CONF-840113--9

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Abbreviated Title: I & C Evaluation for Space Nuclear Power

CONF-840113--9

DE85 000983

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Prepared for the First Symposium on Space Nuclear Power Systems, Albuquerque, New Mexico, January 11-13, 1984

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U. S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-840R21400

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ABSTRACT

Design of control and protection systems should be coordinated with the design of the neutronic, thermal-hydraulic, and mechanical aspects of the core and plant at the earliest possible stage of concept development. An integrated systematic design approach is necessary to prevent uncoordinated choices in one technology area from imposing impractical or impossible requirements in another.

Significant development and qualification will be required for virtually every aspect of reactor control and instrumentation. In-core instrumentation widely used in commercial light water reactors will not likely be usable in the higher temperatures of a space power plant. Thermocouples for temperature measurement and gamma thermometers for flux measurement appear to be the only viable candidates. Recent developments in ex-core neutron detectors may provide achievable alternatives to in-core measurements. Reliable electronic equipment and high-temperature actuators will require major development efforts.

*Operated by Martin Marietta Energy Systems, Inc. under contract DE-AC05-84OR21400 with the U. S. Department of Energy.

INTRODUCTION

Because of the severe environment and the inaccessability, early space nuclear power reactor concepts and designs used the absolute minimum of control and instrumentation sophistication. SNAP-10A, for example, had no provisions for orderly reactor shutdown and restart. Clearly the missions now being considered demand a much higher level of load maneuverability and controllability with appropriately higher levels of mission (and public) protection.

METHODS

STRATEGY - Previous experience in designing advanced reactor systems for any application, ground or space, has shown the need for coordination of the control and protection systems design with the neutronic, thermal-hydraulic, and mechanical aspects of the core and plant design at the earliest possible stage of concept development. The detailing of performance requirements and the development of a comprehensive control strategy is important to establish the requirements and limitations of major plant components, as well as to define the instrumentation and control component requirements. This need may seem obvious, but it is often neglected or deferred in program planning. A well integrated systematic design approach is vital for this application where the state of the art is being pushed in many technology areas. Close coordination is necessary to prevent uncoordinated choices in one area from imposing impractical or impossible requirements in another. Methods to formalize the integrated approach to advanced power plant design are in development (Kisner 1983).

PERFORMANCE GOALS - A large power plant is likely to require assembly and deployment from a shuttle vehicle. This could both simplify and exascerbate safety and control problems. Launch safety requirements would likely be more severe, but manual removal of extra poisons to provide this additional safety would be possible. (Harms 1983), (Jones 1984). After assembly and deployment, the plant will probably require completely unattended startup. This would include preheating and initial thawing of liquid metal coolants, heat pipe initiation and possibly vapor lock release, gradual system heatup to avoid excessive thermal shock, and some degree of restart or realignment capability should startup problems be encountered.

The next, or perhaps concurrent, stage would include initial criticality, power escalation and load assumption. Load management requirements are sure to be more demanding than for previous concepts,

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ORNL capability and interest - A number of research and demonstration reactors have been designed and built by ORNL which exhibit high performance and availability with many advanced features and high degrees of automation (Binford 1968). In addition, considerable experience has been acquired on liquid metal and molten salt systems for high temperature operation (Yarosh 1968). Development work has continued on many detector types for high temperature applications (Valentine 1983). An integrated instrumentation and controls organization provides experience and expertise for the solution of a wide range of I&C problems, that include automation, computerization, robotics, analysis, and detection, as well as process and reactor control (Sadowski 1981).

including a substantial degree of load following and stable operation for unanticipated load changes. Fast or short-term load changes are probably best accomodated in power conditioning equipment with temporary energy dump to radiators. For long term missions it may be necessary to measure and adjust reactor power level and flux distribution to optimize burnup and extend core life. Long periods of low power or standby operation are anticipated with capability for rapid restart to full load conditions. Longer periods of cold shutdown or "dormancy" may be required, with attendant capability for restart from cold conditions.

It will be highly desirable to continue or initiate operation, even with the plant in a degraded state resulting from limited failures, such as partial failure of heat transfer systems, control element malfunctions, non-uniform burn-up, or other unanticipated events.

Some of the performance goals which will have a profound effect on control strategy are enumerated:

- An unattended startup from a cold, safe condition.
- Complex monitoring and control systems for reactor startup and/or setback due to changing mission load requirements.
- Restart capability from various initial conditions because of the unknown length of the mission, and the possibility of long periods of dormancy.
- Stable control under anticipated or unanticipated load changes.

- Additional reactivity control during launch to protect against criticality upon possible immersion or compaction as a result of launch failure.
- Provisions for continued operation with limited failures, such as partial failure of heat transfer systems, stuck control elements, non-uniform burn-up, or other unanticipated events.

RESULTS

Instrumentation needs for effective reactor control and protection typically include both in-core and ex-core sensors and associated signal processing systems. Reactivity and process control actuators are also a part of the integrated system considerations for I&C design This evaluation will concentrate on in-core detectors.

IN-CORE INSTRUMENTATION - STATUS

TEMPERATURE - Temperature measurements are widely used to monitor the thermal power in nuclear reactors and to monitor and control processes in nuclear power plants. Process temperatures rarely exceed 900 K, but coolant exit and in-core temperatures range from about 600 K in light water plants to 900 K in LMFBR's to 1300-1400 K in gas cooled reactors. Experiments on fuel irradiation have required temperature measurements in high neutron fluxes at temperatures as high as 2700 K.

Operating temperatures as high as 1500 K are anticipated for initial space power plant designs and even higher temperatures for later, higher powered concepts. Base metal thermocouples, usually chromel/alumel, have shown acceptable accuracies of better than 1% for periods of 5000-10,000 hrs at temperatures up to 1000 K and have been used for shorter periods of time up to about 1500 K. Chromel/alumel has been shown to be highly radiation resistant by in-pile experiments. For higher temperatures, conventional platinum/rhodium and tungsten/rhenium thermocouples have been used up to 2100 K and 2700 K respectively, but they decalibrate with radiation exposure due to the transmutation of the elements rhodium and rhenium which have large neutron cross sections. ORNL has investigated other platinum alloys using low cross section materials and has had some success with platinum/rhuthenium/molybdenum thermocouples up to about 1800 K (Sadowski 1981). There is active development of nicrosil/nisil, an improved base metal thermocouple that should extend the range over chromel/alumel by several hundred kelvins. Experience has shown that serious thermometry problems can arise if sensors and installation geometries are not carefully selected (Anderson, R. L. 1982). Sheathed thermocouples subjected to extended exposure to temperatures in excess of 1200 K may have shortened lifetimes and significant degradation in accuracy. There are several mechanisms which combine to account for these potential failures and uncertainties. Contributing mechanisms are:

1. Reactions of the thermoelements with sheath and insulation materials.
2. Degradation of the insulation at high temperature.

3. Breakage of the thermoelements.

4. Electrical shunting.

5. Formation of virtual junctions.

6. Grain growth in the thermoelements.

Thermoelectric inhomogeneities can be introduced in the thermoelements by physical changes such as cold working, bending or stressing (Mossman 1982). The errors caused by such changes are usually less than 10 K. A more serious decalibration problem can be brought about at high temperatures by complex chemical interactions between the components. Even though the wires and sheaths are physically separated, exchange of constituents can occur by diffusion through the compacted oxide insulation. These irreversible changes can cause errors of hundreds of degrees at the high temperatures of concern. The choice of sheath material, therefore, becomes critical to the performance of metal-sheathed thermocouples at high temperatures. Use of a sheath material with a composition similar to the thermocouples alloys is essential at temperatures above 1275 K.

Small diameter (0.5 mm-diam or less) sheathed thermocouples have a higher failure rate than thermocouples of large diameter. As the wires are made smaller by repeated drawing and annealing, the grain size may become comparable to the wire diameter and grain boundaries may extend completely across the diameter of the wire. The boundaries are inherently weak and are likely to fracture due to the stresses caused by differential thermal expansion. Consequently, sheathed thermocouple assemblies with less than 3 mm diameter are likely to have very limited life at temperatures above 1400 K.

No gross effects on thermocouples output are caused by the presence of radiation fields (Kelly 1962). However, high radiation exposure will limit the types of insulation which may be used. Refractory metal oxides are the most satisfactory insulating materials for both high radiation and high temperature. Transmutation and nuclear alloying can become significant in thermocouple which remain in high flux for long periods of time. The most popular materials for present high temperature thermocouples have large nuclear cross sections and are significantly effected. Some of these materials have a natural isotope with a much lower cross section. Use of these isotopes could improve radiation life, but would be quite expensive. Other types of temperature sensors have been investigated for high temperature and high radiation environments:

- Ultrasonic thermometers have been tested in radiation environments to 2700 K by ORNL, SNL, and INEL, but have shown large decalibration due to neutron transmutation. Other mechanical problems were encountered (Shepard 1974), (Carlson 1979).
- Johnson noise thermometry has been used in irradiation experiments at ORNL to about 1900 K and at Julich (FRG) to 2100 K. The noise thermometer is inherently immune from irradiation decalibration and aging drift (Blalock 1983).
- An optical radiation thermometer was recently developed by NBS that uses a quartz fiber waveguide and is highly accurate to about 2200 K. No information is yet available on the radiation stability of the quartz fiber, but the possibilities should be investigated (Dils 1983).

° Fluidic and other flowing gas thermometers were investigated for the NERVA nuclear rocket project and offer some possibilities for largely non-electrical temperature monitoring and control systems (Halbach 1969).

Although the technology is reasonably well established, it will be necessary to select, develop and qualify temperature monitoring systems for the specific anticipated space environments of 1600 K and signal processing temperatures as high as 575 K. Accuracy, response time, duration, stability, nuclear environment, size, weight, vibration and power limitations, which can effect the choices, have not been defined.

Thermocouples essentially respond to a temperature difference between measuring and reference junctions. A major design constraint for this program would be establishing and maintaining reference junction temperatures with signal processing electronics operated at up to 575 K within the desired accuracy.

IN-CORE FLUX MONITORING - In-core flux monitors have been used in commercial reactor control and protection systems since they first became operational in the 1960's. Three of detectors are in current use. These are 1) the fission cham... (FC), 2) the self-powered neutron detector (SPND), and 3) the gamma thermometer (GT). FC's or SPND's are used in virtually every commercial power reactor and have been quite successful, but are not without problems (Knoll 1979), (Kroon 1983).

FISSION CHAMBERS - Fission chambers are presently limited to temperatures of about 1000 K because of disassociation of the necessary filling gas, plating difficulties with adherence of the fissile material, and insulator integrity and noise related to dielectric breakdown. In addition, the fission chamber suffers rapid burnup of the fissile material in high flux in-core applications. This problem has been alleviated in recent years by combining fertile material with the fissile material to extend the useful life by regeneration. The most common materials are 234-U/235-U. 238-U/239-Pu is also used, but has no advantages over the U/U type which is easier to manufacture. Regenerative fission chambers are used extensively in Boiling Water Reactors (BWR's) for both protection and control. Regeneration enhances the useful life by about a factor of 3 and is quite cost effective for BWR's. A serious problem with in-core fission chambers for space reactor applications is their continuous decalibration with burnup. The sensitivity degrades non-linearly with fluence, even with regeneration, above a threshold value. This deficiency is circumvented in commercial BWR's by frequent recalibration. Such recalibration is not likely to be possible or practical in space applications. Most fission chambers are thermal neutron detectors and their efficiency is significantly lower in the fast spectrum anticipated in space reactors. Fast neutron sensitivity can be improved by using 238-U. The most limiting developmental problem, however, remains the low operating temperature. Considerable development has been done to extend the useable temperature range, but a major breakthrough is necessary for operation above 1000 K. Existing chambers are not reliable above 850 K.

SELF POWERED NEUTRON DETECTORS - SPND's depend upon the beta emission or secondary electrons from gamma emission resulting from neutron capture in a variety of high cross section materials. Burnup is also a problem, as with the fission chamber, and decalibration occurs with fluence in a complex fashion (Kroon, 1983). Different burnup rates are achievable for the different possible emitter materials. Emitter materials which can tolerate high temperatures can be employed, but because very small currents are produced at high impedance, insulator quality at high temperatures is a very serious problem. Presently, SPND's are not reliable above about 1050 K. All of the SPND's in TMI-2 failed completely at temperatures below 1500 K. As with the fission chamber, something of a breakthrough is necessary in high temperature, high impedance, high radiation insulator technology in order to significantly extend the operating temperature of SPND's. A further disadvantage of most SPND's is slow response time.

GAMMA THERMOMETERS - The GT is basically a differentially connected thermocouple pair which senses the gamma heating of a metal mass in relation to a nearby gas volume (Waring, 1983). The operating life in the in-core environment should be similar to thermocouples alone. The materials used for gamma absortion do not experience significant burnup so that decalibration with fluence is not a serious problem. Although the concept is not new, GT's have not found wide application in commercial reactors and have been used primarily in a few research reactors, both in the United States and abroad. The capability for operation at high temperatures is apparent, but application experience is very limited and further development would be necessary to assure reliable operation in space reactor conditions. Disadvantages are the lack of neutron sensitivity and slow response time. The gamma thermometer is probably the only viable candidate for an in-core radiation sensor for the near-term space reactor program.

ALTERNATIVES TO IN-CORE INSTRUMENTATION - The anticipated high temperatures in the core of a space power plant and the general unavailability of suitably reliable high temperature detectors leads to the obvious consideration of alternatives. The fast neutron spectrum and interference with reloading and breeding brought about similar considerations for the breeder reactor program and development was initiated for high sensitivity fission chambers to infer in-core conditions with ex-core measurements. An ultrahigh-sensitivity fission counter has been developed which might have direct applicability to the space power reactor (Valentine 1983). The counter has a sensitivity of 50 cps/nv in gamma backgrounds of up to 50,000 R/h and will operate in temperatures of up to 500 K. A detector of this type could be used to monitor the startup and low power operation of a space power plant.

A related development has produced a position-sensitive fission counter for in-core flux profile monitoring in light water reactors (LWR) (Kopp 1983). Currently, profiles are measured with multiple or movable detector assemblies. The new position-sensitive detector measures profile by delay-line position encoding and time interval decoding of individual fission pulses from a number of small fission counters incorporated along a coaxial transmission line. Significant improvement in spatial resolution is achieved and only one cable penetration is required. Like other in-core fission chambers, this detector will not be useable above about 850 K, but may find important application in less severe, but still demanding ex-core applications. A long life, fast spectrum core will likely require burnable poisons and knowledge of flux distribution may become essential.

DISCUSSION

<u>DEVELOPMENT REQUIREMENTS</u> - The I&C development requirements fall into four major categories. 1) High temperature electronics will be needed with operational capability up to about 575 K. Even higher operating temperatures are desirable, but such development in a compatible time frame is unlikely. This means that the electronics package will require cooling. Significant advancement in the current capability is necessary to achieve even 575 K. 2) Several types of sensors will be required for a more sophisticated control strategy. These will include nuclear, temperature, flow, pressure, level, displacement, and perhaps others. All of these will require some development for the application and some will require major advances. 3) Control elements for high temperature, high radiation operation in space present a very demanding development task in the I&C category. Problems of suitable bearings, bearing surfaces, material swelling and binding, motion translation, and prime movers are severe for the imposed environmental conditions. 4) In general, the operating temperatures of all electromagnetic devices is limited by the curie temperature of magnetic core materials.

For commonly used materials, this limiting temperature is approximately 1000 to 1075 K which means that virtually all equipment such as motors, alternators, and solenoids, etc. have to be cooled for the anticipated environments. Substantial development will be required both for high temperature designs and for compatible cooling techniques.

HIGH TEMPERATURE ELECTRONICS

The current capabilities of high temperature electronics can be broadly divided into two categories: 475 K applications and 575 K applications. At 475 K an array of monolithic silicon integrated circuits and hybrid circuits are commercially available with demonstrated mean time to failure (MTTF) of about 10,000 hours and a 1000 hour failure rate of typically 5-10%. Many of the 475 K failure modes have been identified but the necessary improvements have not been commercialized due to low market demand (Jurgens 1982). Most military space electronics are currently limited to derated junction temperatures in the 375K - 400K range.

Sophisticated wireless in-core neutron monitoring systems capable of operating at 505 K have been developed at ORNL. Some of the electronic functions required for a complete 475 K reactor instrumentation and control system, such as mircrowave transmitters, high power rectifiers and digital LSI, are not presently available and in fact have not been the object of sustained high temperature research. A fully funded development lead time of 3 to 4 years would be required to fill these gaps and upgrade the 1000 hour reliability of a 475 K system.

Beyond 475 K, the MTTF decreases rapidly. A common rule of thumb is that the rate of degradation doubles every 10 K above 475 K. A 575 K system would not be reliable beyond about 100 hours without major advances in the present state of the art of semiconductor physics.

Although the operation of a few 575 K integrated circuits has been demonstrated, the failure mechanisms are not sufficiently understood. Capacitors with values greater than 0.1 microfarads required for power supply ripple filtering are a major problem at 575 K. An operational 575 K system with suitable 100 hour reliability would probably require a development lead time of at least 5 to 7 years with total funding in the order of $10 million.

State-of-the-art radiation hardened microelectronics can function to 10E5 to 10E6 Rads gamma and to 10E13nv neutrons. These limits can perhaps be extended by a factor of 10 at operating temperatures above 475 K due to high temperature annealing effects.

Other possibilities for high temperature electronics include GaAs semiconductors and ceramic vacuum tubes. Vacuum tubes have been tested to as high as 485 K. More recent work on monolithic vacuum tubes may provide additional choices. Technology and development emphasis for these devices is very limited, but promising. Magnetic devices can operate as high as 775 K.

In summary, to achieve reliability, it appears that the operating temperature of the electronics package should be as low as possible. Conceivable operation of circuits at 475 K is feasible with perhaps reasonable MTTF. Since operation at temperatures beyond 525 K has not been amply demonstrated with a high degree of reliability, it is almost certain that additional power for cooling (e.g., thermoelectric coolers) will be necessary to keep critical temperatures below this value. It may be possible, ultimately, to achieve reasonably reliable 575 K operation of electronic devices, however the program to develop this capability will be long and expensive. For initial applications it may be prudent and economical to provide shielded and cooled locations for most electronic equipment.

PROCESS SENSORS - The same general observations made for temperature channels, i.e., that both the sensor and signal processor require development to meet the system environmental conditions, apply to the measurement of other process variables in a reactor control system that includes flow, pressure, displacement, flux, and level signals. Each of these variables can be obtained and processed electrically, but all require high temperature sensors and processors. An alternate strategy employing optical or pneumatic signal sensing, transmission, processing and actuation should be evaluated.

CONTROL ELEMENTS - Perhaps the single most demanding controls development task is that of developing actuators for high-temperature, high-radiation operation in space. The problems of suitable bearings, bearing surfaces, motion translation to rotary or linear devices, materials swelling and binding, and prime movers are severe for the imposed environmental conditions (Anderson, R. V. 1982).

Testing has been performed on control elements for several thousands of hours in typical reactor environments with temperatures in the range of 600 K to 900 K. The expected reactor outlet temperature for multimegawatt applications is about 2000 K, implying that actuators capable of operation at temperatures in excess of that which has been previously tested will be required. This will require development in virtually all material areas. Because of the severe environmental conditions, conventional actuators, even of the most advanced types may prove unacceptable for high power space applications. Therefore, innovative reactivity control techniques need to be explored for this application.

CONCLUSIONS

Previous experience in designing advanced reactor systems for both space and ground applications has shown the need for coordination of the control and protection systems design with the neutronic, thermal-hydraulic, and mechanical aspects of the core and plant design at the earliest possible stage of concept development. A well integrated systematic design approach is vital for this application where the state of the art is being pushed in many technology areas, to prevent uncoordinated choices in one area from imposing impractical or impossible requirements in another.

In-core instrumentation adaptable for use in high temperature space reactors will likely be limited to thermocouples and gamma thermometers. Developmental breakthroughs would be needed to apply other types of detectors currently used in commercial light water reactors. Electronic equipment will need to be protected from high temperatures and high radiation fields to achieve reasonable reliability. Based on previous experience with both space and ground based reactor systems, control actuators for high temperature applications in the reactor and process systems will require intensive development effort. Alternative control schemes to mechanical actuators are worthy of careful consideration.

ACKNOWLEDGEMENTS

The information contained in this evaluation was obtained from numerous open literature sources. Interpretations and conclusions are those of the authors of this paper.

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