# FINAL TECHNICAL REPORT

1) **DOE Award Number:** DE-FG07-05ID14694
**Recipient:** Texas Engineering Experiment Station
**Project Title:** Application of Entry-Time Processes in Asset Management for Nuclear Power Plants
**Principal Investigator:** Paul Nelson
**Consortium/Teaming Members:** NA

2) **Distribution Limitations:** All publications listed below, and submitted separately, are copyrighted by their respective publishers, of which there are several and various. Distribution should be limited accordingly, in view of prevailing law.

3) **Executive Summary**: A mathematical model of entry-time processes was developed, and a computational method for solving that model was verified. This methodology was demonstrated via application to a succession of increasingly more complex subsystems of nuclear power plants. The effort culminated in the application to main generators that constituted the PhD dissertation of Shuwen ("Eric") Wang. Dr. Wang is now employed by ABS Consulting, in Anaheim, CA. ABS is a principal provider to the nuclear industry of technical services related to reliability and safety.

4) **Comparison of accomplishments with goals and objectives:** Stated objectives were:

   **a)** The development and testing of good computational schemes for the solution of the generalized state-transition equations for entry-time processes;

   **b)** Exploration of the applicability of entry time processes in nuclear asset management.

   The first of these objectives was accomplished, as reported in the peer-reviewed publication listed below as 6.a.i. The second was accomplished, and information so generated was disseminated by reporting at various forums well-attended by the nuclear industry, as indicated for publications 6.a.ii and 6.a.iii listed below. This culminated in application to main generators in PhD dissertation of Dr. Shuwen Wang (6.a.iv below).

   **Important Lesson Learned:** This said, there was a significant lesson learned that relates to applicability of the method, and perhaps more significantly to limitations on the use of quantitative methodologies that underlie much of the assessments of nuclear power plants for both reliability and safety. The applicability of these methodologies is limited, as is that of the entry-time methodology, by the limitations on the quantity and quality of data regarding failure of structures, subsystems and components (SSCs). The quantitative limitations stem from the limited number of plants and failures, and the even more limited numbers of any given type of SSCs that have been employed. This is to some extent inherent in the nature of nuclear power plants, although it eventually will be somewhat ameliorated by the shift toward standardized plant designs. However, the qualitative limitations do not arise from any such fundamental limitation. They are rather the consequence of nonuniform standards of reporting incidents, and of the fact that the databases containing such reports are not openly available, so that (e.g.) the university community can readily employ them to develop better quantitative methodologies for the quantitative assessment of reliability and safety issues in nuclear power plants. *It is strongly recommended that government take steps to develop more stringent, uniform and open reporting requirements*. (The close cooperation with the South Texas Project Nuclear Operating Company that this project allowed us to develop partially helped overcome this obstacle, in that we were able to obtain full accurate understanding of incidents at STP. However, they were inherently limited by the same difficulties of understanding as us in regard to incidents at other plants.)

5) **Project summary:** The basic theory of entry-time processes was developed, in the form of an integrodifferential equation that can, in principal, be solved for the time-dependent state probabilities of an entry-time model (inhomogeneous Markov model). A computational method for the solution of this model was verified by comparison to rudimentary hypothetical systems for which the solutions could be checked by alternative methodologies.

**6) Publications and technology developed:**

**a) Publications**

**i)** Paul Nelson and Shuwen Wang, "Dynamic reliability via computational solution of generalized state-transition equations for entry-time Processes," *Reliability Engineering and System Safety*, **92** (2007), 1281-1293.

**ii)** Paul Nelson, Shuwen Wang and Ernie J. Kee (South Texas Project Nuclear Operating Company), "Application of entry-time processes to asset management in nuclear power plants," Proceedings of ICONE14 (International Conference on Nuclear Engineering), Miami, Florida, July 17-20, 2006.

**iii)** Paul Nelson, Shuwen Wang and Ernie J. Kee (South Texas Project Nuclear Operating Company), "Application of Entry-time Processes within Probabilistic Risk Assessment (EPRA)," Proceedings of the 2007 ASME Pressure Vessels and Piping Division Conference (PVP2007), San Antonio, Texas, July 22-26, 2007.

**iv)** Shuwen Wang, *Dynamic Reliability using Entry-time Approach for Maintenance of Nuclear Power Plants*, PhD dissertation (Nuclear Engineering), Texas A&M University, May 2008.

**b) Technology:** A methodology for deterministically calculating plant reliabilities was demonstrated, and shown to be computationally competitive with direct simulation methods.

7) **Computer models:** Research code only. None intended for use by second parties. Mathematical theory based on conservation of probability; i.e., a form of Chapman-Kolmogorov equation for inhomogeneous Markov processes. New insight was denomination in terms of time since last repair (to presumed "good as new" status), termed as "entry time."