Onset of Fatigue Cracking in Through Wall SG Flaws

An Evaluation of Time Dependent Leak Rates

Jim Begley – TCA Solutions

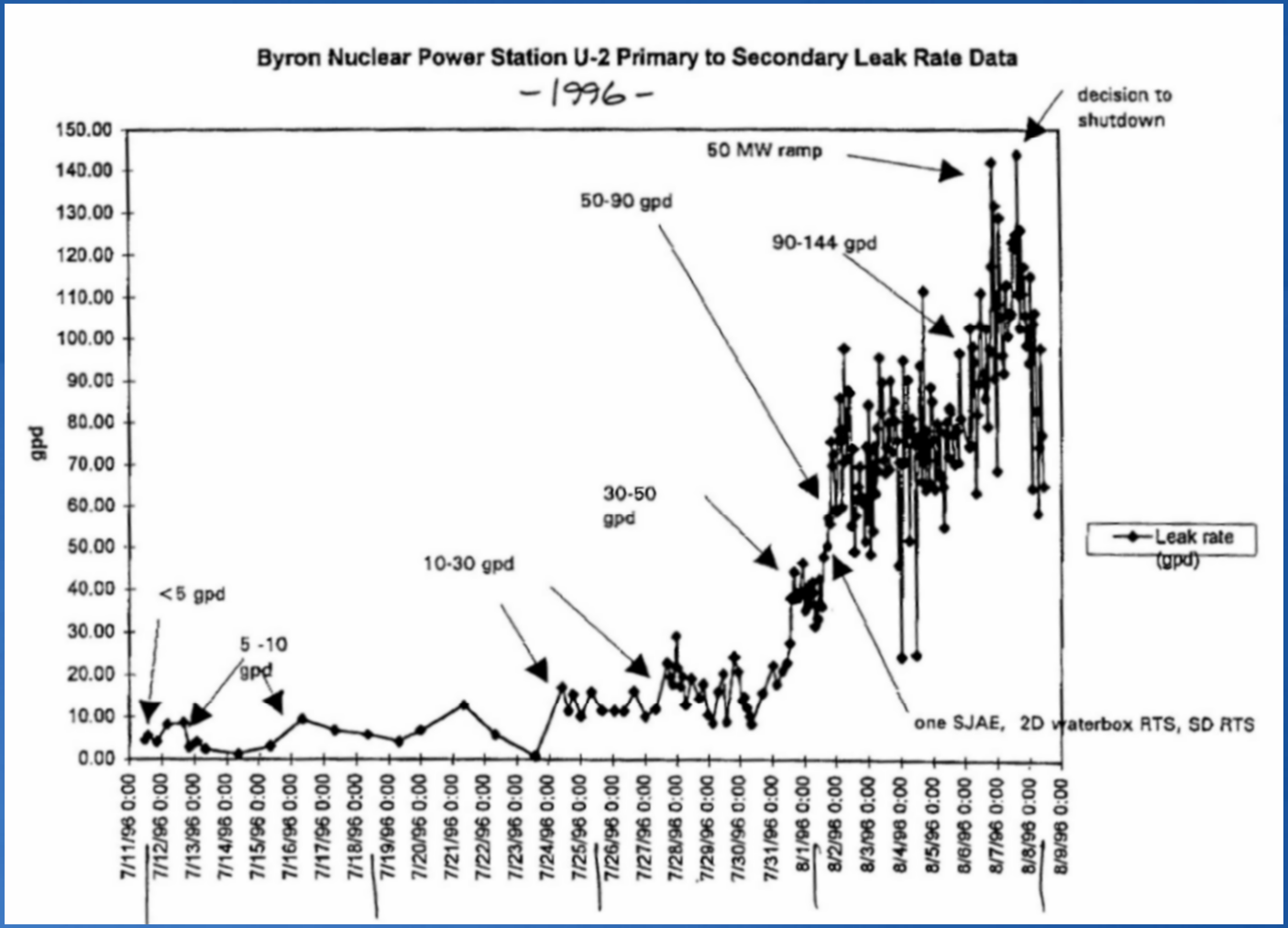
An Evaluation of Time Dependent Leak Rates

- **Argonne National Labs has performed leak rate tests of alloy 600 tubing with lab-grown axial ODSCC flaws and EDM notches**
  - **In some cases dramatic increases in leak rates were observed under nominally constant pressure conditions.**
- **SGMP funded a project to determine the significance of this ANL leak rate test data to the leakage integrity of operating SGs.**
  - **Fractographic studies of some previous leak rate specimens were performed.**
  - **Additional leak rate tests of specimens with sharp fatigue cracks were performed in the ANL High Pressure Blowdown Facility.**

An Evaluation of Time Dependent Leak Rates

- **Time dependent increases in leakage of operating steam generator tubes containing stress corrosion cracks has been observed in the past and interpreted as the gradual failure of small ligaments between crack segments.**
- **Initial ANL leak rate tests raised the possibility of leakage induced fatigue crack growth leading to large increases in leak rates.**

An Evaluation of Time Dependent Leak Rates



An Evaluation of Time Dependent Leak Rates

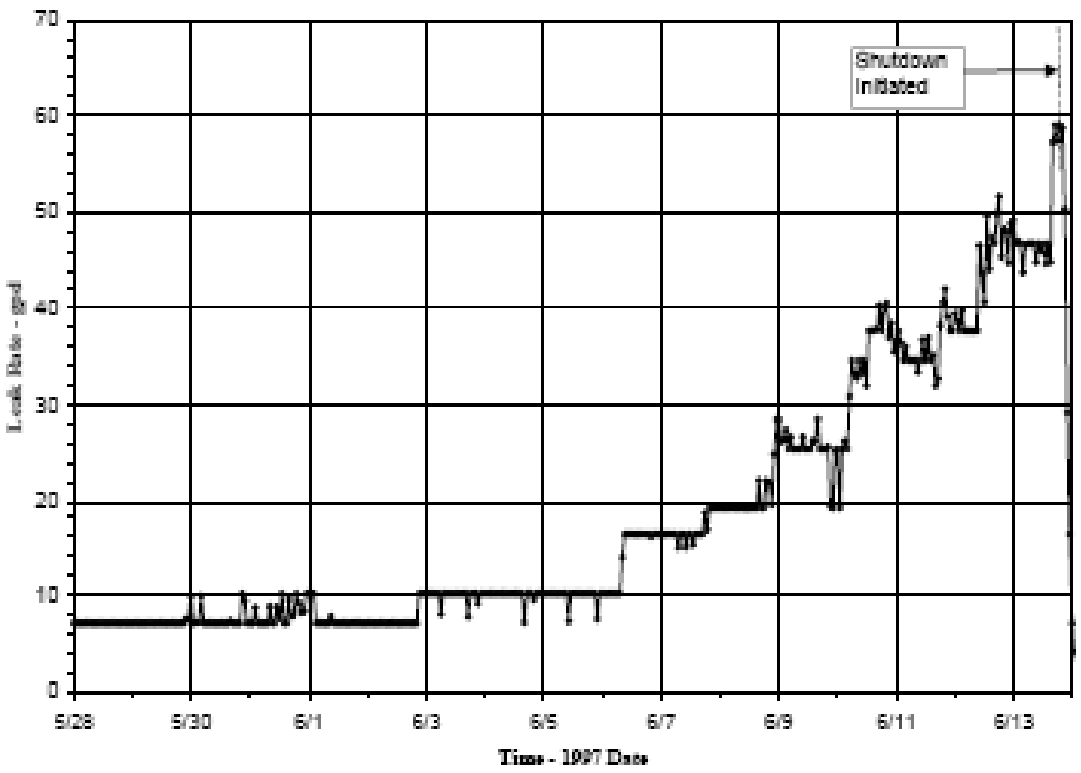
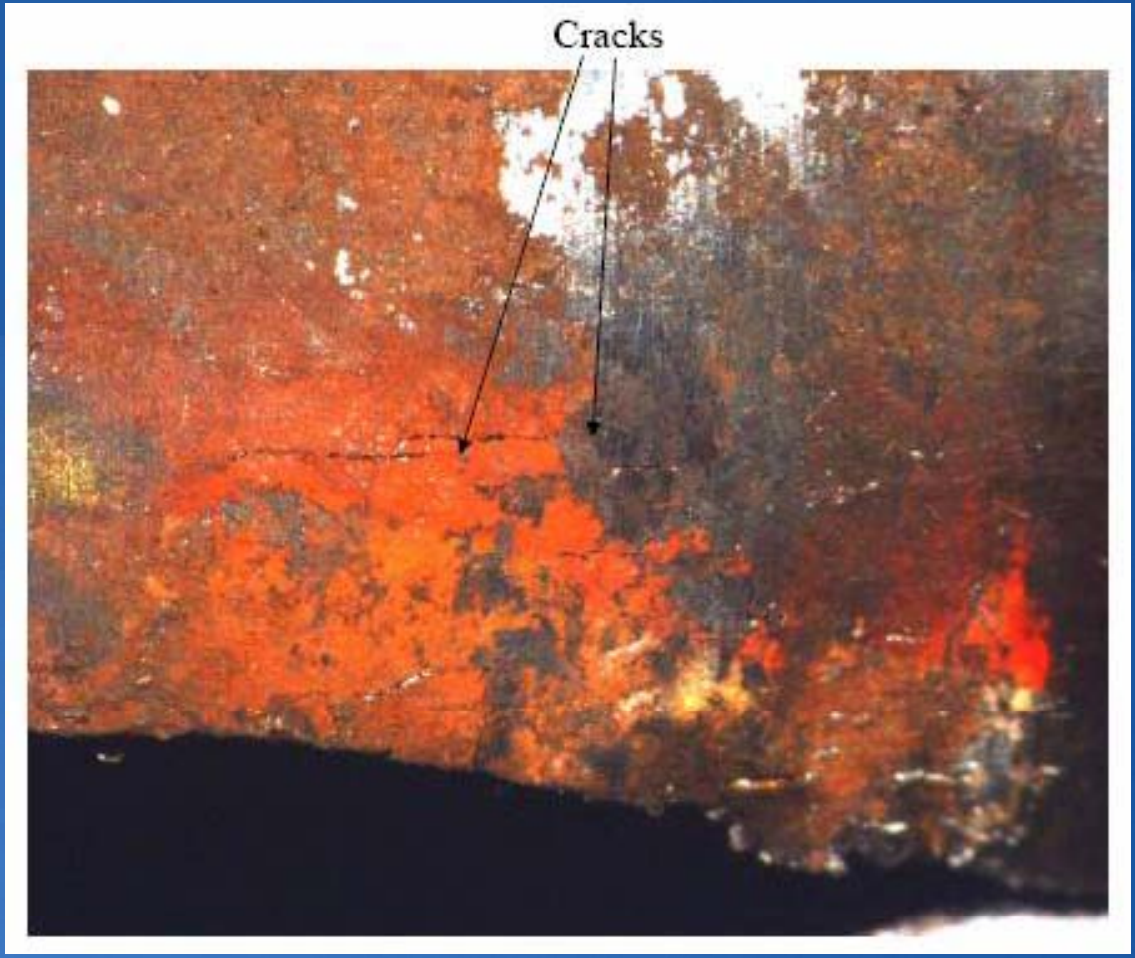


Figure 2-3
McGuire Unit-2 1997 Leak Rate Experience (N-16 Monitor)

An Evaluation of Time Dependent Leak Rates

An Evaluation of Time Dependent Leak Rates

An Evaluation of Time Dependent Leak Rates

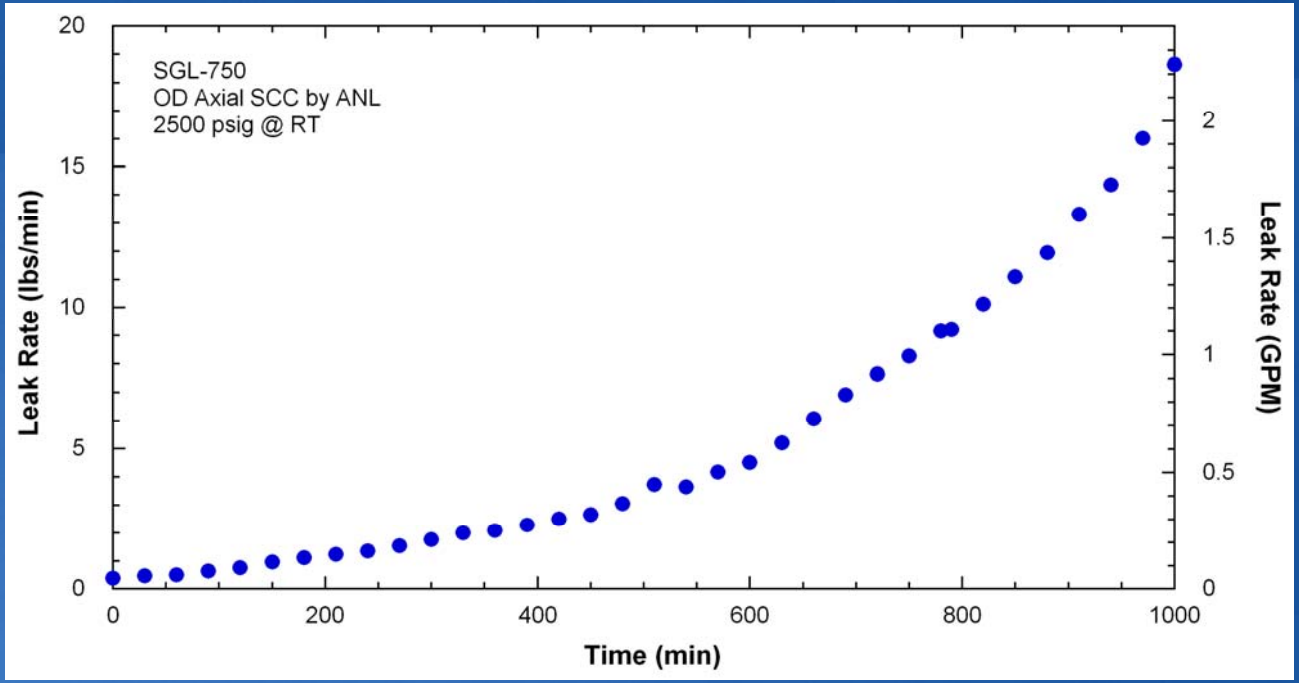


An Evaluation of Time Dependent Leak Rates

- **Five types of crack growth have been identified in ANL leak rate tests:**
  - **Small scale, time independent mechanical tearing of tapered depth ligaments as internal pressure is increased**
  - **Small scale low cycle fatigue failure of small ligaments from stop/start pressurization cycles**
  - **Small scale, time dependent fracture of small ligaments via time dependent plastic deformation at very high stress/strain levels**
  - **Small scale, time dependent fatigue cracking of tapered depth ligaments via pump operation and bypass flow effects in the room temperature, high flow pump test system**
  - **Large scale, time dependent fatigue cracking from fluid jet/structure interactions at high flow rates (?)**

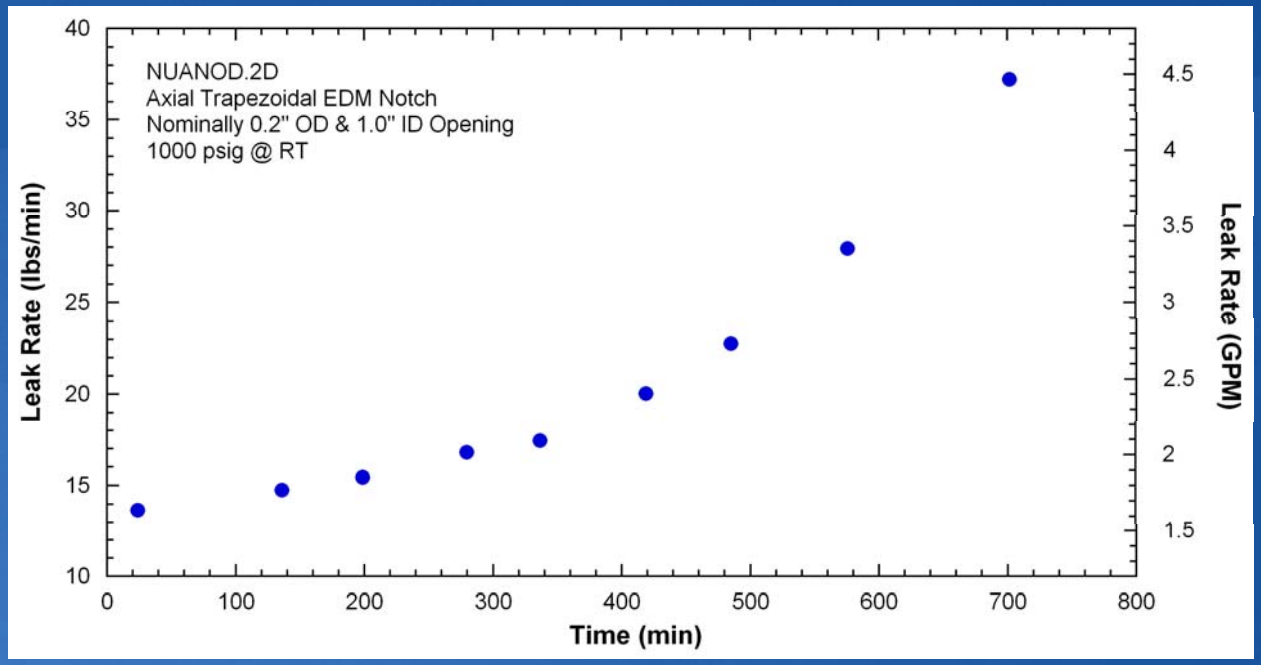
An Evaluation of Time Dependent Leak Rates

- **ANL Room Temperature High Flow Pump**



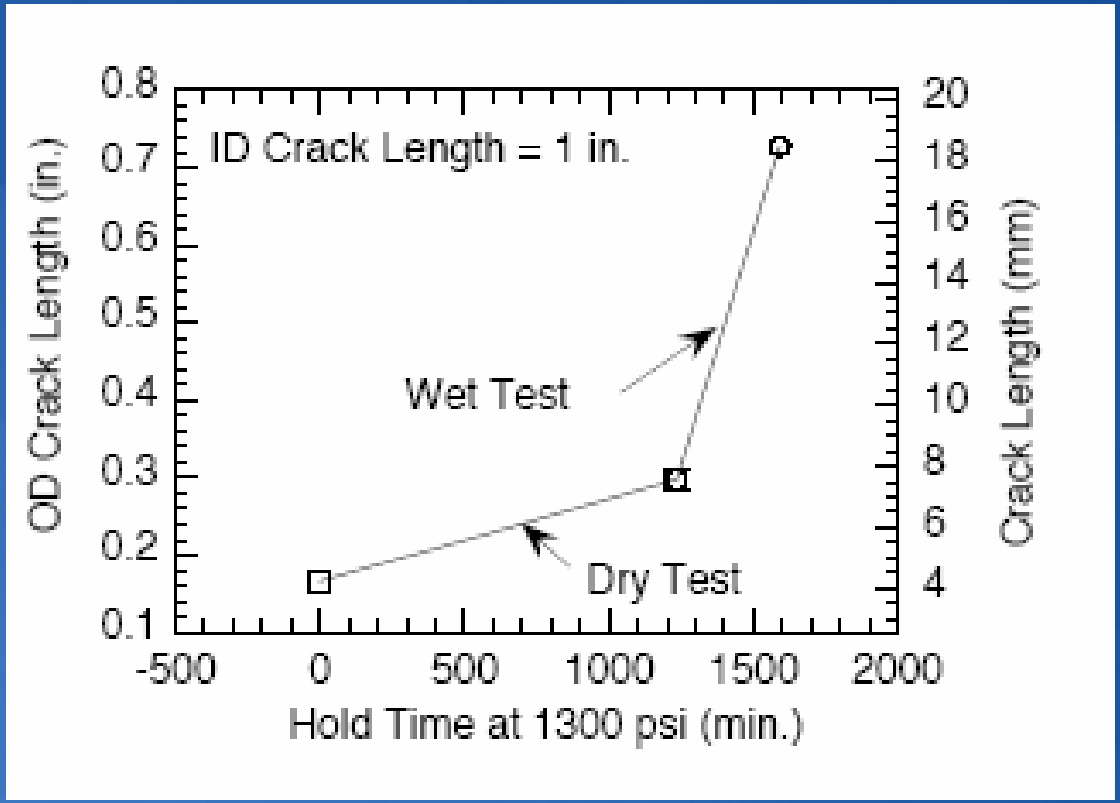
An Evaluation of Time Dependent Leak Rates

- **ANL Room Temperature High Flow Pump**



An Evaluation of Time Dependent Leak Rates

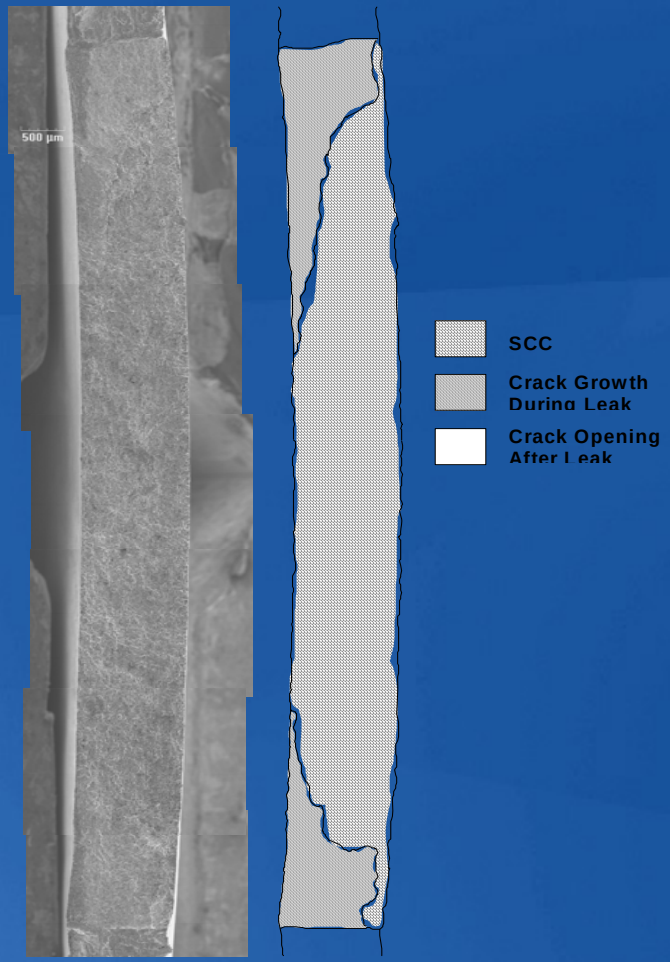
- **ANL Room Temperature High Flow Pump**



An Evaluation of Time Dependent Leak Rates

SGL-750

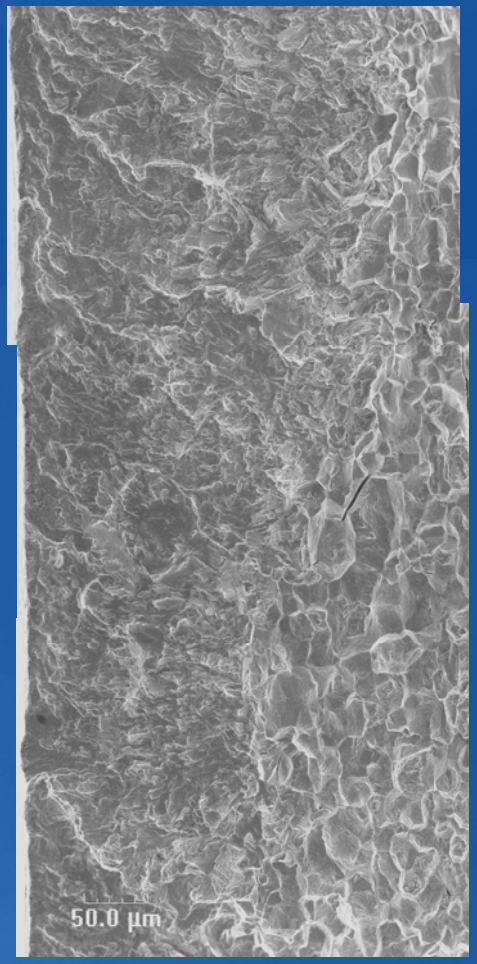
Axial ODSCC



An Evaluation of Time Dependent Leak Rates

SGL-750

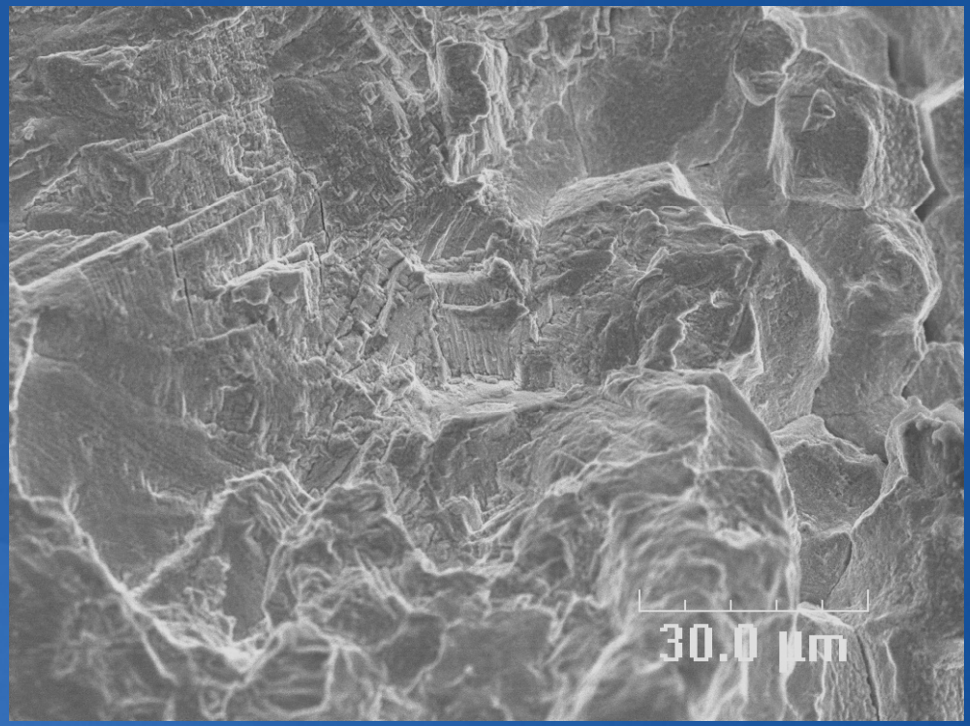
Axial ODSCC



An Evaluation of Time Dependent Leak Rates

SGL-750

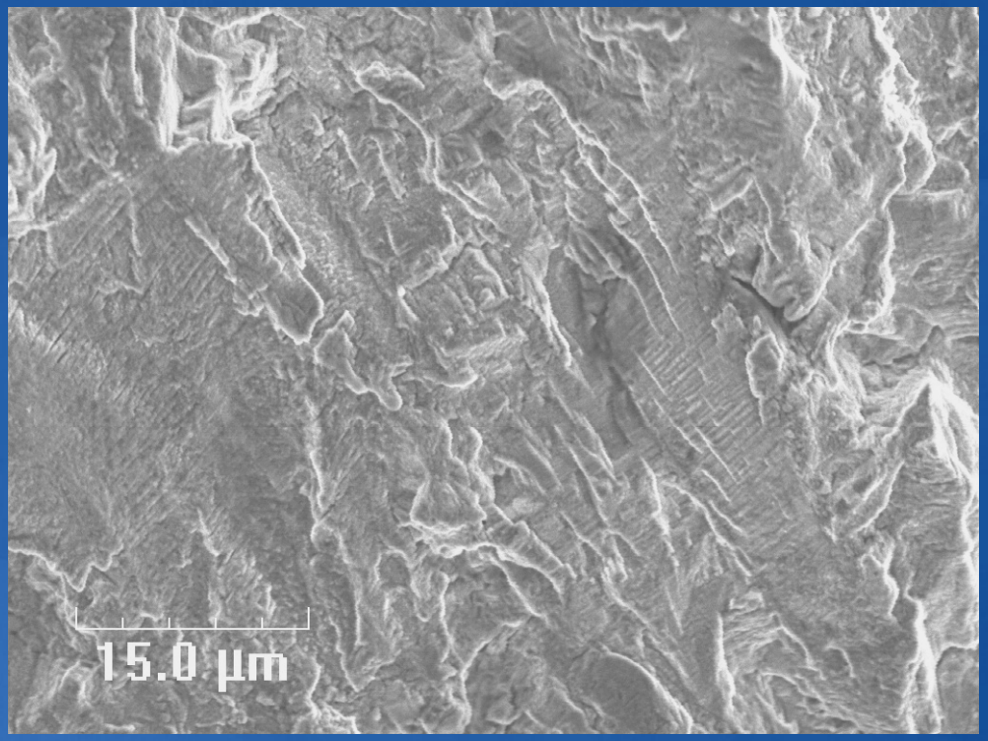
Axial ODSCC



An Evaluation of Time Dependent Leak Rates

SGL-750

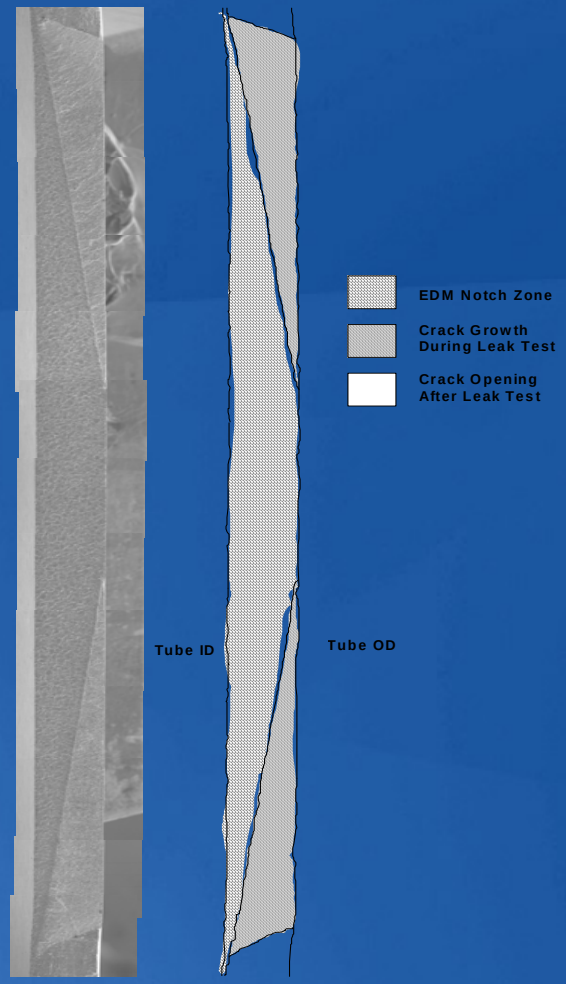
Axial ODSCC



An Evaluation of Time Dependent Leak Rates

NUANOD.2D

Trapezoidal EDM Notch



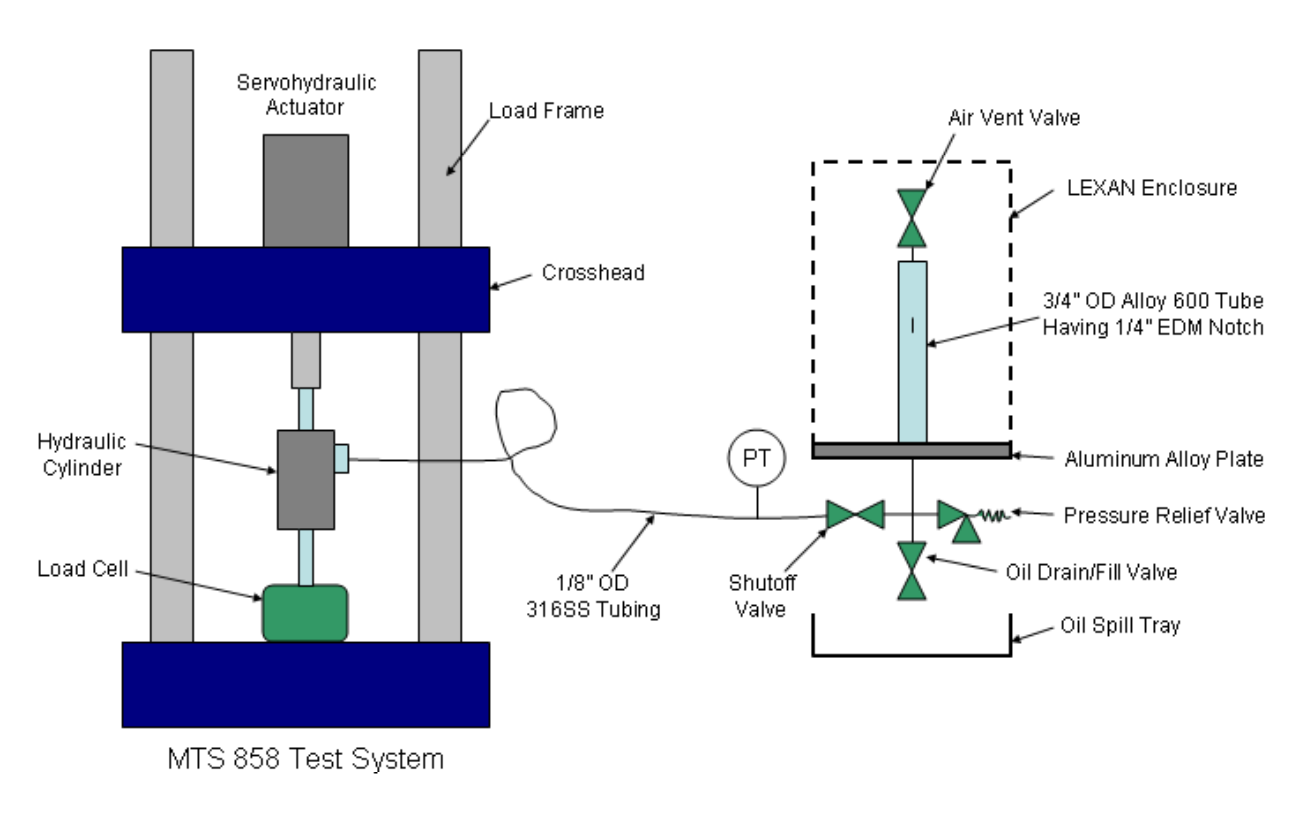
Onset of Fatigue Cracking in Through Wall SG Flaws

- **To perform a leak rate test under absolute constant pressure condition, i.e. no pressure oscillation by a pump, it was decided to use Blowdown Test Facility.**
- **Refurbishment and upgrade of the Blowdown Test Facility was completed in 2010, which was funded by SGMP and NRC.**
- **Leak tests were performed in 2011 at room temperature at a constant pressure of 2500 psig using rectangular axial fatigue crack specimens.**
  - **The time of interest is 1 to 24 hours and the leak rate of interest is 0.05 to 1.5 gpm.**

Onset of Fatigue Cracking in Through Wall SG Flaws

- **Alloy 600 tube specimen is surrounded by six neighboring tubes.**
- **Tube support plates are holding the neighboring tubes.**

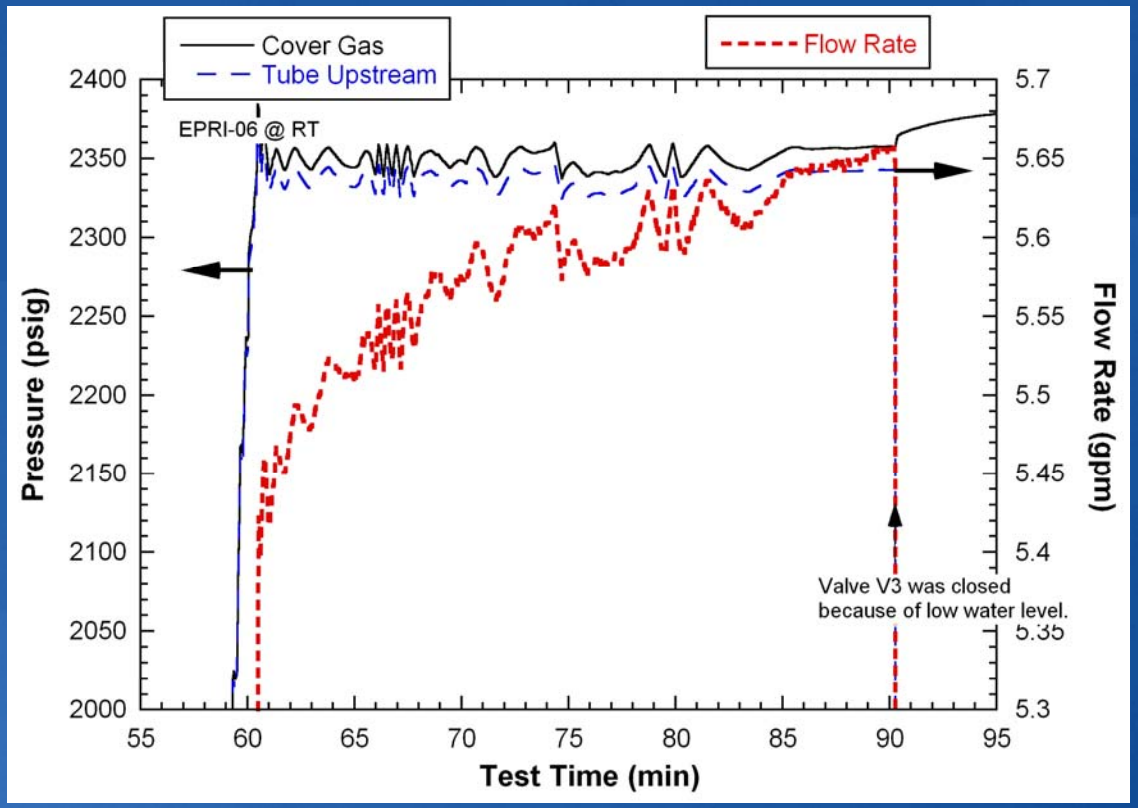
Onset of Fatigue Cracking in Through Wall SG Flaws



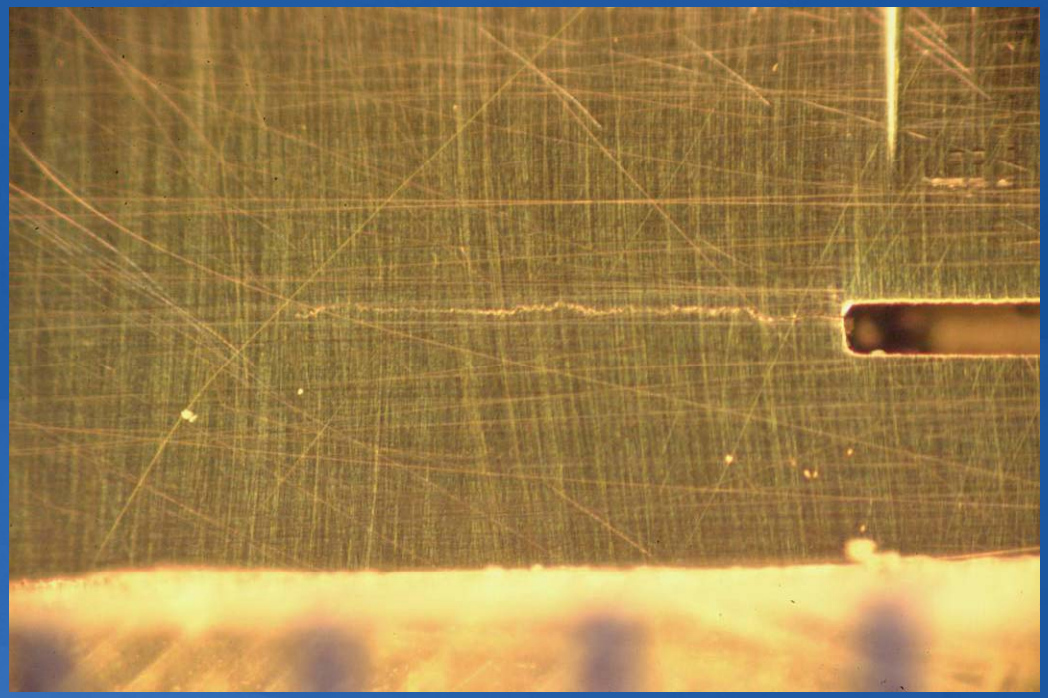
- **Rectangular axial fatigue crack was grown from an EDM starter notch on 3/4” OD Alloy 600 tube specimen**
  - **Hydraulic cylinder generates the pressure oscillation**

Onset of Fatigue Cracking in Through Wall SG Flaws Preliminary Test Specimen

- **Practice to make sure the system worked**
- **0.68 in-long axial through wall fatigue crack, which was grown from a 0.5 in-long & 80%TW EDM starter notch.**
- **The flow rate increased from 5.45 to 5.65 gpm during 30 min leak testing at 2,350 (±7) psig.**
- **Fractography indicated crack tip ductile stretching not fatigue growth**

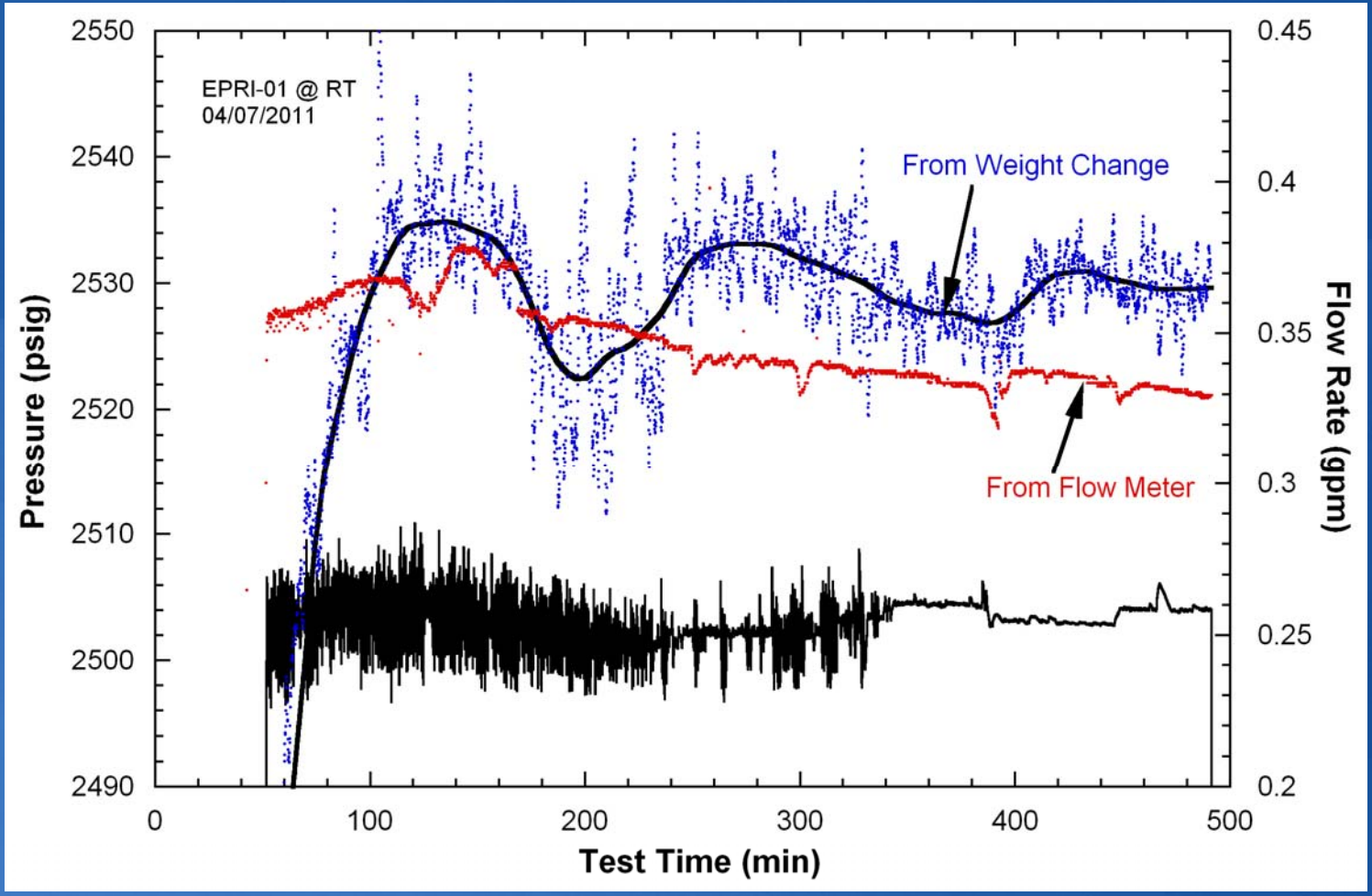


Onset of Fatigue Cracking in Through Wall SG Flaws First Test Specimen

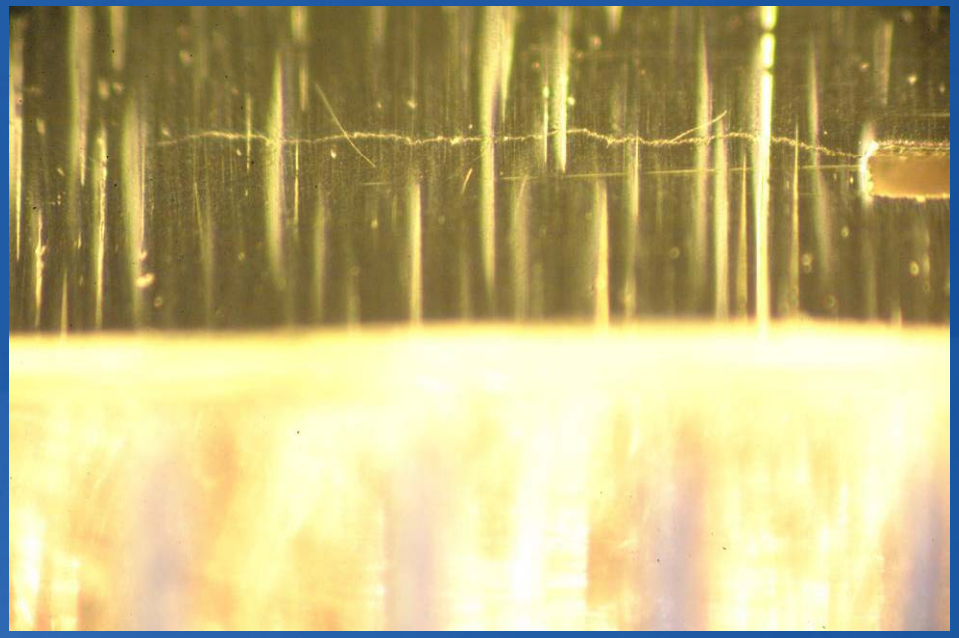


- **0.38 in-long axial through wall fatigue crack, which was grown from 0.25-in long & 40%TW axial EDM starter notch.**
- **Leak rate of ~0.35 gpm.**

Onset of Fatigue Cracking in Through Wall SG Flaws First Test Specimen

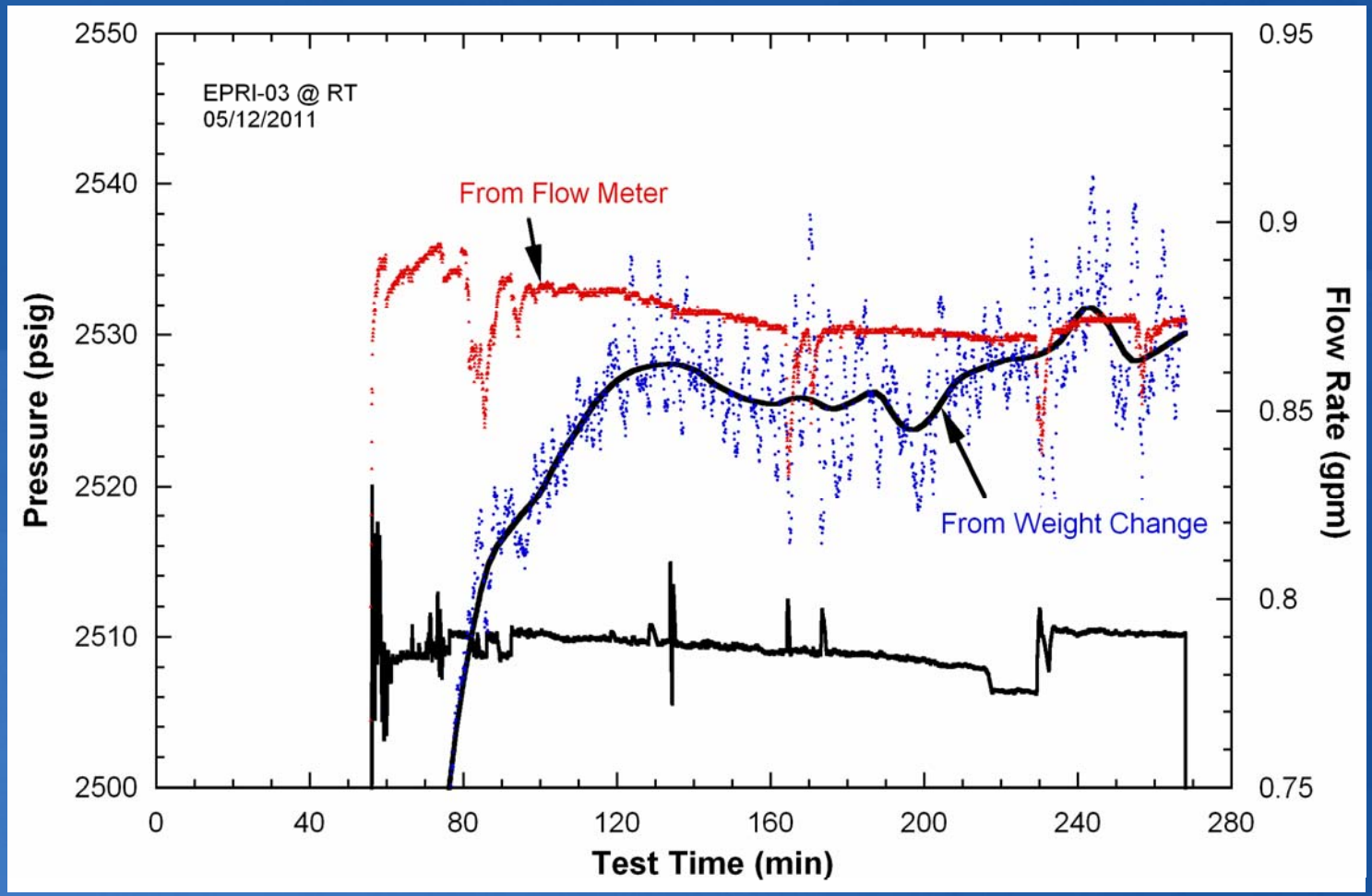


Onset of Fatigue Cracking in Through Wall SG Flaws Second Test Specimen

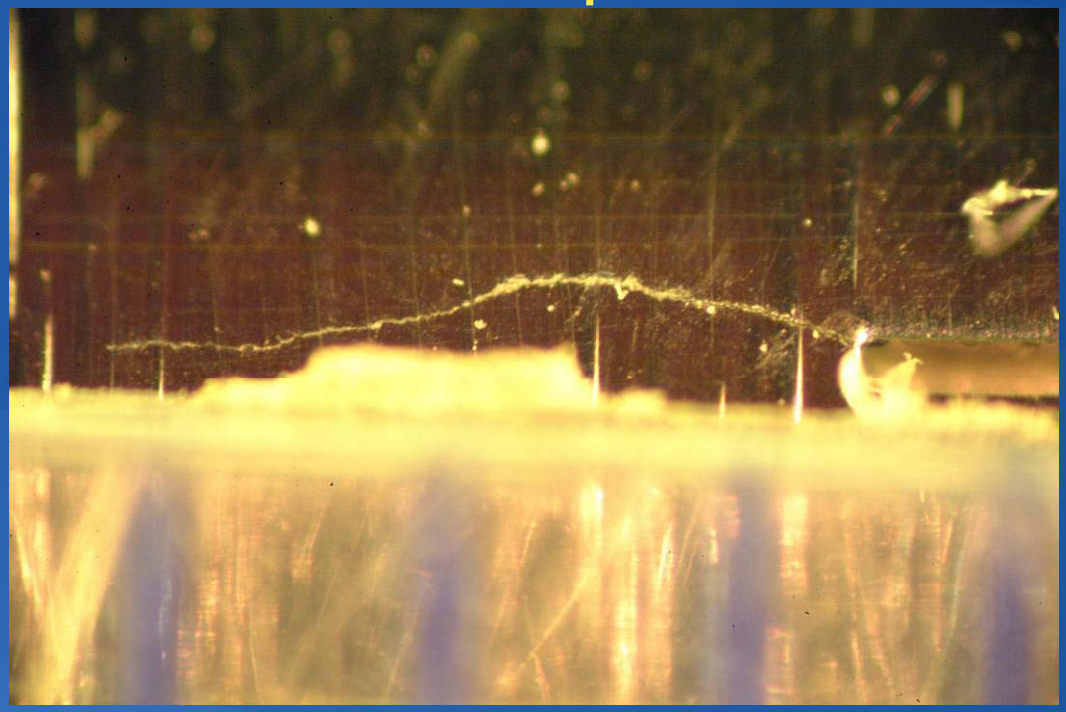


- **0.47 in-long axial through wall fatigue crack, which was grown from 0.25-in long & 40%TW axial EDM starter notch.**
- **Leak rate of ~0.9 gpm.**

Onset of Fatigue Cracking in Through Wall SG Flaws Second Test Specimen

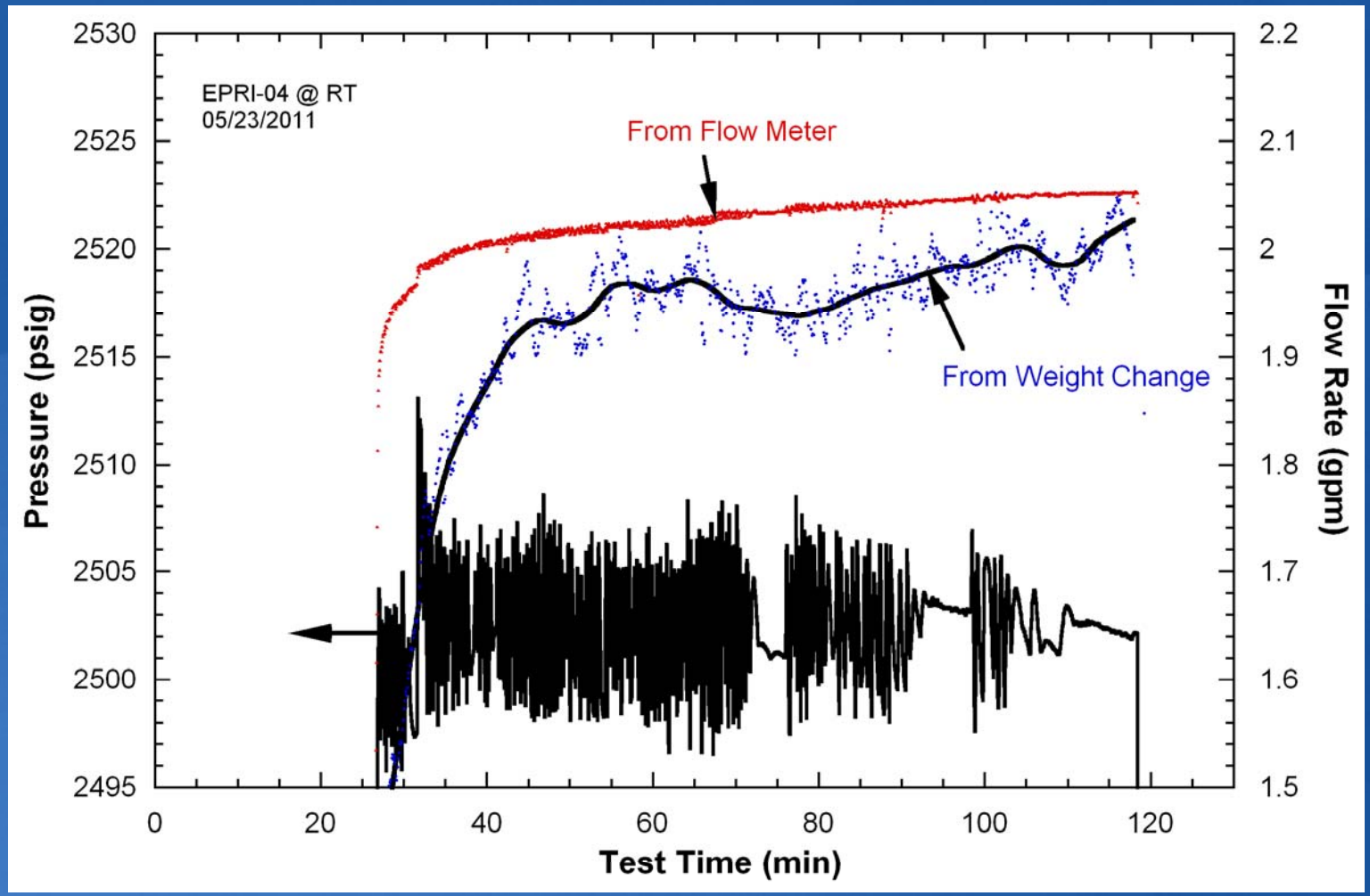


Onset of Fatigue Cracking in Through Wall SG Flaws Third Test Specimen

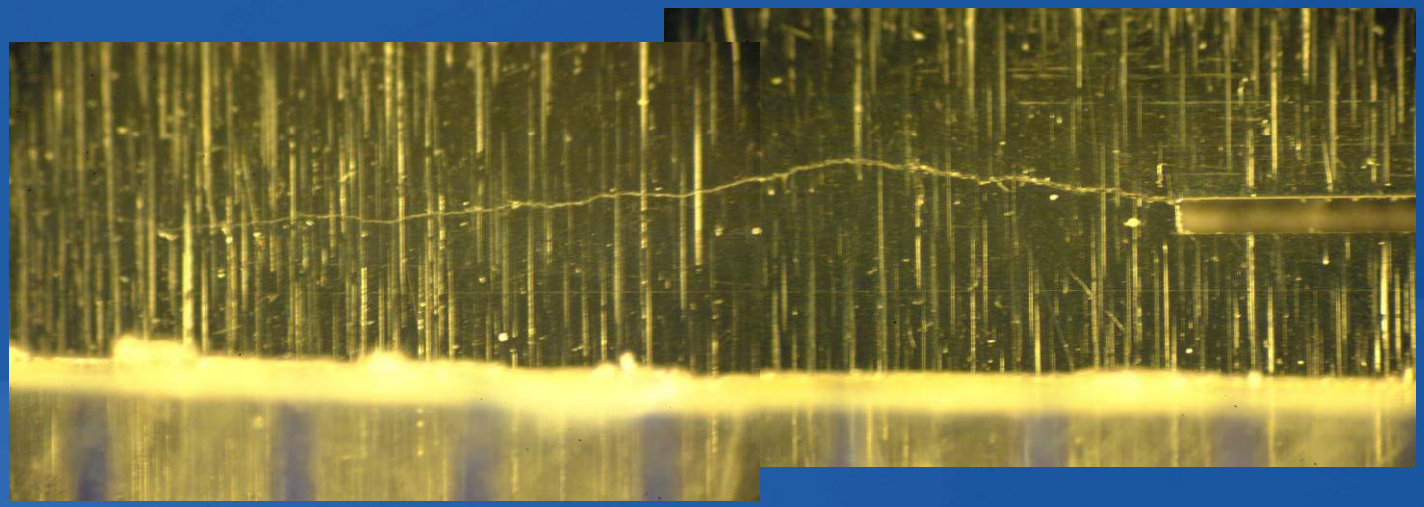


- **0.52 in-long axial through wall fatigue crack, which was grown from 0.25-in long & 40%TW axial EDM starter notch.**
- **Leak rate of ~2 gpm.**

Onset of Fatigue Cracking in Through Wall SG Flaws Third Test Specimen

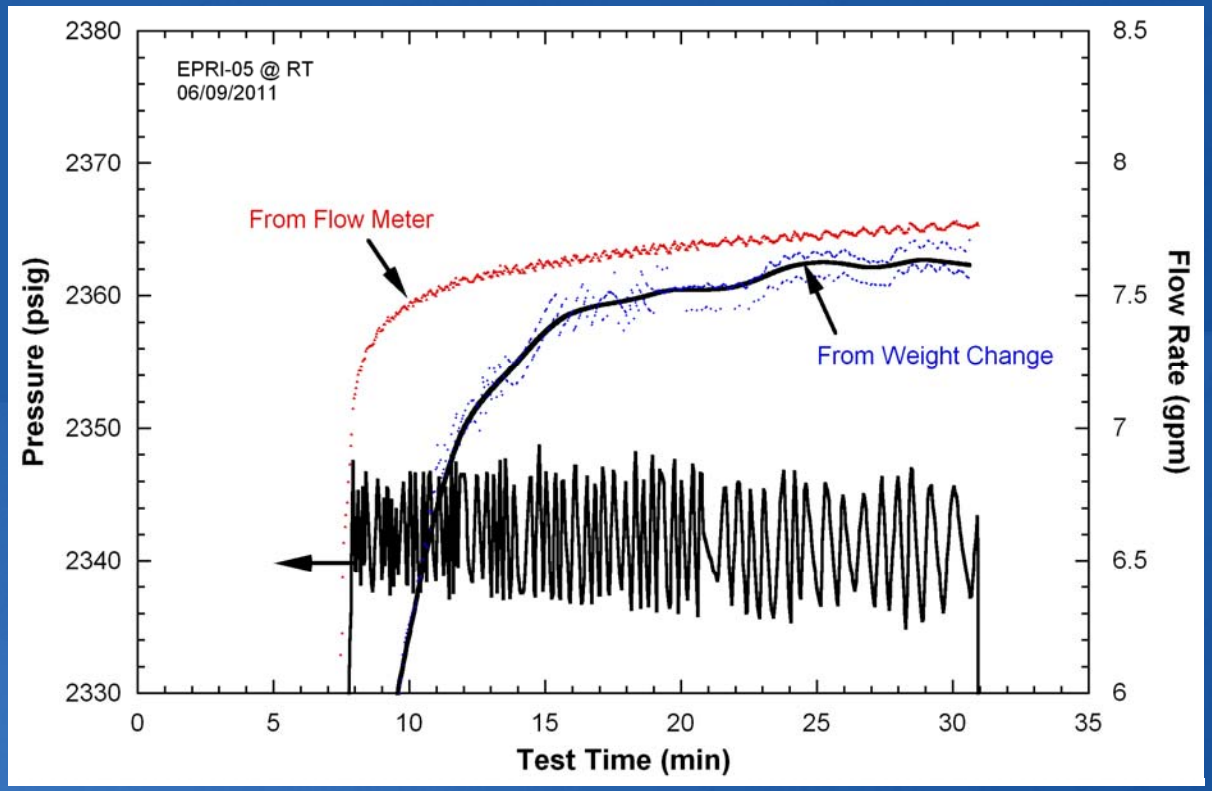


Onset of Fatigue Cracking in Through Wall SG Flaws Fourth Test Specimen



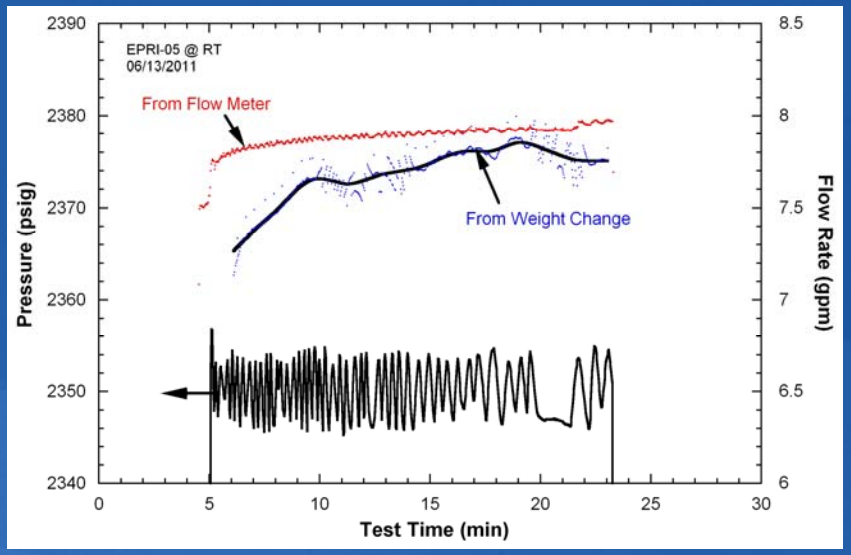
- **0.68 in-long axial fatigue crack, which was grown from 0.25-in long & 40%TW axial EDM starter notch.**
- **Leak rate of ~8 gpm @ 2350 psig and ~11 gpm @ 2500 psig.**

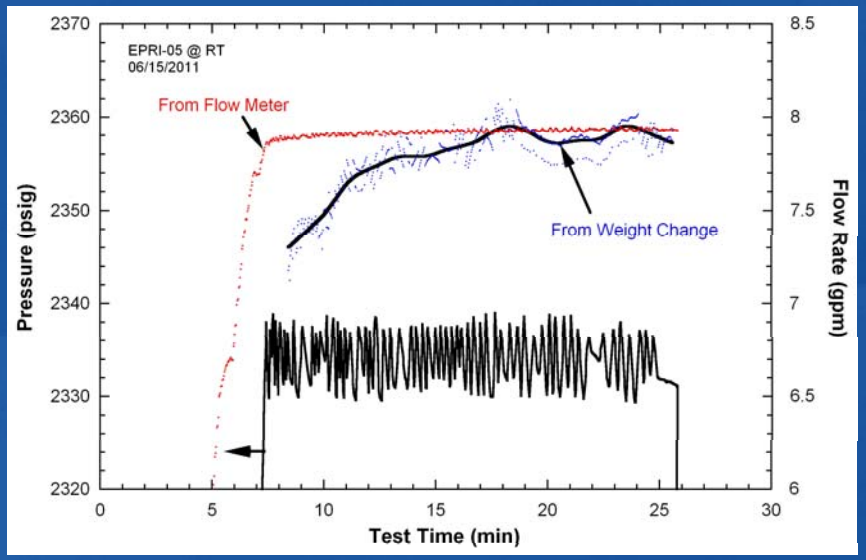
Onset of Fatigue Cracking in Through Wall SG Flaws Fourth Test Specimen



- **Due to the limitation of a turbine flow meter (max. 8 gpm) the pressure was set to 2350 psig.**
- **Gradual increase from ~7 to 7.8 gpm was observed.**

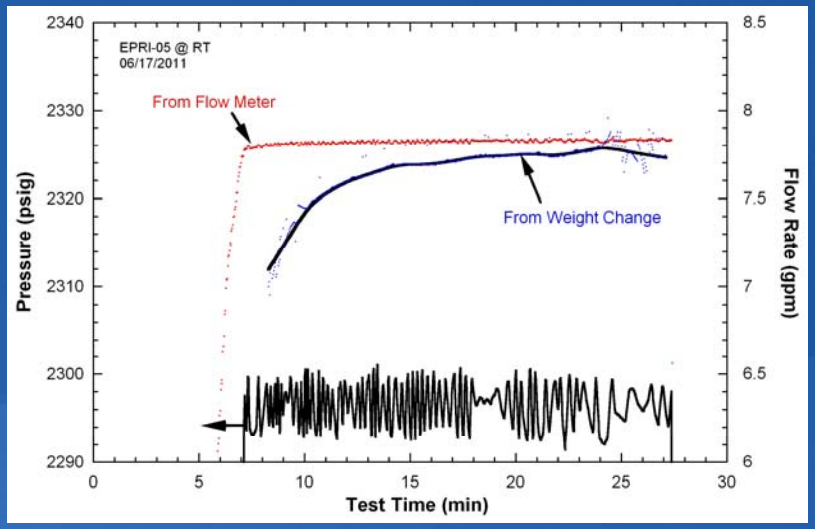
Onset of Fatigue Cracking in Through Wall SG Flaws Fourth Test Specimen (2nd & 3rd Tests)

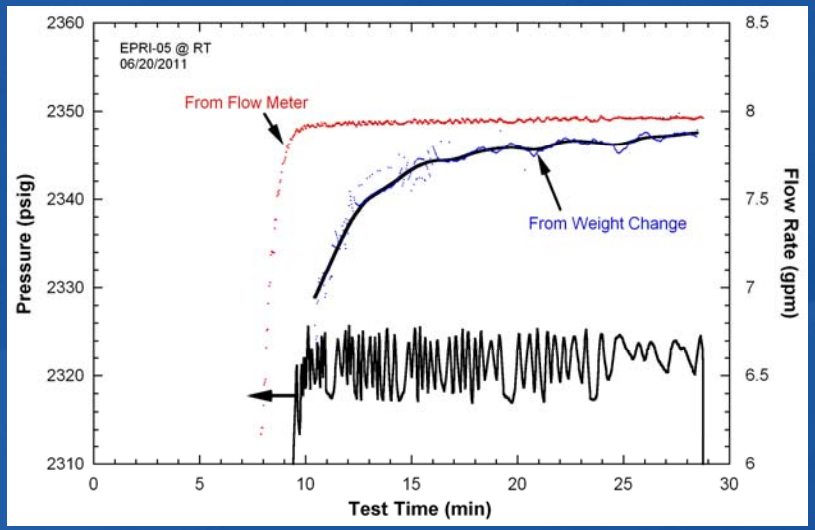


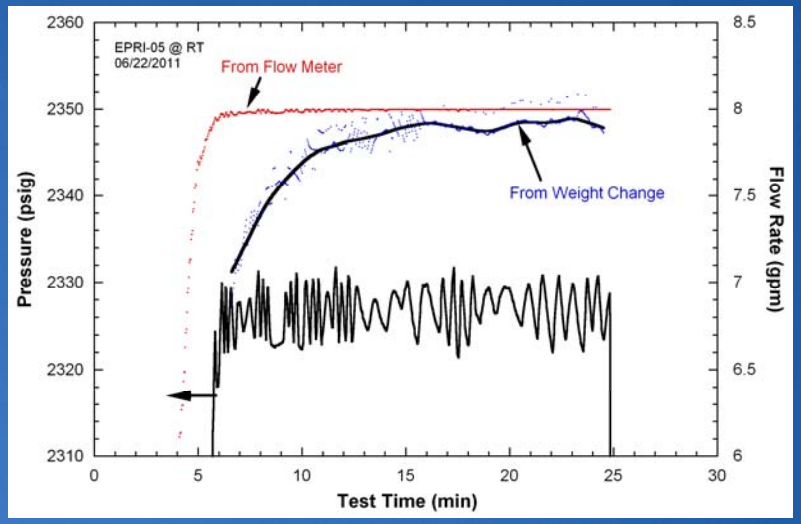


- **During the 2nd test the leak rate still showed slight increase. However, from the 3rd testing the leak rate became stable at ~8 gpm.**
- **During the accumulated test time of 2 hr the leak rate did not increase at the constant pressure.**
- **The leak rate estimated from the weight change appears to agree with that from the turbine flow meter, except the initial 5 min, suggesting that data for the initial 5 min may not be close to actual flow rate.**

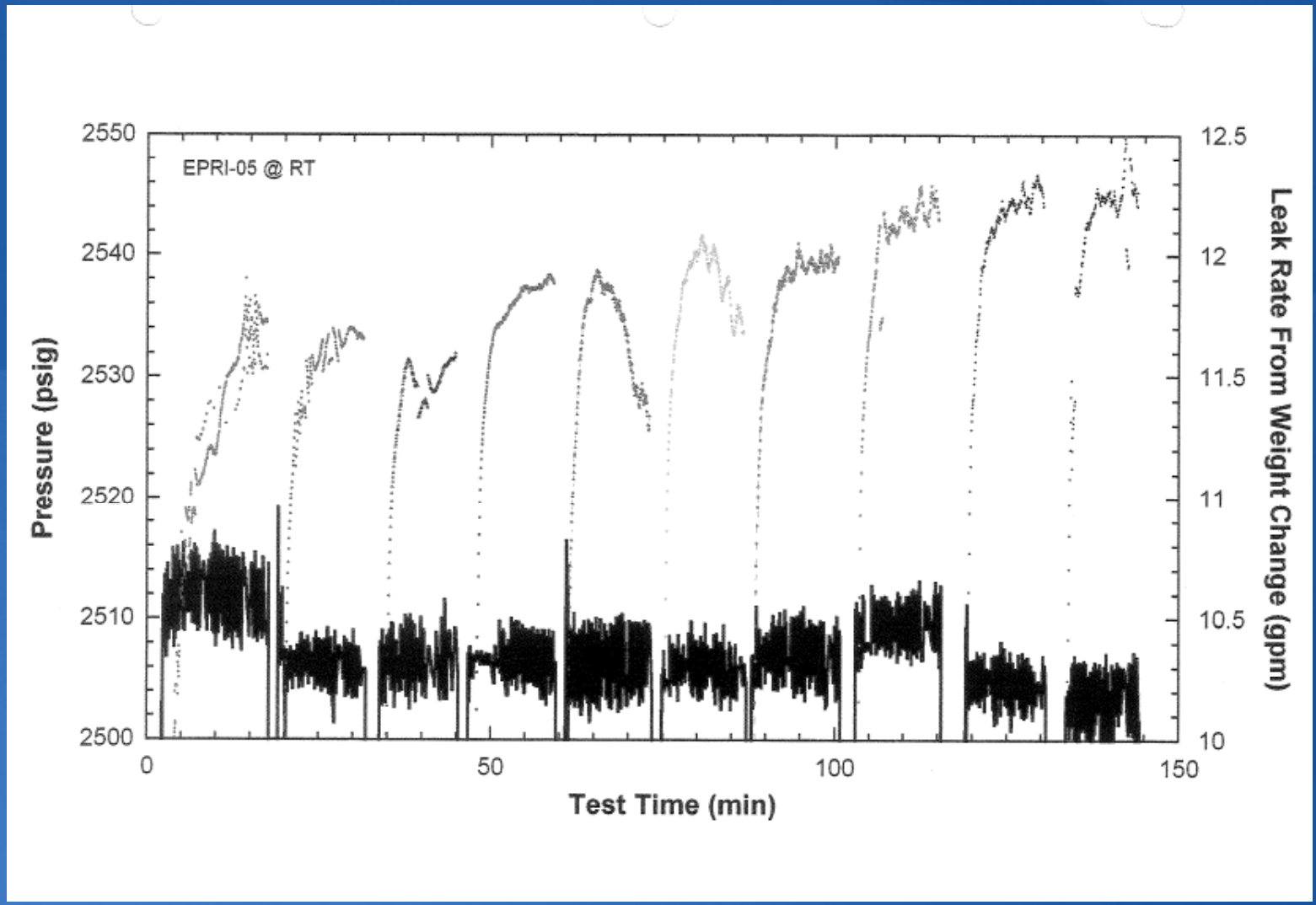
Onset of Fatigue Cracking in Through Wall SG Flaws Fourth Test Specimen (4th, 5th & 6th Tests)



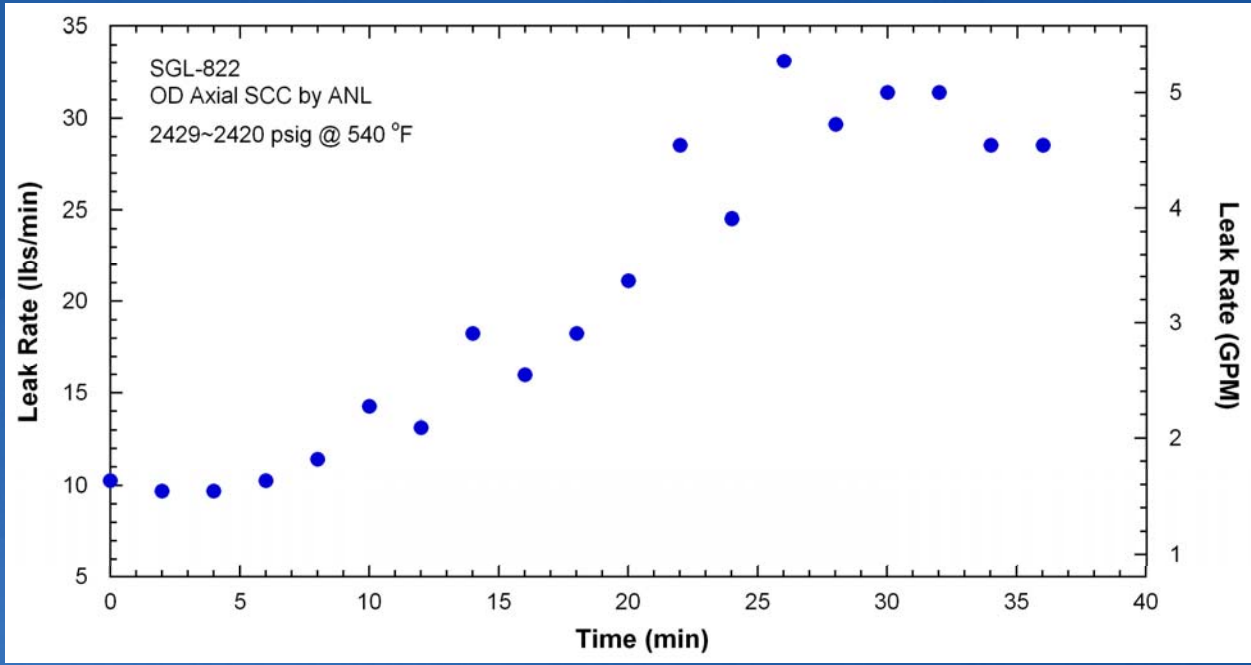




Onset of Fatigue Cracking in Through Wall SG Flaws

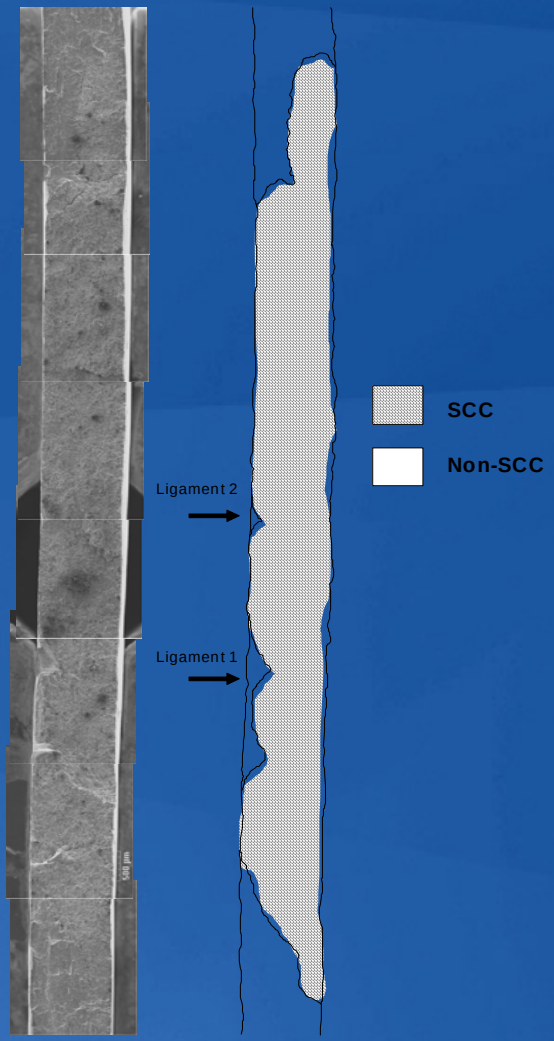


Onset of Fatigue Cracking in Through Wall SG Flaws



Onset of Fatigue Cracking in Through Wall SG Flaws

No fatigue crack growth, even of small ligaments !



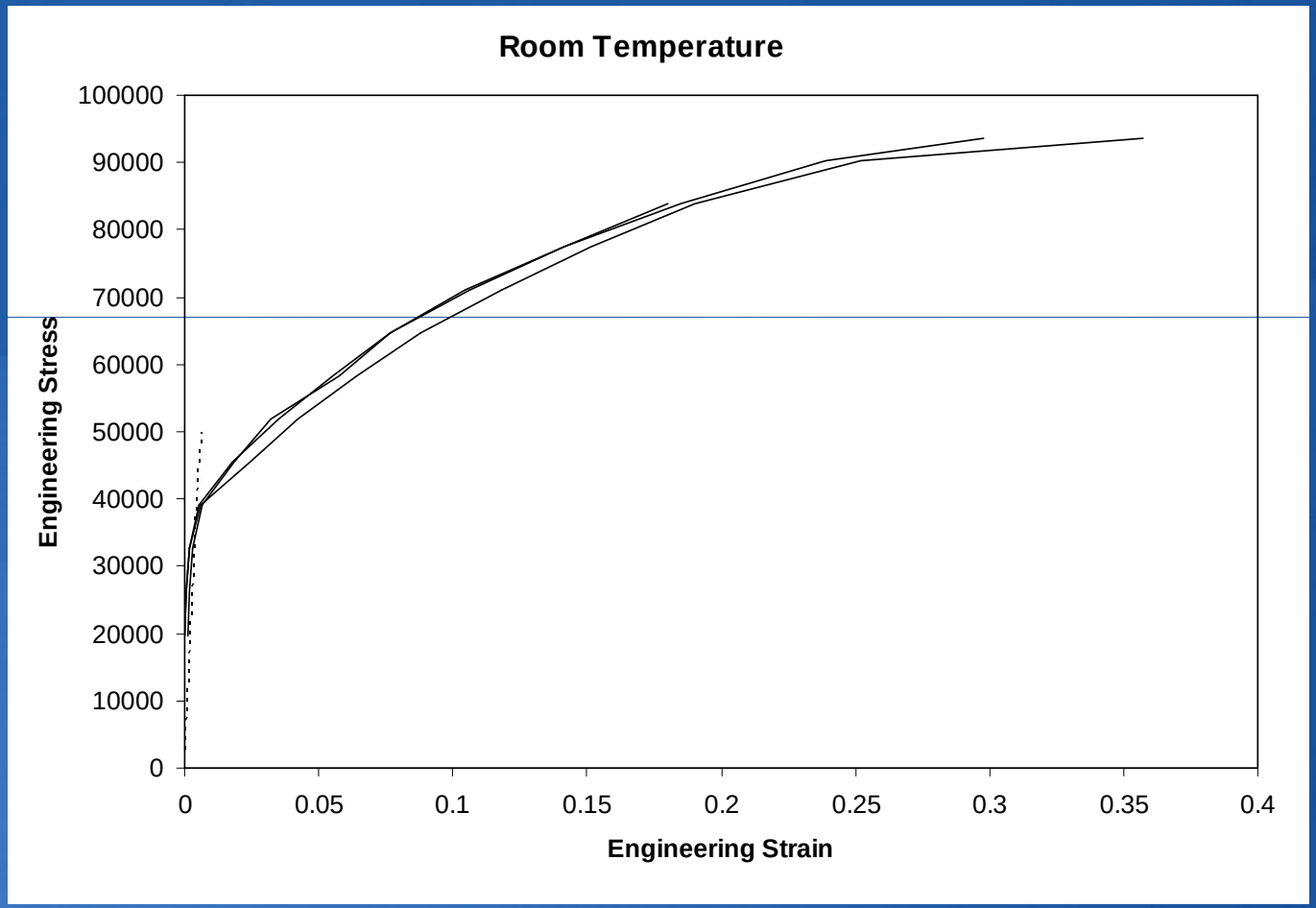
Flow Induced Fatigue Cracking Issue Leak Test Conclusions

- **Test results indicate that for operating steam generator conditions there is no issue of flow induced fatigue crack growth leading to large increases in leak rates.**
- **The slight increases in leak rates in the latest series of test is caused by time dependent crack tip plasticity, not fatigue growth.**
- **The small observed increases of leak rates over time does raise the issue of required hold times for in situ leak testing.**

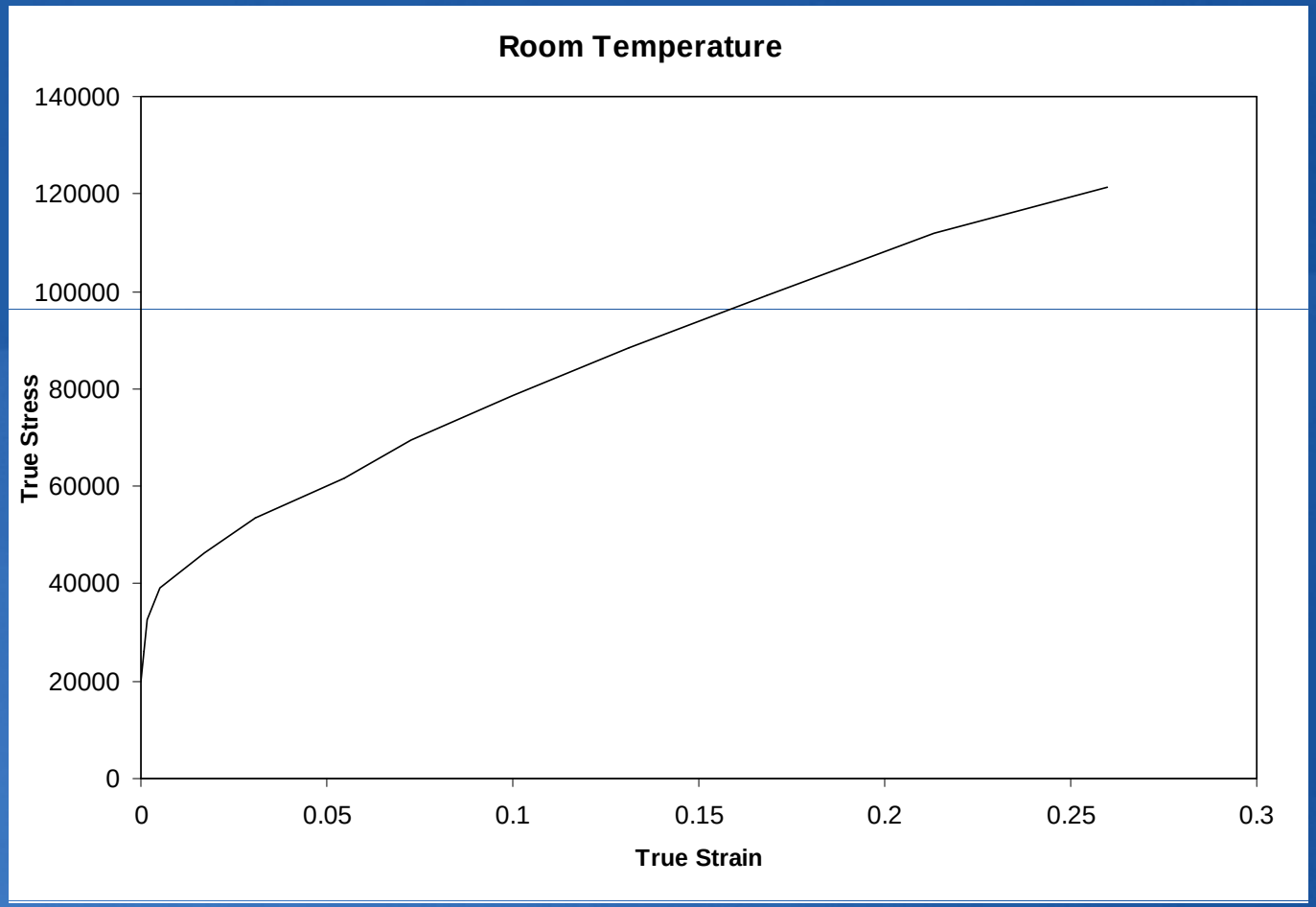
Time Dependent Plasticity in Alloy 600

- At very high stresses primary stage creep is observed for many structural alloys at room temperature.
- Creep testing at high stress levels has been performed for Alloy 600 at room temperature.
- Wire specimens (0.032” diameter) of mill annealed Alloy 600 have been subjected to dead weight loading at room temperature to obtain strain versus time curves.
- This information has been used to evaluate the adequacy of a 5 minute hold time for measurement of leak rates during in situ testing.
- A small increase in test pressure is equivalent to very much longer hold times.

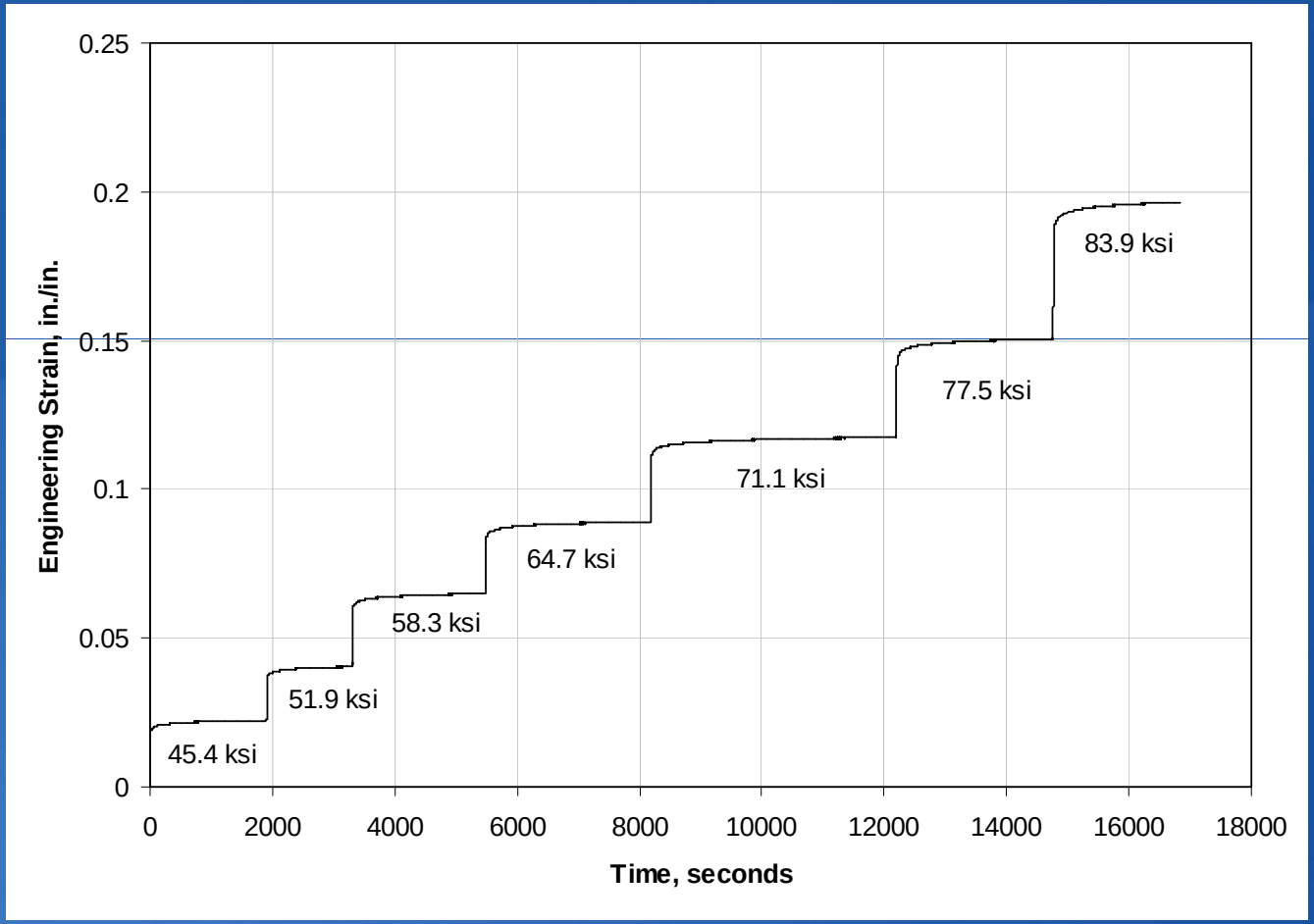
Time Dependent Plasticity in Alloy 600



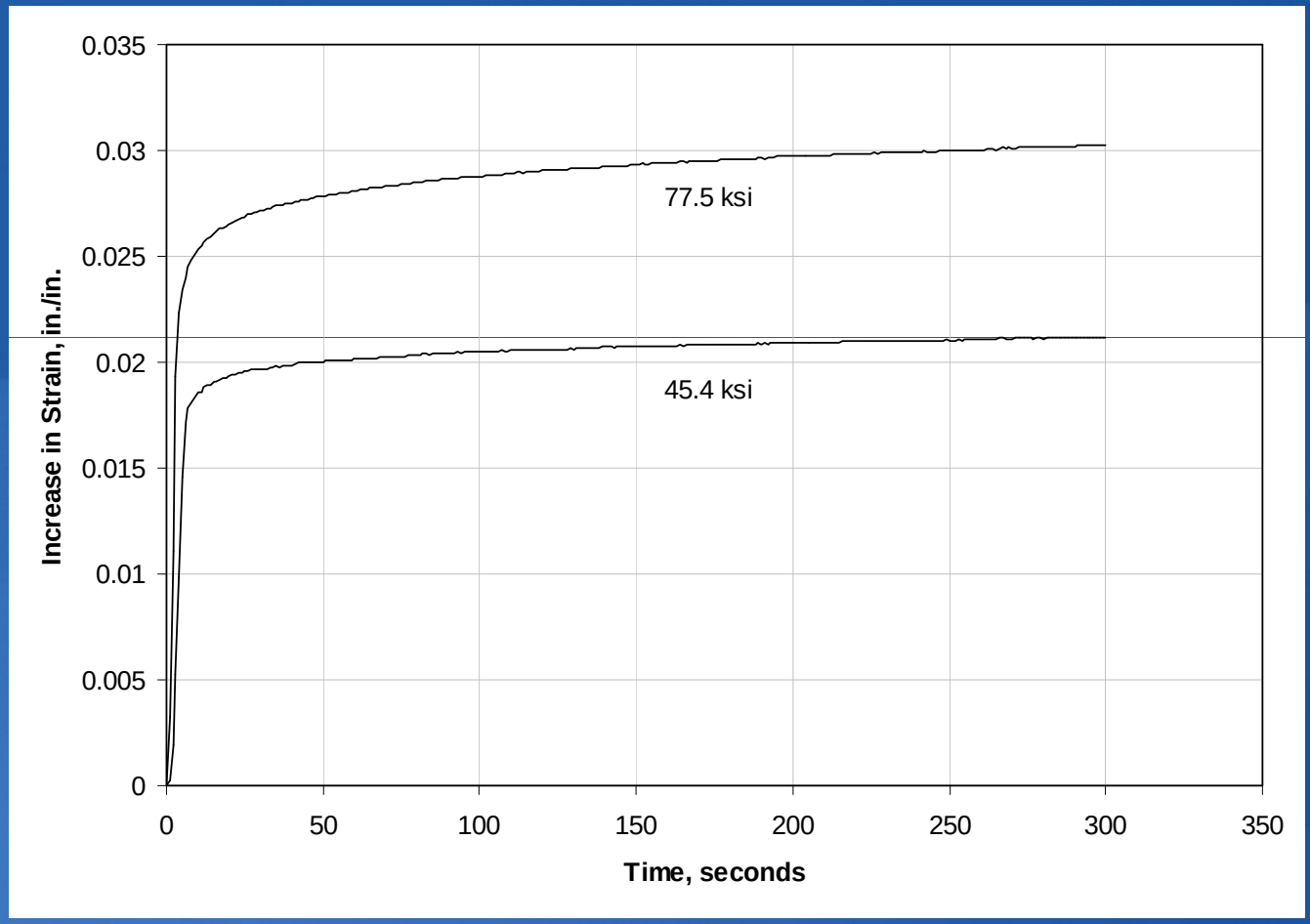
Time Dependent Plasticity in Alloy 600



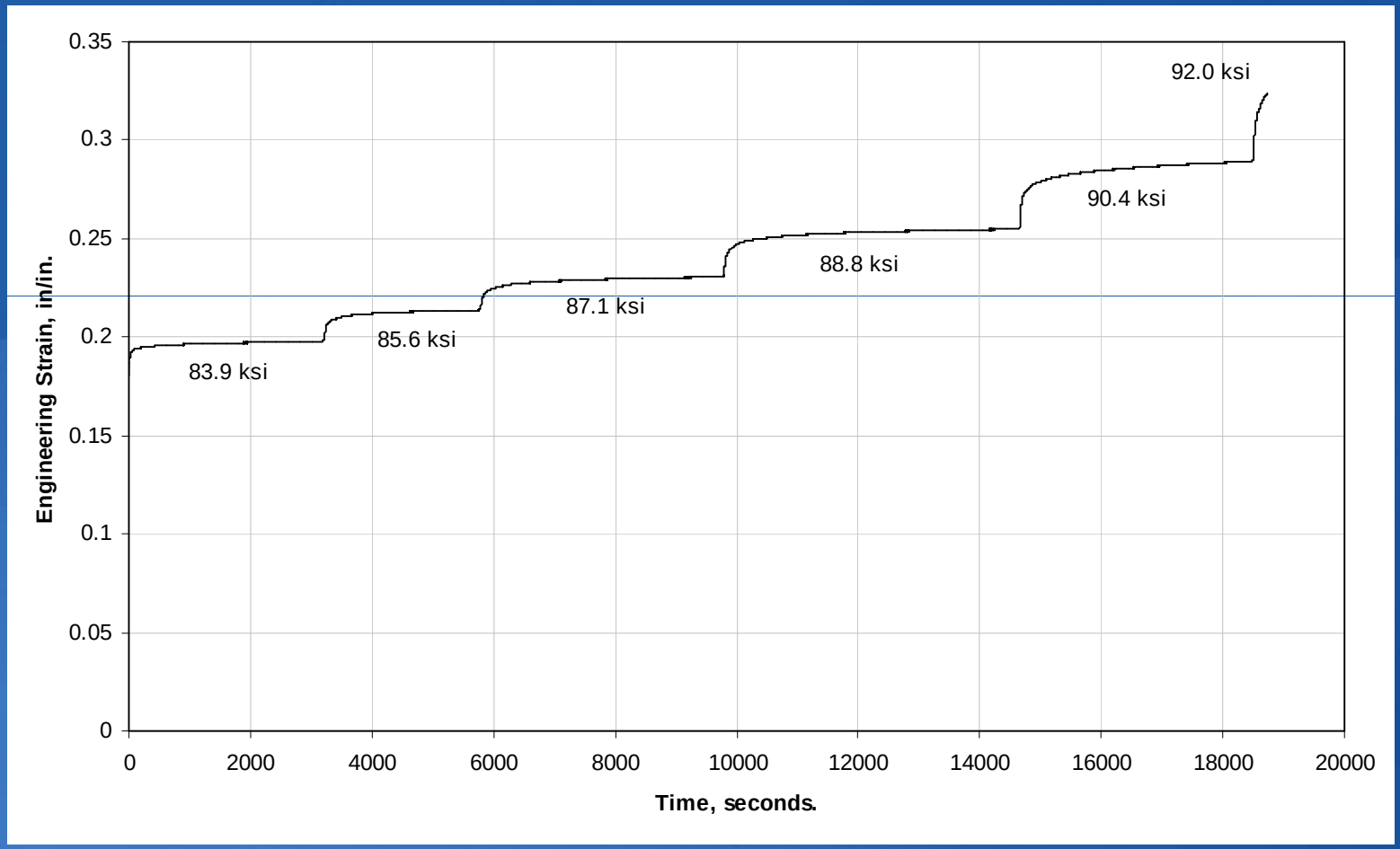
Time Dependent Plasticity in Alloy 600



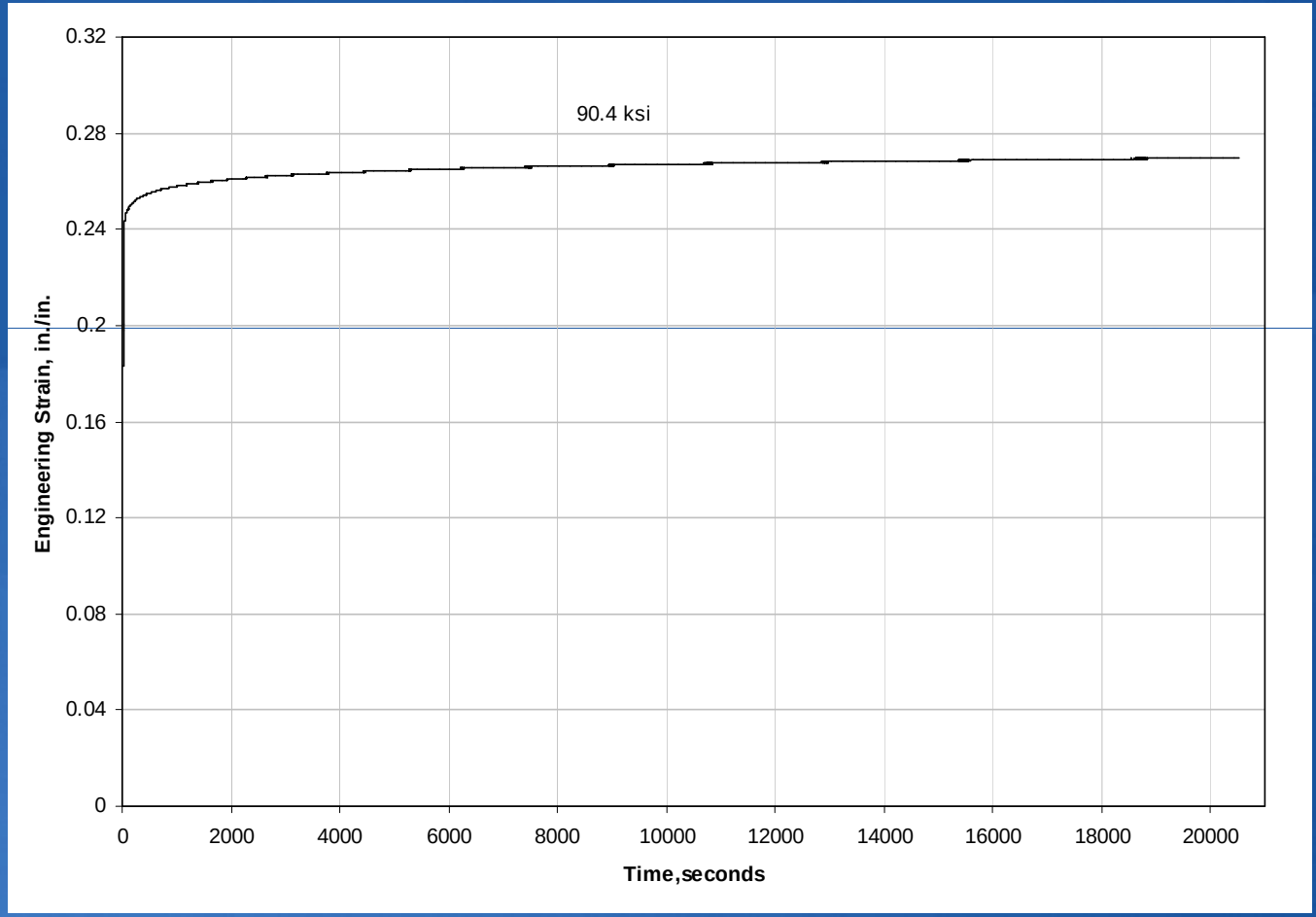
Time Dependent Plasticity in Alloy 600



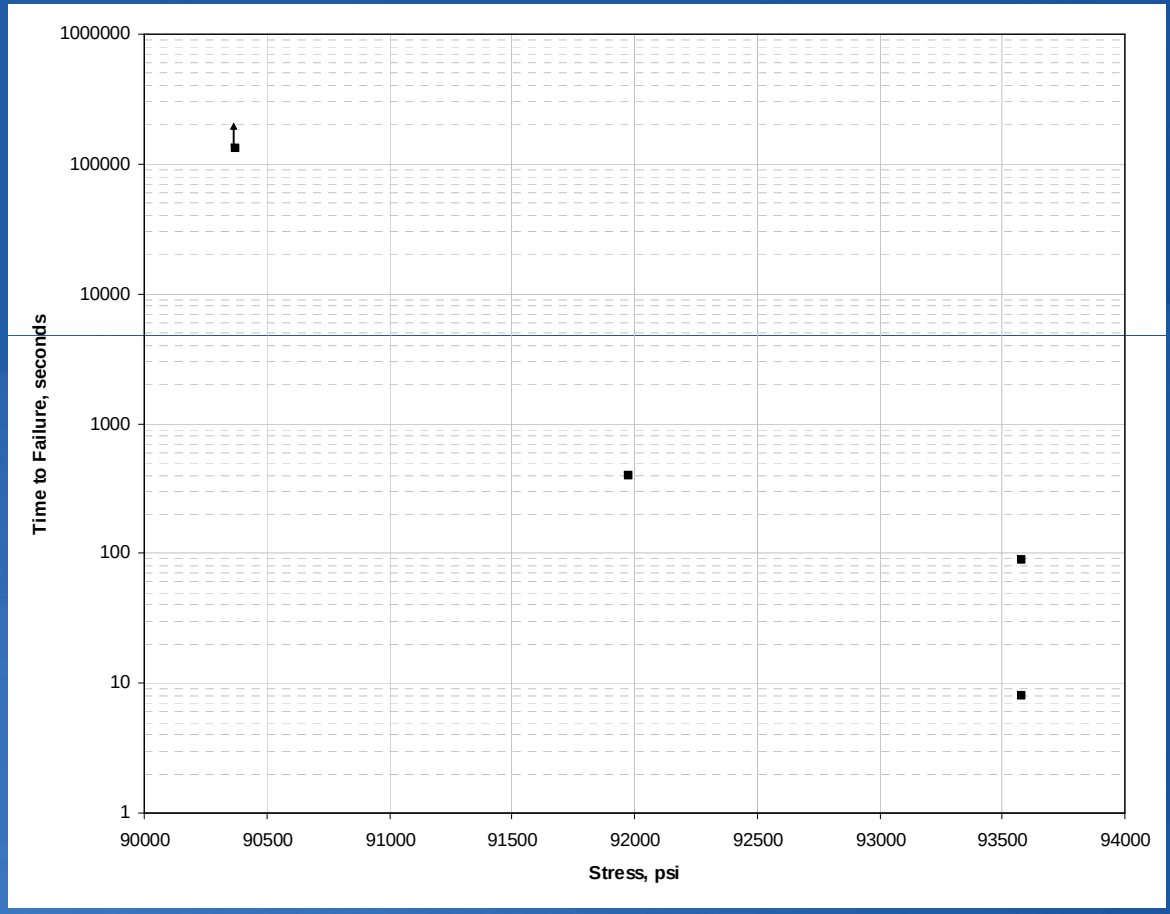
Time Dependent Plasticity in Alloy 600



Time Dependent Plasticity in Alloy 600



Time Dependent Plasticity in Alloy 600



Adjustment of In Situ Leakage Test Time Summary/Conclusion

- **Time dependent plasticity in Alloy 600 is equivalent to about a 2% decrease in the flow strength.**
- **This increases leak rates by about 10%.**
- **A 2% increase in the test pressure for in situ leakage testing is equivalent to increasing the test time to several hours.**
- **The existing conservatisms (15%) in the temperature correction factor between room and operating temperature flow strength and the uncertainty factor of the pressure measurement is sufficient to account for the small level of time dependent increases in leak rate.**

Conclusions

- **Leak test results indicate that for operating steam generator conditions there is no issue of flow induced fatigue crack growth leading to large increases in leak rates.**
- **Existing conservatisms are sufficient to account for the possibility of small time dependent increases of leak rate.**
- **SGTF recommends that this issue be closed.**