- Boiling/condensing system instabilities
- Multiphase pressure drop
- Phase change heat transfer and critical heat flux (CHF)
    - Twisted tapes or serpentine tubes
- Liquid inventory assessment and control
- Freezing and thawing (system start-up and shut-down)

Critical Issues Not Associated with Reduced Gravity

- Boiling initiation and enhancement
    - Liquid metals
    - Augmentation devices (i.e., twisted tapes or serpentine tubes)
- Dryout and rewetting dynamics (thermal fatigue)
- Choked flow
    - Liquid metals
- Thermal stripping
- Pump performance
    - NPSH/cavitation
    - Multiphase degradation

It should be noted that these technical issues are fully consistent with those identified in previous studies associated with the use of multiphase systems and processes in space [Viskanta et al., 2000], [Motil, 2000], [McQuillen et al., 2003], [Chiaramonte and Joshi, 2004].

3.0 REQUIRED RESEARCH

There is a crucial need to develop reliable multidimensional predictive capabilities for the multiphase systems and processes in Rankine cycles operating in reduced gravity environments. However, NASA must first establish in the near term that a Rankine cycle power plant can be reliably used in space. Thus, the SWG partitioned the recommended research program into a short term (~ 2 year) R&D program and a longer term (~ 10 year) R&D program. The SWG felt that an indirect, two-loop, liquid metal cooled Rankine cycle power plant, shown schematically in Figure 1, was the preferred design option (compared to direct cycle power plants) and that, for normal operating conditions where the flow rate (and thus fluid inertia) is relatively high, it should be possible to develop a design which is insensitive to gravity level. Thus, the short term research program was focused on establishing the ability to reliably operate such a system during normal operation in space. A complementary longer term research plan will be required to fully qualify the use of a Rankine cycle power plant in space, and it must address both steady-state and transient conditions during off-normal and postulated accident conditions where gravity level will likely be important.

3.1 SHORT TERM RESEARCH PLAN

The key technology issues associated with the use of a Rankine cycle in space that must be addressed early on are: phase separation and phase distribution (i.e., flow regime), phase change heat transfer (both boiling and condensing), system stability, and the operational conditions associated with gravity insensitivity.

Given the recommended time scale of this research program (~ 2 years) it is unrealistic to expect that a significant amount of new microgravity experiments can be designed and operated. Thus the approach adopted by the SWG was to identify design innovations and/or bounding analysis that could be used to help assure reliable normal operation of a Rankine cycle power plant in space. However, the range of steady-state thermal-hydraulic parameters for which the phase change system is insensitive to gravity must be identified and quantified.

DESIGN INNOVATIONS
While it was not the charter of the SWG to design a Rankine cycle for use in space, some hardware examples will help illustrate the proposed short term research program recommended.

For example, the need to reliably separate liquid from vapor is well known. Referring to Figure 1, it was felt that a passive (e.g., cyclonic) separator could be developed and used at the exit of the boiler to separate liquid droplets from the vapor on the secondary side, thus avoiding potential damage to the turbine blades. Active separators, such as rotary fluid management devices (RFMD) [Fraas, 1967], [Havens and Rogallee, 1988], could be used at both the inlet of the condenser and at the exit of the condenser to enhance the operational efficiency of the condenser and to avoid vapor-binding or degrading the boiler feed pump, respectively. For the relatively high liquid flow rates expected during normal operation, these devices can, and should, be tested for various orientations on earth using prototypical geometries and working fluids (i.e., liquid metals). However, similar tests should also be performed with simulant fluids on earth and in space to assess the fluid-dependence and limits for gravity insensitivity of the

separation technique, since it is unlikely that liquid metals can be tested in space during the short term research program.

Similarly, twisted tapes on the secondary side of the boiler have been proposed to enhance boiling heat transfer and reduce liquid droplet carryover Since, for normal operating conditions, these devices induce a significant lateral acceleration they should not be sensitive to gravity level and thus can also be tested in various orientations on earth using both simulant fluids and prototypical geometries and working fluids. The prototypical experiments should also yield important data on two-phase pressure drop, heat transfer coefficients, boiling inception and hysteresis, etc., which can be used in future analytical models to be developed in the long term research programs. In addition, parametric tests should also be developed to determine the operational parameters required for gravity insensitivity and the resultant nondimensional groups should be verified on small scale μg tests using simulant fluids.

Finally, for normal operating conditions, the use of a shear flow condenser [Havens and Rogallee, 1988] is expected to be gravity insensitive and appears to offer a robust and reliable way to condense the spent vapor exiting the turbine. Nevertheless, the limits of gravity insensitivity should be assessed through tests of various orientations on earth using prototypical geometries and working fluids, and verified using simulant fluids in space.

There are a number of other important issues that need to be addressed (e.g., removal of noncondensible gases that may be formed in the primary coolant (lithium) flowing through the nuclear reactor core), however, the design and testing approach discussed above is expected to be similar.

It is important to stress that , for normal operations, the approach proposed should not be sensitive to gravity level and thus most of the confirmatory experiments can be performed on earth using prototypical geometries and working fluids (i.e., liquid metals). Moreover, in many cases of steady normal operation, the design approaches used on earth for the analysis of multiphase flow and heat transfer can be used. There are, however, other situations where the system may undergo transients (e.g., system instabilities) and the effect of gravity needs to be considered. Fortunately, it appears that in some cases this can be done by performing a bounding analysis.

SYSTEM INSTABILITIES
One of the key technical issues associated with a Rankine cycle that has been identified, both by the SWG and in prior studies [Viskanta et al., 2000], [McQuillen et al., 2003], is the multiphase system instabilities that may occur. These undesirable transients may include excursive and dynamic system instabilities [Viskanta et al., 2000] and the possible interaction between the various instability modes. When these instabilities have occurred in Rankine cycle power plants on earth, they have caused operational problems, violation of thermal limits, and even system failures. The same is anticipated at reduced gravity levels, however, it is not clear at this point in time if the situation will be better or worse than on earth.

Multiphase system instabilities have been predicted reasonably accurately on earth using a one-dimensional drift-flux model of the multiphase thermal-hydraulic phenomena [Lahey and

Podowski, 1989], in which the drift-flux parameter C_o quantifies the integral phasic slip and V_{g_j} quantifies the local phasic slip. There are well established flow-regime-dependent values of these drift-flux parameters for use on earth. The V_{g_j} parameter is directly proportional to buoyancy, thus for microgravity conditions it will be essentially zero while the dependence of C_o on flow regime should be bounded $\left(i.e., 0 \leq C_o \leq C_{o_{max}} \sim 1.6 \right)$.

Thus one should be able to benchmark drift-flux stability models (in both the frequency and time domain) against appropriate system stability data taken on earth with suitable simulant fluids (i.e., freon) and then use this same model (with $V_{g_j} = 0.0$) to parametrically infer system stability boundaries in space for the secondary loop of a Rankine cycle power plant, such as that shown schematically in Figure 1. The results for the C_o which gives the most limiting operating conditions for system stability could then be used by the designers of the Rankine cycle power plant to avoid system instabilities in space.

This approach will need to be verified in suitable microgravity experiments; however, because of the time scale of the system oscillations, it will not be possible to perform those experiments in the KC-135, rather they should be given priority for testing aboard the International Space Station (ISS), the space shuttle or a free flyer.

Nevertheless, it appears that the time at simulated microgravity (~20 sec.) offered by the KC-135 should be sufficient to allow one to measure the drift-flux parameter C_o for the various flow regimes of interest (mostly annular flow) using suitable simulant fluids at microgravity.

Thus, using appropriate design innovations and bounding analyses, it appears that one should be able to demonstrate the viability of the use of a Rankine cycle in space, and, if the proposed research is given proper priority, this could be accomplished within a two-year time frame. However, there are other important issues that also must be addressed under a long term research plan.

3.2 LONG TERM RESEARCH PLAN

The short term research program discussed above in Section 3.1 is focused on verifying the ability of a Rankine cycle power plant to operate reliably at reduced gravity for normal operating conditions. This is obviously a necessary condition to qualify a Rankine cycle for use in NASA's missions, but it is not sufficient. Indeed, we also need to be able to verify the successful performance of this phase change system during operational transients , off-normal operation conditions and postulated accidents (e.g., accidents involving: loss of coolant, pump trip or seizure, loss of heat sink, anticipated transients without scram, etc.).

NASA and its contractors have long recognized the desirability of being able to use phase change systems and processes in space. Nevertheless, because of the uncertainties involved in predicting multiphase flow and heat transfer phenomena at reduced gravity, the extensive use of multiphase systems and processes has not been a viable design option. Rather, NASA has always designed around the extensive use of these systems on their missions. However, this will no

longer be practical as the power requirements for NASA's missions increase [Viskanta et al., 2000].

After careful deliberation, the SWG concurs with the recommendations of previous studies [Viskanta et al., 2000], [McQuillen et al., 2003], [Motil, 2000] that NASA should initiate a well coordinated long term (~ 10 year) experimental and analytical research program, to develop the ability to perform reliable multidimensional simulations of multiphase flow and heat transfer phenomena in Rankine cycle power plants operating at reduced gravity. In fact, the use of such models is essential if NASA is to have the ability for design optimization/assessment and the reliable scale-up of microgravity data on Rankine cycles systems and components.

These computational models should be mechanistically-based (rather than empirical) and should be able to predict the flow regimes (i.e., phase distribution), phase separation, phasic turbulence, two-phase pressure drop and heat transfer in both simple and prototypical geometries at various levels of reduced gravity. Steady-state and transient predictive capabilities are required, since these models will be needed for the evaluation of both off-normal operating conditions and postulated accidents, in which we may have transient multiphase conditions on both the secondary and primary sides of the two-loop Rankine cycle power plant shown schematically in Figure 1.

It is assumed that the longer term research program will be conducted in parallel with the short term program and will utilize some of its results. For example, the data and modeling efforts associated with the effect of twisted tapes on the secondary side of the boiler and the active and passive phase separators, should be used in the development and assessment of the multidimensional computational model discussed below. Nevertheless, the longer term research program must necessarily focus on developing a good physical understanding of how multiphase systems behave at reduced gravity.

Given the current state-of-the-art, the proposed multidimensional computational model is expected to be a multifield, multifluid [Ishii, 1975], [Drew and Passman, 1999] computational multiphase fluid dynamic (CMFD) model, or a hybrid version involving capabilities such as direct numerical simulation (DNS) [Tryggvason et al., 2001], [Dhir, 2001] or lattice Boltzmann techniques [Nourgaliev et al., 2003] coupled with a CMFD model. Moreover, it should be a *multiscale* model, in which important near-field phenomena (e.g., wall heat flux partitioning, critical heat flux – CHF, wall shear, etc.) are mechanistically modeled and coupled with the predicted (CMFD) multiphase thermal-hydraulic phenomena in the far-field. In this way, empiricism can be greatly minimized. Moreover, this computational model should be able to handle both the vapor/liquid phase change and the liquid/solid phase change expected during system shut-down and start-up transients (i.e., system freezing and thawing).

The key to the development of accurate multidimensional computational models for multiphase flow and heat transfer is the proper formulation of the interfacial transfers between the vapor and liquid phases (particularly for momentum transfers). Indeed, this is how the physics that was lost during the averaging process which results in the CMFD model is reintroduced and closure is achieved.

RESEARCH ROAD MAP

It will be a "grand challenge" to obtain the required data and develop the proposed computational model within a ten year time frame. Nevertheless, models of this type have been successfully developed and used on earth [Lahey and Drew, 2001], [Issa and Kempf, 2003] and there appears to be no reason why they can't also be developed for use in space, particularly if NASA becomes actively involved in coordinating, organizing, and monitoring the required research. It should be noted that the recommended modeling approach is very similar to that recommended to the USDOE as a way to advance the field of multiphase science and technology for use in various important energy-related programs on earth [Hanratty et al., 2003], [Theofanous and Hanratty, 2003].

It is not the purpose of this report to develop a detailed list of needed research (e.g., a test matrix); indeed, this is contrary to the SWG's charter. Rather, this should be done by the researchers involved in the conduct of the recommended R&D in order to support the development of the proposed computational models. Nevertheless, in addition to the data to be acquired during the short term research program, it is clear that new multidimensional data on the phasic velocity, volumetric fraction, temperature fields, and wall heat flux will be required. Some of these data can be taken on earth but new data of this type will also be required at microgravity (e.g., new experiments will need to be conducted on the International Space Station, ISS , the space shuttle or free flyers). The near term planning of these experiments should focus on the development of suitable test apparatus, and these experiments will need to be well coordinated with the needs of the model developers to assure that the proper quantities are measured. In fact, this is why it is essential to specify the type of simulation models to be developed. Fortunately, however, since physically-based models are to be developed, it should not be necessary to test all relevant geometries and operating conditions. Rather separate-effect type experiments using suitable simulant fluids (i.e., freon) which isolate and assess the various important terms in the predictive models (e.g., lift, dispersion, drag, virtual mass, etc.) should suffice. In any event, similar experiments using both simulant fluids and liquid metals should be run on earth to verify that the proposed new μg data (with simulant fluids) are relevant to NASA's needs.

The proposed long range experimental and analytical research efforts should focus on phase distribution (i.e., flow regime) and phase separation phenomena, the associated wall and interfacial heat transfers, two-phase pressure drop, dryout and rewet heat transfer, critical heat flux, freezing and thawing, boiling and condensing system instabilities, and liquid inventory distribution. Effort should also be devoted to the development of the instrumentation necessary for the satisfactory conduct of these microgravity experiments and possibly for the operation and diagnosis of a Rankine cycle power plant.

Both adiabatic and diabatic microgravity (μg) experiments should be conducted to study: the role played by twisted tapes on heat transfer and phase distribution, flow pattern transitions, the entrainment and deposition processes and interfacial structures in annular flows, phase change heat transfer coefficients and boiling inception. In boiling experiments, the surface should be well characterized, and measurements should be made of the volume fraction distribution, velocity and turbulence distribution, wall temperature, partitioning of the wall heat flux, liquid film thickness, and droplet size distribution. Flow visualization should be an integral part of any

experimental effort. In two-phase pressure drop experiments, detailed pressure profile measurements should be made, and the associated wall shear stress should also be measured.

The gravity insensitivity of different phase separator designs should be quantified and the ability of the CMFD model to predict the upstream and downstream phase distribution assessed. The performance of the phase separator should be tied to flow regimes and include droplet size and volume fraction distribution during steady and transient operation. The experiments for dryout and rewet phenomena should also include data for the drop size and velocity distribution, liquid film thickness, heat transfer between the drops and superheated vapor, and the vapor temperature. For critical heat flux, visual observations should be supported with detailed data on wall temperature, heat flux, the far-field flow field and regime, near-wall flow regime, and local volume fraction. Boiling and condensing system flow instability experiments should include both density-wave and pressure-drop oscillations, and Ledinegg instabilities, and the potential for complex instability mode interactions.

It is likely that microgravity data will not be readily available (i.e., it takes a significant amount of time to design, plan, and properly execute such experiments on the ISS), however, in the interim, one can use detailed multidimensional, interface-tracking , direct numerical simulations (DNS) of the various turbulent two-phase flows of interest to generate pseudo-data at reduced gravity which can be appropriately averaged so that the required closure laws can be developed in terms of the state variables of the CMFD model [Prosperetti and Tryggvason, 2003], [Lahey and Drew, 2004]. These numerical results can, and should, be assessed against future microgravity data, however this approach is expected to yield valid results and will allow for the early formulation of the necessary gravity and flow regime dependent closure laws.

While the emphasis of the SWG is on the use of a Rankine cycle power plant in space, the computational capabilities that will result should also give NASA predictive capabilities which can be used for the design, scale-up and assessment of other important multiphase systems and processes that may be used in space (e.g., evaporators, multiphase thermal buses, electrolysis units, material processing units, life support units, etc.).

In any event, in order for the proposed research program to be successful, NASA will need to restructure its strategy on funded research to focus on the applied programmatic research needs of their new mission [Bush, 2004].

4.0 RECOMMENDATIONS FOR RESEARCH PROGRAM IMPLEMENTATION

Many of the microgravity research programs that have been funded by NASA in the past have taken advantage of a reduced gravity environment to further our understanding of fundamental phenomena. While this has been a successful scientific research program, very little engineering research has been conducted for the purpose of supporting the mission-oriented needs of NASA. Moreover, while the NRA and peer review processes that have been set up by NASA were appropriate for stimulating and evaluating individual scientific proposals, they are not necessarily appropriate for the conduct of well-coordinated programmatic research. In fact, it is

very unlikely that NRA solicited individual research programs will satisfy the mission-oriented research needs of NASA.

As was noted previously, the research programs which are discussed in Section 3 are inherently interdisciplinary and, to be successful, must be conducted by a <u>team</u> of specialists in multiphase flow and heat transfer experimentation and modeling. In addition, the experimental and analytical research tasks to be performed by this interdisciplinary team of specialists needs to be very well coordinated and directed by NASA.

Industry and other government research agencies, such as the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR), regularly engage in programmatic research of this type. These agencies typically request or invite the formation of appropriate research teams and solicit research proposals from one or more of these teams. Research is initiated based on an <u>internal</u> review and assessment of the team's capabilities and the responsiveness to the sponsor's needs of the proposed research. The sponsor, or its designee, continuously evaluates the performance of the research team or teams through yearly programmatic meetings and the peer reviewed technical publications which result from the research being performed. The process is a dynamic one where research directions are changed as required to accomplish mission goals. The researchers who are involved in such programs normally find this an exciting and rewarding way to do research because they all are on the critical path and peer pressure among team members encourages superior performance.
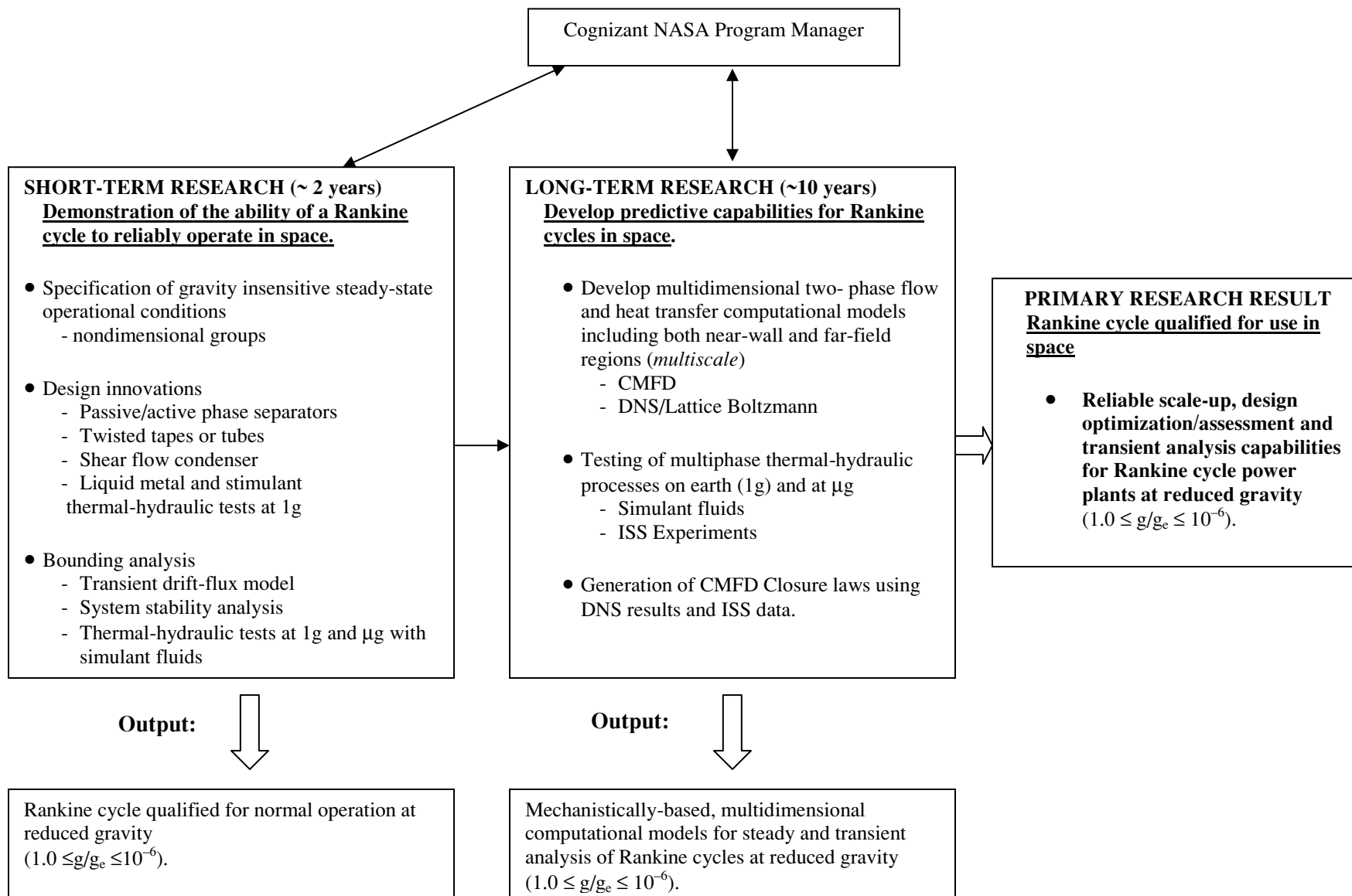
This type of research implementation process has been highly successful and is recommended for consideration by NASA to conduct the proposed research programs in support of the use of a Rankine cycle power plant in space.

5.0 SUMMARY AND CONCLUSIONS

Table I summarizes the proposed research plan. The R&D program has been partitioned into short (~ 2 year) and long term (~ 10 year) research programs. It is anticipated that the various tasks will be coordinated and managed by a cognizant NASA program manager or their designee.

It should be noted that the proposed research program is intended to demonstrate the capability of a Rankine cycle power plant to reliably operate at reduced gravity. To be successful, this program will require the active participation of a dedicated NASA program manager and many of the best multiphase researchers in the country. However, its success is the <u>only</u> <u>way</u> that NASA will ever be able to seriously consider the extensive use of multiphase systems and processes in space; in particular, the use of a Rankine cycle power plant.

Table I. Research Program in Support of the Use of Rankine Cycle Power Plants in Space

Cognizant NASA Program Manager

SHORT-TERM RESEARCH (~ 2 years)
Demonstration of the ability of a Rankine cycle to reliably operate in space.

- Specification of gravity insensitive steady-state operational conditions
  - nondimensional groups

- Design innovations
  - Passive/active phase separators
  - Twisted tapes or tubes
  - Shear flow condenser
  - Liquid metal and stimulant thermal-hydraulic tests at 1g

- Bounding analysis
  - Transient drift-flux model
  - System stability analysis
  - Thermal-hydraulic tests at 1g and μg with simulant fluids

LONG-TERM RESEARCH (~10 years)
Develop predictive capabilities for Rankine cycles in space.

- Develop multidimensional two- phase flow and heat transfer computational models including both near-wall and far-field regions (*multiscale*)
  - CMFD
  - DNS/Lattice Boltzmann

- Testing of multiphase thermal-hydraulic processes on earth (1g) and at μg
  - Simulant fluids
  - ISS Experiments

- Generation of CMFD Closure laws using DNS results and ISS data.

PRIMARY RESEARCH RESULT
Rankine cycle qualified for use in space

- **Reliable scale-up, design optimization/assessment and transient analysis capabilities for Rankine cycle power plants at reduced gravity** $(1.0 \leq g/g_e \leq 10^{-6})$.

Output:

Rankine cycle qualified for normal operation at reduced gravity $(1.0 \leq g/g_e \leq 10^{-6})$.

Output:

Mechanistically-based, multidimensional computational models for steady and transient analysis of Rankine cycles at reduced gravity $(1.0 \leq g/g_e \leq 10^{-6})$.

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13. ABSTRACT *(Maximum 200 words)*

This is the report of a Scientific Working Group (SWG) formed by NASA to determine the feasibility of using a liquid metal cooled nuclear reactor and Rankine energy conversion cycle for dual purpose power and propulsion in space. This is a high level technical report which is intended for use by NASA management in program planning. The SWG was composed of a team of specialists in nuclear energy and multiphase flow and heat transfer technology from academia, national laboratories, NASA and industry. The SWG has identified the key technology issues that need to be addressed and have recommended an integrated short term (~2 years) and a long term (~10 year) research and development (R&D) program to qualify a Rankine cycle power plant for use in space. This research is ultimately intended to give NASA and its contractors the ability to reliably predict both steady and transient multiphase flow and heat transfer phenomena at reduced gravity, so they can analyze and optimize designs and scale-up experimental data on Rankine cycle components and systems. In addition, some of these results should also be useful for the analysis and design of various multiphase life support and thermal management systems being considered by NASA.

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